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Exploration and estimation of morphological and genetic diversity of wheat (Triticum spp.) landraces in Oman

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Dedicated to S. Al Shukaily, Z. Al Harthy and S. Al Khanjari

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1
General introduction

Geography and climate of Oman

The Sultanate of Oman is located at the entrance of the Arabian Gulf. It is bordered by Yemen on the south, the Arabian Sea on the southeast, Iran on the northeast, the United Arab Emirates on the northwest and Saudi Arabia on the west. It lays between latitude 21°00' - 29°00' N and longitudes 51°50' - 59°40' E. Oman's total area is 212,460 km^2, with a coastline length of about 1,800 km^2. According to the latest estimates, the population of the country is 2.3 million (Ministry of National Economy, 2000). The climate is differentiated according to the country's geographical regions. While it is hot-dry in the interior, it is hot-humid in the coastal area and humid in the south with its summer monsoon rains. The annual mean temperature for most of the country is about 26° C and 95% receives a total annual precipitation of <100 mm (Ministry of Transportation and Telecommunication, 2000).

Domestication of wheats

In the last century many expeditions have bee carried out around the globe, studying the geographic distribution of wild and cultivated plant species. The Russian scientist Vavilov (1926) proposed the general concept that the region of greatest varietal diversity of a given species is probably the centre of origin of that species. The domestication of crops refers to the evolution of new crops which are better suited for cultivation. Often domestication leads to a loss of some characters, for example a stronger adhesion of seeds to a spike or a seed coat to avoid premature seed shedding, the fostering of physically uniform crops and the breakage of dormancy. The domestication history of wheat (*Triticum* spp.) dates back approximately 10,000 years in the Near East while wheat has undergone many changes. Recent genetic evidence indicates that 'einkorn wheat' (*T. monococcum*) may have been domesticated from wild einkorn (*T. monococcum* ssp. *aegilopoides)* in the region of the Karacadag Mountains in southeast Turkey (Heun *et al*., 1997), where this wild form of wheat was harvested and later

cultivated. Also, the remains of cultivated emmer (*T. dicoccon*) have been discovered at several archaeological sites in Syria dating to 7,500 BC (Zohary and Hopf, 1993).

The importance of wild wheat for human consumption seems to have decreased after the Bronze age (Zohary and Hopf 1993), when higher yielding and free-threshing tetraploid and hexaploid wheats replaced it. Today einkorn is only cultivated in small areas of the Mediterranean region (Perrino *et al.*, 1996), while its wild form is still common in some locations of that region (Zohary and Hopf 1993). Filatenko and Kurkiev (1975) described also a domesticated, free-threshing form, *T. monococcum* convar. *sinskajae*.

Bread wheat first appeared in Transcaucasia, Southwest of Iran (Dvorak *et al.*, 1998). At that time *Aegilops tauschii* ssp. *strangulata,* which was predominant in the region, hybridized with cultivated emmer to produce *T. aestivum*. Possibly several events of hybridization occurred that contributed to the gene pool of bread wheat (Talbert *et al.*, 1998). The first bread wheats may have looked similar to *T. spelta* found growing in Iran from which free-threshing types were derived by mutation (McFadden and Sears, 1946). The European spelt wheats may have been derived secondarily from a hybridization involving *T. aestivum convar. compactum* and emmer wheat (Ohtsuka, 1998).

In Oman, wheat was cultivated for a long time but so far any formal investigation of the still cultivated traditional germplasm is lacking. Most of the available references refer to the Near East or West Asia, comprising Oman.

Evaluation of germplasm

Modern wheat was formed through hybridisation of different biological donors. Cytogenetic studies confirm the taxonomic classification by showing that each diploid contains a distinct genome (Kihara, 1954). Therefore, a genomic classification was proposed by the Canadian botanist Bowden (1959).

Schulz (1913) initiated the process of wheat classification by studying phylogenetics. This resulted in dividing wheat into the three groups *'Einkornreihe', 'Emmerreihe'* and *'Dinkelreihe'* which were further subdivided into the four classes wild relative, ancestral for the genus, derivative chaffy species and derivative naked cultivated species.

Three groups of polyploids were recognized (Zohary and Feldman, 1962) which was later supported by American cytogeneticists (Morris and Sears, 1967).
Depending on the chromosomal numbers Sakamura (1918) recognized three ploidy groups. Each chromosome of the A, B, and D genomes has been allocated to one of the seven wheat homologous chromosome groups (Sears 1966), *Triticum monococcum* (2n = 14, genome formula AMAM), *T. urartu* (2n = 14, diploid wheat genome formula AA), *T. turgidum* (2n = 28, genome hybridization of expressed formula AABB) and *T. aestivum* (2n = 42, genome formula AABBDD). The A genome of *T. turgidum* was likely contributed by *T. urartu* (Dvorak *et al.*, 1993) and the B genome by *Aegilops speltoides* or a species closely related to it (Sarkar and Stebbins, 1956).

Approaches to wheat taxonomy and classification

Triticum, a member of the *Gramineae* (Poaceae) family, is one of the first domesticated and most important crops worldwide, it is widely used as a staple (FAO, 1999). In 1737 Linnaeus identified the following wheat species:

- *T. aestivum* L. (spring awned forms)
- *T. hybernum* L. (winter awnless forms)
- *T. turgidum* L.
- *T. spelta* L.
- *T. monococcum* L.

The discovery of other species continued and these were added to the *Triticum* genus. The development of the genus resulted in the inclusion of wild relatives. Körnicke (1885) divided wheat into the following three groups:

- *T. polonicum* L.
- *T. monococcum* L.
- *T. vulgare* Vill.

whereby the third group (*T. vulgare* Vill.) was further subdivided into five groups:

- *T. compactum* Host
- *T. turgidum* L.
- *T. durum* Desf.
- *T. spelta* L.
- *T. dicoccon* (Schrank) Schuebl.

The last complete monograph on *Triticum* has been published by the Russian authors Dorofeev *et al*. (1979). A broader species concept was proposed by

Mackey (1966) and further elaborated by Hanelt (2001). In the following we follow the taxonomic approach of Dorofeev *et al.* (1979).

Diversity of wheat on the Arabian Peninsula

Despite its large percentage of desert the South Arabian Peninsula has considerable ecological variation, which is reflected by its diversity in plant genetic resources. The long trading history of the region's seamen resulted in the importation of many crops including wheat varieties, making the region genetically highly heterogeneous (Perrino and Hammer, 1983). For millennia wheat landraces have been cultivated in remote villages and oases of the region.

In Oman the collection and evaluation of germplasm dates back as far as the 1970's, however, there is still very little information about Omani wheats of which the first survey was made by Guarino (1990). By 1996, the total cultivation area of traditional wheat landraces had declined from about 1,000 ha eight years earlier to only 240 ha. Major reasons for this decline were the adoption of higher-yielding modern varieties, increasing salinity of the wheat producing Batinah region, drought and the abandonment of marginal cultivation sites following grain importations (Anonymous, 2000; Toll and Moss, 1995). Apparently many of the old landraces named 'Alaz', 'Sarraya', 'Walidi', 'Cooley', 'Greda', 'Missani', 'Shuaira' and 'Hamira' had suffered from genetic erosion. Despite of this, a large phentoypic variation was still observed during a comprehensive wheat survey conducted in Oman in 2002 (Al Khanjari *et al.*, 2005).

In 2003 the finding of two new *T. aestivum* landraces was reported by Al-Maskri *et al.* (2003) from the Hajar Mountains. These were named *Triticum aestivum* var. *baladseetense* and *T. aestivum* var. *maqtaense.* Subsequently, Hammer *et al.* (2004) discovered *T. dicoccon* subsp. *asiaticum* Vav., an emmer wheat cultivated at Al-Hamra and Misfat Abreen in the same Hajar Mountains of northern Oman.

The diversity of germplasm has traditionally been described using morphological and agronomical traits (Vavilov, 1964). The different spike parts (qualitative and quantitative characters) are frequently used to evaluate, characterize and classify wheat in botanical groups (Tesfaye *et al.*, 1993; Porceddu *et al.*, 1994). Such morphological descriptions also allow to assess bio-diversity and to discriminate between closely related types.

However, morphological characters may not be sufficient to discriminate between accessions and their expression depends on environmental conditions. An understanding of the overall patterns of genetic diversity and the distribution of genetic variability in a crop species is useful for its conservation and also facilitates the selection of parents with diverse genetic backgrounds thereby increasing the efficiency of crop improvement.

Use of wheat landraces

Landraces are varieties of crop plants adapted to specific environmental conditions and have often been subjected to farmers' selection for many generations. They are also called 'farmers' varieties'. As such landraces can be considered culturally unique entities and belong to the national heritage of a nation or geographic region.

Harlan (1975) defined landraces as a mixture of morphotypes evolved through human and natural selection. Often landraces have remained undisturbed over decades as they are well adapted to the selection pressure coming from specific eco-geographical structures (Nevo, 1988).

Given their longstanding adaptation to specific environments, landraces may have developed a broad spectrum of resistance to various biotic and abiotic threats, which can make them a useful resource to breed new cultivars in which high yield is combined with stress resistance. Maxted *et al.* (1997) mentioned the following reasons for the use of landraces in plant breeding: resistance to disease, adaptation to specific environments and changing agricultural practices, yield increase, improvement of growth pattern and growth rate of plant. So far, only about 10% of the total higher plants in the world were evaluated for their agricultural and medicinal value (Prance, 1997), with many more plants waiting to be evaluated for future utilization.

The loss of genetic diversity has promoted the search for new sources of variation that could be used in plant improvement programmes. In this context landraces are hoped to provide novel genes for increased disease resistance, higher protein content, better tillering, greater drought tolerance and other economically desirable attributes (Srivastava and Damania, 1989). Therefore, the collection, conservation and use of landraces of cultivated species is increasingly stressed (Brown *et al.*, 1989).

Methods of assessing biodiversity

Morphological methods

Collection and conservation of germplasm without proper identification is not adequate. This necessarily involves the measurement of genetic variation. Scientific studies of landraces are becoming increasingly important and constitute a pre-requisite for the exploitation of the target species. Lacking other tools in the past most studies mainly recorded morphological and agronomic traits of the investigated material.

Genetic methods - microsatellites

In the last decade molecular markers based on DNA restriction and PCR technologies have become increasingly available to quantitatively assess genetic diversity (Russell *et al.*, 1997). The use of genetic markers displaying DNA polymorphisms avoids any environmental effect on gene expression. The most important aspect of such markers probably is the near unlimited numbers of such markers present in a genome and the relative easiness of analysing them at a large scale.

Microsatellites such as Simple Sequence Repeats (SSR) are based on repeat length variation of simple sequences, generally between 2-8 base pairs. They occur in large numbers in the genome and are distributed on all chromosomes. Their presence has been well documented for many species including cereals (Plaschke *et al.*, 1995; Röder *et al.*, 1995). Their robustness and large allelic variation make microsatellites ideal markers for population and evolutionary genetic studies (Bruford and Wayne, 1993). SSRs are identified by a polymerase chain reaction (PCR) using synthetic oligonucleotides from the surrounding monomorphic DNA as primers. Primers matching these unique flanking sequences constitute a single locus, which is often multiallelic by variation of copy numbers in the tandem repeats.

In view of the above the following thesis reports on the results of a combined morphological and molecular genetic evaluation of wheat germplasm collected during initial surveys in Oman. As such it documents a surprisingly large, still existing bio-diversity of this crop in traditional agricultural systems of the Arabian Peninsula and shows the need for its conservation.

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2

Genetic resources

2.1 A survey of wheat landraces in Oman

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Summary

Little is known about the diversity of wheat (*Triticum* spp.) in Oman. Therefore, a survey was conducted in northern Oman to collect landraces of *Triticum durum, T. aestivum* and *T. dicoccon* for subsequent morphological characterization and investigations on stress adaptation. The results show that the cultivation of these landraces (the genetic composition of which remains to be studied in more detail) is done primarily by traditional farmers who preserve the inherited germplasm on often tiny plots in remote mountain oases. This type of traditional cultivation is under heavy economic pressure. An appendix of landraces of other crops collected in the Batinah region and in the mountain oases can be found online.

Key words: Indigenous knowledge, landraces, mountain agriculture, *Triticum aestivum*, *T. dicoccon*, *T. durum*

بحث حصري عن السلالات المحلية للقمح العماني

الملخص

يندر وجود مصادر معلوماتية عن تنوع سلالات القمح المحلي و المعروف باسم (***Triticum* spp.**) في سلطنة عمان، لذلك أجريت دراسة ميدانية بهدف الجمع و التعرف على السلالات المحلية من أصناف القمح: (***T. durum, T. aestivum*** و ***T. dicoccon***) بالمناطق الشمالية للسلطنة؛ و بغرض تقييم الوصف المظهري (المورفولوجي) للنباتات بالإضافة إلى التحقق من مدى مواءمتها وتحملها للظروف المناخية.وقد أظهرت النتائج سلالات القمح المحلي تزرع عادة من قبل المزارعين الذين يحتفظون بالبذور الموروثة عن الأجيال السابقة. وكثيرا ما تزرع سلالات القمح المحلي في الواحات و على السفوح و المدرجات الجبلية. وتواجه زراعة القمح التقليدي منافسة شديدة و (ضغطا اقتصاديا) نتيجة لظهور الأصناف المحسنة وراثيا الرخيصة الثمن.

كما أظهرت النتائج حاجة إلى دراسات تفصيلية عن التكوين الجيني لسلالات القمح المحلي بصورة أكثر عمقا. ويمكن الرجوع لشبكة المعلوماتية للاطلاع على ملحق بأصناف محاصيل أخرى تم جمعها من منطقة الباطنة والواحات الجبلية.

Introduction

With its ancient history of cultivating both bread wheat, *Triticum aestivum* L. s.l, and durum wheat, *T. durum* Desf. (Schwartz, 1939; Guarino, 1990), Oman has recently come to the attention of scientists interested in agro-biodiversity (Al-Maskri *et al.*, 2003). Collection missions conducted through the Omani Ministry of Agriculture have shown that farmers practicing traditional oasis agriculture continue to cultivate a number of wheat landraces, namely, 'Sarraya', 'Walidi', 'Cooley', 'Greda', 'Missani' and 'Hamira'. However, the area planted to these landraces declined from about 1000 ha in 1988 to 240 ha in 1996 (Akhtar, 1981). Major reasons for this decline were the adoption of higher-yielding modern varieties, increasing soil salinity in the wheat producing Batinah region, and the abandonment of marginal cultivation sites in remote mountain villages following grain imports from Australia (Toll and Moss, 1995; Anonymous, 2000). During the morphological evaluation of wheat germplasm in landraces from farmers' fields in two mountain oases of the Jabal Akhdar Mountains and the Wadi Khabbah of the Al Hajar Ash'sharqi range, two new botanical varieties of *T. aestivum* were discovered (Al-Maskri *et al.*, 2003). While this material is currently being further investigated using micro-satellite techniques and drought stress experiments to characterize it into more detail, a formal field survey covering four regions of northern Oman was conducted to (i) explore farmers' cultivation practices for wheat landraces, (ii) record local names for these landraces and (iii) to collect wheat landraces. Other crops have been included in the exploration programme (Appendix 1).

Materials and methods

This survey was conducted during March 2002 and covered twelve sites within four regions of northern Oman (Figure 1). The survey comprised a total of 69 interviews, which lasted from 9 to 27 March 2002 and covered the following four regions of northern Oman (Figure 1):

(i) the 'Interior' with Al-Hamra, Misfat Al-Abrein, Bahla and Jabal Akhdar (18 farmers interviewed); (ii) the 'Southern Batinah' area with Balad Seet, Wadi Mistal, Wadi Bani Kharus, Wadi Sahtain and Al-Awabi (24 farmers); (iii) the 'Sharqia' with Ibra and Wadi Dama Wa Taeen region (24 farmers); (iv) the 'Al-Quraiat' area with Hubaina (3 farmers).

To identify those inhabitants who still cultivated Omani wheat landraces, informal talks were first conducted with village elders in the areas under study (Plate 1). Those interviews were followed by the use of a formal questionnaire that covered details about the land cultivated with landraces, farming practices, land ownership and local names for the cultivated wheat germplasm (Appendix 2).

Results

The plot size cultivated to landraces by individual farmers in the typical oasis agriculture (Plates 2 and 3) was small, varying between 1 and 10,500 m^2 across the study zone. All wheat germplasm was sown broadcast as a sole crop, without chemical plant protection within the highly diverse mosaic of crops grown within the oases. Apparently, rust diseases were the only agronomic problem hampering yields of landraces. The farmers interviewed during the survey stated that they preferred landraces to government-supported germplasm because of the tastiness of the grain, better adaptation of landraces to the land, lower susceptibility to rust and particularly because they also produced larger amounts of straw which could be fed to ruminants. All the farmers interviewed stated that they stored their grain at home on the head and would only thresh directly before its consumption by their family (Plate 4). Only a minor proportion of the grain was sold at harvest time to village visitors or at the local market. A few times, ill-defined medicinal properties of landrace grain were mentioned as a major nutrition-related advantage of landrace grain over grain from 'modern' varieties. Seed exchange between farmers was reported to be frequent but at the same time, each farmer would do all he could to preserve the seed he had inherited from his father or grandfather.

At the time of the survey, 28% of the interviewed farmers who stated that they cultivated landraces had no seed on hand; 32% had planted all their seed; 4% had stored seed at that time; and 36% had used some of their germplasm for (re)production, but maintained a safety stock at home (Table 1).

The variation between the four study regions with respect to the landraces used appeared to be relatively small and random (Tables 2 and 3). Among the eight landrace names mentioned by the farmers, 'Alas' (Table 3) was comprised of a mixture of *T. dicoccon* varieties, whereas the other landraces were composed of *T. aestivum* and *T. durum*. 'Alas' was preferred by farmers because of its

reportedly higher tolerance to drought and a better taste when used for bread making, even if its preparation is more laborious. Regardless of whether the seed was planted or stored, the most common landraces in use by farmers were Walidi, with about 50%, followed by Missani, with about 20%, Sarraya with 12% and Greda with 5%.

Field observations also indicated that names for material with the same morphological characteristics could vary between regions. For example, the same landrace was named ‘Gradi’ in the Interior and ‘Walidi’ in Sharqia. In addition, prior to this survey, the landrace names ‘Humaira’ and ‘Mufsikha’ have not been recorded.

The material collected during this survey is currently being sown under controlled conditions in a growth chamber and under field conditions in Germany; its morphological and molecular characterization will follow. Only this will allow us to examine the degree of consistency in the indigenous naming of the germplasm and the relatedness of the collected material to other wheats from the Middle East, India and East Africa. Certainly Omani wheat landraces will merit further research to better understand their origin, genetic structure and potential for future breeding programmes.

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Table 1. Numbers of interviewed Omani farmers who had no landrace seed, seed planted, seed stored or seed planted and stored in March 2002.

Area	Status of wheat landrace seed				
	No seed	Planted	Stored	**Planted and stored**	**Total farmers interviewed**
Interior					
Jabal Akhdar	3	0	0	1	4
Bahla	1	0	0	3	4
Misfat Al-Abrein	0	2	0	1	3
Al-Hamra	3	3	1	0	7
Southern Batinah					
Balad Seet	1	0	0	4	5
Wadi Mistal	0	3	0	2	5
Wadi Bani Kaharus	0	6	0	0	6
Wadi Sahtain	2	0	0	2	4
Al-Awabi	1	1	0	2	4
Sharqia					
Ibra	4	2	1	3	10
Wadi Dama Wa Taeen	4	4	1	5	14
Al-Quraiat					
Hubaina	0	1	0	2	3
Total	**19**	**22**	**3**	**25**	**69**

Table 2. Number of times landraces were *planted* by interviewed farmers (see Table 1).

Area	**Landraces**						
	Walidi	Missani	Greda	Mufsikha	Shwairaa	Sarraya	Hamira
Interior							
Jabal Akhdar					1		
Bahla	2	1	1		1	1	1
Misfat Al-Abrein	1	2				1	
Al-Hamra	2	1					
Southern Batinah							
Balad Seet	3	2	1			1	
Wadi Mistal	3	2				2	
Wadi Bani Kharus	2	1	1				
Wadi Sahtain		1	1		1		
Al-Awabi	2	2		1			
Sharqia							
Ibra	8	1				2	
Wadi Dama Wa Taeen	13	1				1	
Al-Quraiat							
Hubaina	3	1					
Total	**39**	**15**	**4**	**1**	**3**	**8**	**1**

Table 3. Number of times landraces were *stored* by interviewed farmers (see Table 1).

Area	**Landraces**							
	Alas	Walidi	Missani	Greda	Mufsikha	Shwairaa	Sarraya	Hamira
Interior								
Jabal Akhdar						1		
Bahla	1	1	1	1		1	2	1
Misfat Al-Abrein	1	1	2				1	
Al-Hamra		2	1					
Southern Batinah								
Balad Seet		3	2	1			1	
Wadi Mistal		1	2				2	
Wadi Bani Kharus		2	1	1				
Wadi Sahtain			1	1		1		
Al-Awabi		2	2		1			
Sharqia								
Ibra		8	1				2	
Wadi Dama Wa Taeen	2	13	1				1	
Al-Quraiat								
Hubaina		3	1					
Total	**4**	**36**	**15**	**4**	**1**	**3**	**9**	**1**

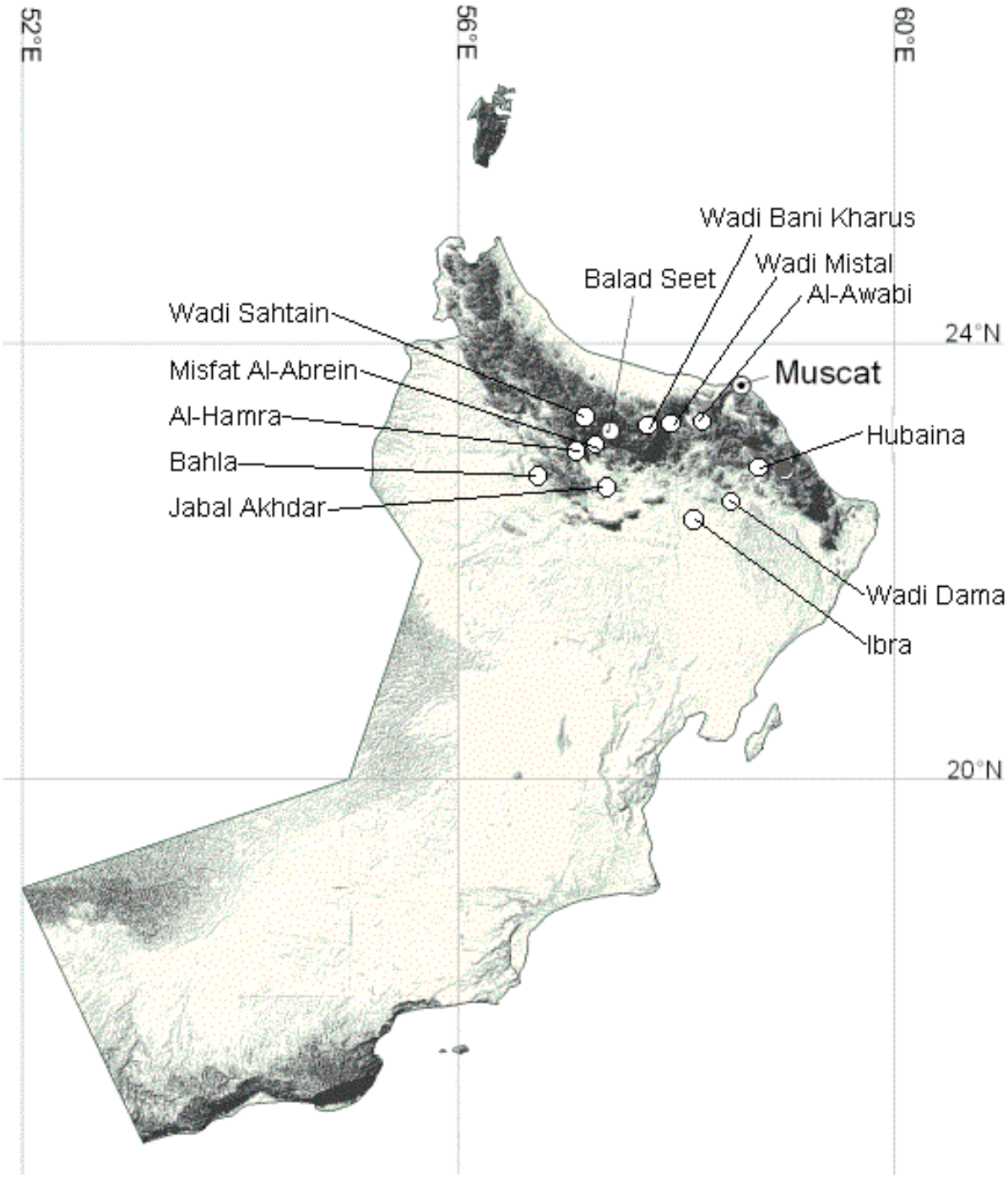

Figure 1. Map of Oman indicating the 12 sites where the surveys of wheat landraces were conducted.

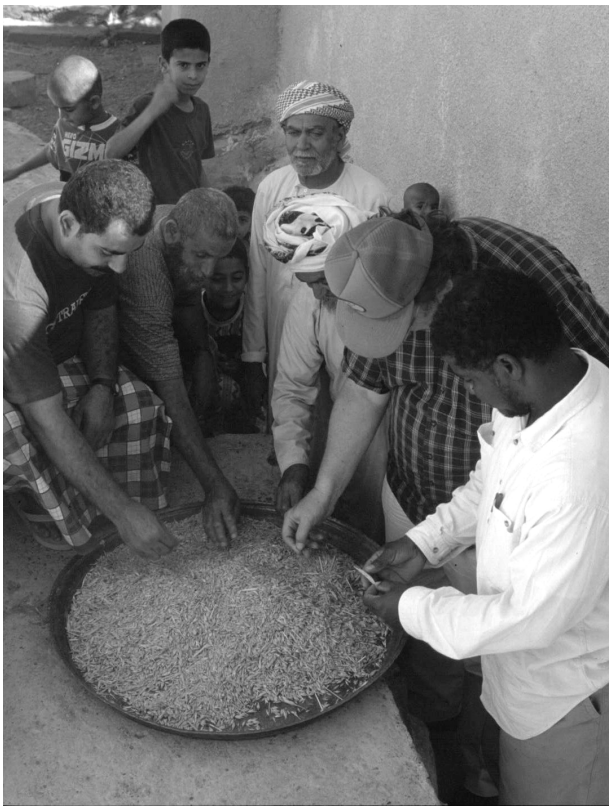

Plate 1. Researchers collecting seed in a small mountain village in Oman in March 2002.

Plate 2. Typical small-scale agricultural setting with small wheat fields in northern Oman.

Plate 3. Aerial photograph of a typical mountain oasis with date palms and wheat fields.

Plate 4. Omani farmer manually threshing wheat.

Appendix 1.
Landraces of other crops collected in the mountain oases and also in the Batinah region is available online from: http://www.ipgri.cgiar.org/pgrnewsletter/last.asp

Species	**Number of samples**
Avena sativa	5
Hordeum vulgare	5
Setaria italica	1
Zea mays	1
Eleusine coracana	1
Lolium temulentum	1
Cereals and grasses	***14***
Cicer arietinum	1
Pisum sativum	2
Trigonella foenum-graecum	1
Vicia faba	3
Pulses	***7***
Beta vulgaris	1
Brassica juncea	1
Brassica sp.	1
Raphanus sativus	3
Vegetables	***6***
Anethum graveolens	1
Carum carvi	1
Coriandrum sativum	1
Foeniculum vulgare	2
Lepidium sativum	1
Majorana hortensis	1
Ocimum basilicum	3
Trachyspermum ammi	1
Pimpinella anisum	2
Condiments and spices	**13**
Grand total	***40***

Appendix 2.

Formal questionnaire covering details about the land cultivated with landraces, farming practices, land ownership and local names for the cultivated wheat germplasm is available online from: http://www.ipgri.cgiar.org/pgrnewsletter/last.asp

Accession number		
Location		
Collector		
Date		
Farmers name:	Age:	Education:
Total farm size (m^2)		Land tenure
1. Crop information		
Local name of landraces used		
Date of sowing		
Expected time of harvest		
Field size (m^2)		
Planting distance between rows (cm)		
Distance within rows (cm)		
Planting method		
Cropping system (intercrop/sole crop)		
2. Source of seed		
Personal collection/heritage		
How long was the seed stored before sowing		
Mode of seed storage		
Problems with the seed		
3. Major problems with local wheat germplasm		
Problems with insects or diseases		
Type of chemical crop protection applied		
4. Marketing		
Proportion of home consumption		
Place of crop sale		
Availability of local germplasm on local market		
Personal preference for local germplasm (if yes, please justify)		
Which problems (if any) do you have in the field with local germplasm?		
How do you make flour (where is the flour mill?)		

2.2 Emmer (*Triticum dicoccon* Schrank) in Oman

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Abstract

Emmer (*Triticum dicoccon*) was collected recently in northern Oman. The material was analyzed morphologically and phenologically. It belongs to the Asiatic emmers (subsp. *asiaticum)* and not to the Ethiopian ones (subsp. *abyssinicum*), distributed in Ethiopia and Yemen, as originally expected. The determination of the material resulted in var. *haussknechtianum* and var. *aeruginosum*.

Key words: *Triticum dicoccon,* morphological classification, Oman

القمح (العلس) (*Triticum dicoccon* Schrank) في سلطنة عمان

الملخص

لقد تم مؤخرا جمع عينات سلالة (علس) من نوع القمح (***Triticum dicoccon***) في المناطق الشمالية لعمان، لمعرفة نوعها انتمائها الوراثي. و أوضحت النتائج التحليلية للوصف المظهري والتشكيلي الوراثي للسلالات.ووجدت أن هذه السلالات تنتسب إلى أصناف القمح الآسيوي (***subsp. asiaticum***) *تحت* نوع "أسياتيكم" و ليس الأثيوبي (***subsp. abyssinicum***) التي تقع تحت نوع "أبسينيكم" الذي تشتهر زراعته في أثيوبيا واليمن كما كان متوقعا أصلا. ولذلك تم استنتاج أن السلالات الموجودة في عمان هي من السلالات الآسيوية و هما الصنف ***haussknechtianum*** والصنف ***aeruginosum*** .

Introduction

Emmer belongs to the oldest crops of the world (Zohary and Hopf, 1993; Damania, 1998). Emmer was domesticated from the wild progenitor *Triticum dicoccoides* (Körn. ex Asch. et Graebn.) Schweinf. in its area of natural distribution, i.e. in the mountains of the Fertile Crescent, in Iran, Iraq, Jordan, Syria, Israel and Palestine (Perrino *et al.*, 1996). Later on, the domesticate experienced a large distribution from Northern Africa through most parts of Europe and the Mediterranean area to Central Asia (Szabó and Hammer, 1996; Filatenko *et al.*, 2001). In the South the emmer reached Ethiopia. But there have been no relevant reports of emmer from the Arabian Peninsula (Schwartz, 1939; Mandaville, 1990) with the exception of Yemen from where it was reported under the folk-name of “alas” (Fljaksberger, 1935; Dorofeev *et al.*, 1979; Wood, 1997). The same folk name was reported for the first time from Oman in the last decennium of the 20th century (Guarino, 1990) indicating the long overlooked *Triticum dicoccon* Schrank for remote parts of northern Oman. New exploration confirmed the existence of emmer in Oman. In March 2002 it was possible to collect seeds (Hammer *et al.*, 2004) as a contribution for conserving and use the genetic diversity of emmer.

Materials and methods

Six populations of emmer were collected in Oman in 2002, however recent cultivation of this crop was observed, that is all samples were obtained from seed stores. Soon after collecting, the material was grown in experimental fields at Witzenhausen (Germany) in May 2002. Four samples showed a reasonably good germination and could be used for a phenological and morphological examination (anatomical differences have been already described by Percival 1921), according to the standard procedure developed by the Vavilov-Institute in St. Petersburg (Russia) (Dorofeev *et al.*, 1979). Chromosome numbers were counted from the root-tips of germinating plants using acetocarmin as a colorant.

Results and discussion

Different morphological types could be found during a first evaluation of the seed samples. All samples contained also seeds of *Triticum durum* Desf., *T. aestivum*

L. s.l., *Hordeum vulgare* L. s.l., *Avena sativa* L. (2n ¼ 42 according to our determination) and other crop plants, such as *Raphanus sativus* L. and weeds.

Description of the emmer plants: Root system little developed. Plant height low or medium (Misfat village, no. 4). Number of shoots per plant low (Misfat, no. 3, somewhat higher). Straw very thin (2.0–2.5 mm), somewhat thicker in Misfat (no. 3). Straw filled or nearly filled, also in the uppermost internodia. Leaves erect, nearly touching the shoot. Leaf-blades short (upper leaf 11–28 cm), narrow (3–10 mm), silky pubescent. Upper leaves with a few cilia. Leaf blade generally without hairs, very seldom with some short hairs. Spikes short, medium dense or dense (D ¼ 30–44). Awns 1.5–2 times longer than the spike, soft. Empty glumes oblong egg-shaped with a short keel-tooth. Side nerve little developed, tapering into a small elevation. Shoulder absent (see Figure 1). Grain 8–10 mm long, 2.0–3.0 mm high and 2.0–3.0 mm wide, of dark colour. Some characters resembled the emmers of Ethiopia (*Triticum dicoccon* subsp. *abyssinicum* Vav.), which are also distributed in Yemen (Wood, 1997) and India, particularly filled straw, cilia on the silky-pubescent upper leaf blades, spikes oblong-rhombic, straw and anthers violet. These characters can be interpreted as a special adaptation to the conditions of Southern Arabia. But most of the characters observed prove that the material belongs to Asiatic emmer (*T. dicoccon* subsp. *asiaticum* Vav.). A detailed infraspecific determination resulted in *var. haussknechtianum* A. Schulz and *var. aeruginosum* Flaksb. which are the most common races from Asia. Both races belong to *convar. transcaucasicum* Flaskb., the known distribution of which also includes Iran.

Therefore, the introduction of emmer into Oman might have occurred from Iran via the Gulf of Oman. The time of introduction is still unclear. Similar introduction routes could be shown for *Coriandrum sativum* L. in which a specific race has been described from Oman (*var. omanense* Diederichsen; Diederichsen and Hammer, 2003).

Based on morphological and phenological traits, the emmer from Oman is not closely related to races from Ethiopia and Yemen. Route and especially time of introduction are still open for further research.

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Figure 1. A sample of *Triticum dicoccon* subsp. *asiaticum* var. *haussknechtianum* from MAF Bahla (northern Oman) reproduced in Witzenhausen (23. 07. 2002) x 1.

2.3 Exploration of wheat landraces (*Triticum* spp.) in Oman

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Abstract

The long trading history of the Omanis in the South Arabian Peninsula region resulted in the importation of foreign germplasm, making the region to be highly heterogeneous with respect to plant genetic resources. In Oman collection and genetic exploration of cereals including wheat (*Triticum* spp.) started in the 1970's. The first reported information of local wheat landraces (*T. aestivum)* was in 1990*,* followed by characterization of wheat in 2003 in the country's northern Hajar mountains. The aim of the study is to present a botanical inventory of cultivated wheat landraces in the different regions of Oman. The widest phenotypic variation was observed in the Dhahira district followed by the Batinah, the Sharqia and the Dakhilia district. In the Sharqia district farmers were found to cultivate a special type of wheat locally called 'Walidi'. In the region of Dank (Dhahira) a specific landrace with reddish seed called 'Cooley' was cultivated. Among the 210 hexaploid accessions 9.5% and 6.6% were identified as the recently described *T. aestivum* var. *maqtaense* and *T. aestivum* var. *baladseetense*, respectively. Among the accessions there also were four new botanical *aestivum* varieties, *T. aestivum* var. *sedabense, T. aestivum omanense, T. aestivum* var. *sedayriense* and *T. aestivum* var. *ibreense*. Among the 26 accessions of tetraploid wheat there also were three varieties new to science named *T. aethiopicum* var*. hajirense, T. durum* var. *affini mahsinense* and *T. durum* var. *densemenelikii (sedarenense).* These results provide evidence about Oman's so far underestimated genetic diversity in wheat with material from Asia, Africa and the Mediterranean. However, more research is needed to better understand the routes through which this germplasm was introduced in Oman.

Key words: Classification and collection, indigenous knowledge, oasis agriculture

استكشاف سلالات من القمح المحلي *(Triticum sp.)* في عمان

الملخص

نظرا لتاريخ سلطنة عمان التجاري الطويل وبحكم موقعها وعلاقتها بالعديد من دول العالم المستمدة من موقعه الجغرافي المتميز في جنوب الجزيرة العربية؛ تم إدخال كثير من الأنواع النباتية التي أدت بدورها إلى وجود كمية كبيرة من المصادر الوراثية النباتية. وفي أوائل سبعينيات القرن الماضي بدأت رحلات استكشاف وجمع المصادر الوراثية. وخلال سنة **1990**م ظهرت أولى المعلومات عن سلالات القمح المحلي و أصناف أخرى ثم توالت بحوث تقييم وتصنيف سلالات القمح المحلي عام 2003م في جبال الحجر.

والهدف من هذه الدراسة هو تقديم قائمة بأصناف القمح المحلي وإظهار مدى التنوع الوراثي لسلالاته السداسية و الرباعية.

ولقد أظهرت النتائج الأولية وجود تباينات وراثية أعلى بمنطقة الظاهرة تليها الباطنة ثم الشرقية وأخيرا الداخلية، كما لوحظ تخصص بعض القرى في زراعة سلالة قمح محلية معينة من أبرزها زراعة سلالة تسمى "وليدي" في المنطقة الشرقية (مقطع) و سلالة ذات بذور حمراء تدعى "كولي" في منطقة الظاهرة (ولاية ضنك).

و كنتيجة لفحص 210 عينات من سلالات القمح السداسي المحلي اكتشفت أربع أصناف جديدة هي:

T. aestivum* var*. sedabense, T. aestivum* convar*. rigidcompactum* var*. omanense و ***T. aestivum* var*. sedayriense*.**

كما أكدت هذه الدراسة وجود أصناف محلية من القمح السداسي المكتشفة سابقا في عام 2003 م *بنسبة* 9.5% من صنف ***T. aestivum* var*. maqtaense*** و 6.6% من صنف ***T. baladseetense* var*. aestivum*.** أما بالنسبة للقمح الرباعي فقد تمت دراسة 26 نوعا وتم خلالها اكتشاف ثلاثة أصناف جديدة:***T. aethiopicum* var*. hajirense*** و ***T.durum* var*. affini mahsinense*** و ***T. durum* var*. deusemeneliki sedarenense*** كما ثبت أيضا وللمرة الأولى وجود القمح الأثيوبي ***T. aethiopicum*** في سلطنة عمان. ونستطيع استنتاج أن هناك تنوعا وراثيا واسعا؛ وأن معظم القمح المحلي الموجود هو من أصول آسيوية وإفريقية ومن منطقة البحر الأبيض المتوسط. على أن بحوثا مستقبلية ينبغي إجراءها للتعرف على كيفية دخول هذه الأنواع للسلطنة.

Introduction

The South Arabian Peninsula has a wide range of ecological variation, which covers a large diversity of agroecosystems and genetic resources. The long trading history of the Omanis in the region resulted in the importation of many varieties of wheat and explains why the region has a particularly high diversity of wheat landraces (Perrino and Hammer, 1983). In recent years the Peninsula has received increasing interest for the collection of germplasm of a number of crops (Chapman, 1985).

Wheat (*Triticum* div. spp.) is one of the most important staple foods worldwide and its importance is likely to grow further with increasing global population. Thus, the characterization of traditional wheat landraces as a still underexploited reservoir of potentially new traits which may be used in future breeding programmes is crucial. The collection of germplasm in Oman dates back as far as to the 1970's, however, there is still very little information about local wheat. The first information on wheat landraces in Oman was provided by Guarino (1990). In 2003 two new findings of *T. aestivum* botanical varieties in Omani landraces were reported by Al-Maskri *et al.* (2003) from the Hajar Mountains. These were *Triticum aestivum* var. *baladseetense and T. aestivum* var. *maqtaense.* Hammer *et al.* (2004) first described emmer wheat *T. dicoccon subsp. asiaticum* Vav. in landraces from Al Hamra and Misfat Abreen in the same Al Hajar mountains.

Normally landraces are genetically heterogeneous, developed in traditional agricultural systems often in remote niche environments over hundreds or thousands of years and have been constantly subjected to natural and farmers' selection pressure (Nevo, 1988). However, morphological, physiological or agronomical traits on the one hand and biochemical or molecular markers on the other can be used to assess genetic variability among genotypes within landrace populations (Oliveira *et al.*, 1997; Tranquilli *et al.*, 2000).

The description of agronomically important characteristics is an important prerequisite for the conservation, evaluation and utilization of genetic resources in breeding programmes (Franco *et al.*, 2001; Duvick, 1984; Gadea, 1954). Wheat can be classified in its respective taxonomic species with a large degree of certainty (Belay and Furuta, 2001). Its morphological characteristics were among the earliest genetic markers used for scientific investigation and are still being used to manage germplasm (Klug and Cummings, 1994). This is particularly true

for the wheat spike, which has a wide genetic variability in its morphological structure (Sharman, 1944). On this background this study focused on spike characteristics to classify wheat landraces and to present an inventory of their distribution across the different regions of Oman.

Materials and methods

Collection

The collection of wheat germplasm covered almost all its areas of on-farm cultivation in Oman. For each accession 20 spikes were sampled directly from the fields taking into account apparent morphological differences. The target areas where the samples were taken comprised the following regions (Table 1):

1. Batinah, Wadi Bani Kharus, Al Awabi, Sohar and Al Khabura
2. Dakhilia, Al Hamra and Bahla
3. Sharqia, Wadi Dama Wa Taeen, Wadi Bani Khalid and Sur (including Jabal Bani Jabr)
4. Dhahira, Ibri, Dhank, Yanqul, Buraimi and Mahada
5. Musandam, Khasab and Lima

Morphological description

The preliminary morphological classification and evaluation of the germplasm to group the samples at the species level to *T. aestivum* and *T. durum* was done in winter 2002/3. Wherever necessary, this grouping was confirmed by cytological analyses. Subsequently, a more detailed morphological classification to the level of botanical varieties was conducted with well formed spikes following the guide of Dorofeev *et al.* (1979) which has been found useful for Omani wheat previously (Al-Maskri *et al.*, 2003; Hammer *et al.*, 2004).

Results and discussion

The high genetic variability within wheat species, the effects of inter-species crossings and hybridization within groups of different ploidy levels and the fact that the genus *Triticum* is a young unit make its exact taxonomic classification a challenge (Mac Key, 1966). Nevertheless is became clear that the majority of the wheat landraces from Oman was hexaploid (2n = 42). Tetraploid wheat varieties

(2n = 28), especially of *T. durum*, were rare. Most of the *aestivum* wheats had a compact spike sized 5-8 cm and cylindrical in shape. The glume shape was between oblong oval to ovoid and glumes shoulder shapes were between acute to round. The glume colour varied widely between straw-coloured to black, black-blue on a white background with black glume edge, black and black-blue on a white background.

Regional distribution of the accessions

The amount of variation within districts varied widely. Morphological variation of accessions was largest in the Dhahira district where cultivated fields were biggest. Following smaller field sizes, variation in wheat accessions was lower in the Batinah district. Although this district has many fields, most have been affected by increasing salinity as a result of salt water intrusion from the coast or poor irrigation techniques. Despite its large size only few landraces are being cultivated in the Sharqia district. Farmers there raise a special type of wheat locally called 'Walidi'. Finally, the Dakhilia district is the smallest in size with smallest fields and morphological variation (Tables 2 and 3).

Out of the total of 210 hexaploid accessions 9.5% and 6.6% were classified as *T. aestivum* var. *maqtaense* and *T. aestivum* var. *baladseetense*, respectively, two varieties recently discovered in two remote mountain oases (Al-Maskri *et al.*, 2003) and an additional two *T. aestivum* wheats are new to science. Of the 26 tetraploid wheat accessions four were classified as new to science (Table 4; Final Appendix 1 and 2).

Description and origin of the new botanical varieties

1. *T. aestivum* var. *sedabense* (nom. nud.). Draft region: *Oman* Peninsula arabica, varietas localis (Sharqia and Dhahira). Compact spikes, black awns, grains red, glumes smooth blackness at edge.
2. *T. aestivum* convar. *rigidcompactum* var. *omanense* (nom. nud.). Draft region: *Oman* Peninsula arabica, varietas localis (Batinah). Compact spikes; keel is well expressed black, grains red, glumes smooth and yellow.
3. *T. aestivum* var. *sedayriense* (nom. nud.). Draft region: Oman Peninsula arabica, varietas localis (Dhahira). Compact spikes, without awns, grains yellow, glumes smooth, straw (off) white colour.

4. *T. aestivum* var. *ibreense* (nom. nud.). Draft region: Oman Peninsula arabica, varietas localis (Dhahira). Compact spikes, yellow to red awns, grains red, glumes smooth yellow, keel long in size.
5. *T. durum* var. *mahsinense* (nom. nud.). Draft region: Oman Peninsula arabica, varietas localis (Wadi Bani Kharus, Batinah region). Compact spikes; spike width is very wide 12 mm, with white awns, grains light red, glumes pubescent.
6. *T. aethiopicum var. hajirense* (nom. nud.). Draft region: Oman Peninsula arabica, varietas localis (Wadi Bani Kharus Batinah region). Compact spikes; spike width is very wide 12 mm, yellow with black awns, grains red, glumes pubescent.
7. *T. durum* var. *densemenelikii (sedarenense)* (nom. nud.). Draft region: *Oman* Peninsula arabica, varietas localis (falaj Sedaryin Dhahira region). Compact spikes; spike width is very wide 15 mm, off white awns, grains red, glumes black colour with pubescent.

T. aestivum var. *sedabense*, is widely grown in the Dhahira district, followed by the Batinah. However, this race was first discovered in the Sharqia district. The second new race *T. aestivum* var. *omanense* was found in the Batinah region only.

A slightly different race was also found in the Sharqia district. Two new varieties of tetraploid wheat *T. aethiopicum* var. *hajirense*, and *T.durum* var. *mahsinense* were found at Wadi Bani Kharus in the southern Batinah district. The new *T. durum* var. *densemeneliki (sedarenense)* (nom. nud.) was found at Falage Sedayrien in the Dahira district.

Most wheat fields also contained other cereal crops. Approximately 90% of the visited wheat fields contained oat (*Avena sativa* L.) and approximately 10-20% contained barley (*Hordeum vulgare* L. s.l). These findings confirm earlier reports (Al-Maskri *et al.*, 2003).

Conclusions

Oman contains an unexpectedly large genetic diversity of wheat landraces. Most of the landraces seem to have originated from the Mediterranean, Asia and a few from Africa, particularly from Ethiopia. The entry routes for wheat into Oman,

however, are not yet clear, but there is archeological evidence that wheat and other cereals may have arrived to this country as early as 3,000 BC. There is urgent need for more studies on genetic resource of Oman wheat landraces.

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Table 1. Geographical location of the collection areas in Oman.

District	Altitude	Latitude	Longitude
Dahira	300m – 700m	56°30' – 56°37'	23°41' – 23°18'
Batinah	400m – 800m	56°29' – 57°37'	23°59' – 23°11'
Dakhilia	300m – 900m	57°04' – 57°12'	22°48' – 23°06'
Sharqia	300m – 1500m	59°09' – 58°45'	22°59' – 23°47'
Musandam	50m – 400m	55°57' – 56°18'	26°04' – 24°24'

Table 2. Distribution of different *Triticum aestivum* landraces collected in four districts of Oman, OMTRI (referring to the Oman wheat classification catalogue), districts and botanical names.

OMTRI	District	Local name[+]	Botanical name
145,151,152,140	Sharqia	Walidi	*T. aestivum* var. *maqtaense*
50	Dhahira	Buwaida Alwadi	*T. aestivum* var. *maqtaense*
160,167,171,173,188,189, 256,257,261,262,268	Batinah	M, H, W	*T. aestivum* var. *maqtaense*
181,183,185,186	Batinah	Hemaira	*T. aestivum maqtaense*
165,187,255,259,272	Batinah	C, H	*T. aestivum* var. *baladseetense*
139,143,144,150	Sharqia	SR, W	*T. aestivum* var. *baladseetense*
65,331	Dhahira	C, SR	*T. aestivum* var. *baladseetense*
299	Dhahira	Buwaida Alwadi	*T. aestivum* var. *baladseetense*
182,184	Batinah	Hemaira	*T. aestivum* var. *baladseetense*
100,101,104,105, 287,301,312,321,326	Dhahira	C, W, SHL, M	*T. aestivum* var. *sedabense (nom. nud.)*
142,333	Sharqia	M, W	*T. aestivum* var. *sedabense (nom. nud.)*
37,40	Dakhilia	C, SHW	*T. aestivum* var. *sedabense (nom. nud.)*
241,242	Batinah	Greda	*T. aestivum* var.*omanense (nom. nud.)*
131	Sharqia	Walidi	*T. aestivum* var.*omanense (nom. nud.)*
178,179	Batinah	Missani	*T. aestivum n.v.*
117	Dhahira	Sarraya	*T. aestivum n.v.*
238	Dhahira	Cooley	*T. aestivum n.v.*
42,47,304	Dakhilia	SHW, C, M	*T. aestivum* var. *anglicum*
314	Dhahira	Cooley	*T. aestivum* var. *anglicum*
279	Sharqia	Unkwon	*T. aestivum* var. *anglicum*
94	Dhahira	Cooley	*T. aestivum* var. *barbarossa*
92,95,329	Dhahira	SHW, SHL	*T. aestivum* var. *hostianum*
148	Sharqia	Walidi	*T. aestivum* var. *hostianum*
33,38,302,303,317,318,319	Dakhilia	Cooley	*T. aestivum* var. *leucospermum*
67,88,103,309,310	Dhahira	C, G	*T. aestivum* var. *leucospermum*
316	Dakhilia	Cooley	*T. compactoid* var. *leucospermum*
127	Sharqia	Malki	*T. aestivum* var. *lutescens*
176	Batinah	Walidi	*T. aestivum* var. *lutescens*
58276,289	Dhahira	C, S, H, W	*T. aestivum* var. *lutescens*
91,330,334	Dhahira	Shalut, C	*T. aestivum* var. *pseuohostianum*
332	Sharqia	Missani	*T. aestivum* var. *pseuohostianum*
49	Dakhilia	Cooley	*T. aestivum* var. *pulchrum*
83,97	Dhahira	Shwaira, G	*T. aestivum* var. *pulchrum*
51, 78,113,237,248,320	Dhahira	M, H, SR, C, SHL	*T. aestivum* var. *aestivum*
164,175,252,260,278	Batinah	H, C, SHL, K	*T. aestivum* var. *aestivum*
240	Dhahira	Cooley	*T. aestivum* var. *anglicum*
250,285	Batinah	G, SR	*T. aestivum* var. *graecum*
290	Dhahira	Cooely	*T. aestivum* var. *graecum*
39	Dakhilia	Cooley	*T. aestivum* var. *hostianum*
258	Batinah	Hamira	*T. aestivum* var. *icterinum*
263	Batinah	Walidi	*T. aestivum* var. *icterinum*
166	Batinah	Greda	*T. aestivum* var. *oblivense*
74,75,79,82,83	Dhahira	C, H, W	*T. aestivum* var. *pseudocaeruleovelutinum*
180,266,267,269	Batinah	H, W	*T. aestivum* var. *pseudocaeruleovelutinum*

[+] BA=Buwaida Alwadi, C=Cooley, G=Greda, H=Hemaira, K=Khati, M=Missani, MK=Malki, SHL=Shalut, SHW=Shawiara, SR=Sarraya, W=Walidi

Table 2. continued

OMTRI	District	Local name[+]	Botanical name
239	Dhahira	Hamira	*T. aestivum* var. *pseudocaeruleovelutinum*
254	Batinah	Hamira	*T. aestivum* var. *pseudocaeruleovelutinum aristatum*
98,294,315	Dhahira	H, C, SHW	*T. aestivum* var. *pseudoerythrospermum*
66,96,273,274,288,295,307	Dhahira	Mufsikha, C, H, W	*T. aestivum* var. *pseudohostianum*
146,147,155	Sharqia	W, K	*T. aestivum* var. *pseudohostianum*
286	Batinah	Cooley	*T. aestivum* var. *pseudohostianum*
306	Dakhilia	Unknown	*T. aestivum* var. *pseudovelutinum*
265	Batinah	Cooley	*T. aestivum* var. *nov.*
45	Dakhilia	Shwiara	*T. aestivum* var. *villosum*
128,280,281	Sharqia	Walidi	*T. aestivum* var. *villosum*
174,190,191,284	Batinah	C, H, G, W	*T. aestivum* var. *villosum*
72,118,119,275,291,296	Dhahira	C, SR	*T. aestivum* var. *villosum*
244	Batinah	Greda	*T. aestivum* var. *villosum forma aristatum*
80	Dhahira	Cooley	*T. aestivum* var. *wernerianum*
177,29,72,98	Dhahira	C, W, S	*T. aestivum* var. *wittmackianum*
270,271,283	Batinah	C, SHW	*T. aestivum* var. *wittmackianum*
247	Dhahira	Cooley	*T. aestivum compactum* var. *wittmackianum*
81	Dhahira	Cooley	*T. aestivum* var. *Linaza*
41,46	Dakhilia	Cooley	*T. aestivum* var. *linaza*
63,64,111,112	Dhahira	Cooley	*T. aestivum* var. *linaza*
115,130	Dhahira	Walidi	*T. aestivum* var. *linaza*
135,138	Sharqia	Unkwon	*T. aestivum* var. *linaza*
21	Sharqia	Sarraya	*T. aestivum* var. *linaza*
168,251,246,243,249,163	Batinah	C, G, H, W	*T. aestivum* var. *linaza*
30, 31, 32, 34	Dakhilia	Cooley	*T. aestivum* var. *mutico linaza*
132	Sharqia	Cooley	*T. aestivum* var. *mutico linaza*
292,293,308,311,313,323, 324,325,69,71,84	Dhahira	Cooley	*T. aestivum* var. *mutico linaza*
277	Sharqia	Unknown	*T. aestivum* var. *mutico linaza*
300	Dhahira	Walidi	*T. aestivum* var. *mutico linaza*
114	Dhahira	Walidi	*T. aestivum* var. *mutico linaza*
116	Dhahira	Cooley	*T. aestivum* var. *mutico linaza*
60	Dhahira	Cooley	*T.aestivum* var. *villosum*
57,59,61	Dhahira	Cooley	*T. aestivum* var. *wittmackianum*
129,134	Sharqia	Walidi	*T. aestivum* var. *wittmackianum*
245	Batinah	Greda	*T. aestivum* var. *icterinum*
102	Dhahira	Cooley	*T. aestivum* var. *leucospernum*

[+] BA=Buwaida Alwadi, C=Cooley, G=Greda, H=Hemaira, K=Khati, M=Missani, MK=Malki, SHL=Shalut, SHW=Shawiara, SR=Sarraya, W=Walidi

Table 3. Distribution of different *Triticum durum* landraces collected in four districts of Oman, OMTRI (referring to the Omani wheat classification catalogue), districts, local names and botanical names.

OMTRI	District	Local name	Botanical name
196	Batinah	Missani	*T. durum* var. *africanum*
197	Batinah	Missani	*T. durum* var. *africanum*
198	Batinah	BA	*T. durum* var. *affine*
199	Batinah	Missani	*T. aethiopicum* var. *bialbum*
200	Batinah	Missani	*T. aethiopicum* var. *comitans*
202	Batinah	Missani	*T. aethiopicum* var. *comitans*
224	Batinah	Missani	
203	Batinah	Missani	*T. aethiopicum* var. *hajirense (nom. nud.)*
204	Batinah	Missani	*T. durum* var. *africanum*
205	Batinah	Missani	*T. aethiopicum* var. *densifulvum*
206	Batinah	Missani	*T. durum* var. *africanum*
207	Batinah	Missani	*T. durum* var. *melanopus*
208	Batinah	Missani	*T. durum* var. *mahsinense (nom. nud.)*
209	Batinah	Missani	*T. aethiopicum* var. *comitans*
225	Batinah	Missani	
210	Batinah	Missani	*T. aethiopicum* var. *ptolomaeum*
226	Batinah	Missani	
211	Batinah	Missani	*T. durum* var. *densemenelikii*
212	Batinah	Missani	*T. aethiopicum* var. *comitans*
237	Batinah	Missani	
227	Batinah	Missani	
228	Batinah	Missani	
213	Batinah	Missani	*T. aethiopicum* var. *pseudorarum*
229	Batinah	Missani	
214	Sharqia	Mufsikha	*T. aethiopicum* var. *ptolomaeum*
215	Sharqia	Malki	New variety?
216	Sharqia	Missani	*T. aethiopicum* var. *ptolomaeum*
217	Sharqia	Missani	*T. aethiopicum* var. *ptolomaeum*
218	Dhahira	Missani	*T. aethiopicum* var. *comitans*
230	Sharqia	Malki	*T. aethiopicum* var. *comitans*
219	Dhahira	Missani	*T. aethiopicum* var. *ptolomaeum*
220	Dhahira	Missani	
221	Dhahira	Missani	*T. durum* var. *densemenelikii (nom. nud.)*
231	Dhahira		*T. aethiopicum* var. *comitans*
232	Musandam	Missani Arabic	*T. durum* var. *pilosonigrum*
233	Musandam	Missani Arabic	
234	Musandam	Missani Arabic	
238	Musandam	Missani Arabic	*T.durum* var. *tchertchericum*
239	Dhahira		*T.durum* var. *pseudorubripubescens*

Table 4. Botanical names and origins of seven new botanical wheat varieties from Oman.

Botanical name	Origin
T. aestivum var. *sedabense (nom. nud.)*	Sharqia, Dhahira
T. aestivum convar. *rigidcompactum* var. *omanense (nom. nud.)*	Batinah, Sharqia
T. aestivum var. *sedayriense* (nom. nud.)	Dhahira
T. aestivum var. *ibreense* (nom. nud.)	Dhahira
T. durum var. *mahsinense (nom. nud.)*	Batinah
T. aethiopicum var. *hajirense (nom. nud.)*	Batinah
T. durum var. *densemenelikii (sedarenense) (nom. nud.)*	Dhahira

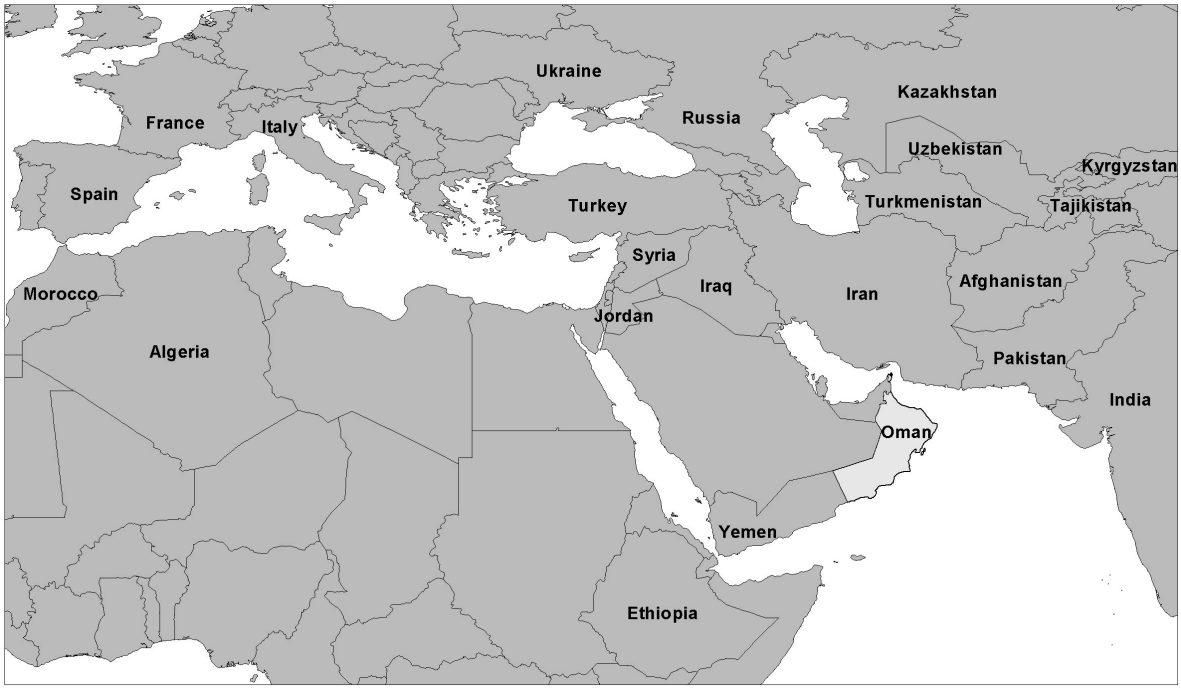

Figure 1. Position of Oman with respect to the Centres of origin and diversity of wheat (*Triticum* spp.).

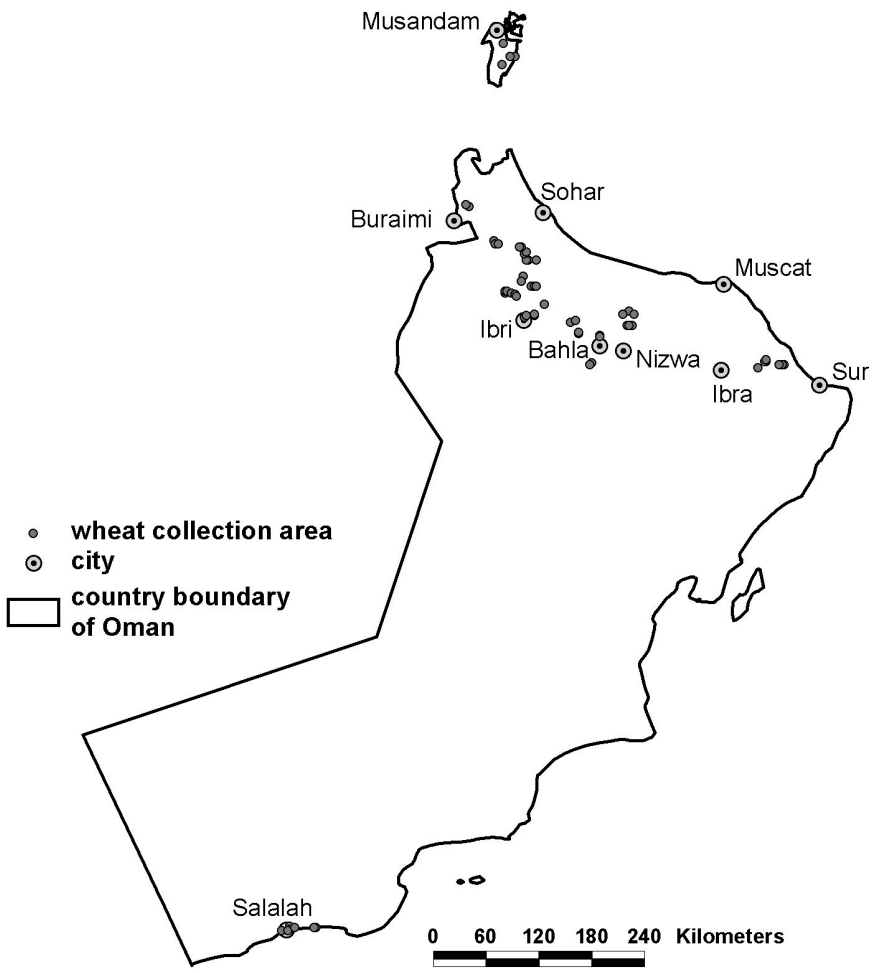

Figure 2. Map of Oman indicating the collection areas of wheat germplasm.

Figure 3. Landrace wheat field in an Omani mountain oasis.

Figure 4. Irrigated wheat fields in a remote mountain oasis of northern Oman.

3

Morphological diversity

3.1 Morphological spike diversity of Omani wheat: I. Tetraploid landraces

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Abstract

The objective of this study was to characterize tetraploid wheat accessions from Oman using individual spikes collected from different wheat cultivation areas in the country. The phenotypic assessment of 15 qualitative and 17 quantitative characters showed variations among of Omani tetraploid wheat landraces. The standardized phenotypic diversity index (H') was with 0.66 higher for quantitative characters than for qualitative characters (0.52). The phenotypic frequency distribution indicated variation in the spike characteristics. The majority of the awns' directions (73%) were between parallel to slightly straight. The frequency of rough awns was 89% and their size was slightly long with a frequency of 63% for the first and 44% for the second awns. The awns colour was dominantly black (88%). Monomorphism was found for grain height (94%), grain number per spikelet (92%) and spike length (79%). Overall, however, the morphological data revealed a relatively high diversity among landraces and that simple morphological characters can be used for the characterization of diversity in Omani wheat.

Key words: Diversity index, morphological traits, *Triticum durum*

تنوع الوصف المظهري لسنابل القمح العماني

1. سلالات القمح الرباعي المحلي

الملخص

يتمثل غرض الدراسة في توصيف سلالات من القمح الرباعي المحلي النامي بسلطنة عمان، باستخدام الوصف المظهري للسنبلة، وقد تمت الدراسة على عينات من سنابل القمح التي جمعت من مختلف المناطق. وتم اعتماد 15 صفة نوعية و 17 صفة كمية ولقد أظهرت النتائج أن هناك اختلافات بين صفات سنابل سلالات القمح الرباعي المحلية. أوضحت النتائج أن الدليل الوراثي (مؤشر) (diversity index) للتنوع المظهري (H) 0.66 مرتفع بالنسبة للصفات الكمية مقارنة مع الصفات النوعية (H) 0.52.كما أظهرت وجود اختلافات بمكونات الشكل المظهري للسنبلة.

كما دل توزيع التردد المظهري على وجود اختلافات في اتجاه حسكة (سفا) السنبلة كانت الغالبية منها 73% بين المتوازي والمائل للاستقامة. أما بالنسبة لخشونة الحسكة، فإن 89 % منها كان خشنا، في حين وجد أنها كانت طويلة قليلا بمعدل تكرار يصل إلى 63% للحسكة الأولى و44% للحسكة الثانية. وكان اللون الأسود هو اللون السائد في القمح المحلي 88%، وبلغ التردد المظهري لارتفاع حجم الحبة 94% (أحادية الشكل) ولعدد الحبوب في السنيبلات 92% في السنبلة وكانت السنبلة تميل للطول (79%)، ويمكننا القول بأن دراسة بيانات الوصف المظهري للسلالات تشير إلى وجود تنوع نسبي واسع في المصادر الوراثية والحيوية، كما يمكن استنتاج أن المزارعين يزرعون خليطا من محاصيلها. وتشير الدراسة كذلك إلى إمكانية استخدام الخصائص المظهرية في دراسات لاحقة.

Introduction

Wheat is a major globally grown cereal, second largest in total production (FAO, 2005). 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 ancient times. The discovery of emmer wheat in Oman underlines the old presence of wheat cultivation in the country (Alkhanjari *et al.*, 2005; Hammer et al., 2004). 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, 1946). 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 (Willcox and Tengberg, 1995; Potts, 1993).

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 (Sneller *et al.*, 2005; Skovmand *et al.*, 2001).

The boundary between 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 (Belay and Furuta, 2001; Hanelt and Hammer, 1995).

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 between 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 some studies (Belay *et al.* 1994; Berhane *et al.,* 1997; Maxted *et al.*, 1997). 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* by Al-Maskri *et al.* (2003) and for *T. dicoccon* by Hammer *et al.* (2004). The reported findings of *Triticum aestivum* var. *baladseetense, T. aestivum* var. *maqtaense* and *T. dicoccon* ssp. *asiaticum* var. *haussknechtianum* were extremely interesting. Subsequent more thorough surveys revealed an additional four scientifically new *aestivum* varieties (*T. aestivum* var. *sedabense, T. aestivum* convar. *rigidcompactum* var. *omanense, T. aestivum* var. *sedayriense* and *T. aestivum* var. *ibreense*) and three tetraploid wheats (*T. aethiopicum* var*. hajirense, T. durum* var. *mahsinense* and *T. durum* var. *densemenelikii (sedarenense)*; Al Khanjari *et al.*, unpublished).

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.

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 (Table 1). 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, 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 (for a definition see Final Appendix), 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 Pi is the genotype frequency or the proportion of the total number of entries in the i^{th} 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

For qualitative characters, the standardized diversity index (H') varied from 0.0 (monomorphic) in keel tooth roughness to 0.80 in spike shape. Over all accessions H' was with 0.52 relatively moderate (Table 2). For quantitative characters, H' ranged from 0.26 in the number of grains per spikelet to 0.91 in lemma length with an overall average H' of 0.66 (Table 3).

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 Firdissa *et al.* (2005), Negassa (1986) and Jain *et al.* (1975), respectively. Observations indicate that a landrace's character variation depends on the farmers' regional preference. As reported previously for Ethiopian wheat, total phenotypic variation was highest among populations and lowest among regions (Bekele, 1984; Negassa, 1986a; Belay, 1997).

Frequency distribution

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 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 his 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 (Bechere *et al.*, 1996; Bekele, 1984; Firdessia *et al.*, 2005) in which brown seed colour (dark red) was predominant.

For the quantitative characters, a frequency of 94% for grain height was found over all the landraces followed by a frequency of 92% for the number of grains per spikelet. The majority of the spikelets had five flowers, ranging from 3 to 4 fertile flowers and a few of them were sterile. The number of spikelets per spike 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 (1986).

Most of the Omani farmers preferred large, full spike, black awns, long straight awns and tasty grains for home consumption. The awns 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 (Firdissa *et al.*, 2005 and Tamiru, 1999).

Multivariate analysis of phenotypic characters

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 4). 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 5). 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 (Figure 1). The first principal component was the most important in 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.

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. durum* var. *pilosinigrum* (Oman Triticum, OMTRI, 232), *T. aethiopicum* var. *comitans* (OMTRI 233), *T. durum* var. *pseudorubripubescens* (OMTRI 236), *T. durum* var. *comitans* (OMTRI 234) and *T. durum* var. *tchertchericum* (OMTRI 235).

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

In the third quadrant (below, left) 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 genetic distance of the quantitative characters of the 39 tetraploid wheat accessions from Oman shows distinct groupings (Figure 2) 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 (NV), a yet unclassified accession.

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 possibly crossability after a long joint cultivation history. This would require introgression across different ploidy levels, thus leading to increased polymorphism in the landraces.

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Table 1. List of *durum* wheat accessions collected from different districts of Oman with their respective catalogue number (Oman Triticum, OMTRI), accession number, district of collection and botanical name.

OMTRI	District	Botanical Name
197	Khabura Batinah	*T. durum* var. *africanum*
198	Khabura Batinah	*T. durum* var. *affine*
199	Khabura Batinah	*T. aethiopicum* var. *bialbum*
200	Khabura Batinah	*T. aethiopicum* var. *comitans*
202	Khabura Batinah	*T. aethiopicum* var. *comitans*
224	Khabura Batinah	*T. durum* var. *africanum*
203	Rustaq	*T. aethiopicum* var. *hajirense*
196	Awabi Batinah	*T. durum* var. *africanum*
204	Wadi Bani Kharus	*T. durum* var. *africanum*
205	Wadi Bani Kharus	*T. aethiopicum* var. *densifulvum*
206	Wadi Bani Kharus	*T. durum* var. *africanum*
207	Wadi Bani Kharus	*T. durum* var. *melanopus*
208	Wadi Bani Kharus	*T. durum* var. *mahsinense*
209	Sohar Batinah	*T. aethiopicum* var. *comitans*
225	Sohar Batinah	*T. aethiopicum* var. *grum*
210	Sohar Batinah	*T. aethiopicum* var. *ptolomaeum*
220	Sohar Batinah	*T. aethiopicum* var.*ptolomaeum*
211	Sohar Batinah	*T. durum* var. *densemenelikii*
212	Sohar Batinah	*T. aethiopicum* var. *comitans*
226	Sohar Batinah	*T. aethiopicum* var. *pseudarabicum*
227	Sohar Batinah	*T. aethiopicum* var. *comitans*
228	Sohar Batinah	*T. aethiopicum* var. *rarissimum*
213	Sohar Batinah	*T. aethiopicum* var. *pseudorarum*
229	Sohar Batinah	*T. aethiopicum* var. *comitans*
214	Wadi Bani Khalid	*T. aethiopicum* var. *ptolomaeum*
215	Wadi Bani Khalid	*T. aestivum* var. *linanza*
216	Wadi Bani Khalid	*T. aethiopicum* var. *ptolomaeum*
217	Wadi Bani Khalid	*T. aethiopicum* var. *ptolomaeum*
218	Wadi Bani Khalid	*T. aethiopicum* var. *comitans*
230	Wadi Bani Khalid	*T. aethiopicum* var. *comitans*
219	Wadi Bani Khalid	*T. aethiopicum* var. *ptolomaeum*
231	Sur Sharqia	*T. aethiopicum* var. *comitans*
231	Yanqul Dhahira	*T. aethiopicum* var. *ptolomaeum*
221	Yanqul Dhahira	*T. durum* var. *densemenelikii (sedarense)*
232	Khasab Musandam	*T. durum* var. *pilosinigrum*
233	Khasab Musandam	*T. aethiopicum* var. *comitans*
234	Khasab Musandam	*T. aethiopicum* var. *comitans*
235	Khasab Musandam	*T. durum tchertchericum*
236	Lima Musandam	*T. durum* var. *pseudorubipubescens*

Table 2. Genetic diversity (H') according to Shannon-Weaver (1949) and phenotypic frequencies (classes) for spike characters as percentages of the number of qualitative observations for tetraploid (*T. durum*) wheat landrace accessions from Oman (for a class definition see Final Appendix 17).

Character	Phenotypic frequencies and classes							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**H'**
Spike shape	1.95	10.39	29.22	9.74	19.48	29.22		0.90
Spike awns	0.32	3.16	1.90	17.72	76.90			0.57
Directions of the awns	25.61	47.56	18.29	8.54				0.71
Colour of the awns	11.96		88.04					0.87
Rudeness of the awns	0.52	1.55	4.12	69.59	6.19	18.04		0.56
Roughness of the awns	0.87	1.74	88.70	8.70				0.33
Sector hairiness	0.87	2.04	97.08					0.22
Glume hairiness	6.92	34.62	3.08	50.00	5.38			0.78
Sector hairiness density	12.15	11.60	63.54	8.84	6.63	8.84		0.66
Glume shape	88.10	4.76	7.14					0.22
Glume shoulder shape width	34.18	7.59	35.44	6.33	7.59	8.86		0.56
Glume colour	68.63	11.76	7.84	11.76				0.32
Glume rigidity	0.53	8.47	87.30	3.70				0.41
Keel tooth roughness	95.80	4.20						0.00
Grains colour	0.65	1.31	3.92	81.05	13.07			0.47
Average								**0.52**

Table 3. Phenotypic diversity for spike characters of seventeen quantitative characters for tetraploid (*T. durum*) wheat landrace accessions from Oman (for a class definition see Appendix 18).

Character	Phenotypic frequencies and classes					H'
	1	2	3	4	5	
Spike length (cm)	17.95	79.49	2.56			0.53
Spike width (mm)	71.79	25.64	2.56			0.62
Spikelets number per spike	2.56	10.26	17.95	33.33	35.90	0.85
Spikelets sterile number per spike	69.23	25.64	5.13			0.46
First awn of spikelet, length (cm)	2.63	28.95	63.16	5.26		0.65
Second awn of spikelets, length (cm)	12.82	38.46	43.59	5.13		0.83
Spikelet length (mm)	2.56	51.28	46.15			0.72
Spikelet width (mm)	12.82	46.15	41.03			0.90
Number of grains per spikelet	2.56	92.31	2.56	2.56		0.26
Glume length (mm)	20.51	74.36	5.13			0.34
Lemma length (mm)	10.26	35.90	38.46	15.38		0.91
Palea length (mm)	53.85	43.59	2.56			0.72
Keel tooth length (mm)	46.15	51.28	2.56			0.72
Grain length (mm)	2.56	82.05	12.82	2.56		0.37
Grain width (mm)	17.95	76.92	5.13			0.60
Grain height (mm)	5.13	94.87				0.29
Spike density	17.95	43.59	17.95	15.39		0.80
Average						**0.66**

Table 4. 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 (*T. durum*) 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 5. 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 (*T. durum*) wheat landraces from Oman.

Character	PCA 1	PCA 2	PCA 3	PCA 4
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

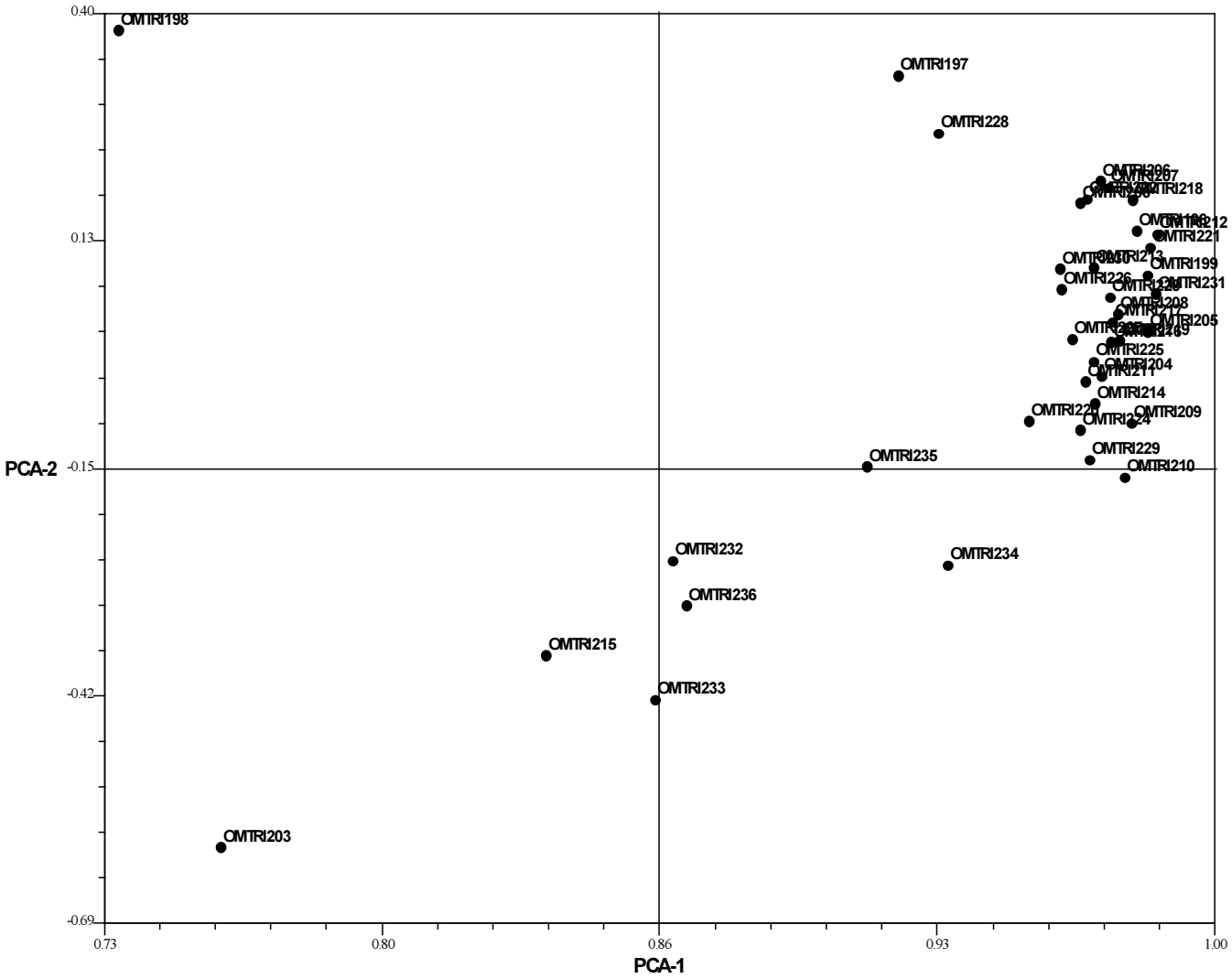

Figure 1. Scattergramme showing the results of a principal component analysis (PCA) of 17 quantitative characters of 39 tetraploid wheat landraces from Oman named according to the OMTRI (Oman Triticum) catalogue established by the author.

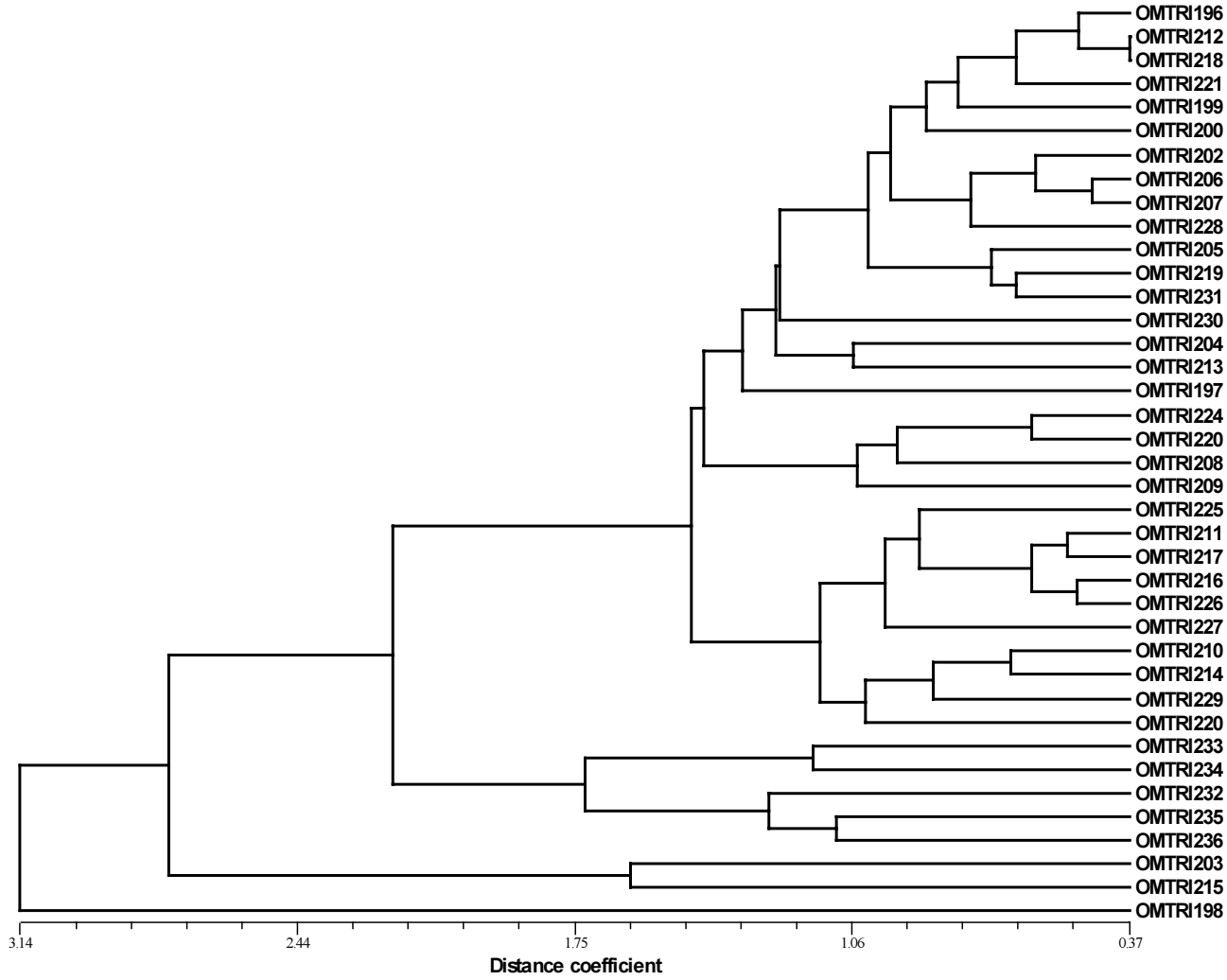

Figure 2. Dendrogramme showing the results (genetic distance) of a cluster analysis of 17 quantitative characters of 39 tetraploid wheat landraces from Oman.

3.2 Morphological spike diversity of Omani wheat: II. Hexaploid landraces

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Abstract

As the major staple after date palm (*Phoenix dactylifera* L.) hexaploid wheat has been cultivated in Oman since ancient times. Currently under economic heavy pressure, *Triticum* ssp. are still being grown in remote villages and mountain oases preserving largely unknown genepools of the past. The objective of this study was to morphologically evaluate these hexaploid wheat landraces and to compare their varietal compositions within and between the different districts of Oman. To this end 15 qualitative and 17 quantitative traits of 210 *aestivum* wheats collected during a survey from farmers' fields were examined. The results indicate that most traits were polymorphic. Across all accessions the standardized Shannon-Weavor diversity index (H') was 0.63 for qualitative and 0.62 for quantitative traits. For qualitative traits between-district H' was highest in Dakhilia (0.69) and lowest in Sharqia (0.57). Within-district H' was highest in Ibri-Dhahira (0.72) followed by Southern Batinah (0.71). Lowest within-district H' values were found in Taeen-Sharqia (0.30). For quantitative characters H' values differed only slightly between districts with the highest one found in Sharqia (0.72) and the lowest in Dhahira (0.66). Within-district H' values were highest in South Batinah (0.78) followed by Dank-Dhahira (0.74). The lowest within-district H' was found at Bahla-Dakhilia (0.58). There was no evidence for the predominance of specific landraces across the entire country. In contrast, the results indicate that there may have been substantial introgression between landraces at different ploidy levels leading to substantial morphological polymorphisms. This further enhanced the already high genetic diversity resulting from the likely widespread origin of Omani wheat landraces. The data also show that Omani wheats, despite their morphological overlaps, can be classified into their species and botanical varietal components with a high degree of certainty.

Key words: Archaeobotany, genetic diversity, introgression, oasis agriculture, Shannon-Weaver index

تنوع الوصف المظهري لسنابل القمح العماني
2. سلالات القمح السداسي

الملخص

يعد القمح من المحاصيل الغذائية الأساسية ويأتي بعد نخيل التمر المعروف باسم (*Phoenix dactylifera* L.) وله تاريخ عريق من الناحية الزراعية في عمان. بالرغم من الضغط الاقتصادي على السلالات القمح المحلية إلا إنها مازالت تزرع في كثير من القرى والواحات و المدرجات الجبلية. الهدف من الدراسة هو تقييم عينات السلالات من القمح السداسي ومقارنة السلالات داخل و بين المناطق العمانية باستخدام وتقييم الصفات المظهرية للسنبلة، حيث تم جمع 210 عينات و قسمت الصفات على حسب الشكل المظهري إلى 15 صفة نوعية و 17 كمية.

أوضحت النتائج للأدلة الوراثية (مؤشر) (diversity index) (H) أن هناك تنوعات وراثية عديدة في كل من الصفات الكمية والنوعية للسنابل؛ حيث كان الاختلاف (H) 0.62 و 0.63 على التوالي في كليهما. وأوضحت النتائج أن الصفات الكمية كانت مختلفة بصورة طفيفة بين المناطق، حيث كان أعلى معدل تباين (H) في الشرقية 0.72 وأقلها في الظاهرة (H) 0.66 أما الصفات النوعية فكان أعلاها في الداخلية (H) 0.69 وأقلها بمنطقة الشرقية (H) 0.57. وعند مقارنة داخل المنطقة وجد أن ولاية عبري بمنطقة الظاهرة تحتوى على أعلى تباين (H) 0.72 وتليها منطقة الباطنة (0.71) وأقلها ولاية دماء والطائيين بمنطقة الشرقية بمقدار (H) 0.30. أما بالنسبة إلى الصفات الكمية فوجدت مختلفة كذلك ولكن بنسب أقل من سابقتها, حيث وجد أعلاها بمنطقة جنوب الباطنة (H) 0.78 ثم ولاية الضنك بمنطقة الظاهرة (H) 0.74 وأقلها بولاية بهلاء بمنطقة الداخلية (H) 0.58. وقد اتخذت السنبلة أشكالا عدة، كان أغلبها ذو شكل كمضرب الكرة يليه الشكل الأسطواني والمغزلي، وبلغ أعلى توزيع تكراري في شكل السنبلة في منطقة الداخلية للشكل الأسطواني وبدرجة خشونة مرتفعة بالحسكة.وتباين لون الحبوب بدرجة كبيرة بين الأصناف حيث تراوح بين الأبيض إلى الأحمر إلى البني المحمر، فكان اللون السائد في منطقة الداخلية هو الأبيض (58%) و في الباطنة (57%) و الشرقية (40%) و الظاهرة (38%) هو الأحمر. ومن حيث الصفات الكمية فقد بلغ معدل تكرار طول الحب 83% في كل من الداخلية والشرقية، و98% في الباطنة و91% في الظاهرة وهي أعلى من بقية المناطق. غالبية السنيبلات بها 6 زهرات الخصبة منها 4 إلى 5 زهرات، ومعدل عدد السنيبلات بالسنبلة 23.5. والسنبلة ممتلئة بالحبوب ومتراصة. وتبلغ معدل طولها 7 سم. وتراوحت غالبية السنابل من المتوسط إلى، وتندر الأنواع ذات السنابل المتراخية في الأصناف العمانية. كان معدل الاختلاف الوراثي متماثلا بين الصفات الكمية والنوعية، وبالرغم من وجود اختلافات مظهرية ووراثية في

سلالات القمح المحلي؛ إلا أنه لم يلاحظ وجود سيادة وراثية لسلالة معينة من سلالات القمح المحلي. كذلك يمكن أن نستنتج أن هناك حالة تطورية في سلالات القمح المحلي وذلك لوجود تهجين بين سلالات القمح. ومع ذلك نستنتج بأنه يمكن التقييم و التصنيف بدرجة عالية باستخدام الصفات الوصفية الظاهرية للنباتات رغم وجود تنوع في المصادر الوراثية و الحيوية في القمح المحلي.

Introduction

West Asia is the primary centre of diversity for wheat (*Triticum* spp.) and barley (*Hordeum vulgare* L.), and most certainly the region in which these crops were first cultivated about 10,000 years ago (Zohary, 1969). In Oman hexaploid and tetraploid wheat has, as the major crop after date palm (*Phoenix dactylifera* L.), been cultivated in genetically heterogeneous landraces since ancient times in irrigated oasis agriculture across the country and under rainfed conditions in Mussandam and Dhofar. Thereby landraces are defined as populations exposed and adapted to century- or millennia-old farmer selection and to specific stresses. They contain a genetic variability that determines their ability to adapt to sudden changes in environmental conditions and makes them interesting for modern plant breeding efforts (Brush, 1995; Frankel and Brown, 1995; Allard, 1997; Mariana *et al.,* 2004).

Despite rapid modernization leading to the vanishing of many traditional production sites in remote areas, wheat landraces are still cultivated under the same archaic conditions as intervarietal and inter-species mixtures of *Triticum* spp. (Al-Maskri *et al.*, 2003; Hammer *et al.*, 2004; Alkhanjari *et al.*, 2005). Reasons for the still existing cultivation of ancient wheat landraces are their preferred taste for traditional dishes, their agronomic characteristics and their double purpose use as human food (grains) and animal fodder (straw; Millot *et al.*, 1981).

An understanding of the geographical distribution of genetic diversity is necessary to effectively manage and preserve crop germplasm *in situ.* Similarly, any analysis of plant diversity requires well defined sampling targets and habitats (Bekele, 1984; Ferguson *et al.*, 1998, Loveless and Hamrick, 1984). Genetic variation between and within landraces can be assessed by morphological, agronomical, biochemical or by molecular tools (Oliveira *et al.*, 1997; DeLacy *et al.,* 2000; Tranquilli *et al.*, 2000; Hammer *et al.*, 2004) whereby Sokal and Sneath (1963) and Stalker (1990) suggested that morphological characters can contribute much to the study of relationships between taxa and may thus be effectively used as an initial step in defining relationships that can subsequently be studied further.

Previous studies suggested that spike characters are little affected by the environment, which makes them particularly suitable as markers for germplasm characterization in landraces (Belay, 1997). The objective of this study therefore

was to compare the morphologically expressed diversity in *T. aestivum* landraces between and within districts, the major administrative units of Oman.

Materials and methods

Plant materials and morphological evaluation

In the two spring seasons of 2002 and 2003 several surveys were conducted across the four major wheat growing districts of Oman with their eleven regions (Figure 1) to collect a total of 210 of hexaploid wheats (Table 1). Most of their spikes were suitable for taxonomical characters and morphological characterization for which 15 qualitative and 17 quantitative traits were chosen after visual classification of all accessions according to the standard procedure developed by the Vavilov-Institute in St. Petersburg, Russia (Dorofeev *et al.*, 1979). From each accession comprising 2-5 heads, each single head was characterized and analyzed. 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, 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.

Data 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 (for details see the Final Appendix), and analyzed using the Shannon-Weaver diversity index (H; Shannon and Weaver, 1949) as defined by Jain *et al.* (1975) to calculate phenotypical variation for each accession:

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

where n is the number of phenotypic classes for a character and Pi is the genotype frequency or the proportion of the total number of entries in the i^{th} class.

The genetic diversity index is sensitive to both the type of phenotypic descriptor and number of descriptor classes used (Grenier *et al.*, 2004). 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 the 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).

Results and discussion

Morphological diversity

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. These values were lower than those reported by Bechere *et al.* (1996) and Eticha *et al.* (2005) for Ethiopian wheat where respective H'-values were 0.70 and 0.71.

For qualitative characters across-district H' ranged from 0.15 in keel tooth roughness to 0.79 in spike awns. For quantitative characters across-district H' ranged from 0.16 in grain length to 0.94 in glume length (Tables 2 and 3).

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. In Batinah and Dhahira lowest H'-values were found in keel tooth roughness and highest ones in awn roughness (0.96) and spike awns (0.94; Table 3).

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 4). 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 5). 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 between regions (Bekele, 1984; Bechere *et al.*, 1996; Pecetti and Damania, 1996). For tef (*Eragrostis tef*), however, Kebebew *et al.* (2003) reported for all measured traits a similarly large variation among populations regardless of the geographic unit.

Frequency distribution

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%).

It has been debated whether the function of the spike's hairiness is to protect it from insects and to prevent diseases (Warham, 1988; Jain *et al.*, 1975). 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 Eticha *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 (Eticha *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 4 to 5 being fertile. This let 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 a 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 (1986).

Multivariate analysis of phenotypic characters

In qualitative characters the first four principal components accounted for more than 99% of the total variation (Table 6). The dendrogramme constructed to describe the relationship among the landraces (Figure 2) divided the accessions into two main groups, in which the first group contained only accessions from Ibri and second one comprised a first subgroup with the three sub-subgroups of South Batinah, Taeen and Sohar (North Batinah). Within the second subgroup was Bahla (Dakhilia) and Yanqul (Dhahira) but there was no discrimination between 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 between 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.

Traditionally, the genetic diversity of germplasm has been described using morphological and agronomical traits (Vavilov, 1964), whereas nowadays molecular markers are available that many scientists feel are superior to morphological, pedigree, heterosis and biochemical data (Doebley, 1989; Melchinger *et al.*, 1991). Despite the often limited comparability of data from both methods, their combined interpretation would be most useful.

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Table 1. Distribution of the hexaploid wheat accessions collected in Oman.

District	Region	Number of accessions
Dairhah		
	Dank (DDH)	22
	Ibri (IDH)	38
	Yanqul (YDH)	35
Batinah		
	Sohar (SBT)	40
	Kabura (KBT)	11
	South Batinah (SOBT)	11
Dakhilia		
	Bahla (BDK)	16
	Al Hamra (HDK)	8
Sharqia		
	Al Raky (WSH)	13
	Maqta (MSH)	8
	Taeen (TSH)	8
Total		**210**

Table 2. Estimation of the standardized Shannon-Weaver diversity index (H') for 15 qualitative characters across four districts of Oman. DK = Dakhilia, SH = Sharqia, Bt = Batinah, DH = Dhahira.

	Total	**Districts**			
Qualitative character	**H**	**DK**	**SH**	**BT**	**DH**
Spike shape	0.73	0.89	0.85	0.86	0.76
Spike awns	0.79	0.97	0.89	0.71	0.94
Direction of the awns	0.59	0.95	0.00	0.70	0.71
Colour of the awns	0.75	0.47	0.85	0.63	0.86
Rudeness of the awns	0.60	0.95	0.96	0.60	0.62
Roughness of the awns	0.46	0.00	0.00	0.96	0.53
Hairness of the glume	0.70	0.35	0.66	0.75	0.63
Sector hairness	0.45	0.05	0.33	0.72	0.39
Sector thickness of haireness density	0.60	0.99	0.48	0.83	0.66
Glume shape	0.57	0.99	0.00	0.37	0.66
Glume shoulder shape width	0.73	0.95	0.79	0.68	0.77
Glume colour	0.77	0.93	0.94	0.78	0.68
Glume rigidity	0.71	0.58	0.79	0.37	0.78
Keel tooth roughness	0.15	0.40	0.16	0.30	0.17
Grain colour	0.70	0.92	0.81	0.64	0.74
Average	**0.62**	**0.69**	**0.57**	**0.66**	**0.66**

Table 3. Estimation of the standardized Shannon-Weaver diversity index (H') for 17 quantitative characters across four districts of Oman. DK = Dakhilia, SH = Sharqia, Bt = Batinah, DH = Dhahira.

	Total	Region			
Quantitative character	**H**	**DK**	**SH**	**BT**	**DH**
Spike length (cm)	0.57	0.74	0.81	0.82	0.63
Spike width (mm)	0.64	0.87	0.68	0.86	0.89
Spikelet number per spike	0.65	0.63	0.69	0.68	0.68
Number of sterile spikelets at base	0.68	0.58	0.68	0.70	0.63
Length of first awn of spikelet (cm)	0.59	0.99	0.87	0.40	0.47
Length of second awn of spikelet (cm)	0.81	0.92	0.91	0.81	0.72
Spikelet length (mm)	0.76	0.86	0.83	1.00	0.69
Spikelet width (mm)	0.83	0.83	0.73	0.86	0.83
Number of grains per spikelet	0.41	0.43	0.47	0.50	0.46
Sector length (mm)	0.83	0.94	0.96	0.87	0.80
Glume length (mm)	0.94	0.99	0.98	0.94	0.89
Lemma length (mm)	0.70	0.78	0.96	0.72	0.85
Palea length (mm)	0.66	0.64	0.70	0.66	0.64
Keel tooth length (mm)	0.77	0.99	0.73	0.68	0.79
Grain length (mm)	0.43	0.44	0.40	0.46	0.44
Grain width (mm)	0.16	0.00	0.32	0.31	0.26
Grain height (mm)	0.34	0.34	0.46	0.07	0.50
Average	**0.63**	**0.70**	**0.72**	**0.67**	**0.66**

Table 4. Estimation of the standardized Shannon-Weaver diversity index (H') for 15 qualitative characters between regions within four districts of Oman. 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.

	Region										
Qualitative character	**YDH**	**DDH**	**IDH**	**SOBT**	**CEBT**	**NOBT**	**BDK**	**HDK**	**MSH**	**TSH**	**WBK**
Spike shape	0.89	0.82	0.74	0.88	0.68	0.79	0.95	0.86	0.94	0.73	0.81
Spike awned	0.74	0.87	0.70	0.90	0.44	0.89	0.00	0.70	0.87	0.83	0.91
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
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
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
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
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
Sector hairiness	0.48	0.59	0.81	0.94	0.81	0.68	0.00	0.34	0.95	0.65	0.60
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
Glume shape	0.51	0.77	0.18	0.55	0.00	0.17	0.00	0.99	0.00	0.00	0.00
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
Glume colour	0.24	0.77	0.65	0.83	0.75	0.80	0.95	0.34	0.89	1.00	0.66
Glume rigidity	0.19	0.32	0.48	0.00	0.00	0.21	0.95	0.78	0.54	0.00	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
Grain colour	0.79	0.82	0.98	0.81	0.00	0.41	0.67	0.85	1.00	0.00	0.95
Average	**0.59**	**0.70**	**0.72**	**0.71**	**0.41**	**0.54**	**0.35**	**0.69**	**0.62**	**0.30**	**0.56**

3.2 Morphological spike diversity: II. Hexaploid wheat landraces

Table 5. Estimation of the standardized Shannon-Weaver diversity index (H') for 17 quantitative characters between regions within four districts of Oman. 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.

	Region										
Character	**YDH**	**DDH**	**IDH**	**SOBT**	**CEBT**	**NOBT**	**BDK**	**HDK**	**MSH**	**TSH**	**WBK**
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
Average	**0.72**	**0.74**	**0.73**	**0.78**	**0.66**	**0.71**	**0.58**	**0.66**	**0.66**	**0.62**	**0.60**

Table 6. Eigenvectors, Eigenvalues, total variance and cumulative variance of the first four principal components (C1 to C4) of 17 quantitative characters of 210 *Triticum aestivum* 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

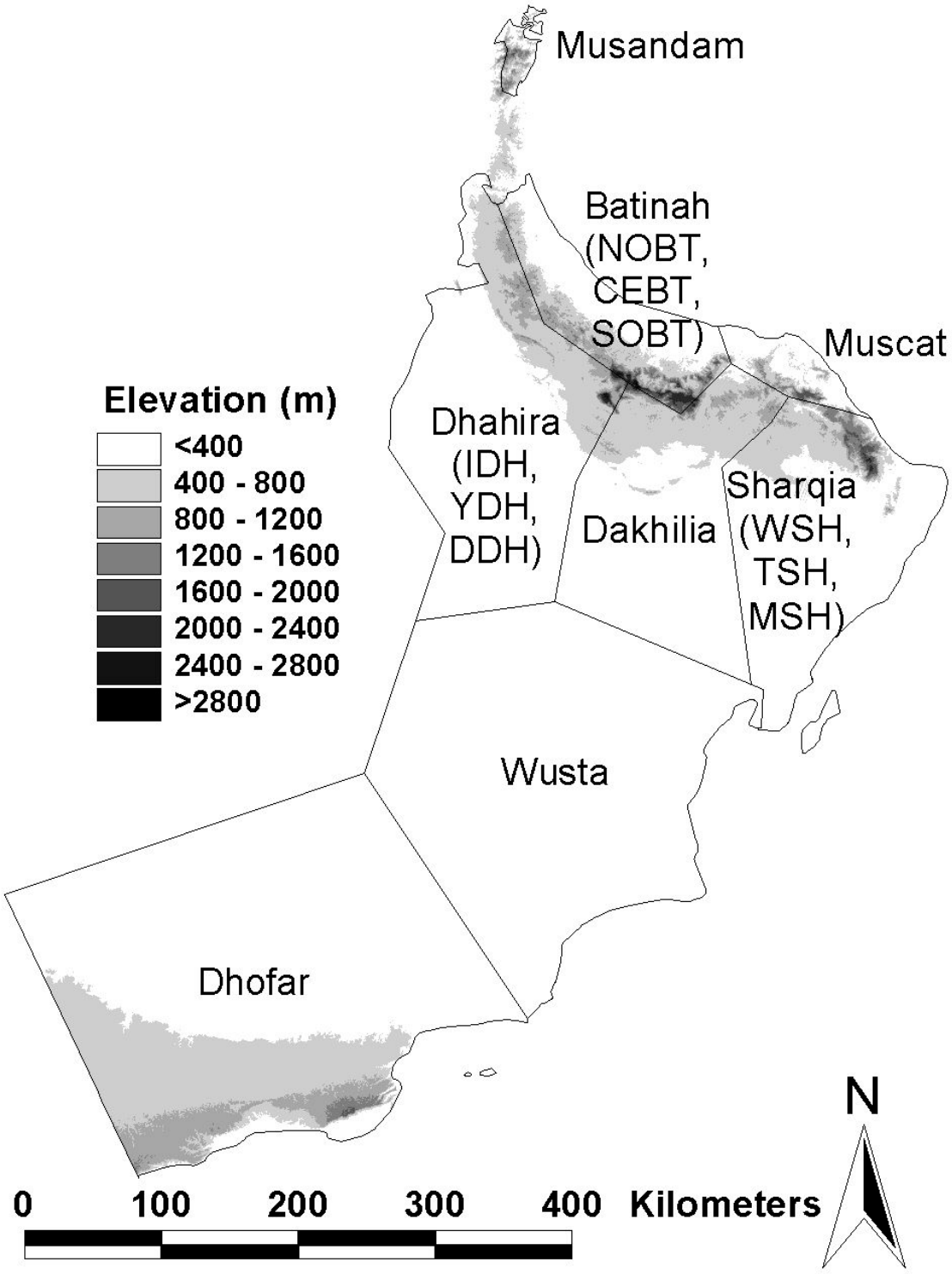

Figure 1. Map of Oman indicating the districts where the hexaploid wheat landraces were collected.

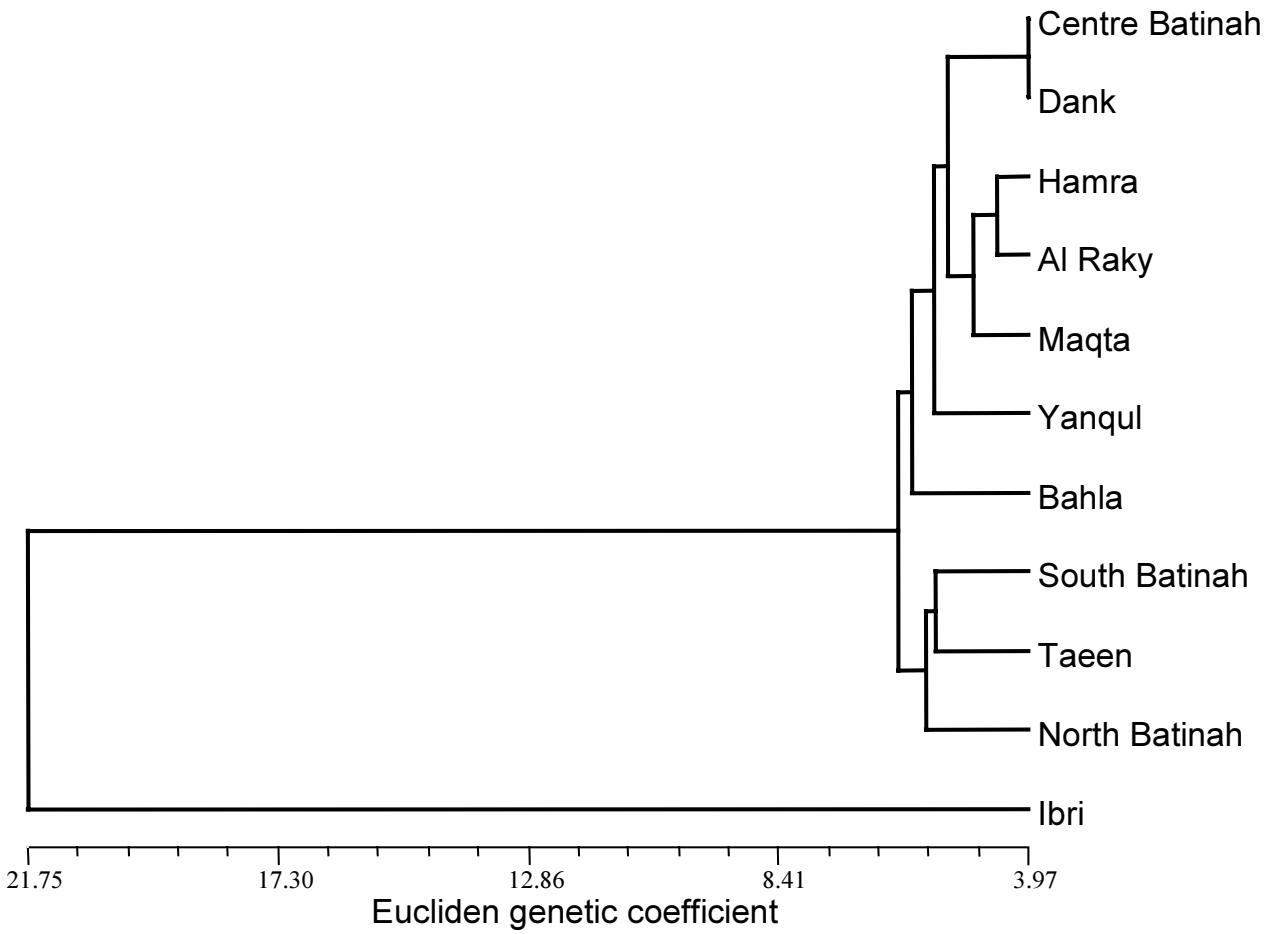

Figure 2. Dendrogramme showing the clustering patterns in phenotypic variation of 17 quantitative characters of 210 hexaploid wheat accessions from 11 regions of Oman.

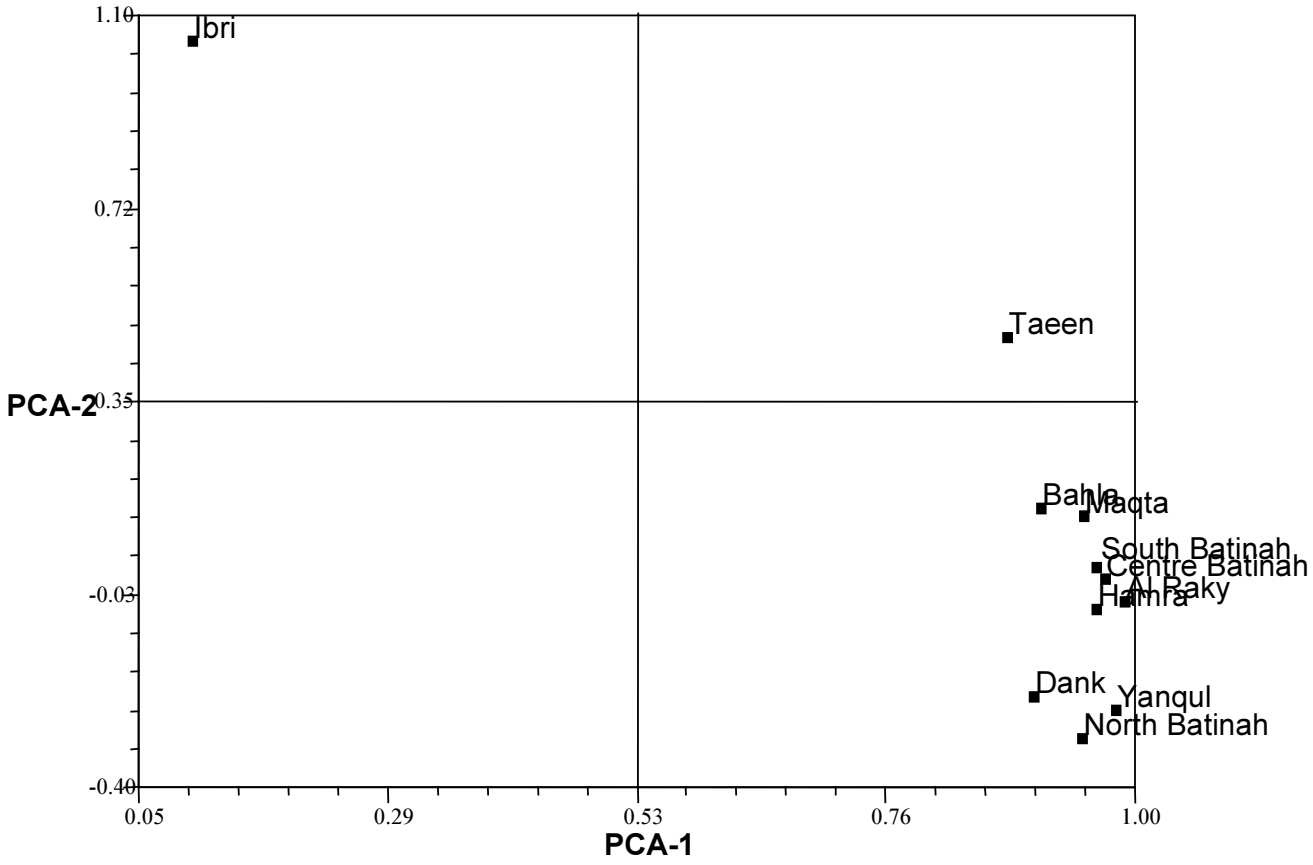

Figure 3. Principal component analysis (PCA)-based grouping pattern of 11 regions in Oman from where 210 hexaploid wheat landrace accessions were collected and analysed for 17 quantitative characters.

4

Molecular diversity

4.1 Molecular diversity of Omani wheat revealed by microsatellites: I. Tetraploid landraces

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Abstract

Results of archaeological studies indicate a millenia-old cultivation history for wheat (*Triticum* spp.) in Oman. However, despite of numerous collection surveys and efforts for phenotypic characterization of Omani wheat landraces, no attempts have been made to use modern, molecular tools to characterize this germplasm. To fill this gap, 29 microsatellite markers revealing 30 loci were used to study the gene diversity of 38 tetraploid wheat landrace accessions comprising the species *T. dicoccon, T. ispahanicum, T. durum and T. aethiopicum*. A total of 219 alleles were detected whereby the number of alleles per locus ranged from 2 to 16 with an average number of 7.1 alleles per locus. The highest number of alleles occurred in the B genome with on average 7.9 alleles per locus as compared to the A genome with 6.5 alleles per locus. Heterogeneity (heterozygosity) was detected for all microsatellites except for *GWM 312*, *GWM 601*, and *GWM 192B* with an average heterogeneity over all primers and lines of 14.4%. Approximately 10% of the accessions contained rare alleles with an average allele frequency < 4%. Gene diversity across microsatellite loci ranged from 0.26 to 0.85. The pairwise comparison of genetic similarity ranged from 0.03 to 0.91 with an average of 0.2. Cluster analysis revealed a clear separation of the two species groups *T. dicoccon* and *T. ispahanicum versus T. durum* and *T. aethiopicum*. Within the species clusters regional patterns of subclustering were observed. Overall, this study confirmed the existence of a surprisingly high amount of genetic diversity in Omani wheat landraces as already concluded from previous morphological analyses and showed that SSR markers can be used for landraces' analysis and reliable diversity evaluation.

Key words: Gene diversity, molecular markers, *Triticum* spp.

التنوع في الجزيئات الوراثية للقمح العماني باستخدام المعلمات الوراثية أحادية الجزيئية (microsatellites)

1. سلالات القمح الرباعي

الملخص

يرجع تاريخ زراعة القمح في عمان لعصور عابرة كما تشير عدد من دراسات الآثار، وحتى الآن لم يتم تقييم وتصنيف القمح العماني من الناحية الوراثية، و تعتبر هذه الدراسة من أول الدراسات لتقييم التنوع الوراثي للقمح العماني باستخدام المعلمات الوراثية احادية الجزيئية **(microsatellites)**. في هذه الدراسة تم استخدام 29 من المعلمات الجزيئية الوراثية حيث تم استكشاف 30 موقعا وراثيا لتحليل الاختلافات الوراثية ل 38 سلالة من القمح المحلي الرباعي من أنواع: (***T. dicoccon, T. ispahanicum*** و***T. durum, T.aethiopicum***)

وتم تمييز 219 أليلا و تراوح عدد الأليلات في كل موقع ما بين 2 و 16 بمتوسط 7.06 أليلا لكل موقع. أما على مستوى الجينوم "**genome**" فكان أعلى بالجينوم (ب) بمعدل 7.88 أليلا لكل موقع و أقل بالجينوم (أ) بمعدل (6.54). وكما أظهرت النتائج وجود وحدات هجينة لكل المعلمات الوراثية أحادية الجزيئية ماعدا المعلمات الآتية: **GWM 312** و **GWM 601** و **GWM 192B** وكانت الهجينة منها 14.4 % و النادرة 10% و الفريدة أقل من 4%.

أما الاختلافات الجينية لكل النباتات فإنها تتراوح بين 0.26 و 0.85 وكان تشابه الجينات يتراوح بين 0.03 و0.91 و بمتوسط 0.2. وأبرز التحليل العنقودي **(cluster analysis)** للمقارنات بين السلالات وداخل الصنف ظهور مجموعتين: الأولى ***T. dicoccon, T. ispahanicum*** و الثانية ***T. durum*** و ***T.aethiopicum*** و تتوافق هذه النتائج مع النتائج السابقة في تحليل الوصف المظهري للقمح المحلي العماني.

وخلاصة فإن هذه الدراسة بينت التنوع الوراثي الكبير في أصناف القمح العماني، كما بينت إمكانية استخدام المعلمات الجزيئية الوراثية **SSR** في تحليل الأصناف المحلية بدرجة ثبات عالية.

Introduction

Wheat (*Triticum* spp.) is the world's most important crop based on cultivation area and the second most important after maize (*Zea mays* L.) in total production (FAO, 1999). In Oman, where it is traditionally cultivated in remote mountain oases and used for human consumption and medicinal purposes, wheat has a long cultivation history as indicated by numerous archaeological studies conducted on the Arabian Peninsula. The carbonized rachises and seeds found at archaeological sites dates back to 3,500 or even 5,000 BC (Willcox and Tengberg, 1995; Potts, 1993). These archaeological studies provide evidence that wheat was first introduced through trade from ancient Mesopotamia (Willcox and Tengberg, 1995). Subsequently, the introduced germplasm experienced evolutionary modifications resulting from natural selection and adaptation to the harsh desert environment prevailing in the country (Zohary and Hopf, 1993).

In the past most assessments of genetic diversity of germplasm were based on morphological traits or isozyme analysis. However, morphological traits may not be sufficient to discriminate significantly between accessions and their expression often depend on environmental conditions. An understanding of the overall patterns of genetic diversity and the distribution of genetic variability in a crop species is useful for germplasm conservation efforts. It also facilitates the selection of parents with diverse genetic background thereby rendering crop improvement programmes more efficient.

The power of molecular markers as powerful tools to evaluate the genetic diversity of germplasm is increasingly recognized (Szabó and Hammer, 1995; Melchinger *et al.*, 1991, 1994). Such markers have been used to trace the geographic origins of accessions by comparing genetic fingerprints of diverse material (Wei *et al.*, 2003; Salamini *et al.*, 2002; Baek *et al.*, 2003) and to classify germplasm resources (Zhang *et al.*, 2004; Alamerew *et al.*, 2004). Microsatellites are, compared to other marker types, abundant, ubiquitous in presence, possess a high polymorphism information content (PIC) and are often multiallelic (Röder *et al.*, 1995; Gupta *et al.*, 1996). A limited number of microsatellite markers is often sufficient to detect differences even in very closely related wheat genotypes (Plaschke *et al.*, 1995). Furthermore, a large number of wheat microsatellite markers have been developed which are widely used in genomic mapping,

population and evolutionary studies, as well as for fingerprinting and pedigree analyses (Röder *et al.*, 1998; Röder *et al.*, 2004).

Crop diversity studies using molecular markers have been conducted in different cereals such as barley (*Hordeum vulgare* L.; Macaulay *et al.*, 2001; Matus and Hyes, 2002; Koebner *et al.*, 2003), rice (*Oryza sativa* L.; Ishii and McCouch, 2001; Temnykh *et al.*, 2001), maize (*Zea mays* L.; Mumm and Dudley, 1994; Smith *et al.*, 1997; Lu and Bernardo, 2001), in winter triticale (*Triticosecale* Wittm.; Tams *et al.*, 2004) and in wheat (*Triticum* spp. Donini *et al.*, 2000; Prasad *et al.*, 2000; Russell *et al.*, 2000; Röder *et al.*, 2002; Huang *et al.*, 2002; Eujail *et al.*, 2002; Soleimani *et al.*, 2002). Microsatellites have a high potential for genome analyses of self-pollinating crops because of their specific properties and their high degree of polymorphism (Plaschke *et al.*, 1995; Röder *et al.*, 1995). Genetic variation in the studied crop can be detected by primers flanking the microsatellite locus in the selected DNA sequences (Johansson *et al.*, 1992; Rongwen *et al.*, 1995).

Given its overall limited economic importance for small-scale farmers and the remoteness of most cultivation sites, no attempt has been made so far to characterize Omani wheat by molecular means. This study was therefore conducted to evaluate the genetic diversity of Omani tetraploid wheat landraces collected across the country, using microsatellites (SSR) as molecular markers.

Materials and methods

Plant material

A total of 38 tetraploid wheat landraces were collected from different cultivation areas of Oman (Figure 1; Table 1). Several seeds of representative spikes of all accessions were sown for further study at the greenhouse of the Institute of Plant Genetics and Crop Plant Research (IPK), Gatersleben, Germany.

DNA extraction Polymerase chain reaction amplification

Total genomic DNA was extracted from pooled leaves of six seedlings derived from six seeds of any one spike. The extraction was performed according to Fulton *et al.* (2000) with an extraction buffer described by Plaschke *et al.* (1995). Amplifications by polymerase chain reaction (PCR) were performed as described by Röder *et al.* (1998). The PCR reaction substrate contained 50-100 ng template DNA, 250 nM cy5-labelled forward primer, 250 nM unlabelled reverse primer, 0.2

mM dNTPs, PCR buffer with a final concentration of 1.5 mM $MgCl_2$ and 1 U *Taq* DNA polymerase in a total volume of 25 µl. Fragment detection was performed as described by an Automated Laser Fluorescence (ALFexpress) sequencer (Amersham Biosciences) and fragment sizes were calculated using the computer programme Fragment Analyser 1.02 (Amersham Biosciences) by comparison with internal size standards (Röder *et al.*, 1998). In the case of weak or lacking fragment products, PCR amplifications were repeated to exclude failed PCR reaction as the cause of a null allele.

Microsatellite loci

Twenty-eight Gatersleben Wheat Microsatellites (GWM) and one microsatellite from a pseudogliadine gene, *Taglgap*, representing approximately two markers for each chromosomes of the A and B genomes were used in the study (Table 2). These microsatellite primers were described by Röder *et al.* (1998) and the primer *Taglgap* by Devos *et al.* (1995). Microsatellite loci *GWM337-1DS, GWM157-2DL, GWM3-3DS, GWM190-5DS, GWM325-6DS and GWM4377DL* that represent the D genome were used to check for the presence of mixtures of hexaploid accessions in the Omani tetraploid wheat landraces. These primers failed to amplify fragments from all lines except for the hexaploid standards.

Data analysis

The presence and absence of specific microsatellite alleles was scored in a binary data matrix. The wheat varieties Chinese Spring and Aztec were used as controls to standardize different gel runs. The gene diversity also called polymorphism information content (PIC) was computed according to Nei (1973) as:

$$PIC = 1 - \sum P^2_{ij}$$

where P_{ij} is the allele frequency of the *j*th allele for the *i*th marker summed over numbers of alleles. Anderson *et al.* (1993) suggested that gene diversity is the same as the polymorphism information content (PIC). Genetic Similarity (GS) was calculated as:

$$GS = 2Nij / (Ni + Nj)$$

where *Nij* is the number of fragment common to lines *i* and *j*, and *(Ni+Nj)* is the total numbers of fragment in both lines.

All fragments were used to generate a genetic similarity matrix with the software NTSYS (Numerical Taxonomy and Multivariate Analysis System, vers. 2.1 for PC (Rohlf, 2002). The relationships among accessions were analyzed using the unweighted pair-group method (UPGMA) and principle component analysis (PCA; Sneath and Sokal, 1973). The ordination analysis was carried out using the similarity coefficient introduced by Dice (1945).

Results

Analysis of allelic diversity by microsatellites

A total of 219 alleles was detected with the 29 microsatellites markers for 30 loci used to evaluate and characterize the genetic diversity of the 38 tetraploid wheat landraces of Oman. The number of alleles per locus ranged from two for *GWM752*, *GWM619* and sixteen from *GWM192a* to *GWM186* with an average number of 7.3 alleles per locus (Table 2). All microsatellites used in this study yielded polymorphic fragments for the evaluated accessions. At the genome level, a larger number of alleles per locus occurred in the B genome (7.88 alleles per locus) compared to the A genome (6.54 alleles per locus).

Heterogeneity represented by more than one amplification product for one microsatellite locus was detected in all microsatellites except for *GWM312*, *GWM601* and *GWM192B* (Table 2). The average of the heterogeneity estimated over all 30 primers was 14.4% and represents the heterogeneity within durum landraces investigated as bulked DNA from six plants in the analysis. A particularly large amount of heterogeneity was present in the accessions *T. durum* var. *affine* (OMTRI 198) and *T. aethiopicum* var. *bialbum* (OMTRI199). Both were collected in the Khabura region in the Centre of the Batinah district.

Rare alleles were detected across all microsatellite loci. Ten percent of the investigated accessions contained rare alleles which occurred only once. In total, 51 different rare alleles were detected ranging from one rare allele per locus (*GWM357, GWM192b* and *GWM427*) to 5 alleles per locus (*GWM577* and *GWM 720*) with an average frequency of rare alleles of 4% (Table 2).

Some primers *GWM268, GWM655, GWM601, GWM192B, GWM898, GWM219* and *GWM577* were unable to produce fragments in some accessions (Table 2). Before considering them as null alleles, the experiments were repeated. However, in all cases no fragments were detected and the null alleles appeared therefore as

truly existing. The polymorphism information content (PIC) across the 30 microsatellite loci ranged from monomorphic for *GWM415* to 0.85 for *GWM268* (Table 2). The B genome was with a PIC value of 0.69 more polymorphic than genome A (0.58). The correlation coefficient over the 30 microsatellites loci, calculated to evaluate the relationship between the gene diversity and number of alleles, was 0.54 (Figure 2). This indicated a significant correlation between gene diversity and numbers of alleles in all accessions.

Cluster analysis

The genetic similarity (GS) values between accessions were used to produce a dendogramme. The analysis was derived from a UPGMA cluster analysis which helps to explain the relationship between landraces. The genetic similarity level ranged from 0.09 for OMTRI 216 (*T. aethiopicum* var. *syrovatski*) and OMTRI 217 (*T. aethiopicum* var. *syrovatski*) and 0.97 for OMTRI 192 (*T. ispahanicum*) and OMTRI 201 (*T. aethiopicum* var. *comitans*).

Cluster analysis allowed to discriminate two major groups. The first cluster consisted only of emmer wheat *(T. dicoccon* and *T. ispahanicum)*, while the second cluster comprised and other botanical varieties (Figure 3). The second cluster contained several subclusters which partly represented the geographical distribution of the collection sites. One subcluster contained accessions collected in the districts of Dakhilia (*OMTRI 19A, 19B*), Dhahira (OMTRI 220 and 221) and Sharqia (OMTRI 215, 216 and 217). Another subcluster combined two accessions from the Dhahira district (OMTRI 218 and 219) with two accessions collected in the Musandam district (OMTRI 222 and 223) and one accessions from the Batinah district (OMTRI 213). The other subclusters were represented by accessions from the Batinah district, which present the majority of the collected accessions. Here also subclustering was observed, for example for accessions collected at Sohar (OMTRI 208-213) or accessions collected at Khabura (OMTRI 196-201).

Similar to the cluster analysis also PCA separated the accessions into two groups with *T. dicoccon and T. ispahanicum vs. T. durum and T. aethiopicum* confirming the results of the UPGMA clustering. The first three principle components accounted for 54.1% of the total variation in the microsatellite markers.

Discussion

A total of 219 alleles were generated from 38 cultivated tetraploid wheat landraces using 29 microsatellite markers. The average number of alleles was 7.3 and genome B was more polymorphic than A. These results were similar to previous studies in wheat (Figliuolo and Perrino, 2004) who reported that 15 markers produced 63 bands with an average of 7.7 alleles. Moreover, Teklu *et al.* (2005) reported a higher number of alleles per locus for *T. durum* than for *T. turgidum* and *T. dicoccon*. Their 29 SSR markers revealed 320, 202 and 271 alleles in *T. durum*, *T. dicoccon* and *T. turgidum* landraces, respectively. The average number of alleles per locus was 11.0 in *T. durum*, 7.0 in *T. dicoccon* and 9.3 *in T. turgidum* wheats. On the other hand Eujayl *et al.* (2001) found an average of 5.5 alleles per locus with 64 genotypes. Bertin *et al.* (2001) detected an average number of 5.2 alleles per locus in spelt wheat (*T. spelta* L.), and Ben Amer *et al.* (2001) used 24 wheat microsatellites to estimate 15 Libyan wheat genotypes thereby detecting 116 alleles with an average of 4.5 alleles per locus. The occurrence of null alleles in the material of our study was also observed in earlier work (Röder *et al.*, 2002, Ben Amer *et al.*, 2001; Alamerew *et al.*, 2004; Teklu *et al.*, 2005). In general, the present study confirmed the presence of a high genetic diversity in Omani wheat landraces as it was suggested by previous investigations of morphological diversity (Al-Maskri *et al.*, 2003; Hammer *et al.*, 2004).

The average gene diversity obtained in the present investigation was 0.64. These results confirm earlier studies in tetraploid wheat species from Ethiopia using microsatellite analysis where the average gene diversity across the 29 microsatellite loci was 0.68 for *T.* durum, 0.616 for *T. dicoccon* and 0.688 for *T. turgidum* wheat (Teklu *et al.*, 2005). The results were also similar to those reported by Khlestkina *et al.* (2004) who showed an averaged gene diversity of 0.70 in 54 Siberian wheats. Anderson *et al.* (1993) found a PIC of 0.71 in spring wheat varieties. In his study of 105 Argentinean wheat varieties Manifesto *et al.* (2001) found an average gene diversity of 0.72 compared to a PIC value in European wheat varieties reported by Röder *et al.* (2002). Huang *et al.* (2002) characterized 998 wheat accessions at the Gatersleben gene bank and reported a gene diversity of 0.77. All of these values were high compared to a gene diversity of 0.24 for winter wheat reported by Bohn *et al.* (1999).

The rather high genetic diversity in the Omani durum landraces could be the result of its long cultivation history in relatively isolated mountain oasis systems which enhanced the effects of natural and artificial selection on germplasm diversity.
Gene diversity per locus showed a linear correlation with the number of alleles. These results confirm previous findings by Huang *et al.* (2002) and Roussel *et al.* (2004). On the other hand, Prasad *et al.* (2000) reported that the PIC value was not correlated with the number of alleles. The levels of heterozygosity found in our germplasm were similarly high than those reported by Alamerew *et al.* (2004) and Röder *et al.* (2002) for Ethiopian and European wheats but much higher than those found by Kudryavtsev *et al.* (2004) for his Russian *T. durum* varieties.
The cluster analysis was able to differentiate the Omani landraces into two major groups, emmer wheat and other *Triticum* spp. Moreover, in the dendrogramme, accessions belonging to *Triticum aethiopicum* were mostly grouped together in clusters indicating the uniqueness of this group from others. Khlestkina *et al.* (2004) and Huang *et al.* (2002) reported that not all accessions originating from the same geographic region clustered in the same group. These findings are in agreement with the current study. In contrast, Ben Amer *et al.* (2001) showed that clustering of accessions can be strongly related to geographic origin and ploidy level of the germplasm.

Conclusions

The molecular analyses of tetraploid wheats reported in this study confirm earlier morphological work showing a surprisingly high diversity in traditional landraces from Oman. This likely reflects the effects of the germplasm's millennia-old selection history and of the many agro-environmental niche environments in remote mountain oases. The study also shows the power of microsatellites in discriminating landraces and revealing heterogeneity from individual accessions. Finally it calls for continued efforts to further study and preserve Omani wheats *in-situ* and *ex-situ* through proper policy measures.

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Table 1. List of *Triticum durum* accessions collected from different districts of Oman with their catalogue number (OMTRI) and botanical name.

OMTRI	Collection district	Botanical name
192	Batinah (BT)	*T. ispahanicum*
193		*T. ispahanicum*
195		*T. aethiopicum*
196		*T. durum* var. *africanum*
197		*T. durum* var. *africanum*
198		*T. durum* var. *affine*
199		*T. aethiopicum* var. *bialbum*
200		*T. aethiopicum* var. *comitans*
201		*T. aethiopicum* var. *comitans*
202		*v.n.*[+]
203		*T. aethiopicum* var. *hajirense (nom. nud.)*
204		*T. durum* var. *africanum*
205		*T. aethiopicum* var. *densifulvum*
206		*T. durum* var. *africanum*
207		*T. durum* var. *melanopus*
208		*T. durum* var. *mahsinense (nom. nud.)*
209		*T. aethiopicum* var. *comitans*
210		*T. aethiopicum* var. *syrovatskyi*
211		*v.n.*
212		*T. aethiopicum* var. *comitans*
213		*T. aethiopicum* var. *pseudorarum*
218	Dhahira (DH)	*T. aethiopicum* var. *comitans*
219		*T. aethiopicum* var. *syrovatskyi*
220		*v.n.*
221		*v.n.*
25	Dakhilia (DK)	*T. dicoccon* ssp. *asiaticum* var. *haussknechtianum*
23		*T. dicoccon* ssp. *asiaticum* var. *haussknechtianum*
19A		*T. aethiopicum* var. *tchertchericum*
19B		*T. aethiopicum* var. *tchertchericum*
194	Dhofar (DO)	*T. dicoccon*
222	Musandam (MS)	*T. aethiopicum* var. *pilosinigrum*
223		*T. aethiopicum* var. *tchertchericum*
24	Sharqia (SH)	*T. dicoccon* ssp. *asiaticum* var. *haussknechtianum*
29		*T. dicoccon* ssp. *asiaticum* var. *aeruginosum*
214		*T. aethiopicum* var. *syrovatskyi*
215		*v.n.*
216		*T. aethiopicum* var. *syrovatskyi*
217		*T. aethiopicum* var. *syrovatskyi*

[+] *v.n.* = unidentified (potentially new) botanical variety

Table 2. Thirty wheat microsatellite loci (GWM) of known chromosomal location used to evaluate allele variation, product size (bp), number of alleles (rare alleles), gene diversity (PIC) and percentage of heterogeneity per locus in Omani durum wheat landraces.

GWM Chromosomal location	Range of allele size (bp)	No. of alleles (rare alleles)	PIC	Heterogeneity per locus (%)
Xgwm 357 – 1AL	118-126	6 (1)	0.643	2.63
Xgwm 752 – 1AS	121-123	2 (1)	0.411	5.26
Xgwm 268 – 1BL	Null, 177-24	11 (4)	0.851	5.26
Xgwm 18 – 1BS	177-189	7	0.769	15.79
Taglap – 1BS	232-271	8 (2)	0.742	15.79
Xgwm 148 – 2BL	141-167	10 (2)	0.575	34.21
Xgwm 312- 2AL	204-250	8 (2)	0.753	0.00
Xgwm 95 – 2AS	108-122	6	0.722	5.26
Xgwm 619 – 2BL	143-155	2	0.260	18.42
Xgwm 155 – 3AL	129-149	7	0.757	23.68
Xgwm 720 – 3AS	130-168	12 (5)	0.733	21.05
Xgwm 655 – 3BL	Null, 160-174	6 (2)	0.585	7.89
Xgwm 389 – 3BS	102-156	12 (2)	0.771	39.47
Xgwm 160 – 4AL	176-1186	5 (1)	0.563	10.53
Xgwm 192 – 4AL	128-134	2	0.303	7.89
Xgwm 601 – 4AS	Null, 150-160	8 (2)	0.819	0.00
Xgwm 192 – 4BL	Null, 197-209	7 (1)	0.801	0.00
Xgwm 513 – 4BL	139-149	6	0.535	36.84
Xgwm 898 – 4BS	95-119	7 (2)	0.318	31.58
Xgwm 186 – 5AL	Null, 94-152	16 (2)	0.744	76.32
Xgwm 415 – 5AS	126-132	2	0.000	5.26
Xgwm 408 – 5BL	147-193	6	0.658	15.79
Xgwm 540 – 5BS	126-130	3	0.467	10.53
Xgwm 427 – 6AS	186-212	6 (1)	0.609	23.68
Xgwm 219 – 6BL	Null, 120-184	14 (8)	0.983	7.89
Xgwm 680 – 6BS	126-132	2 (4)	0.767	21.05
Xgwm 631 – 7AS	190-202	5	0.527	13.16
Xgwm 297 – 7b(C)	152-178	10 (5)	0.823	21.05
Xgwm 577 – 7BL	Null, 126-210	13 (2)	0.959	28.95
Xgwm 333 -7BL	148-168	10	0.813	5.26
Minimal		**2**	**0.00**	
Maximal		**16**	**0.96**	
Total		**219 (51)**	**19.26**	
Average		**7.3 (1.7)**	**0.64**	

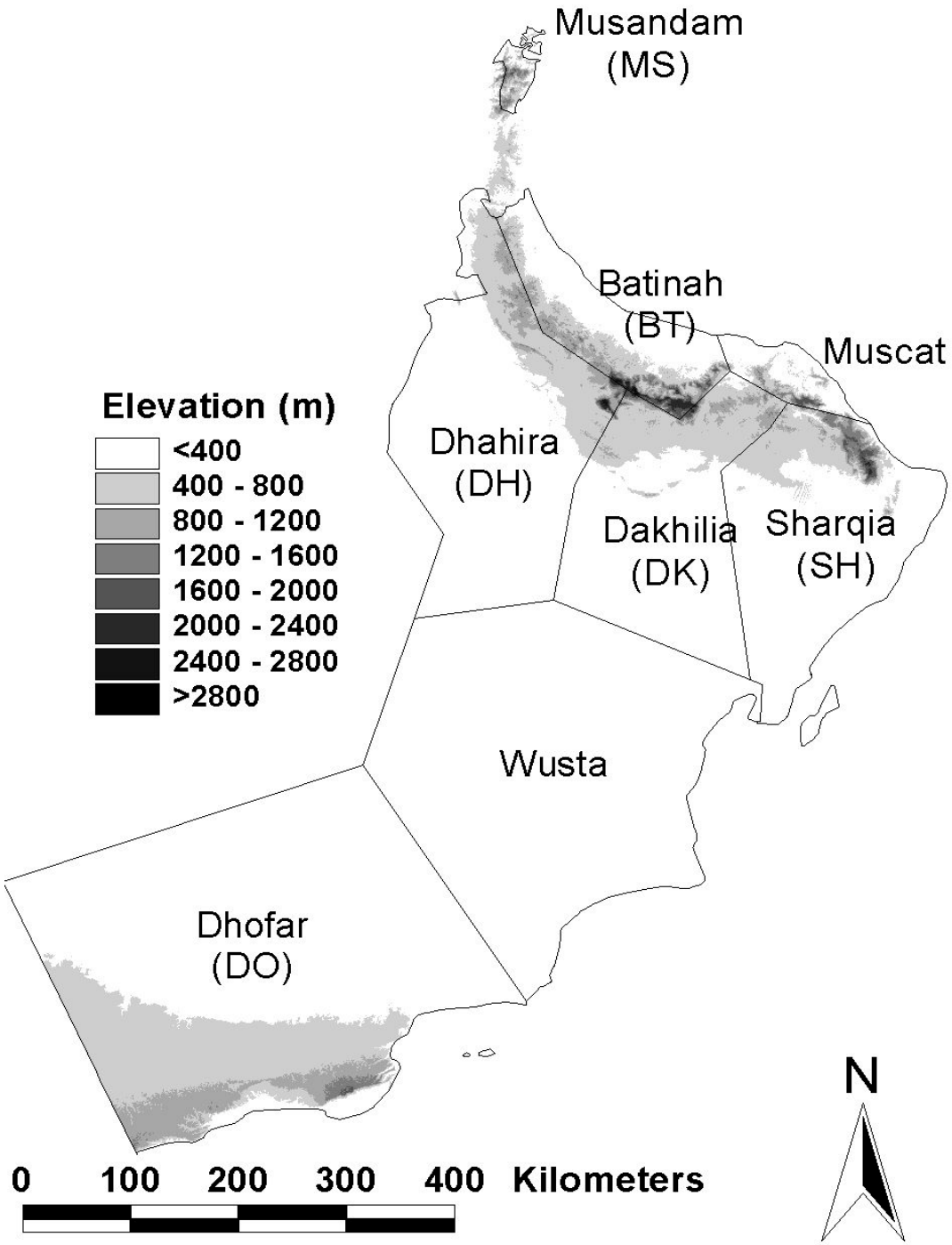
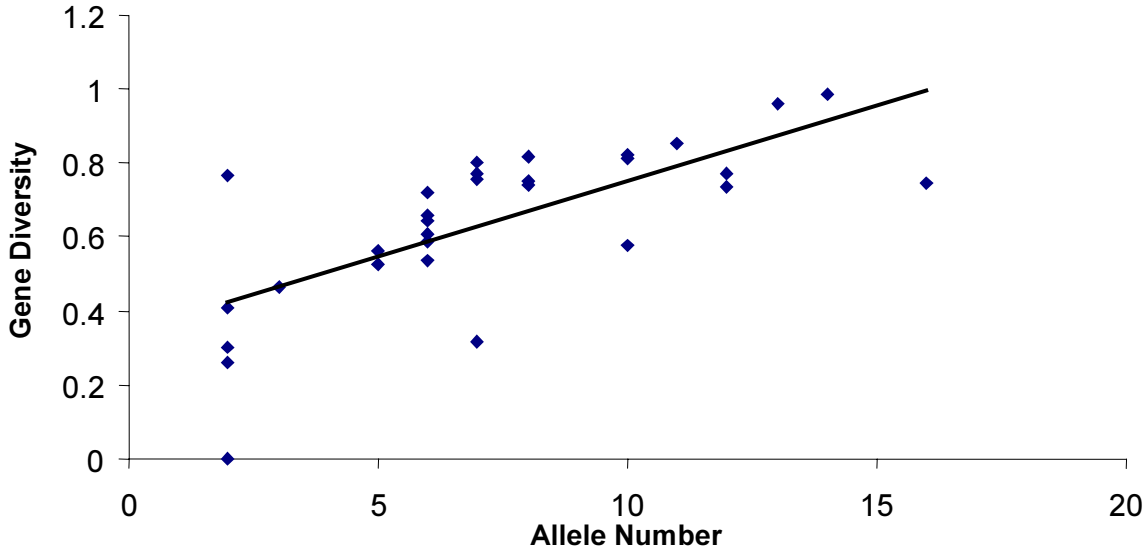


Figure 1. Map of Oman indicating the districts where the hexaploid wheat landraces were collected.



$y = 0.343 + 0.0412$, $R^2 = 0.504$, $r = 0.710$

Figure 2. Relationship between the number of alleles and gene diversity of 38 Omani cultivated tetraploid wheat landraces.

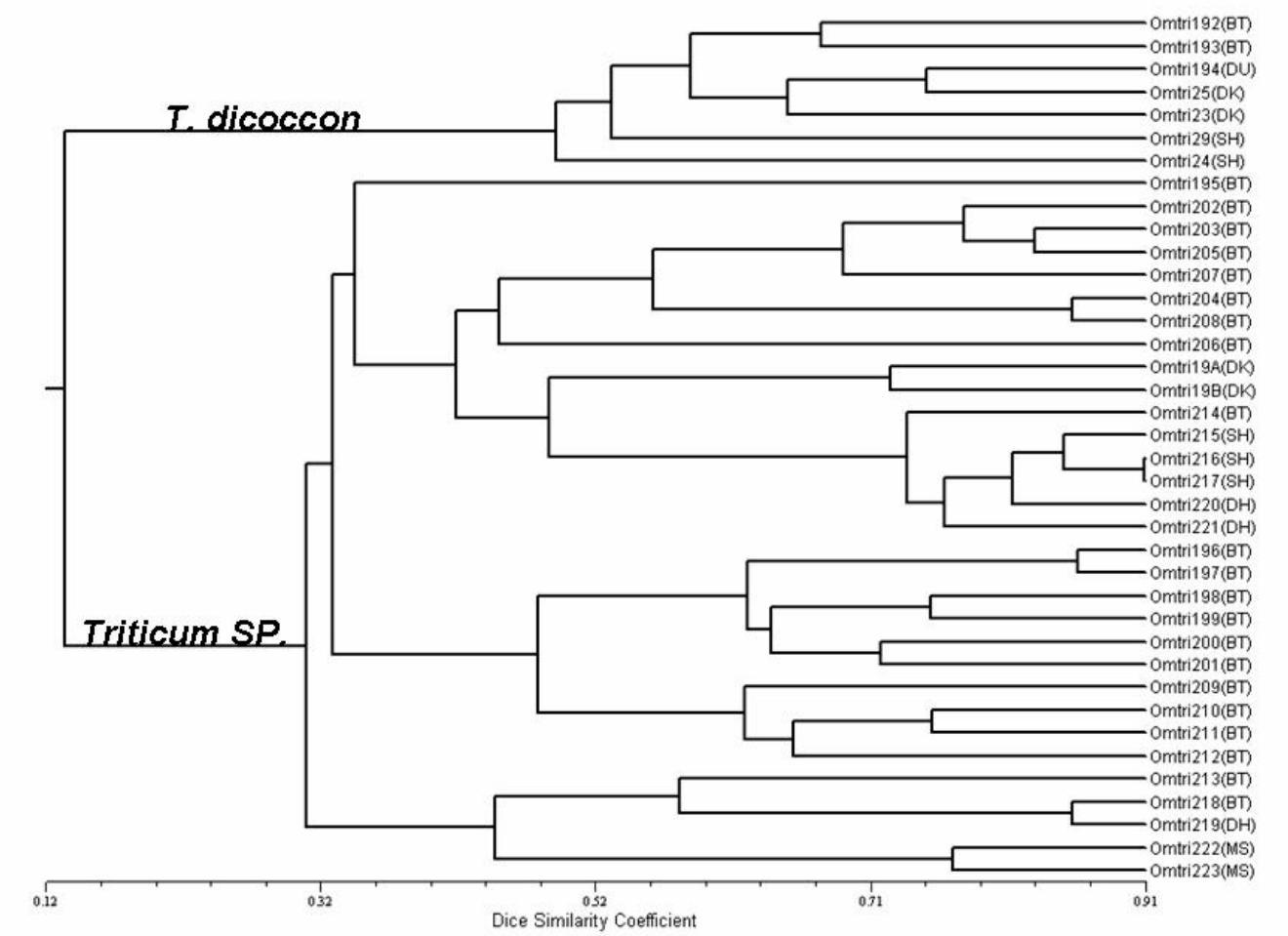


Figure 3. Dendrogramme of 30 microsatellites loci based on 38 UPGMA constricted durum wheat landraces accessions from Oman.

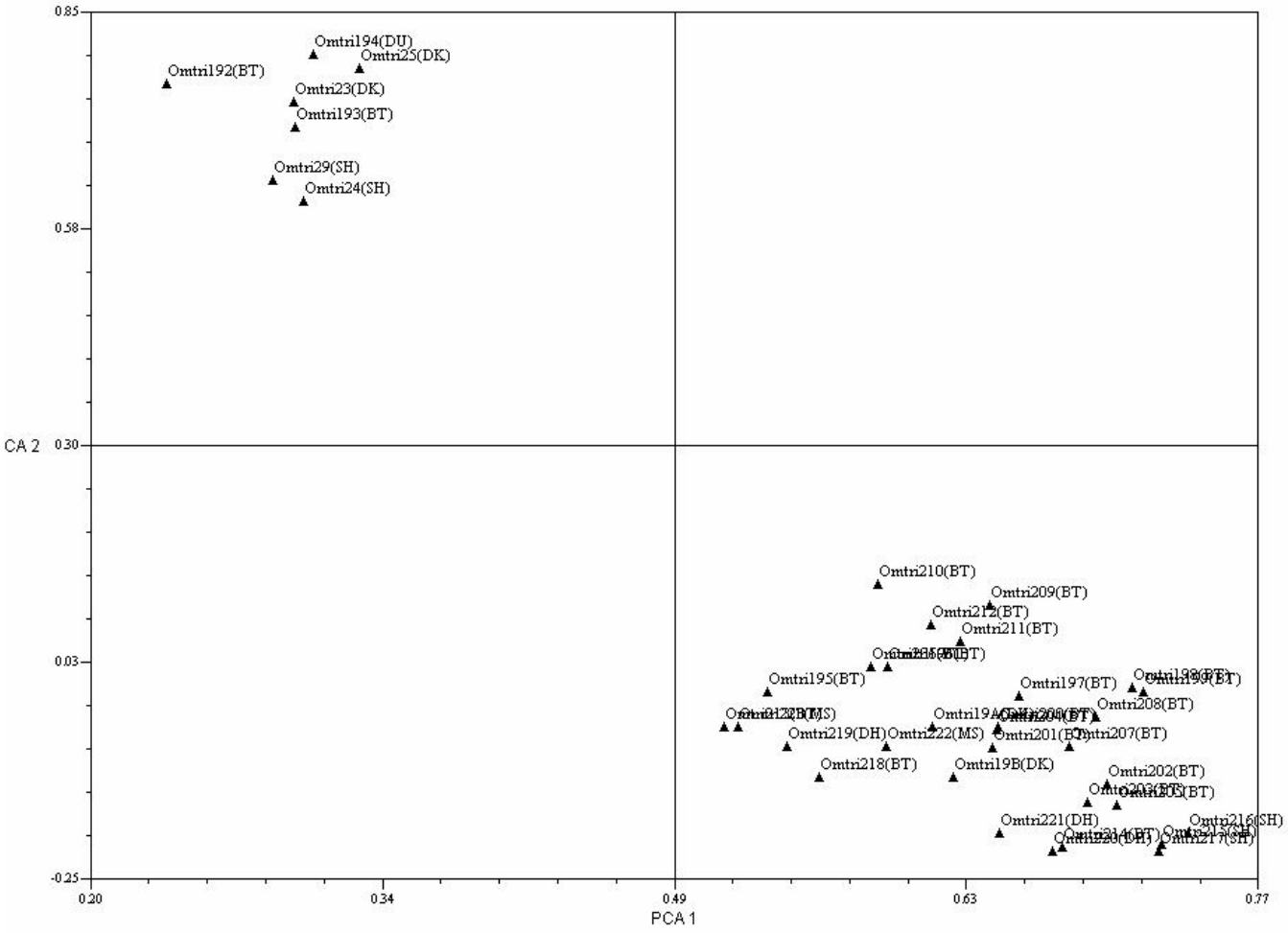


Figure 4. Scattergramme derived from a principal component analysis (PCA) of 38 tetraploid wheat landraces from Oman.

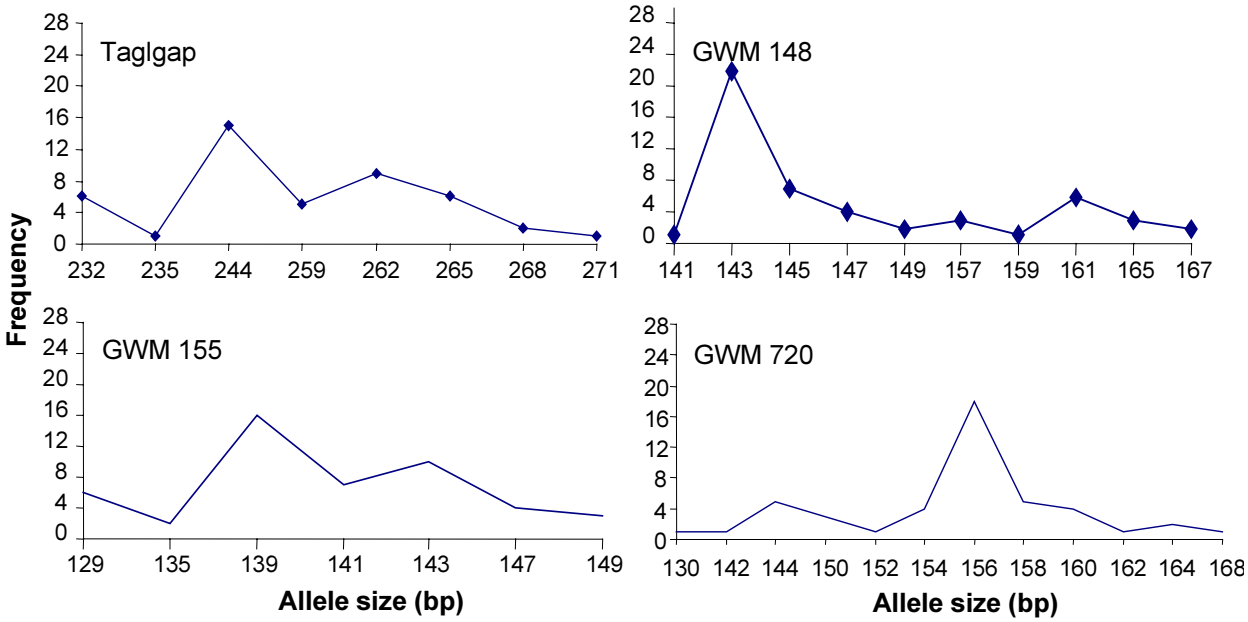


Figure 5. Allele frequency distributions of 38 cultivated tetraploid wheat landraces from Oman based on the analysis of the Taglgap, GWM 148, GWM 155 and GWM 720 microsatellite loci.

4.2 Molecular diversity of Omani wheat revealed by microsatellites: II. Hexaploid landraces

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Abstract

For millennia wheat (*Triticum* spp.) has been grown in traditional aflaj-irrigation systems of remote mountain oases in Oman. However, little is known about the diversity of the ancient landraces used. Given initial reports about the occurrence of novel germplasm in such material, the objective of this study was to evaluate the genetic diversity of hexaploid wheat landraces in relation to their geographic origin using microsatellites. The collection covered most of the cultivation areas in northern Oman where wheat landraces are growing. Total genomic DNA was extracted from six pooled plants. A total of 161 wheat accessions were assayed using 35 microsatellite loci. A total of 305 polymorphic bands were recorded for the 35 microsatellites. The Polymorphic Information Content (PIC) across the 35 microsatellite loci ranged from 0.02 to 0.89 with an average of 0.50. A heterozygosity percentage value of 9.09 was determined and the highest level recorded for accessions from the Batinah district. Rare alleles averaged 1.85 with the highest value being from the Dakhilia district. The results indicated a significant correlation between genetic diversity and number of alleles across district. The correlation coefficient between these two variables over the 35 loci was 0.657, whereby correlation coefficients of 0.718, 0.706, 0.657 and 0.651, respectively, were found for the Batinah, Dhahira, Dakhilia and Sharqia materials. Genetic distances indicated that all landraces were closely related. The cluster analysis discriminated most of the landraces accessions. However, it failed to achieve region-specific groupings of landraces. The present study demonstrated the presence of high diversity in Omani landraces and also indicated the effectiveness of microsatellites to describe it.

Key words: Oasis agriculture, Polymorphic Information Content (PIC), SSR

التنوع في الجزيئات الوراثية للقمح العماني باستخدام المعلمات الوراثية احادية الجزيئية (microsatellites)

2. السلالات من القمح السداسي

الملخص

منذ قرون و زراعة القمح منتشرة في ربوع عمان بالواحات والمدرجات الجبلية ويتم ريها بطريقة الأفلاج. ولكن يندر الحصول على معلومات علمية لتنوع الأصناف والسلالات المحلية المزروعة. لذلك فإن هذا البحث يهدف إلى دراسة التنوع الجيني للسلالات المحلية من القمح السداسية وعلاقتها بالأصل الجغرافي باستخدام المعلمات الوراثية أحادية الجزيئية microsatellites إذ تم استخلاص (genomic DNA) من 6 عينات نباتية وتم تحليل 161 سلالة قمح باستخدام 35 من المعلمات الوراثية أحادية الجزيئية وكنتيجة لذلك تم إظهار 305 أليلا.

و تتراوح الاختلافات الوراثية (PIC) بين 0.20 و 0.89 بمتوسط 0.50، وتبلغ النسبة المئوية للهجين 9.1% حيث سجلت أعلى نسبة بمنطقة الباطنة، وبلغ متوسط عدد الأليلات النادرة 1.85 و يوجد أعلاها بمنطقة الداخلية. متوسط عدد الأليلات اختلف فيما بين المناطق ويوجد ارتباط قوي بين التنوع الجيني وعدد الأليلات حيث كان معامل الارتباط الكلي 0.657 أما بالنسبة للمناطق فكان أعلاها بمنطقة الباطنة 0.718 والظاهرة 0.706 ثم الداخلية 0.657 وأخيرا منطقة الشرقية 0.651. أما التحليل العنقودي (cluster analysis) لعينات القمح فقد أظهر اختلافات وراثية عديدة بين النباتات بمختلف المناطق الزراعية.

دلت هذه الدراسة على وجود اختلافات وراثية عديدة بين أصناف القمح المحلي وعلى فاعلية استخدام المعلمات الوراثية أحادية الجزيئية (microsatellites) في وصف هذه الاختلافات.

Introduction

Only recently Omani wheat landraces, grown in remote mountain oases, have attracted the attention of scientists despite the millenia-old cultivation history of *Triticum* spp. on the Arabian Peninsula (Schwartz, 1939; Potts, 1993; Zohary and Hopf, 1993; Willcox and Tengberg, 1995). First morphological studies showed a surprisingly large phenotypic variation and the presence of at least six so far undescribed hexaploid and three tetraploid wheat varieties (Chapman, 1985; Guarino, 1990; Al-Maskri *et al.*, 2003; Hammer *et al.*, 2004; Al Khanjari *et al.*, unpublished).

The diversity of germplasm has traditionally been described using morphological and agronomical traits (Vavilov, 1964). However, molecular markers such as microsatellites (SSRs) in some cases have been found to be superior to morphological, pedigree, heterosis and biochemical data (Tolbert *et al.* 1979; Doebley, 1989; Melchinger *et al.*, 1991). Microsatellites have a high potential use for the genetic analysis of self-pollinating crops because of their high degree of polymorphism (Akkaya *et al.*, 1992; Plaschke *et al.*, 1995; Röder *et al.*, 1995; Röder *et al.*, 2004). Also, they allow detecting dominant and co-dominantly inherited genes. Primers flanking the microsatellite locus in the selected DNA sequences even allow to detect multiallelic variation (Johansson *et al.*, 1992, Rongwen *et al.*, 1995). Previously microsatellites have been successfully used in diversity studies of barley (Koebner *et al.*, 2003, Prasad *et al.*, 2000; Russell *et al.*, 2000; Eujail *et al.*, 2002; Soleimani *et al.*, 2002; Melchinger *et al.*, 1994). Also, extensive information about their use is available for rice (*Oryza sativa* L.; Ishii and McCouch, 2001; Temnykh *et al.* 2001) and maize (*Zea mays* L.; Mumm and Dudley, 1994; Smith *et al.*, 1997; Lu and Bernardo, 2001).

Lastly, microsatellites have been used to trace the geographic origin of accessions by fingerprinting diverse germplasm from different regions and may thus also help to trace the pre-historic spread of germplasm (Baek *et al.*, 2003; Huang *et al.,* 2002; Li *et al.*, 2002; Röder *et al.*, 2002; Salamini *et al.*, 2002; Zhang *et al.*, 2005).

In view of the above the purpose of this study was to assess the value of molecular markers in unrevealing the genetic structure of hexaploid wheat landraces from Oman.

Materials and methods

Plant material

A survey was conducted in the two spring seasons of 2002-2003 across the wheat growing districts of Oman which covered about 80% of total cultivated area in the country (Figure 1). At each location, a few randomly chosen farmers were interviewed to identify individuals who still grew landraces of wheat. All of the indicated fields, in remote mountain oases, were visited, whenever physically possible and representative germplasm for each of the 161 hexaploid wheat landraces were collected. Seeds from all accessions were planted in the green house at the Institute of Plant Genetics and Crop Plant Research (IPK), Gatersleben, Germany (Table 1).

DNA extraction

Total genomic DNA was extracted from pooled leaves of six 3-week old plants. The young seedling leaves of each accession were harvested and frozen in liquid nitrogen. Subsequently, approximately 3-5 g of leaf material were ground into a fine powder and poured into 50 ml propylene tubes.

The extraction was performed according to Fulton *et al.* (2000) with an extraction buffer described in Plaschke *et al.* (1995). Polymerase Chain Reaction amplifications were performed as described by Röder *et al.* (1998). The substrate subjected to PCR contained 50-100 ng template DNA, 250 nM cy5-labelled forward primer, 250 nM unlabelled reverse primer, 0.2 mM dNTPs, 2.5µl. PCR buffer (10x), 1 .5 mM $MgCl_2$ and 1 U *Taq* DNA polymerase in a total volume of 25 µl.

Fragment detection was performed with an Automated Laser Fluorescence (ALFexpress) sequencer (Amersham Biosciences Europe GmbH, Freiburg, Germany) as described by Röder *et al.* (1998) and fragment sizes were calculated using the computer programme Fragment Analyser 1.02 (Amersham Biosciences) by comparison with internal size standards. The two varieties Chinese Spring and Aztec were used as a reference to standardize different gel runs. In the case of weak or lacking fragment products, PCR amplifications were repeated to exclude failed PCR reaction as the cause of the null allele.

Microsatellite markers (SSR)

A total of 35 SSR primers were produced from Gatersleben Wheat Microsatellites (GWM) and one of them from a pseudogliadine gene, Taglgap. The markers were selected based on their uniformity of distribution in the genome level. Approximately three markers for each chromosome of the A, B and D genomes were used in the study. The microsatellite primers used (Table 2) were previously described by Röder *et al.* (1998) and for the primer Taglgap by Devos *et al.* (1995).

Polymerase chain reaction (PCR)

The amplification profile of the PCR underwent a denaturation for 3 min at 94 °C followed by 32 cycles of 1 min at 94 °C and 1 min at the annealing temperature (50–60 °C, depending on primer design), 2 min elongation at 72 °C and a final extension step of 7 min at 72 °C for a total of 45 cycles.

Data analysis

Clusters scored as binary data matrix that is, scored the presence (1) and absence (0) of alleles. Chinese Spring and Aztec were used as controls to standardize different gel runs. The gene diversity also called polymorphism information content (PIC) was computed according to Nei (1973) as:

$$PIC = 1 - \sum P^2_{ij}$$

were P_{ij} is the allele frequency of the j^{th} allele for the i^{th} marker summed over the number of alleles. Anderson *et al.* (1993) suggested that gene diversity is the same as the Polymorphism Information Content (PIC).

Genetic Similarity (GS; Dice, 1945) was calculated as:

$$GS = 2Nij / (Ni + Nj)$$

where *Nij* is the number of fragment common to lines *i* and *j*, and *(Ni+Nj)* is the total number of fragment in both lines.

Genetic distance (GD) among groups pairs was calculated following (Nei and Li, 1979).

$$(GD_{xy}) = 1 - (2Nxy / N_x + N_y)$$

To calculate allele frequency (A_{xy}) from one group of variation to another in each locus the formula of Khlestkina *et al.* (2004) was used:

$$\text{Allele frequency variation} = \sum|Pxi\text{-}Pyi| / N_{xy} \; x100\%$$

where *Pxi* and *Pyi* are the frequencies of the *i*th allele in regions *X* and *Y*, respectively, and N_{xy} is the total number of alleles for the two groups *X* and *Y*.
The allelic frequency variation *(Axy)* was calculated separately for each of the 35 loci and then for all of them as an average.
All fragments were used to generate a genetic similarity matrix with the software NTSYS (Numerical Taxonomy and Multivariate Analysis System, vers. 2.1) for PC (Rohlf, 2002). The relationships among accessions were analysed using the un-weighted pair-group methods (UPGMA) and principle component analysis (PCA; Sneath and Sokal, 1973).

Results

Microsatellites

The 35 wheat microsatellite markers used revealed a total of 305 alleles. Their fragment size ranged from 77 bp in *GWM3* located on chromosome 3DS to 265 bp in Taglgap on chromosome 1BS. The average number of allele was 8.70 and the largest numbers of allele (28 alleles) were detected on locus *GWM459*. The lowest number of alleles (2 alleles) was at *GWM261* (Table 2).
District-wise, calculations were based on the number of accessions. Averages of allele numbers were different for each district. With 245 allele number was highest in the Dhahira district followed by Batinah (198), Sharqia (161) and Dakhilia (126). The number of rare alleles significantly varied between markers ranging from 0 for *GWM357*, *GWM155*, *GWM655, GWM192A* and *GWM192D* to 5 on *GWM540* with total alleles averaging 1.76 (Table 2). The highest number of district-specific alleles was observed for Batinah (67) followed by Dhahira (57), Dakhilia (38) and Sharqia (36) (Table 3). The proportion of unique alleles reached eight loci at a level of 5% of total accessions. The eight unique alleles were found at *GWM752, GWM18, GWM3, GWM192B, GWM898, GWM408, GWM44* and *GWM333.*
Hetrozygosity was observed for all microsatellite loci but the heterozygosity level varied among microsatellite markers. It was highest at locus *GWM186* of

chromosome 5A and lowest at *GWM192* of chromosome 4D. The highest percentage of heterozygosity was in Dakhilia district (14.4%) and the lowest in Sharqia (12.6%, Table 3)

The allelic frequency variation within loci indicated the highest variation for *GWM459* and the lowest for *GWM192A* with 9.2 and 0.7%, respectively (Table 2).

Analysis of gene diversity

The PIC-value reflecting the gene diversity of the 35 microsatellite loci ranged from 0.02 at locus *GWM 192A* to 0.89 at locus *GWM459* with an average of 0.50 (Table 2). The gene diversity varied within districts (Table 3). The correlation coefficient between gene diversity and numbers of alleles over the 35 microsatellites loci was 0.66 with district-specific differences (Figure 2).

Cluster analysis

The genetic similarity (GS) values between accessions used to produce a dendogramme ranged from 0.19 between Sohar and Yanqul to 0.81 between Bahla and Dhank. The accessions clustered in two groups; one group for Sharqia, Batinah and Dhahira comprising 159SBT, 161SBT, 50DDH *T. aestivum* var. *maqtaense*, 53YDH, 90YDH, 126YDH and 158SSH (most accessions were from farmers' seed stocks). The second group was larger and divided into two subgroups of which one comprised Sharqia Sur (123SSH, 124SSH, 155WSH, 157SSH *T. aestivum* var. *pseudohostianum*). However, the analysis could not group the accessions according to districts. This was particularly true for accessions from Dakhilia which were scattered and mixed with accessions from other districts (Figure 3).

Genetic distance

Genetic distance values indicated that the landraces were closely related. Averages of genetic distance over regions ranged from 0.86 to 0.19 (Table 4). The genetic similarity coefficients across regions ranged from 0.19 between Bahla and Dhank to 0.88 between Sharqia and most of the other regions. The assessment of genetic similarities coefficients on the regional level yielded approximately 12,880 pairs. The 161 Omani hexaploid wheat landraces ranged from 0.06 to 0.89 with a mean of 0.46. The low genetic similarity coefficient values

indicate the presence of high gene diversity in Omani hexaploid wheat landrace accessions.

Principle component analysis

The analysis for the 10 collection regions separated the accessions into two clearly separated groups with Sur and Yanqul in the first quadrant and the other regions in the third quadrant (Figure 4). The first three principle components had Eigenvalues of 47.7%, 5.1% and 3.3%. The results show the distribution of the landrace accessions spreading in three quadrants only. Some of Sharqia's accessions were relatively grouped and distanced from the others. Accessions from Batinah, Sharqia and Dhahira clustered in two quadrant boxs (Figure 5).

Discussion

In this study 35 microsatellites revealing 305 alleles from the 161 hexaploid wheat landraces were enough to discriminate all accessions. These results are in contrast with the minimum number of alleles reported by Zhang *et al*. (2002) who suggested a minimum of 350 to 400 alleles were needed to detect genetic relationships among common wheat varieties (Zhang *et al.*, 2002). They examined 43 Chinese wheat varieties with 90 polymorphic SSR to determine the minimum number of alleles required to detect genetic relationships in their accessions. In a study of the French breed wheat, however, a set of 41 wheat microsatellite markers (WMS) was enough to detect 609 alleles from 559 landraces and registered varieties Roussel *et al.* (2004).

The highest average allele number obtained in the present investigation of Omani hexaploid wheats was 8.70. This compares well to previous results on genetic diversity of wheat using microsatellite analysis. Khlestkina *et al.* (2004) detected average allele numbers of 6.6 in 54 common spring wheat varieties and Prasad *et al.* (2000) found averages allele numbers of 7.4 in 55 varieties. Manifesto *et al.* (2001) reported an average allele number of 10.5 from 500 European wheat varieties whereas Huang *et al.* (2002) investigated with microstallites nearly 1,000 accessions of hexaploid wheat originating from all over the world and thereby recorded an average allele number of 18.1.

The average gene diversity (PIC) obtained in the present investigation was comparable with previous results on genetic diversity of wheat using microsatellite

analysis. Khlestkina *et al.* (2004) found a PIC-value of 0.70 in 54 common spring wheat varieties, while Prasad *et al.* (2000) reported a PIC-value of 0.71 in their 55 elite wheat genotypes. Analysing 105 Argentinean wheat varieties, Manifesto *et al.* (2001) reported an average gene diversity (PIC) of 0.72. For 500 European and world-wide collected wheats Röder *et al.* (2002) and Huang *et al.* (2002) found respective PIC-values of 0.67 and 0.77. The highly significant (P<0.001) correlation coefficient of 0.635 between gene diversity and number of alleles per locus for the 161 cultivated landraces (Figure 2) confirms previous findings by Huang *et al.* (2002) and Roussel *et al.* (2004). However, it contradicts results of Prasad *et al.* (2000) who reported that the PIC-value was uncorrelated with the number of alleles in their material.

The relatively large number of rare alleles in Batinah and Sharqia may be due to the sample size or modern commercial activities. High frequencies of rare alleles have also been reported in *Triticum urartu* (Moghaddam *et al.*, 2000), in *Aegilops tauschii* (Dudnikov, 1998), in European wheat varieties (Röder *et al.*, 2002) and for the Gatersleben wheat collection (Huang *et al.*, 2002). Similarly, Roussel *et al.* (2004) reported that on average about 72% of the total number of alleles had a frequency lower than 5% and were therefore considered as rare.

The cluster analysis discriminated most of the hexaploid landraces accessions in our study. However, it did not group the landraces according to their geographic location. Similar results were obtained by Khlestkina (2004) for old and modern Siberian spring wheat varieties. Also Huang (2002) reported that not all accessions originating from the same region clustered in the same group, indicating that the genetic diversity of *T. aestivum* is not completely related to geographic distribution. In contrast, Alamerew *et al.* (2004) reported that all of his accessions could be separated, clustering in two large groups.

The results of our study might also show the effects of seed exchange between farmers within or even between districts. The Sharqia data indicated a high genetic diversity within a district which may reflect the effects of cultural isolation and distinct agricultural practices. On the other hand there is the observation that farmers will give different names to wheat landraces based on their agronomic performance or minor phenotypic differences regardless of the outcome of morphological or molecular genetic studies.

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Table 1. OMTRI (Oman *Triticum*) accession numbers of hexaploid wheat landraces from Oman used for molecular genetic analysis in this diversity study.

District	Region	OMTRI	Total
Batinah			
	Sohar (SBT)	45, 46, 51, 88, 89, 90, 91, 92, 93, 94, 96, 97, 98, 99, 100, 101, 102, 103, 104, 105, 106	21
	Khabura (KBT)	163, 164, 165, 166, 167, 223, 24, 226, 227, 228, 229, 245	12
Dhahira			
	Ibri (IDH)	72, 73, 74, 108, 109, 110, 111, 112, 113, 149, 150, 151, 152, 153, 155, 158, 160, 161, 162, 219, 220, 221, 232, 233, 234, 235, 236, 237, 238, 239	30
	Dank (DDH)	56, 131, 132, 133, 134	5
	Yanqul (YDH)	57, 68, 69, 135, 136, 137, 138, 139, 141, 192, 194, 195, 196, 197, 198, 199, 200, 201, 202, 203, 204, 205, 207, 208, 209, 210, 212, 213, 214, 215, 216, 217, 18, 240, 241, 242, 243, 244	38
Dakhilia			
	Bahla (BDK)	142, 143, 144, 145, 146, 147, 148, 168, 169, 170, 171, 172, 173, 174, 175, 176, 177, 178, 179, 180	20
Sharqia			
	Sur(SSH)	21, 22, 230, 231	4
	Al Raky (WSH)	55, 67, 114, 115, 116, 117, 118, 119, 120, 121, 122, 123, 124, 130, 222,	14
	Taeen (TSH)	125, 126, 127, 128, 129	7
	Maqta (TMSH)	181, 182, 183, 184, 185, 186, 187, 188, 189, 190, 191	10
Total			**161**

Table 2. List of the 35 microsatellite loci of chromosome locations used to evaluate allele variation, rage of fragment size, genetic diversity, polymorphism onformation content (PIC), allele number, rare alleles, heterozygosity (H) and allele variation (AV) of 161 hexaploid wheat landraces from Oman.

SSR and chromosomal location	Fragment size range	PIC	Allele no	Rare alleles	H (%)	AV (%)
XGWM357-1AL	120-126	0.49	4	0	2	1.31
XGWM752-1AS	Null, 120-154	0.71	6	1	8	1.97
XGWM18-1BS	177-193	0.47	8	1	16	2.62
Taglgap-1BS	Null, 212-265	0.49	9	2	6	2.95
XGWM458-1DL	Null, 108-170	0.32	8	2	7	2.62
XGWM337-1DS	110-168	0.41	11	2	15	3.61
XGWM95-2AS	Null, 129-124	0.17	8	3	5	2.62
XGWM619-2BL	143-179	0.54	9	3	32	2.95
XGWM157-2DL	Null, 98-112	0.2	8	2	6	2.62
XGWM261-2DS	Null, 163-175	0.29	4	2	3	1.31
XGWM155-3AL	Null, 129-149	0.53	7	0	27	2.30
XGWM720-3AS	130-182	0.73	15	3	36	4.92
XGWM655-3BL	Null, 158-172	0.65	8	0	12	2.62
XGWM389-3BS	Null, 102-160	0.67	14	3	23	4.59
XGWM3-3DS	Null, 77-85	0.41	6	1	4	1.97
XGWM160-4AL	176-198	0.52	7	2	7	2.30
XGWM192-4AS	128-134	0.02	2	0	1	0.66
XGWM192-4BL	Null, 191-225	0.71	11	1	13	3.61
XGWM513-4BL	143-151	0.39	6	2	16	1.97
XGWM898-4BS	103-115	0.23	4	1	10	1.31
XGWM192-4DL	Null, 134-140	0.27	4	0	1	1.31
XGWM186-5AL	Null, 126-152	0.54	13	3	34	4.26
XGWM415-5AS	120-134	0.91	11	2	10	3.61
XGWM408-5BL	Null, 175-183	0.34	6	1	10	1.97
XGWM540-5BS	114-138	0.65	10	5	34	3.28
XGWM190-5DS	200-214	0.55	7	2	12	2.30
XGWM459-6AS	Null, 162-190	0.89	28	2	26	9.18
XGWM680-6BS	123-147	0.38	6	1	7	1.97
XGWM325-6DS	Null, 122-142	0.74	7	1	24	2.30
XGWM631-7AS	Null, 190-204	0.39	6	2	20	1.97
XGWM297-7B(C)	Null, 150-178	0.71	10	2	15	3.28
XGWM333-7BL	148-166	0.16	6	1	4	1.97
XGWM577-7BL	Null, 126-224	0.72	13	2	10	4.26
XGWM437-7DL	Null, 98-118	0.55	11	3	28	3.61
XGWM 44-7DS	Null, 152-186	0.78	12	1	28	3.93

Table 3. Comparison of gene diversity (Polymorphism Information Content, PIC values) of cultivated bread wheat landraces among the different districts of Oman.

	Dhahira	**Batinah**	**Sharqia**	**Dakhilia**	**Total**
No. of accession	74	34	33	20	161
Alleles numbers	245	198	161	126	305
Average no of alleles per marker	7.00	5.67	5.00	5.57	8.70
No. of rare alleles	57	67	36	38	61
No. of unique alleles	5	1	1	0	8
Heterozygosity %	9.00	10.57	12.57	14.38	9.09
Average PIC value	**0.45**	**0.48**	**0.42**	**0.33**	**0.5**

Table 4. Nei's gene distances between the different collection regions of hexaploid wheat landraces from Oman.

Region	Sur	Yanqul	Dhank	Bahla	Ibri	Sohar	Khabura	Maqta	Al Raky	Taeen
Sur										
Yanqul	0.88									
Dhank	0.86	0.79								
Bahla	0.88	0.76	0.19							
Ibri	0.88	0.76	0.41	0.35						
Sohar	0.86	0.81	0.49	0.49	0.46					
Khabura	0.88	0.73	0.22	0.21	0.36	0.50				
Maqta	0.85	0.85	0.46	0.41	0.54	0.61	0.42			
Al Raky	0.80	0.78	0.31	0.28	0.33	0.49	0.31	0.47		
Taeen	0.88	0.70	0.43	0.42	0.54	0.60	0.43	0.55	0.45	

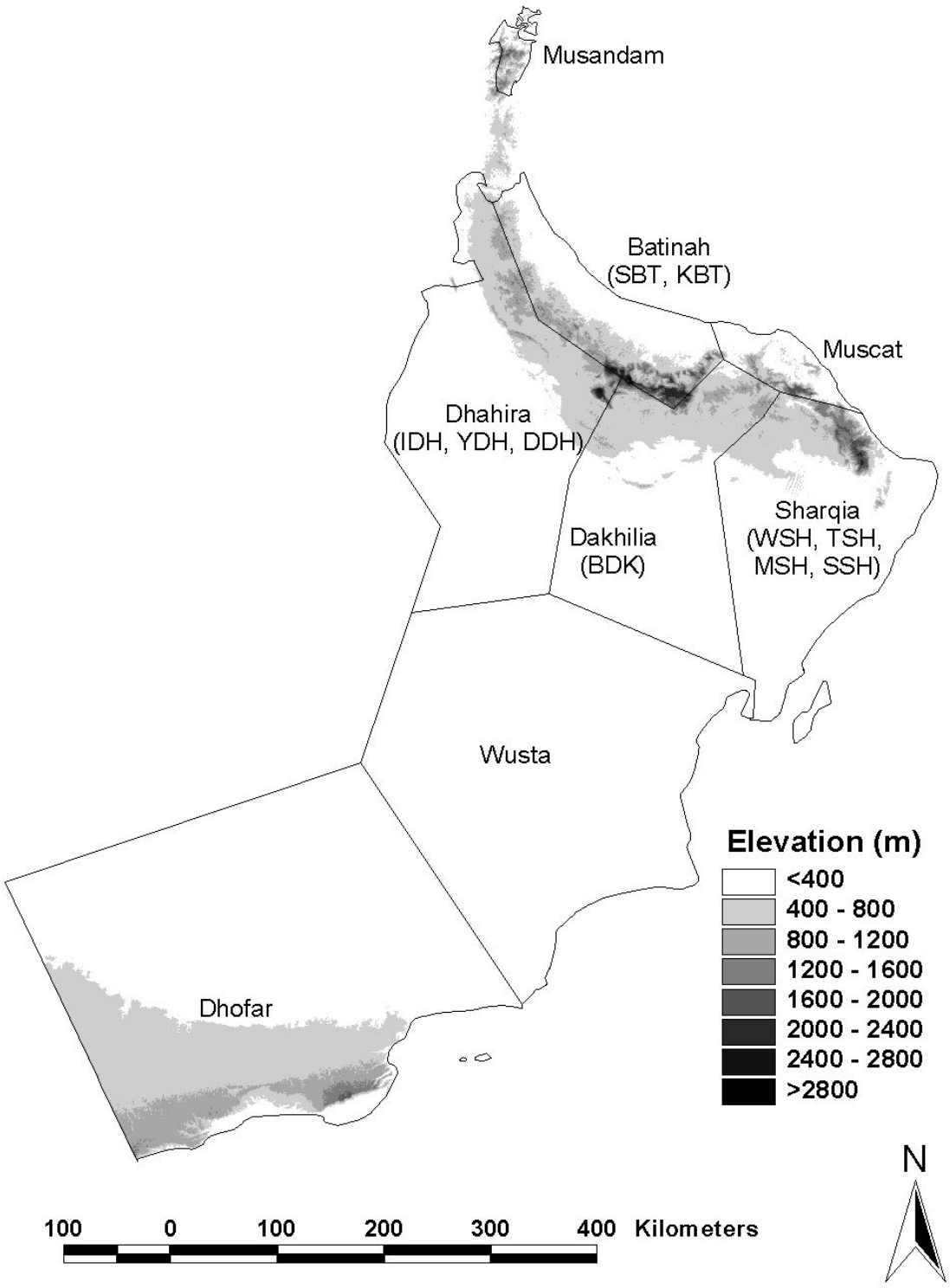


Figure 1. Map of Oman indicating the four districts Dhahira (YDH = Yanqul, DDH = Dank and IDH = Ibri), Batinah (Sohar = SBT, Khabura = KBT), Dakhilia (Bahla = BDK) and Sharqia (Sur = SSH, Al Raky = WSH, Taeen = TSH and Maqta = MSH) where the hexaploid wheat landraces were collected.

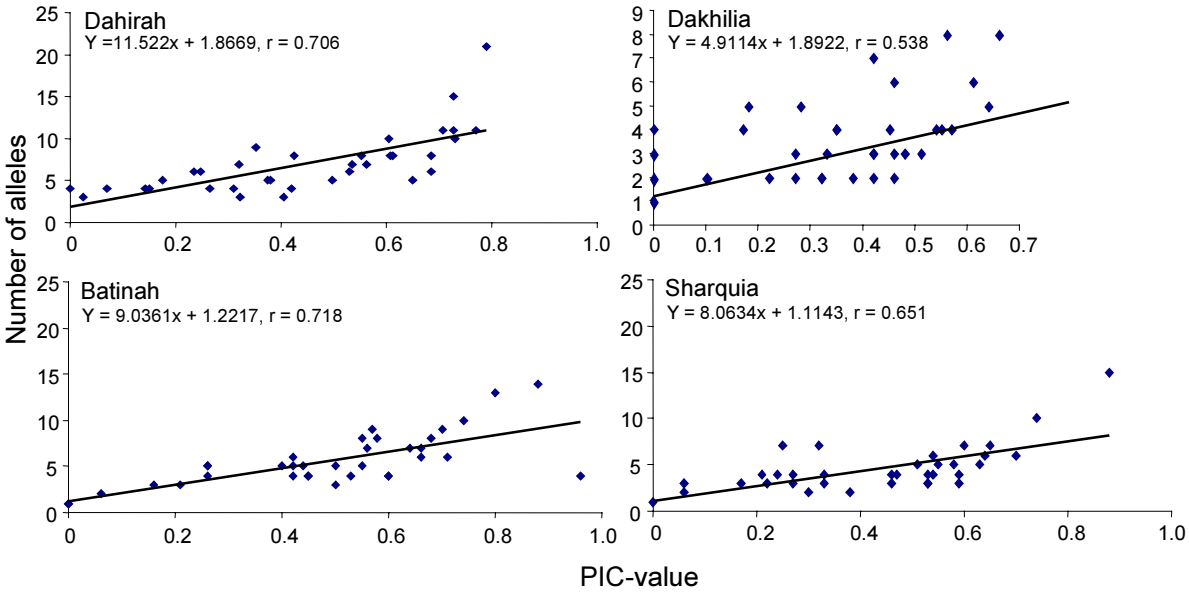


Figure 2. Correlation between gene diversity and the number of alleles over 35 microsatellites loci in hexaploid wheat landraces. The accessions were analyzed separately for their collection districts in Oman (Dhahira, Batinah, Sharqia and Dakhilia).

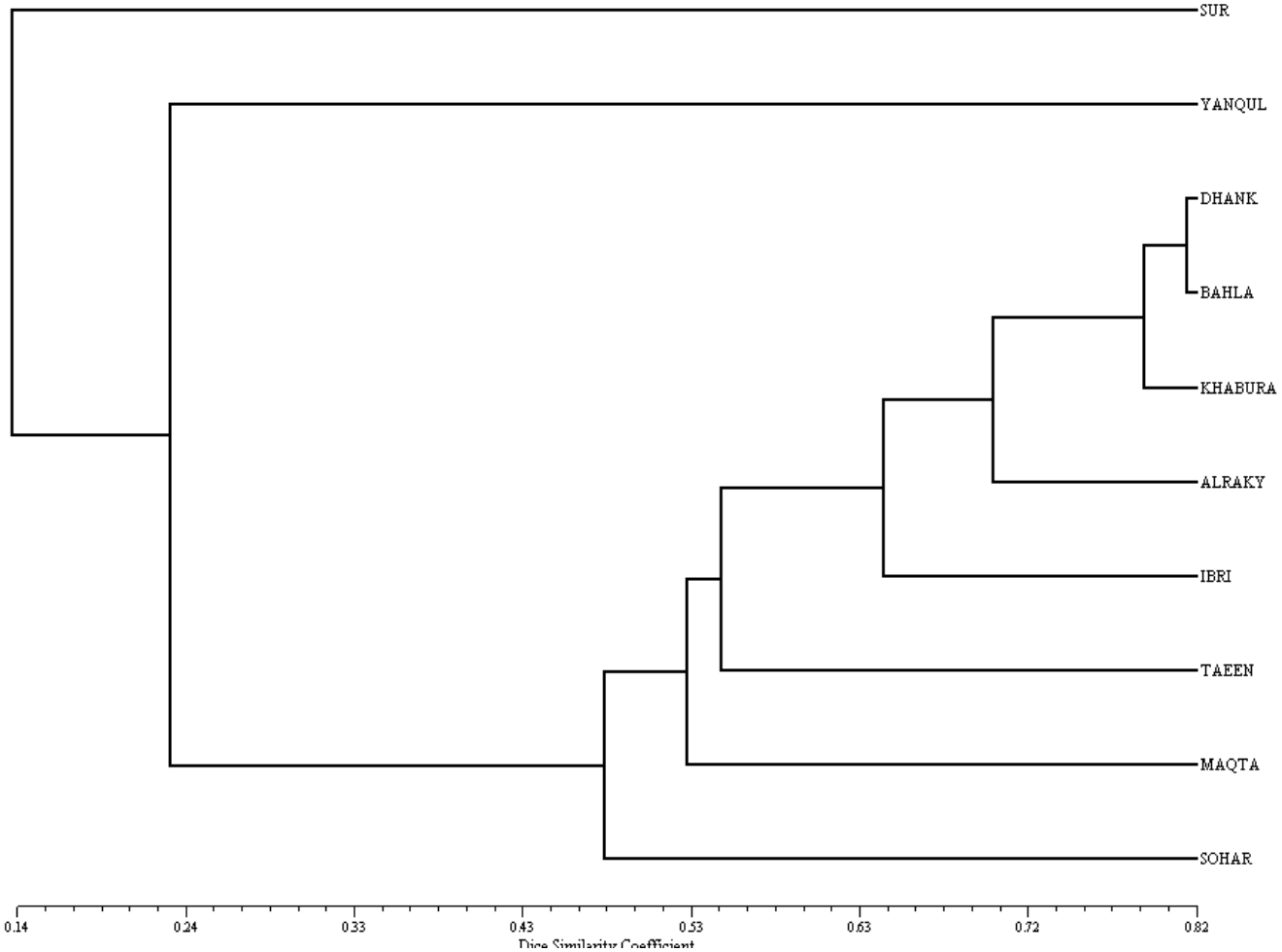


Figure 3. Dendrogramme of Omani landraces accessions grouped for 10 regions of Oman according to UPGMA using Dice's similarity coefficients.

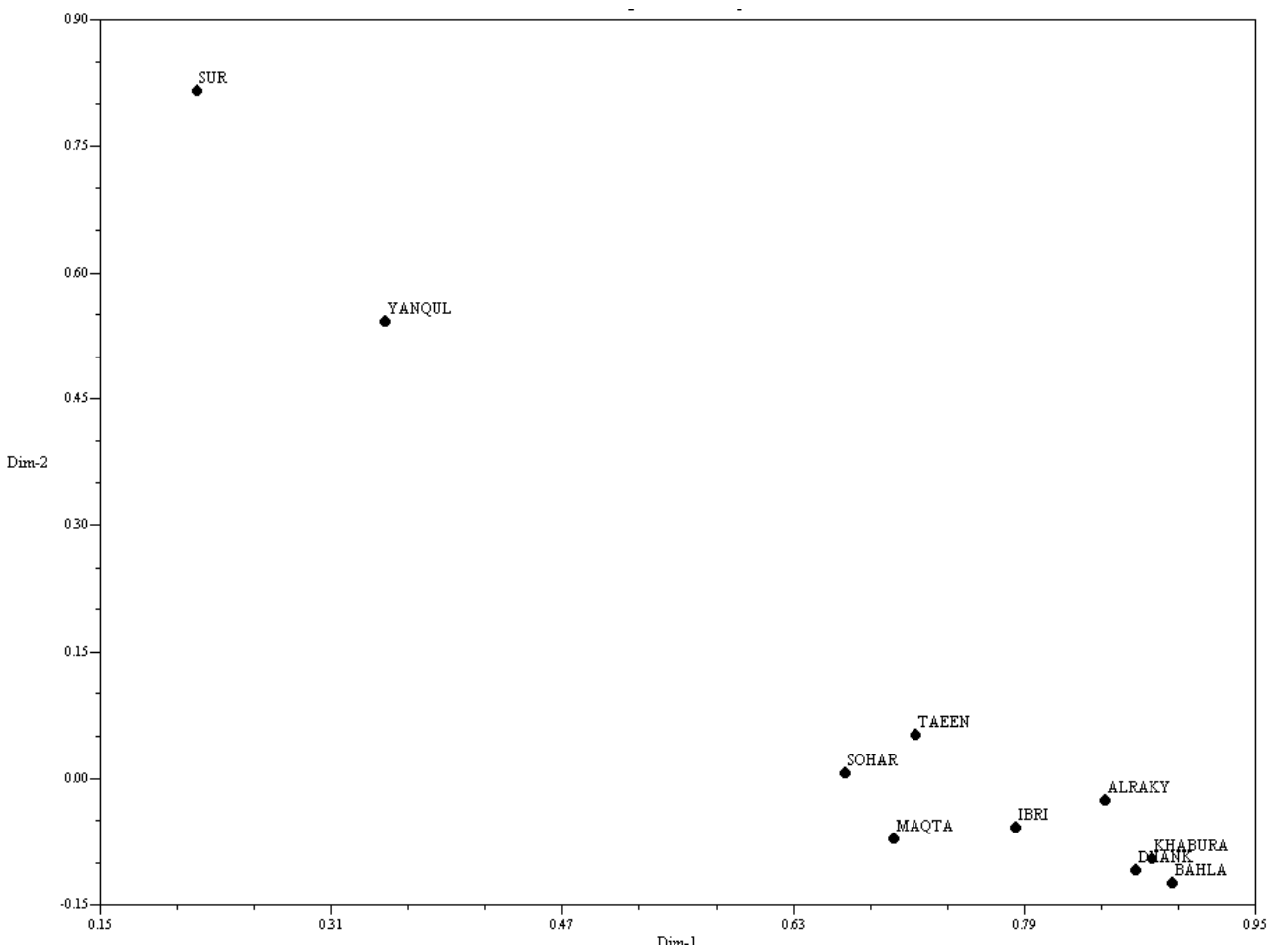


Figure 4. Results of a Principal Component Analysis (PCA) of 161 hexaploid wheat accessions from Oman. The grouping for the 10 collection regions is based on Dice's similarity coefficients.

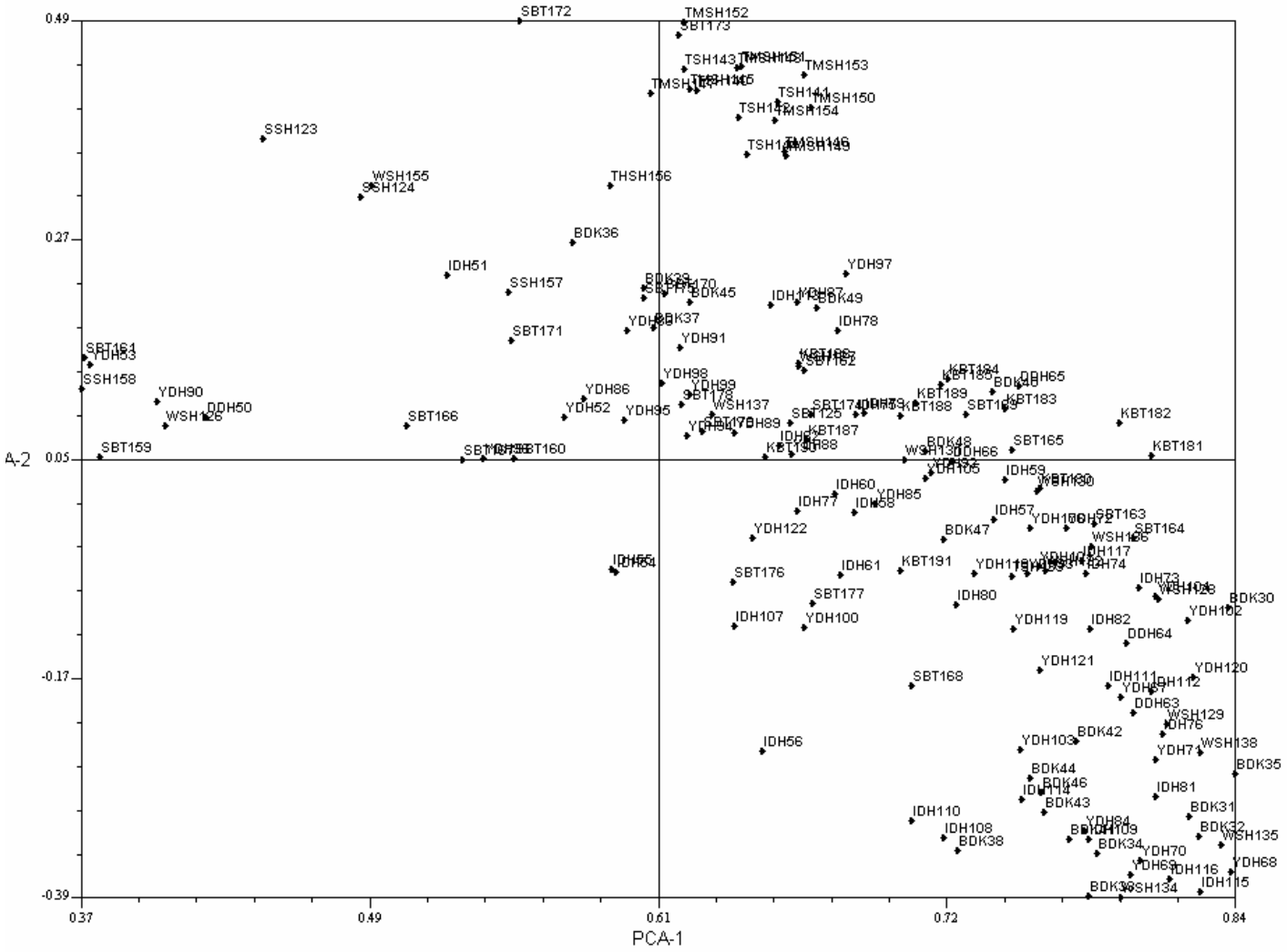


Figure 5. Results of a Principal Component Analysis (PCA) of 161 hexaploid wheat accessions from 10 regions of Oman. The grouping is based on Dice's similarity coefficients.

5
Conclusions

So far Oman was not known to comprise a region with an important diversity in wheat germplasm. This study shows that this impression was incomplete. In a relatively modest exploration programme of farmers' wheat landraces different species were collected at the tetraploid (*T. durum*, *T. aethiopicum*, *T. dicoccon*, *T. ispahanicum*) and hexaploid (*T. aestivum*) genome levels with a surprisingly high intra-species variation and the description of at least nine botanical varieties new to science. The characterization and evaluation of the collected germplasm has been carried out using classical (mainly morphological) and modern (molecular) markers which both confirmed the high degree of variation in the landraces.

The results are promising with respect to the possibility of identifying agronomically interesting traits within the material. Such identification should be carried out through an intensive screening programme at the national and international level.

Given the country-wide rapidly progressing genetic erosion as a consequenece of Oman's modernization, policy efforts leading to *in-situ* (on-farm) conservation are urgently needed to preserve the culturally unique, ecological niche environments which led to the evolution of the ancient wheat landraces. However, for security reasons it might be wise to transfer duplicates of the collected germplasm into an (international) genebank (*ex-situ* conservation) to ensure its future use as a world-wide heritage.

الخلاصة

نظرا لقلة وجود مصادر المعلومات حول أنواع و سلالات القمح المحلي بسلطنة عمان تم عمل مسح ميداني لمناطق زراعة القمح المحلي و جمع سلالات القمح ثم تحليلها و تقييمها باستخدام الشكل المظهري و التقنية الحيوية بطريقة المعلمات الوراثية أحادية الجزيئية (**microsatellites**). رغم الجهود المبذولة من قبل سلطنة عمان في المحافظة على المصادر الوراثية المحلية فقد تبين خلال هذا البحث وجود حاجة ملحة على مزيد من الدراسات الحصرية لتلك المصادر لدى القمح و في هذا السياق تمت دراسة عينات القمح المزروع في عمان (القمح المحلى) لعدة سلالات من أنواع القمح الرباعي (***T. ispahanicum, T. dicoccon, T durum*** و ***T.aethiopicum***) و القمح السداسي (***T. aestivum***) و كانت النتائج مبشرة بوجود التهجين الوراثي الخارجي المتباين. و قد تم التعرف على حوالي تسعة من السلالات الجديدة لم تكن معروفة في ميدان العلم مسبقا. وكنتيجة لاستخدام طريقتي التحليل سالفتي الذكر تم التأكد من وجود درجة عالية للتنوع الوراثي لدى القمح المحلي و تتجلى أهمية هذه النتيجة في تسهيل إمكانية التعرف على الصفات الزراعية التي تتعلق بالإنتاجية عند السلالات المدروسة.

ونظرا للفقد السريع لمصادر البلاد الوراثية نتيجة للتحديث و التطوير المستمر الذي تعرفه سلطنة عمان، يحبذ الإسراع بوضع خطة وطنية أو مع التعاون الدولي بهدف حماية وصيانة الأوساط الوراثية الفريدة من نوعها التي سمحت لحفظ تواصل زراعة سلالات القمح التقليدية على مدى التاريخ. و لتواصل هذه الجهود ينبغي تكثيف جهود مباشرة المزارع والإسراع بإيداع السلالات التي تم جمعها في الأماكن الخاصة بها (مصارف الجينات الوراثية) لضمان استعمالها المستقبلي كموروث علمي وطني.

6

Final appendices

Appendix 1. Images of new botanical bread wheat (*Triticum aestivum*) varieties determined within landraces from Oman.

T. aestivum var. *baladsetense*

T. aestivum var. *maqtaense*

T. aestivum var. *sedabense*

T. aestivum convar. *rigid-compactum* var. *omanense*

T. aestivum var. *sedayriense*

T. aestivum var. *ibreense*

Appendix 2. Images of new botanical durum wheat (*Triticum durum*) varieties determined within landraces from Oman.


T. durum var. *mahsinense*


T. aethiopicum var. *hajirense*


T. durum var. *densemenelikii (sedarenense)*


T. var. nov.

Note: Appendices 3-10 provide additional data of qualitative morphological characters in hexaploid wheat landraces from Oman.

Appendix 3. Phenotypic frequencies for qualitative spike characters of hexaploid wheat (*Triticum durum*) accessions from the **Dakhilia** district in Oman.

	Frequency in class					
Character	**1**	**2**	**3**	**4**	**5**	**6**
Spike shape	41.7	8.3	20.8	16.7	4.2	8.3
Spike awns	82.6	8.7	8.7			
Direction of the awns	50.0	50.0				
Colour of the awns	25.0	75.0				
Rudeness of the awns	50.0	50.0				
Roughness of the awns	100.0					
Hairiness of the glume	8.3	12.5	79.2			
Sector hairiness	4.2	95.8				
Sector thickness of hairiness density	78.3	21.7				
Glume shape	70.8	29.2				
Glume shoulder shape width	79.2	20.8				
Glume colour	70.8	12.5	16.7			
Glume rigidity	21.7	17.4	52.2	8.7		
Keel tooth roughness	54.2	45.8	58.4	12.5	8.3	20.8
Grain colour	58.3	12.5	8.3	20.8		

Appendix 4. Phenotypic frequencies for qualitative spike characters of hexaploid wheat accessions from the **Sharqia** district in Oman.

	Frequency in class				
Character	**1**	**2**	**3**	**4**	**5**
Spike shape	26.7	13.3	23.3	36.7	
Spike awns	48.3	10.3	27.6	10.3	3.5
Directions of the awns	100.0				
Colour of the awns	53.3	46.7			
Rudeness of the awns	57.9	42.1			
Roughness of the awns	100.0				
Hairiness of the glume	6.9	44.8	48.3		
Sector hairiness	14.3	3.6	7.1	75.0	
Sector thickness of hairiness density	96.3	3.7			
Glume shape	100.0				
Glume shoulder shape width	48.3	51.7			
Glume colour	62.1	13.8	24.1		
Glume rigidity	93.1	6.9			
Keel tooth roughness	3.5	3.5	93.1		
Grain colour	28.0	32.0	40.0		

Appendix 5. Phenotypic frequencies for qualitative spike characters of hexaploid wheat accessions from the **Batinah** district in Oman.

	Frequency in class							
Character	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Spike shape	38.7	3.2	21.0	24.2	1.61	6.5	0.1	4.8
Spike awns	24.2	6.5	50.0	19.4				
Direction of the awns	6.5	50.0						
Colour of the awns	36.4	63.6						
Rudeness of the awns	84.8	13.0	2.2					
Roughness of the awns	73.3	26.7						
Hairiness of the glume	17.7	11.3	43.6	27.4				
Sector hairiness	51.6	1.6	1.6	16.1	25.8	3.2		
Sector thickness of hairiness density	85.2	11.1	3.7					
Glume shape	95.2	3.2	1.6					
Glume shoulder shape width	43.6	53.2	3.2					
Glume colour	54.8	11.3	32.3	1.6				
Glume rigidity	96.7	1.6	1.6					
Keel tooth roughness	96.8	3.2						
Grain colour	6.6	8.2	57.4	27.9				

Appendix 6. Phenotypic frequencies for qualitative spike characters of hexaploid wheat accessions from the **Dhahira** district in Oman.

	Frequency in class							
Character	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Spike shape	1.1	1.1	30.5	12.6	25.3	5.3	2.4	24.2
Spike awns	60.6	9.6	16.0	13.8				
Direction of the awns	2.8	63.9	27.8	5.6				
Colour of the awns	54.1	46.0						
Rudeness of the awns	47.1	50.0	2.9					
Roughness of the awns	77.8	16.7	5.6					
Hairiness of the glume	16.0	10.6	61.7	11.7				
Sector hairiness	21.3	9.6	5.3	62.8	1.1			
Sector thickness of hairiness density	87.6	11.2	1.1					
Glume shape	85.3	1.1	12.6	1.1				
Glume shoulder shape width	71.6	24.2	3.2	1.1				
Glume colour	83.2	5.3	10.5	1.1				
Glume rigidity	53.7	25.3	2.1	16.8	1.1	1.1		
Keel tooth roughness	7.4	92.6						
Grain colour	26.1	10.9	2.2	38.0	22.8			

Appendix 7. Phenotypic frequencies for quantitative spike characters of hexaploid wheat accessions from the **Dakhilia** district in Oman.

	Frequency in class			
Character	**1**	**2**	**3**	**4**
Spike length (cm)	20.8	66.7	12.5	
Spike width (mm)	30.4	47.8	17.4	4.4
Spikelet number per spike	4.2	8.3	45.8	41.7
Number of sterile spikelets	75.0	18.8	6.3	
Length of the first awn (cm)	66.7	33.3		
Length of the second awn (cm)	75.0	25.0		
Spikelet length (mm)	83.3	16.7		
Spikelet width (mm)	20.8	58.3	20.8	
Number of grains per spikelet	4.2	87.5	8.3	
Sector length (mm)	33.3	41.7	25.0	
Glume length (mm)	50.0	33.3	16.7	
Lemma length (mm)	13.3	33.3	6.7	53.3
Palea length (mm)	16.7	58.3	20.8	4.2
Keel tooth length (mm)	70.8	29.2		
Grain length (mm)	16.7	83.3		
Grain height (mm)	12.5	44.7		
Grain width (mm)	100.0			
Spike density	34.0	34.0	31.0	

Appendix 8. Phenotypic frequencies for quantitative spike characters of hexaploid wheat accessions from the **Sharqia** district in Oman.

Character	Frequency in class				
	1	**2**	**3**	**4**	**5**
Spike length (cm)	58.6	34.5	3.5	3.5	
Spike width (mm)	17.2	69.0	10.3	3.5	
Spikelet number per spike	3.1	6.3	25.0	28.1	37.5
Number of sterile spikelets	70.6	5.9	11.8	5.9	5.9
Length of the first awn (cm)	78.6	21.4			
Length of the second awn (cm)	66.7	26.7	6.7		
Spikelet length (mm)	65.5	31.0	3.5		
Spikelet width (mm)	6.9	62.1	31.0		
Number of grains per spikelet	93.1	6.9			
Sector length (mm)	55.2	34.5	10.3		
Glume length (mm)	48.3	31.0	20.7		
Lemma length (mm)	37.9	41.4	20.7		
Palea length (mm)	27.6	51.7	17.2	3.5	
Keel tooth length (mm)	44.8	41.4	10.3	3.5	
Grain length (mm)	27.6	72.4			
Grain height (mm)	17.2	82.8			
Grain width (mm)	17.2	79.3	3.5		
Spike density	34.0	34.0	31.0		

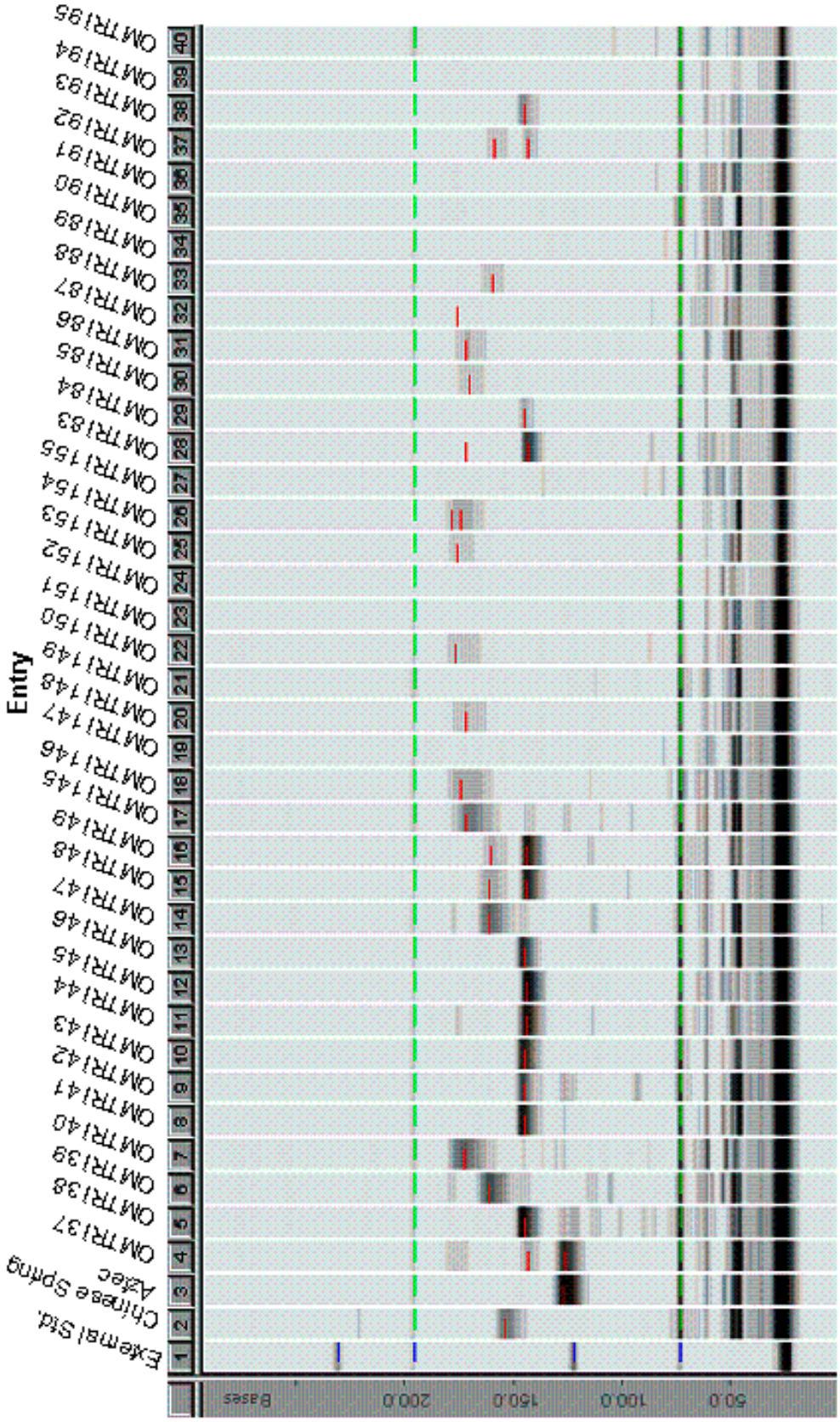
Appendix 9. Phenotypic frequencies for quantitative spike characters of hexaploid wheat accessions from the **Batinah** district in Oman.

	Frequency in class				
Character	**1**	**2**	**3**	**4**	**5**
Spike length (cm)	40.3	59.7			
Spike width (mm)	30.7	43.6	22.6	3.2	
Spikelet number per spike	1.6	1.6	30.8	48.4	17.7
Number of sterile spikelets	43.1	37.3	11.8	3.9	3.9
Length of the first awn (cm)	18.0	76.9	5.1		
Length of the second awn (cm)	53.2	29.0	17.7		
Spikelet length (mm)	21.0	51.6	27.4		
Spikelet width (mm)	6.5	83.9	9.7		
Number of grains per spikelet	45.2	32.3	21.0	1.6	
Sector length (mm)	43.6	43.6	12.9		
Glume length (mm)	29.0	48.4	21.0	1.6	
Lemma length (mm)	16.1	48.4	32.3	3.2	
Palea length (mm)	21.7	51.7	20.0	6.7	
Keel tooth length (mm)	19.4	66.1	14.5		
Grain length (mm)	1.6	98.4			
Grain height (mm)	3.2	91.9	4.8		
Grain width (mm)	40.0	53.0	7.0		

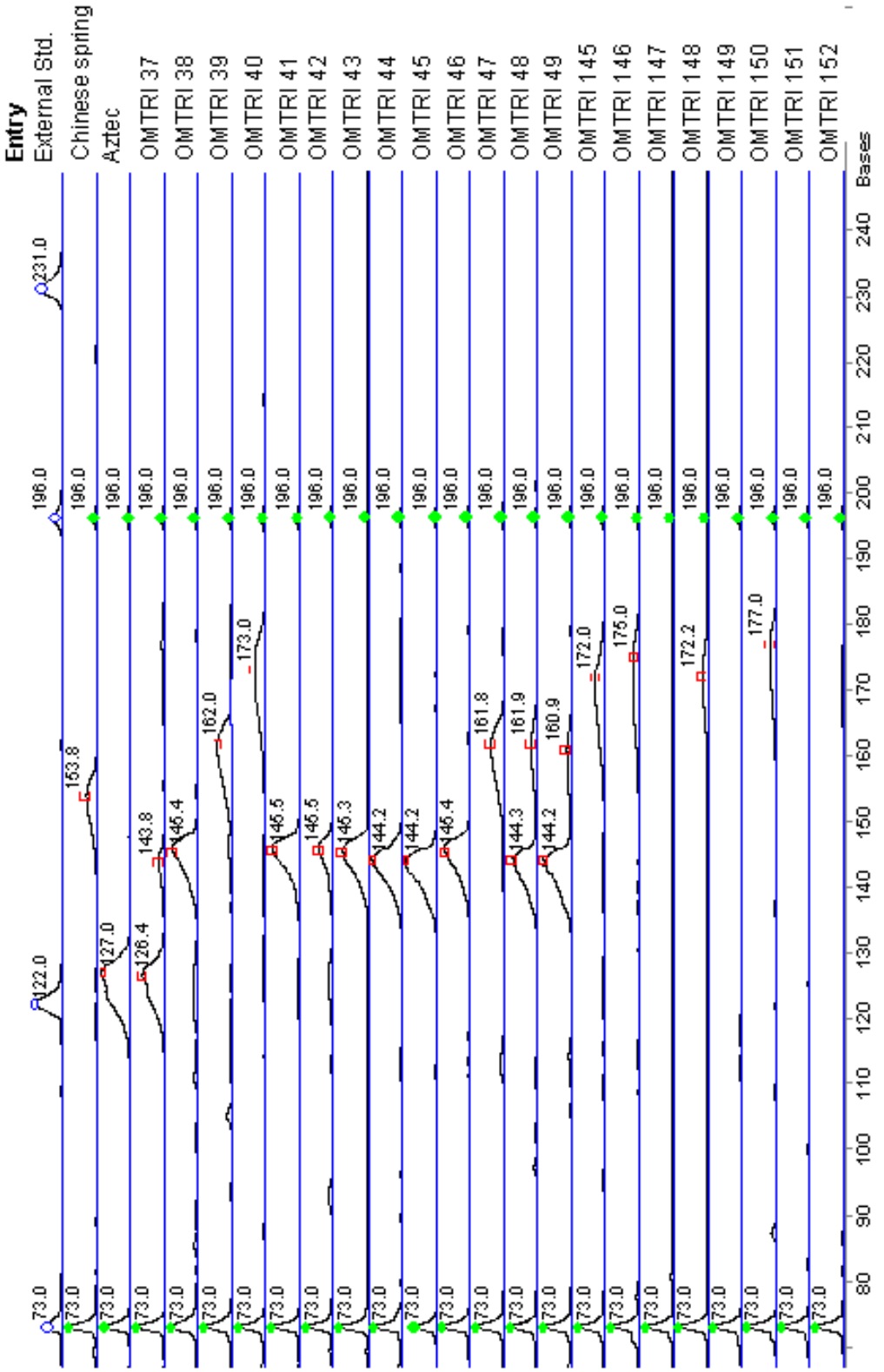
Appendix 10. Phenotypic frequencies for quantitative spike characters of hexaploid wheat accessions from the **Dhahira** district in Oman.

	Frequency in class				
Character	**1**	**2**	**3**	**4**	**5**
Spike length (cm)	23.2	71.6	5.3		
Spike width (mm)	34.4	44.1	17.2	4.3	
Spikelet number per spike	1.1	12.6	42.1	44.2	
Number of sterile spikelets	37.1	37.1	21.4	2.9	1.4
Length of the first awn (cm)	10.8	73.0	16.2		
Length of the second awn (cm)	33.3	61.1	5.6		
Spikelet length (mm)	69.2	27.7	2.1	1.1	
Spikelet width (mm)	19.0	57.9	23.2		
Number of grains per spikelet	3.2	83.0	12.8	1.1	
Sector length (mm)	32.2	40.0	26.7	1.1	
Glume length (mm)	41.1	48.4	10.5		
Lemma length (mm)	23.2	56.8	20.0		
Palea length (mm)	13.7	52.6	32.6	1.1	
Keel tooth length (mm)	59.6	22.3	17.0	1.1	
Grain length (mm)	25.3	68.4	6.3		
Grain height (mm)	17.2	78.5	4.3		
Grain width (mm)	6.4	91.5	2.1		
Spike length (cm)	13.0	58.0	29.0		

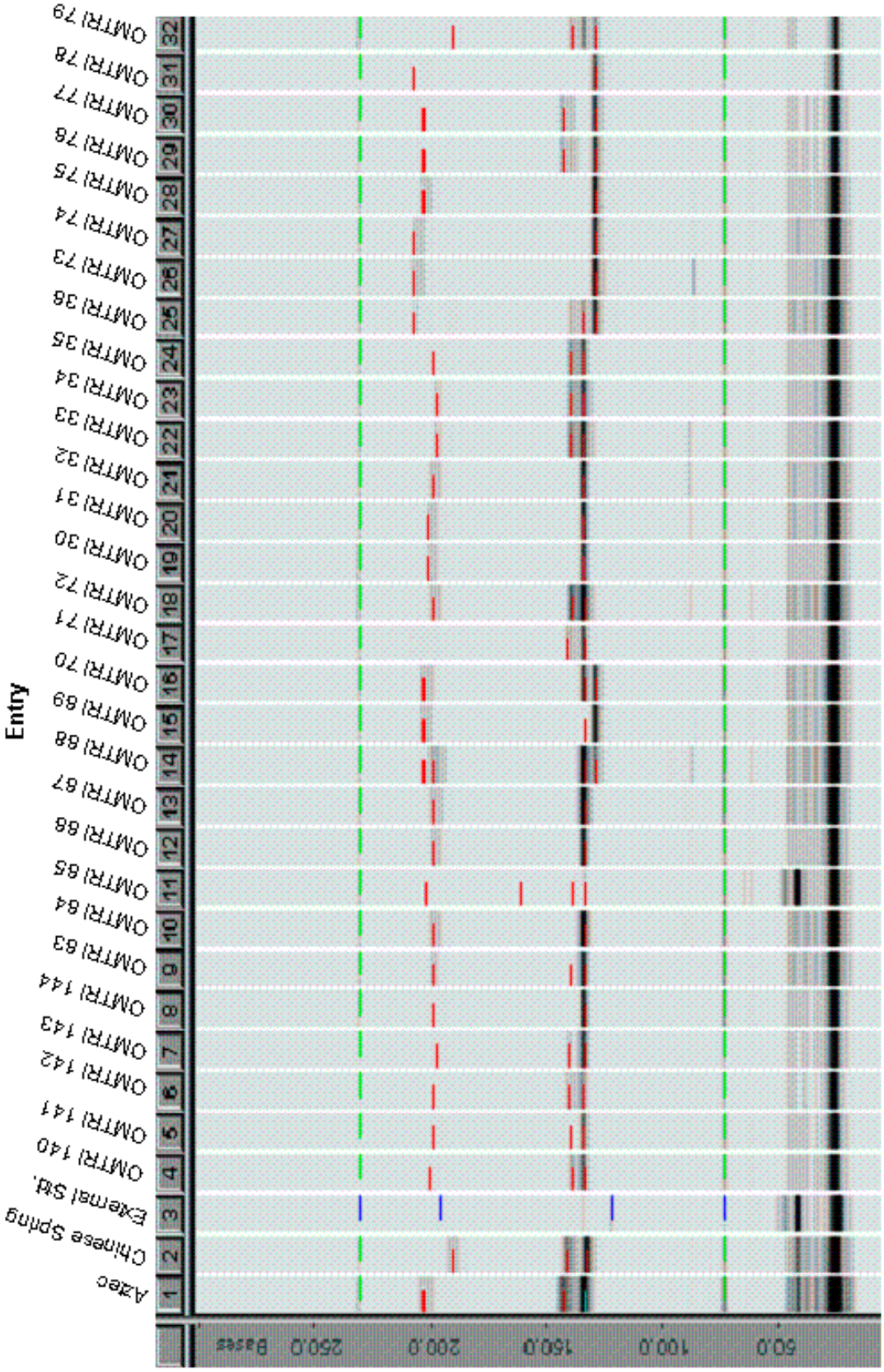
Appendix 11. Microsatellite fingerprints of *Triticum* landrace accessions from Oman. Lane descriptors refer to reference lines and varieties from the Oman Triticum (OMTRI) database established by the author.



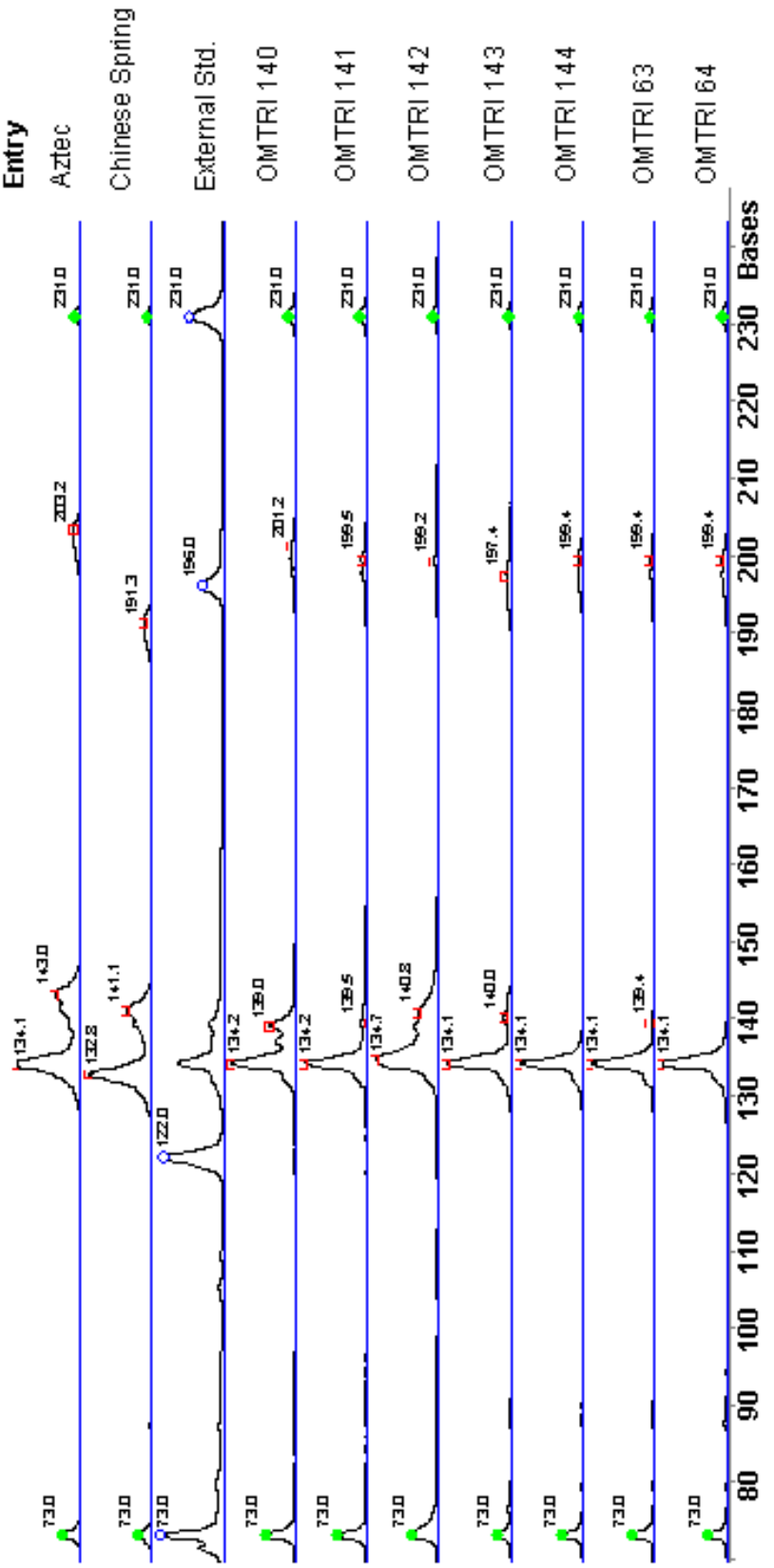
Appendix 12. Selected line graphs derived from microsatellite fingerprints (see Appendix 11) of *Triticum* landrace accessions from Oman. Lane descriptors refer to reference lines and varieties from the Oman Triticum (OMTRI) database established by the author.



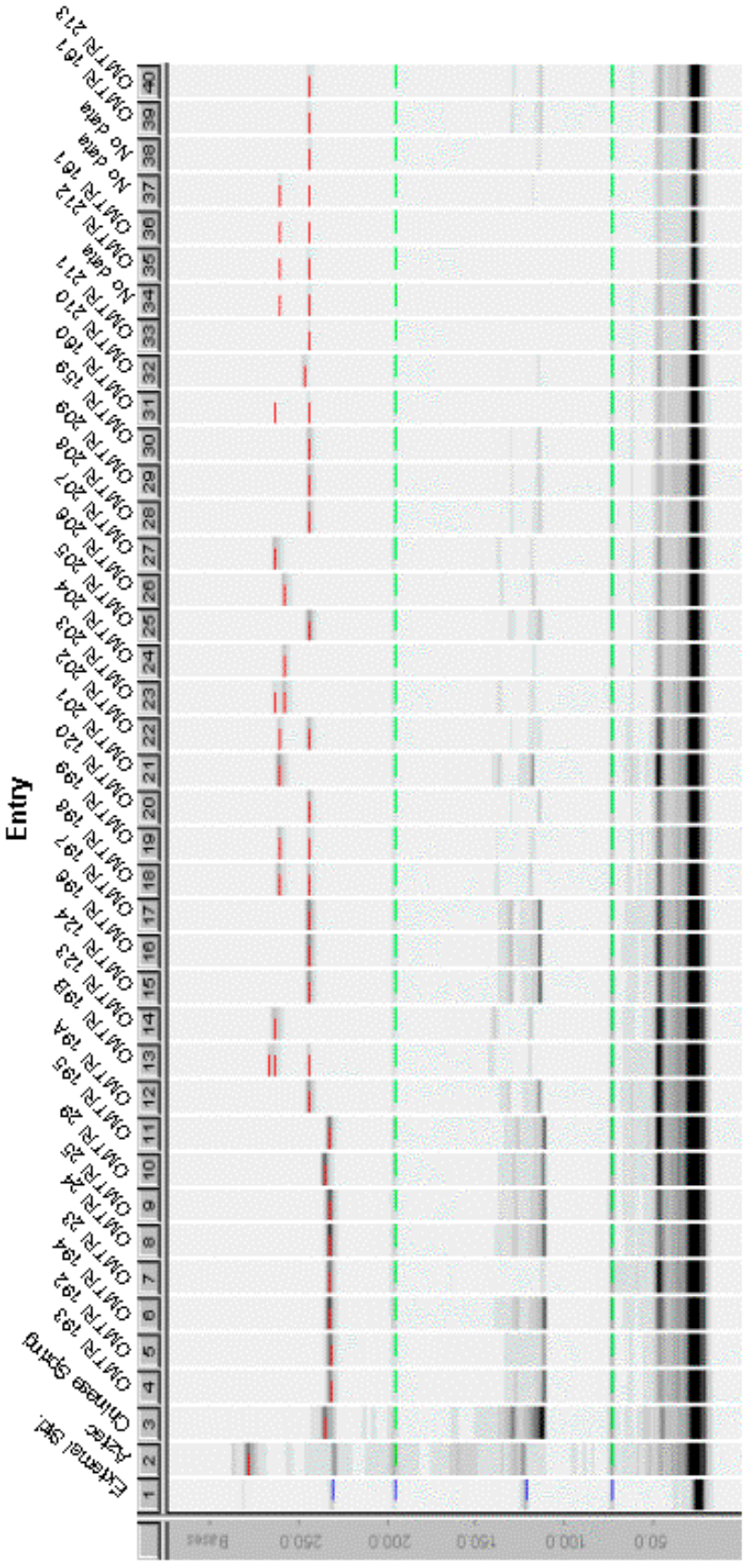
Appendix 13. Microsatellite fingerprints of *Triticum* landrace accessions from Oman. Lane descriptors refer to reference lines and varieties from the Oman Triticum (OMTRI) database established by the author.



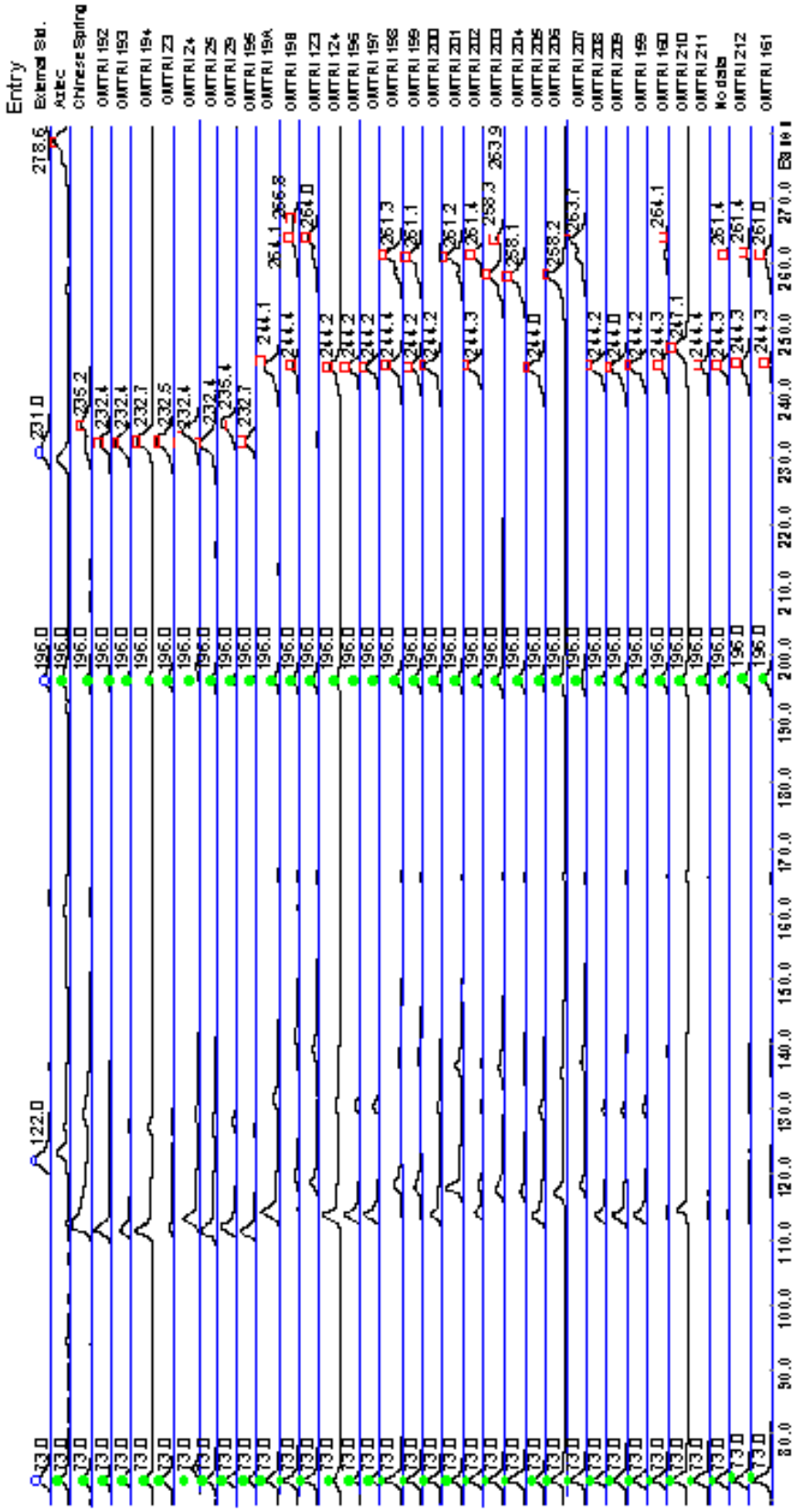
Appendix 14. Selected line graphs derived from microsatellite fingerprints (see Appendix 13) of *Triticum* landrace accessions from Oman. Lane descriptors refer to reference lines and varieties from the Oman Triticum (OMTRI) database established by the author.



Appendix 15. Microsatellite fingerprints of *Triticum* landrace accessions from Oman. Lane descriptors refer to reference lines and varieties from the Oman Triticum (OMTRI) database established by the author.



Appendix 16. Selected line graphs derived from microsatellite fingerprints (see Appendix 15) of *Triticum* landrace accessions from Oman. Lane descriptors refer to reference lines and varieties from the Oman Triticum (OMTRI) database established by the author.



Appendix 17. Definition of phenotypic classes for qualitative characters of tetraploid (*T. durum*) and hexaploid (*T. aestivum*) wheat landraces from Oman.

Characters	Class definition
Spike shape	1 pyramid-shaped; 2 pyramidal, cylindrical; 3 cylindrical; 4 cylindrical, club; 5 club-shaped; 6 spindle-shaped; 7 spindle-shaped, cylindrical; 8 egg-shaped, ovoid
Spike awns	1 absent; 2 awnless (awns on upper spiklets up to 21 mm); 3 semi-awned (21-60); 4 awned (61-100); 5 long-awned (>100)
Directions of the awns	1 parallel; 2 slightly spreading; 3 spreading; 4 strongly spreading
Colour of the awns	1 white; 2 red; 3 black
Rudeness (jaggedness) of the awns	1 absent; 2 aggregate; 3 weak; 4 intermediate; 5 strong; 6 very strong
Roughness (coarseness) of the awns	1 very fine; 2 fine; 3 intermediate; 4 coarse; 5 very coarse
Sector hairiness	1 absent; 2 weak; 3 on spikelet base; 4 on rachilla sides; 5 on spikelet base and on rachilla sides
Glume hairiness	1 absent; 2 tuberculous; 3 weak; 4 intermediate; 5 dense; 6 very dense
Sector hairiness (density)	1 very lax; 2 lax; 3 intermediate; 4 dense; 5 very dense
Glume shape	1 oblong-oval; 2 oval; 3 ovoid; 4 spatulate; 5 lance-shaped; 6 inflatum; 7 wing-shaped
Glume shoulder shape width	1 acute (angle >135); 2 rounded (90-135); 3 straight (~90); 4 blunt (45-90); 5 blunt with the formation of the second tooth (<45)
Glume colour	1 white, straw-coloured; 2 white with black glume edge; 3 black, black-blue on white background; 4 red; 5 red with black glume edge; 6 black, black-blue on red background; 7 grey-smoky on white background; 8 grey-smoky on red background; 9 other
Glume rigidity	1 very weak; 2 weak; 3 intermediate; 4 rigid; 5 very rigid
Keel tooth roughness	1 fine; 2 intermediate; 3 coarse; 4 very coarse
Grain colour	1 light-white; 2 white; 3 light red; 4 red; 5 light-brown; 6 brown; 7 amber-brown; 8 violet

Appendix 18. Description of classes for spike characters of seventeen quantitative characters for tetraploid (*T. durum*) and hexaploid (*T. aestivum*) wheat landrace accessions from Oman.

Character	Class definition
Spike density	(1) 10-15, coarse; (2) 16-21, intermediate; (3) 22-27, dense; (4) > 28, very dense
Spike length (cm)	(1) < 4, short; (2) 4-6, intermediate; (3) 7-9, long; (4) > 9, very long
Spike width (mm)	(1) narrow; (2) intermediate; (3) wide
Spikelet number per spike	(1) 0-10; (2) 11-15; (3) 16-20; (4) 21- 25; (5) 25-30
Number of sterile spikelets per spike	(1) 0-1; (2) 2; (3) ≥ 3
Length of first awn of spikelet (cm)	(1) 0-5, short; (2) 6-10, intermediate; (3) 11-15, long; (4) 16-20, very long
Length of second awn of spikelet (cm)	(1) 0-5, short; (2) 6-10, intermediate; (3) 11-15, long; (4) 16-20, very long
Spikelet length (mm)	(1) 0-5, short; (2) 11-15, intermediate; (3) 16-20, long
Spikelet width (mm)	(1) 6-10; (2) 11-15; (3) 16-20
Number of grains per spikelet	(1) 0-2; (2) 3-5; (3) 6-8; (4) ≥ 9
Lemma length (mm)	(1) 9-9.5, short; (2) 10-10.5, intermediate; (3) 11-11.5, long; (4) ≥ 12, very long
Palea length (mm)	(1) < 10.5, short; (2) 10.5-11.5, intermediate; (3) > 11.5, long
Glume length (mm)	(1) 5-6.5, short; (2) 7-8.5, intermediate; (3) 9-10.5, long; (4) > 11, very long
Grain length (mm)	(1) 5-6.5, short; (2) 7-8.5, intermediate; (3) 9-10.5, long; (4) > 11, very long
Grain width (mm)	(1) 4-5, narrow; (2) 6-7, intermediate; (3) 8-9, wide; (4) > 9, very wide
Grain height (mm)	(1) < 2.5, low; (2) 3-3.5, high; (3) > 4, very high

Appendix 19.

Genetic diversity and relationships of wheat landraces from Oman investigated with SSR markers

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Abstract

Little is known about genetic diversity and geographic origin of wheat landraces from Oman. The objectives of this study were to investigate the genetic relationships and levels of diversity of six wheat landraces collected in Oman with a set of 30 evenly distributed SSR markers. The genetic diversity conserved in the three durum wheat (*Triticum durum* ssp.) landraces (H_T = 0.46) was higher than in the three bread wheat (*Triticum aestivum* ssp.) landraces (H_T = 0.37), which were similar to Turkish and Mexican bread wheat landraces. Genetic variation was mainly distributed within rather than among the durum (G_{ST} = 0.30) and bread wheat (G_{ST} = 0.19) landraces. Based on modified Roger's distance (MRD), the durum and bread wheat landraces were distinct from each other except for a few individuals according to principal coordinate analysis (PCoA). One bread wheat landrace (Greda) was separated into two distinct sub-populations. A joint cluster analysis with other landraces of worldwide origin revealed that Omani bread wheat landraces were unique from other landraces. However, two landraces from Pakistan were grouped somewhat closer to Omani landraces indicating a possible, previously unknown relationship. Implications of these results for future wheat landrace collection, evaluation and conservation are discussed.

Key words: Genetic diversity, landrace, Oman, *Triticum aestivum, Triticum durum*

التنوع الوراثي وعلاقته بالقمح المحلي العماني باستخدام المعلمات الوراثية أحادية الجزيئية (microsatellites)

الملخص

يعرف القليل عن التباينات الوراثية في سلالات القمح المحلي العماني والموطن الأصلي لهذه السلالات. هدفت الدراسة إلى استقصاء العلاقة الوراثية ومستويات الاختلاف بين 6 سلالات من القمح المحلي العماني باستخدام 30 من المعلمات الوراثية أحادية الجزيئية (SSR) متساوية الانتشار. وقدر المؤشر الوراثي الجيني لدى أصناف القمح الرباعي ب (*Triticum durum* ssp.) وهو أعلى من الأصناف السداسية (قمح الخبز) H_T= 0.46 (*Triticum aestivum* ssp.) الذي كان مشابها لأصناف قمح الخبز التركية H_T=0.37 والمكسيكية. ووجد أن الاختلافات الوراثية بين سلالات الصنف الواحد كانت أكبر عنها فيما بين القمح الرباعي G_{ST} = 0.30 والسداسي G_{ST} = 0.19. وباستخدام تحليل البعد الوراثي (Modified Rogers MRD) أشارت النتائج إلى أن سلالات القمح الرباعي والسداسي المحليين بعيدين وراثيا؛ وذلك استنادا إلى تحليل التناسق الأساسي principal coordinate analysis (PCoA). كما أن صنف "الجريدا" المحلي من القمح السداسي ينقسم أيضا إلى مجموعتين متميزتين. وباستخدام التحليل العنقودي المفصليjoint cluster analysis تم التوصل إلى أن سلالة قمح الخبز العماني متفرد وراثيا عن الأصناف الأخرى، وأن سلالتين باكستانياتين قريبتين وراثيا من سلالات القمح العماني و لكن العلاقة بينهما غير معروفة. ولذلك يجب العمل على جمع عينات من سلالات القمح المحلية وحفظها لدراسة وافية في المستقبل.

Curriculum vitae

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