Genet Resour Crop Evol (2007) 54:465–481
DOI 10.1007/s10722-006-9205-2

RESEARCH ARTICLE

Mountain oases in northern Oman: An environment for evolution and *in situ* conservation of plant genetic resources

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Received: 11 September 2006 / Accepted: 13 December 2006 / Published online: 28 February 2007

Abstract Several botanical studies have been conducted in different parts of Oman, but knowledge about agro-biodiversity in the rapidly decaying ancient mountain oases of this country remains scarce. To fill this gap we assessed the genetic resources of three mountain oases in the al-Hajar range using a GIS-based field survey and farmer interviews. While arid conditions prevail throughout the mountain range, the different elevations of Balad Seet (950–1020 m a.s.l.), Maqta (930–1180 m a.s.l.) and Al Jabal al Akhdar (1750–1930 m a.s.l.) provide markedly differing agro-climatic conditions. Overall, 107 different crop species were identified belonging to 39 families. Species number was highest among fruits (33 spp.), followed by vegetables (24 spp.). Intensive irrigation allows cultivation of a broad range of species at all oases. However, the number of species varied significantly between sites. Fruit species diversity and homogeneity of distribution of individual fruit species was highest at Balad Seet and lowest at Maqta as indicated by respective Shannon indices of 1.00 and 0.39 and evenness values of 32% and 16%. Century plant (*Agave americana* L.), faba bean (*Vicia faba* L. var. *minor* Peterm. em. Harz) and lentil (*Lens culinaris* Medik.) were identified as relict crops, supporting oral reports of past cultivation and providing evidence of genetic erosion. Some species, such as the temperate fruits of Al Jabal al Akhdar, were exclusively found at the coolest site, while others only occurred at the hotter locations. Overall greatest species similarity was found between Balad Seet and Al Jabal al Akhdar as indicated by a Sørensen coefficient of similarity of 67%. At all oases a multilayered vegetation structure dominated with a canopy, an understory and a ground layer. Greatest species richness was recorded in the lowest stratum. Overall the study shows a location-specific but surprisingly diverse mosaic of crops in Omani mountain oases which merits further studies and conservation efforts.

Keywords Agroforestry systems · Arabian Peninsula · Arabic ethnobotany · Crop diversity · Cultivated flora · Genetic erosion · Home gardens · Indigenous knowledge · Multicropping systems

Dedicated to the memory of Richard N. Lester (1937–2006), keen researcher of plant genetic resources.

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Introduction

Situated at the eastern edge of the Arabian Peninsula, the infrastructure of the Sultanate of Oman, like that of other oil producing countries in the Middle East, is developing rapidly (Ministry of National Economy 2004). Asphalt roads, housing and other amenities are being built to fulfill the needs of a fast growing nation.

Due to the hyper-aridity of its climate, agriculture in Oman depends heavily on irrigation (Norman et al. 1998). Currently, only 0.3% of Oman's surface is used for crop production (FAO 2006). Which is dominated by two types of intensive irrigation agriculture. About 74% of the total agricultural land is irrigated by sprinkler systems, which are located in the Batinah region near the northeastern coast (Victor and Al-Farsi 2001). In contrast in the mountain region of northern Oman, a completely different form of agriculture has persisted for millennia (Nagieb et al. 2004). Agricultural and horticultural crops such as alfalfa (*Medicago sativa* L.), date palm (*Phoenix dactylifera* L.), garlic (*Allium sativum* L.), lime (*Citrus aurantiifolia* [L.] Swingle), oats (*Avena sativa* L.), onion (*Allium cepa* L.), sorghum (*Sorghum bicolor* [L.] Moench) and wheat (*Triticum aestivum* L.) are intensively cultivated (Buerkert et al. 2005) in traditional, mainly subsistence-oriented oasis systems. Fields consist of small man-made terrace systems, which are often squeezed between cliffs.

Due to their green vegetation, pleasant microclimate and availability of fresh water, these oases contrast strikingly with the dry and rough landscape of northern Oman, and have in recent years gained increasing attractiveness for tourism (Rienhardt 2006).

The crops of the oases are surface-irrigated by elaborate canal systems called *aflaj* (singular *falaj*; Wilkinson 1977; Norman et al. 1998) in Arabic, which are fed by natural springs. This irrigation system has been investigated by several authors (Abdel-Rahman and Omezzine 1996; Omezzine and Lokman 1998; Al-Marshudi 2001). Once the *falaj* system has been established, irrigation water flow is ensured by gravity and does not require direct energy inputs. Shahalam (2001) estimated that 4,000 *aflaj* exist in the Sultanate of Oman supplying about one third of the country's water demand.

Several botanical studies have been conducted in different parts of the country (e.g., Mandaville 1977, 1985; Radcliffe-Smith 1980; Cope 1988; Miller and Morris 1988; Ghazanfar 1992; Ghazanfar and Rappenhöner 1994; Ghazanfar 2003; Patzelt 2004; Gebauer et al. 2006b). However, information about agro-biodiversity, especially in the complex mountain oasis systems of northern Oman remains scarce (Guarino 1990a, b; Hammer et al. 2004). This is perhaps because cultivated plants are usually neglected by botanists and collectors of crop genetic resources, who often follow crop-specific programs and are therefore less interested in the wealth of species found (Hammer 1991). To fill this gap of knowledge and to determine the *status quo* of cultivated species, this study summarizes survey data from three ancient oases in the western and eastern part of the al-Hajar mountain range of northern Oman.

Our underlying hypothesis was that mountain oases in the extremely xeric northern Oman are rich in crop diversity and that they differ greatly in species richness and composition.

The study did not aim to collect seeds for future storage in a genebank. Instead its objective was to assess the current species composition of sustainable cropping systems in specific areas of northern Oman thereby providing baseline data for future work. This will allow future analysis of time-related changes (Bruelheide et al. 2003) and assessment of the degree of genetic erosion (Hammer and Laghetti 2005; Buerkert et al. 2006). It may also provide criteria to select specific oasis systems for *in situ* on farm conservation of crop germplasm.

Materials and methods

Study sites

Our survey was conducted in the al-Hajar mountains (Fig. 1), the main mountain range in northern Oman. At Jabal Shams, this range reaches approximately 3,000 m above sea level. At the upper altitudes, the climate is distinctly cooler

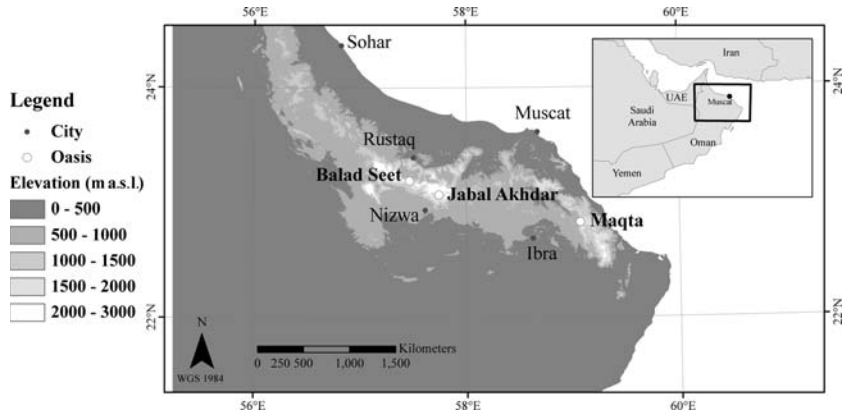

Fig. 1 Map of Oman indicating the locations of the three mountain oases of Balad Seet, Maqta and Al Jabal al Akhdar, where the vegetation surveys were conducted

and more humid than in the lowlands. Nevertheless, the climatic conditions of the whole mountain range are arid to semi-arid with a potential evapotranspiration of more than 2,000 mm year^{-1} (Nagieb et al. 2004) and even in the higher parts of the mountains, mean annual precipitation does not exceed 400 mm (Mandaville 1977). Occasional torrential rainfalls in winter can lead to flash floods that rush through the barren *wadis*.

The sparse natural vegetation in the al-Hajar range is characterized by different plant communities dominated by tree and shrub species, such as *Acacia ehrenbergiana* Hayne, *Acacia tortilis* (Forssk.) Hayne, *Nerium mascatense* DC., *Prosopis cineraria* (L.) Druce and *Ziziphus spina-christi* (L.) Desf. (below 1,000 m a.s.l.), *Acridocarpus orientalis* A. Juss., *Dyerophytum indicum* (Gibs. ex Wight) Kuntze, *Ficus palmata* Forssk., *Grewia erythraea* Schweinf. and *Moringa peregrina* (Forssk.) Fiori (1000–2000 m a.s.l.), *Dodonaea viscosa* Jacq., *Juniperus excelsa* M. Bieb. subsp. *polycarpos* (K. Koch) Takhtajan, *Olea europaea* L. subsp. *cuspidata* (Wall. ex G. Don) Ciferri, *Sageretia thea* (Osbeck) M.C. Johnst.

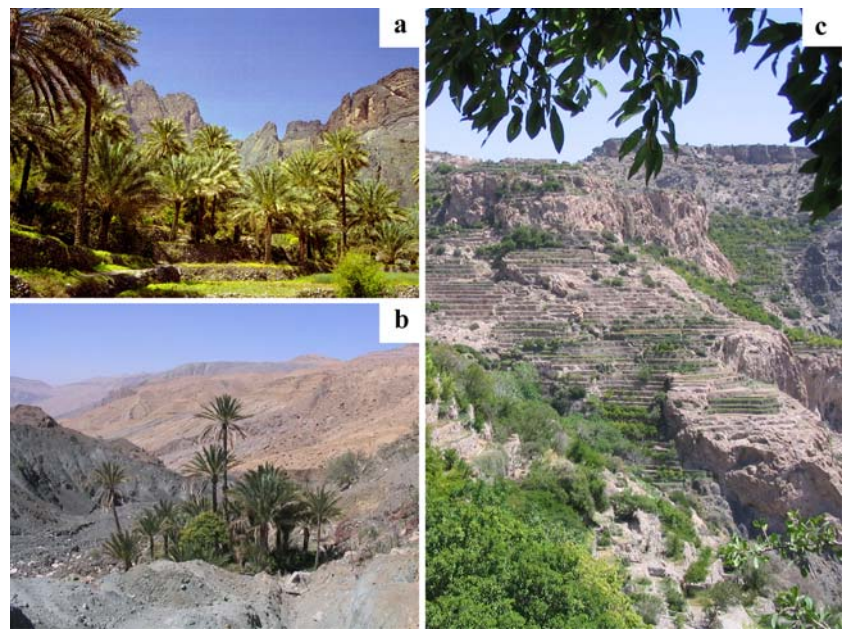

Fig. 2 Study oases Balad Seed (**a**), Maqta (**b**) and Al Jabal al Akhdar in northern Oman

Table 1 Characteristics of the three study oases in northern Oman

Characteristics	Balad Seet	Maqta	Al Jabal al Akhdar
Type of oasis	Core oasis	Scattered oasis	Core oasis
Altitude (m a.s.l.)	950–1020	930–1180	1750–1930
Mean annual rainfall (mm)	100	148[a]	336
Rainfall range (mm)	30–240	42–255[a]	128–901
Mean Temperature (°C)	23	[b]	19
Temperature range (°C)	3–43	[b]	–4[c]–32
Terraced land (ha)	13.48	4.40	13.92
Number of springs	12	22	2
Available water (m^3 d^{-1})	601	115	856
Water m^3 ha^{-1} d^{-1}	44.8	25.6	65.6
Number of houses	120	73	147
Number of inhabitants	650	200	330
Number of households	80	73	45
Number of survey plots	385 agricultural fields and 3 palm groves	130 agricultural fields and 17 palm groves	375 agricultural fields and 1017 orchard terraces

[a] Based on records from Ibra (2003–2005), 48 km west of Maqta

[b] No data available

[c] According to World Conservation Union (1987, quoted in Guarino 1990b)

and *Sideroxylon mascatense* (A. DC.) T.D. Penn. (above 2,000 m a.s.l.).

Our study comprised three spring-fed oases (Fig. 2), which have existed in this area for centuries to millennia and whose characteristics are listed in Table 1. Balad Seet and Al Jabal al Akhdar are located in the western al-Hajar Mountains (al Gharbi), while Maqta is situated in the eastern al-Hajar Mountains (ash Sharqi). The two parts of the mountain range are divided by the Semail Gap. Despite being at the upper end of large watersheds, none of the three oases has a regular runoff. The agricultural fields and orchards at all sites are situated on irrigated man-made terraces of 0.4–4 m profile depth. The soils at all sites were classified as Irragric Anthrosols (FAO 2001).

Balad Seet (23.19°N, 57.39°E, 950–1020 m a.s.l.) is located in the Al Batinah region of Oman and is situated in a small valley at the upper end of the Wadi Bani Awf watershed. It is a core oasis with a central settlement on a rocky outcrop, which is surrounded by cliffs of up to 1,200 m height. The 2,500 year-old central settlement is populated by 632 inhabitants (Nagieb 2004). The agricultural area comprises six terrace systems, where field crops are grown, and three palm groves. Most of the area is intensively irrigated throughout the year.

Maqta (59.00°E, 22.83°N, 930–1180 m a.s.l.) lies in the Ash Sharqiyah region of Oman at the upper end of Wadi Khabbah in the Jabal Bani Jabir mountains. It is a scattered oasis with a central village area made up of 73 houses. The agricultural area comprises 17 small terrace systems and 12 scattered temporary settlements within a large rocky grazing area. In March 2003 the total agro-pastoral population of this area was approximately 200 people (Siebert et al. 2005).

Al Jabal al Akhdar (23.07°N, 57.66°E, 1750–1930 m a.s.l.) is situated in the Al Dakhiliya region of Oman. The study area there is located below the Sayq plateau at the upper edge of a large erosion crater which drains into Wadi Muaydin. It comprises three agricultural settlements named Al ′Ayn, Al ′Aqr and Ash Sharayjah. Today the total population of these villages is approximately 330 but two decades ago their population was much higher (Scholz 1984). The recent establishment of the town of Sayq Qataynah on the Sayq plateau has made more than half of the villages' traditional population abandon their old houses and move to more modern residences in the new town.

Data sampling

In this study, GIS-based field work was conducted in the oasis systems of Balad Seet, Maqta and Al Jabal al Akhdar. Geo-referenced digital maps of the oases were produced from satellite images and low altitude aerial photography

(Buerkert et al. 1996). Ground-truth data collected with a Differential Global Positioning System (DGPS; Trimble Pathfinder, Sunnyvale, CA, USA) with decimeter precision were used to record the outlines of the terraces. The oasis maps containing the terraces provided the basis for the botanical survey.

The field work was conducted during August and September of 2005 and March and April of 2006. In the three oases each single terrace was visited resulting in a total of 1,907 survey plots. In addition three extensive palm groves in Balad Seet (8.88 ha) and 17 palm groves in Maqta (3.6 ha) were also studied in detail. Different farmers in each oasis were interviewed about the local names and primary uses of each species. Scientific names and abundances were recorded for all cultivated plants. The checklist of Hammer et al. (2004) comprising 66 species for Balad Seet was used to facilitate the field work. In the survey, three classes of species abundance were distinguished for perennials: (i) low abundance for <2 specimens ha^{-1}, (ii) medium abundance for 2–10 specimens ha^{-1} and (iii) high abundance for >10 specimens ha^{-1}. For field crops, the three classes were distinguished as follows: (i) low abundance for only a single specimen, (ii) medium abundance when up to two fields $(5\ ha)^{-1}$ of the species were cropped and (iii) high abundance when more than two fields $(5\ ha)^{-1}$ of the species were cultivated.

To structure the data set, based on farmers' information and literature (Rehm and Espig 1991; Franke 1997; Nowak and Schulz 1998), crop species were assigned to one of the following ten broad use categories: fruits, vegetables, pulses, tubers, spices and condiments, cereals, medicinal plants, ornamentals, fodder and others (e.g., fibers and dyes).

Plants which could not be identified in the field were collected for a field herbarium. These species were identified with the help of an experienced botanist at Sultan Qaboos University, Al Khod (Oman) and are now conserved at the Institute of Crop Science in Witzenhausen, Germany. Scientific plant names for cultivated plants in this paper mainly follow Hanelt and Institute of Plant Genetics and Crop Plant Research (2001).

Data analysis

As the three oases differed largely in size, their relative species richness was calculated according to Evans et al. (1955) using the following equation:

$$A = \frac{s}{\ln(x+1)} \cdot \ln(X+1),$$

where A is the species number found in a standard unit of area, s is the species number in a given unit of area, x is the size of the given unit of area and X is the size of the chosen standard unit of area.

For the fruit category, the Shannon index (Shannon and Weaver 1949, Magurran 1988; Spellerberg and Fedor 2003) was calculated based on number of individuals, to analyze the fruit diversity of oases using

$$H = -\sum_{i=1}^{s} p_i \cdot \ln p_i,$$

where H is the Shannon index of species diversity, s is the number of species and p_i is the proportion of individuals found in the ith species.

To estimate the homogeneity of plant distribution in the oases of northern Oman, the evenness based on the Shannon index (Magurran 1988) was calculated as

$$E = \frac{H}{\ln s},$$

where E is the Evenness, s is the number of species and H is the Shannon index.

The similarity of crop species composition between the three study oases was compared using the Sørensen coefficient of similarity (Mueller-Dombois and Ellenberg 1974). The Sørensen coefficient was calculated as

$$S = \frac{2c}{a+b} \cdot 100\%,$$

where S is the Sørensen coefficient in %, a is the number of species common in oasis A, b is the number of species common in oasis B and c is the number of species common in both oases.

Results

In total, 107 different plant species from 84 genera and 39 families were identified (Table 2). In the appendix, they are grouped according to their priority uses. Species abundance in each oasis, vernacular names in Arabic and common names in English are also listed. Amongst the 39 families, Leguminosae (11 spp.), Gramineae (10 spp.), Rosaceae (7 spp.), Rutaceae (7 spp.) and Solanaceae (6 spp.) have the highest numbers of species. 91% of species are of exotic origin, while the remaining ones are indigenous to northern Oman. Of the 107 taxa found in the oases, 46 species are woody perennials and 61 are herbaceous crops. With a total of 85 cultivated species, Balad Seet was the oasis richest in species. At Maqta and Al Jabal al Akhdar the numbers of species were lower by 52% and 18%, respectively. The relative species richness was also highest at Balad Seet with 22 species ha^{-1}, followed by Al Jabal al Akhdar and Maqta with 18 and 17 species ha^{-1}, respectively.

The analysis of the species distribution among the three oases revealed that 27 species were common to Balad Seet, Maqta and Al Jabal al Akhdar (Fig. 3). These comprised the fruits banana (*Musa* × *paradisiaca* L.), christ thorn (*Ziziphus spina-christi* [L.] Desf.), grape vine (*Vitis vinifera* L.), lime, pomegranate (*Punica granatum* L.) and sweet lime (*Citrus limettioides* L.); the vegetables bottle gourd (*Lagenaria siceraria* [Mol.] Standl.), onion and radish (*Raphanus sativus* L. convar. *sativus*); the tuber sweet potato (*Ipomoea batatas* [L.] Lam.); the spices basil (*Ocimum basilicum* L. ssp. *basilicum*) and garlic; the cereals barley (*Hordeum vulgare* L.), durum wheat (*Triticum durum* Desf.), maize (*Zea mays* L.) and oats; the medicinal plants barbados aloe (*Aloe vera* [L.] Burm.), castor bean (*Ricinus communis* L.) and fringed rue (*Ruta chalepensis* L.); the ornamental oleander (*Nerium mascatense* A. DC.); and the fodder alfalfa and fountain grass (*Pennisetum setaceum* [Forssk.] Chiov.). A total of 45 species were exclusively found in only one of the three oases, comprising the century plant (*Agave americana* L.), citron (*Citrus medica* L.), marjoram (*Origanum majorana* L.), sapodilla (*Manilkara zapota* [L.] van Royen), sword bean (*Canavalia ensiformis* [L.] DC.) and water melon (*Citrullus lanatus* [Thunb.] Matsum. et Nakai).

Table 2 Numbers of plant species, genera and families inventoried in the three study oases in northern Oman

Sites	Number of species	Number of genera	Number of families
Overall	107	84	39
Balad Seet	85	73	36
Maqta	41	36	23
Al Jabal al Akhdar	70	56	28

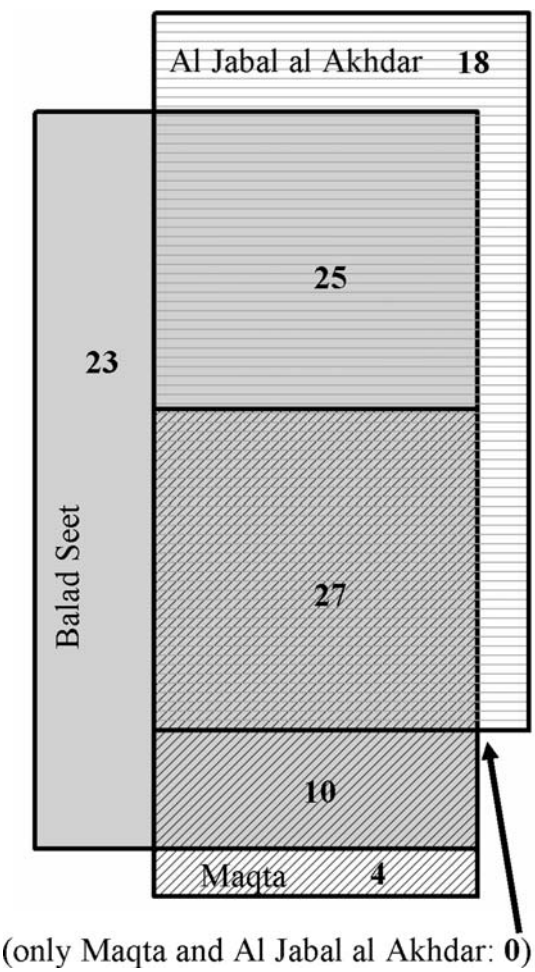

Fig. 3 Species distribution among the three oases. The areas shown in the graph are proportional to the relative numbers of species. The empty area at the point of the black arrow indicates that no species were exclusively found at Maqta and Al Jabal al Akhdar

Balad Seet had most crops that were not found in the other oases (23 spp.). In the fruit category, Al Jabal al Akhdar had most species that were not cultivated at the other locations (11 spp.).

In general, fruits were the use category with the highest number of species (Fig. 4). Species diversity of fruits as shown by the Shannon index was highest at Balad Seet (Table 3). Fruit species were least homogeneously distributed at Maqta indicated by the low evenness values of 16% (Table 3). At Balad Seet and Maqta, date palm and lime were the most common fruit species, while at Al Jabal al Akhdar the most common species was pomegranate. For date palm, 16 and 13 varieties were cultivated at Balad Seet and Maqta, respectively. Temperate fruit trees such as apple (*Malus domestica* Borkh.), apricot (*Prunus armeniaca* L.), pear (*Pyrus communis* L.), plum (*Prunus domestica* L.) and walnut (*Juglans regia* L.) occurred only at the high altitude of Al Jabal al Akhdar oasis settlements.

Vegetables were the second largest group containing 24 different taxa. Bottle gourd, coriander (*Coriandrum sativum* L.), onion, radish and red pepper (*Capsicum annuum* L.) were the preferred species. The pulses most frequently identified at Balad Seet or Al Jabal al Akhdar were chick pea (*Cicer arietinum* L.) and faba bean (*Vicia faba* L. var. *minor* Peterm. em. Harz). At Maqta no pulses were found. The most common tuber was sweet potato, which was present at all three oases. Potato (*Solanum tuberosum* L.) was only found at the high altitude of Al Jabal al Akhdar with a moderate abundance. At all three oases, four different species of spices and condiments were found. The most common one was garlic, which was present at all oases. Some cereals, such as barley, durum wheat, maize and oats were frequently planted, while pearl millet (*Pennisetum glaucum* L.) and triticale (*Triticosecale* Wittm.) were found only sporadically. In addition to the food crops, eight medicinal, nine ornamental, six fodder and five other plants were

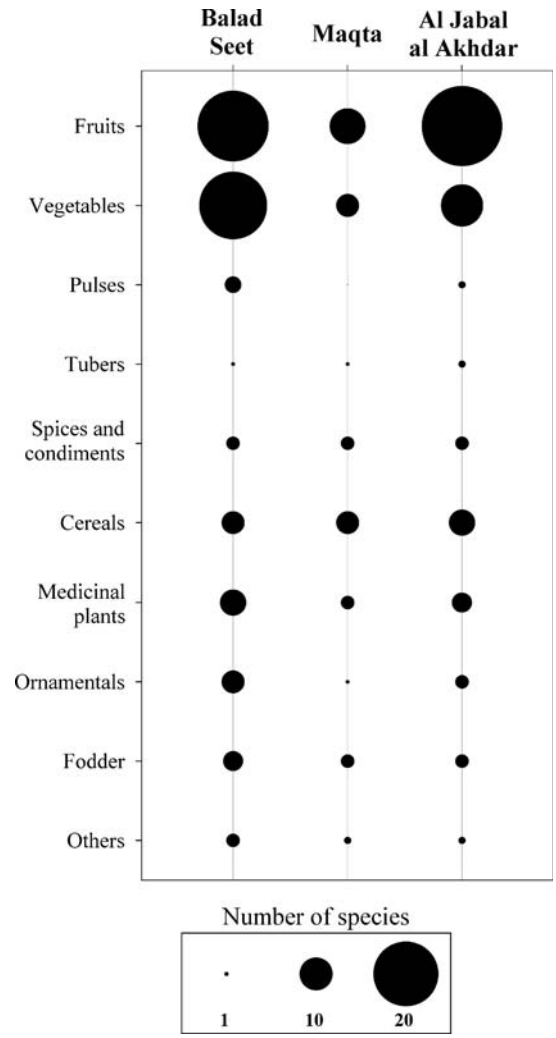

Fig. 4 Plant species of different use categories of the three oases in northern Oman

Table 3 Species richness, number of individuals and diversity indexes of fruits in three study oases in northern Oman

Sites	Species richness	Number of individuals in each species			Shannon Index	Evenness in %
		Minimum	Maximum	Average		
Overall	33	1	5958	403	1.48	42
Balad Seet	22	1	2690	161	1.00	32
Al Jabal al Akhdar	25	1	5894	299	0.96	30
Maqta	11	2	2128	208	0.39	16

identified (appendix). An interesting observation was the presence of several weed species with reportedly medicinal value which were noted after the heavy rains of February 2006.

The spectrum of cultivated species was different among the three oases. Overall, there was a higher similarity of crop species composition between the oases Balad Seet and Al Jabal al Akhdar (Table 4) than between Balad Seet and Maqta or Maqta and Al Jabal al Akhdar. However, regarding the fruits, tubers and cereals, similarity was highest between Balad Seet and Maqta.

Most cultivated terraces had different vegetation layers making them typical agroforestry systems. Three main vertical layers were present and many important species are typical of every stratum. The top layer (canopy layer, >5 m) was composed mostly of date palms and some mangos (*Mangifera indica* L.). In an intermediate layer (understory layer, 1–5 m), woody perennials such as lemon (*Citrus limon* [L.] Burm. f.), black mulberry (*Morus nigra* L.), peach (*Prunus persica* L.), and pomegranate were found mixed with bananas and papayas (*Carica papaya* L.). In the ground layer (shrub and herb layer, 0–1 m) different vegetables, spices and medicinal plants such as basil, garlic, onion, red pepper, castor bean and fringed rue were cultivated; the latter two also grew spontaneously. In Al Jabal al Akhdar, a top layer (>5 m) was absent due to the lack of mature date palms and mangos. Only two full-grown almond (*Prunus dulcis* [Mill.] D. A. Webb) trees and few tall walnut trees reach a size of more than 5 m. In all three oases, crop species diversity decreased from the lower to the higher strata.

Table 4 Sørensen coefficient of similarity of plant categories in three study oases in northern Oman

Category	Sørensen coefficient of similarity in %		
	Balad Seet—Maqta	Balad Seet—Al Jabal al Akhdar	Maqta—Al Jabal al Akhdar
Overall	59	67	49
Fruits	67	60	39
Vegetables	36	71	40
Pulses	0	57	0
Tubers	100	67	67
Spices and condiments	50	75	50
Cereals	100	93	93
Medicinal plants	67	86	60
Ornamentals	25	36	40
Fodder	80	80	50
Others	67	33	0

Fourteen of the detected species had different vernacular names in the three oases (appendix). For barbados aloe, fountain grass, fringed rue, oats and sorghum, three different vernacular names were used. There were also pairs of species, such as bread wheat and triticale, christ thorn and indian jujube (*Ziziphus mauritiana* Lam.), guava (*Psidium guajava* L.) and olive (*Olea europaea* L.), leuceaena (*Leucaena leucocephala* [Lam.] De Wit) and neem (*Azadirachta indica* Juss.) and pearl millet and sorghum, for which the same local name was used for both species.

At Maqta, 12 out of the 17 different terrace systems were fenced with industrially manufactured fences, barbwire or natural products like dead thorny branches of the christ thorn. At Balad Seet and Al Jabal al Akhdar only few terraces were fenced. In both oases, barbados aloe and prickly pear (*Opuntia vulgaris* Mill.) were used as living fences.

Discussion

The floristic inventory contained in this study describes the *status quo* of plant genetic resources in three different oasis systems in northern Oman. With a total of 107 different plant species, the number of crops was very high in comparison to other small scale cropping systems under arid or semi-arid conditions (Hammer and Perrino 1985; Ceccolini 2002; Gebauer 2005). Hammer et al. (1988) investigated the crop diversity of different oasis systems in Libya and highlighted the value of remote oases for *in situ* conservation and as a source of plant genetic resources for plant breeding. The lower number of cultivated plants in Omani oases compared to some agroforestry systems in the humid tropics (Soemarwoto and Conway 1992; Moreno-Black et al. 1996; Lamont et al. 1999; Méndez et al. 2001; Kehlenbeck and

Maass 2004), reflects the difficult growing conditions under arid conditions and the limited growing area. The number of species varied significantly from oasis to oasis. With 74%, food and fruit producing plants clearly dominated the species spectrum. Fruits were the dominant use category with the highest number of species followed by vegetables, cereals and medicinal plants (Fig. 4).

Fruit species richness was highest at Al Jabal al Akhdar comprising 25 species. However, the Shannon indices indicated that species diversity was slightly higher in Balad Seet compared to Al Jabal al Akhdar. This is reflected in the highly heterogeneous distribution of individual fruit species at Al Jabal al Akhdar compared to Balad Seet, which translates to evenness values of 30% (Al Jabal al Akhdar) and 32% (Balad Seet) (Table 3). The individuals of the 22 fruit species at Balad Seet were more homogeneously distributed than the 25 species at Al Jabal al Akhdar. Lowest species richness and species diversity was recorded at Maqta. Reasons for this may be the marginal agro-ecological conditions of this site, particularly the limited availability of irrigation water, the very shallow soil profiles and the mostly pastoral orientation of the inhabitants (Siebert et al. 2005).

Only three medium-sized date palms were found on the whole agricultural area of 13.9 ha at Al Jabal al Akhdar. Apparently, the climate at this high altitude site is too cold for successful establishment of palm groves. At Balad Seet and Maqta, however, the date palm is by far the most important multipurpose perennial crop. Besides the fruits, palm fiber has been used intensively for making strings and ropes. To compensate for the lack of date palm fiber at Al Jabal al Akhdar, farmers used to grow century plant for fiber production, since strings and ropes are very important in conjunction with farming, irrigation, herding activities and general household use. Today the perennial century plant is still found at medium abundance at Al Jabal al Akhdar, although the natural fiber (leaves) is not intensively used any more given the availability of cheap nylon strings and ropes from outside the oasis. Century plant can therefore be regarded as a relict crop. Other annual relict crops in the oasis systems were faba bean with small seeds and lentil (*Lens culinaris* Medik.). The occurrence of some individual plants in the fields and field borders supports the local oral records that some decades ago landraces of these species were widely cultivated. The complete loss of a species is only a last step in a long way of disappearance which reduces agricultural and horticultural biodiversity. Relict crops can also be considered as indicators for genetic erosion (Hammer et al. 1999).

In total, only eight cultivated medicinal plants occurred in the different oases studied, mainly at low or medium abundance. Some of them, such as thorn apple (*Datura innoxia* Miller), myrtle (*Myrtus communis* L.) and aloe vera, are planted, but also grew spontaneously in the fields. Only few people seemed to have a broader knowledge about medicinal plants. During the interviews in the fields, especially old farmers pointed to a high number of weeds and ruderal plants, which were claimed to have unspecified, yet important medicinal uses. These non-cultivated plants are not listed in the appendix. Women are reported to have a broader knowledge about medicinal plants than man (Ertuğ 2003; Turner 2003). However, due to Islamic cultural restrictions only very few women could be interviewed during our survey.

According to the different climatic situations of the study oases (Table 1), some species were exclusively found under cooler or hotter conditions. This was especially obvious in the fruit category and is reflected by the Sørensen coefficients of similarity which were calculated to compare the three oases (Table 3). The similarity between warm Balad Seet and warm Maqta is 67% and the similarity between warm Maqta and cool Al Jabal al Akhdar is only 39%. Typical temperate fruits, which were exclusively found at Al Jabal al Akhdar, are almond, apple, apricot, pear, plum and walnut. The main reason for the absence of these fruits at Balad Seet and Maqta is the lack of sufficient hours with a temperature < 7°C to fulfill their chilling requirements and to break the trees' dormancy (Westwood 1978; Luedeling et al. 2006). The highest similarity of crop composition was found between Balad Seet and Al Jabal al Akhdar and the lowest between Maqta and Al Jabal al Akhdar (Table 3, Fig. 3). The high Sørensen coefficient in cereals was due

to the fact that out of the eight cereal species at least seven were found in each oasis. Alkhanjari et al. (2005) studied the diversity of wheat germplasm in different Omani oases and reported that the farmers often cultivated different traditional landraces of wheat because of the tastiness of the grain, good adaptation to land and climate, low susceptibility to rust and, in particular, because they produced large amounts of straw to be fed to ruminants. These features of the landraces slow down their replacement by commercial cultivars and promote their continued cultivation in the oases. Al-Maskri et al. (2003) discovered two botanical wheat varieties which were new to science and point out that remote Omani mountain oases have suitable niches in arid environments for ancient wheat germplasm and therefore important for *in situ* on farm conservation which allows the continuation of evolutionary processes in the field.

Introgressions have been characterized as spectacular hints for ongoing evolution (Hanelt 1997). In their study of Cuban home gardens, Esquivel and Hammer (1992) described differentiation of crop types due to introgression, which are valuable for plant breeding because of fruit characters or disease tolerance. Introgression for example between the cultivated olive and its common wild relative (*Olea europaea* L. subsp. *cuspidata* [Wall. ex G. Don] Ciferri) is likely to occur in the remote Omani oases. However, so far no intermediate forms have been discovered.

At Balad Seet and Maqta, three vertical strata were determined consisting of the canopy, the understory and the ground layer. A multilayered vegetation structure offers advantages in reducing soil erosion and allows efficient use of water, nutrients, light and space. Ceccolini (2002) found up to four vertical strata on the arid tropical Soqotra island of Yemen. Vertical stratification is a common structure among agroforestry systems throughout the Tropics and Subtropics. In the humid Tropics, up to six different strata are common in home gardens (Millat-E-Mustafa et al. 1996; Kumar and Nair 2004). Multistrata systems are recognized as the most productive, remunerative, environmentally sound and ecologically sustainable land use systems (Young 1989; Nair 1993).

Discussions with the inhabitants of the oases clearly showed that older people have much more traditional knowledge regarding agricultural practices than younger people as also described by Khoshbakht and Hammer (2005). Nowadays, young people often work outside the oases, are less interested in continuing agricultural practices and often do not know local names of plant species, which their fathers grow in their fields. This observation indicates the ongoing transformation process of the oasis systems including the loss of indigenous knowledge.

Field observations indicate that species names often varied between the study sites. Guarino (1990b) and Alkhanjari et al. (2005) also reported some cases of traditional crops and landraces that had different names throughout Oman.

Agricultural fields and fruit orchards in the study oases are still an important factor for the economy and self-sufficiency of many households. The high species diversity provides year-round produce for household consumption (Gebauer et al. 2006a), but the degree to which the plant cultivation contributes to the provision of the household's diet varies widely.

Maqta is a typical scattered oasis, where 12 of the 17 terrace systems are very small and widely dispersed around the central village. These 12 systems are heavily fenced to protect the crops against the high number of freely roaming domestic animals. The agro-pastoral inhabitants of Maqta own about 900 sheep and goats, which feed on the sparse natural vegetation in the xeric mountain environment around Maqta (Siebert et al. 2005). Balad Seet and Al Jabal al Akhdar are core oases where, for the most part, fields are only fenced at the margins of the cultivated area. In some places, hardy species such as barbados aloe and prickly pear are used as living fences. The use of living fences is receiving more and more attention in research since it offers multiple environmental advantages (Levasseur et al. 2004; Zahawi 2005; León and Harvey 2006).

Comparison of species numbers at a certain location at different points in time, so-called re-sampling studies, can provide an indication of genetic erosion, as demonstrated by Hammer et al. (1996). Similarly, comparison of the species abundances of different areas at a single point in

time can be useful to indicate the impacts of various conditions, such as local climate, socio-economic framework, and access to transportation and markets. Specific knowledge regarding the number of different crop species in Balad Seet, Maqta and Al Jabal al Akhdar, coupled with follow up studies in a period of some years will be necessary to better describe and discuss the transformation processes of Omani oases agricultural systems.

Conclusions and recommendations

A surprisingly diverse mosaic of crops was found in the three study oases of the arid al-Hajar mountain range of northern Oman with area-specific species composition and species richness. Germplasm collection activities, *in situ* conservation programs and interdisciplinary analysis of socioeconomic aspects or rural communications are urgently needed to better understand and preserve the heritage of these ancient agro-ecosystems. Genebanks should be integrated into such programs to guarantee the conservation of the rare crop plants and as starting point of their possible reintegration into those agro-ecosystems of Omani oases from where they have been lost during the rapid transformation process following the development of the oil-driven economy.

Note

Multicropping in small scale agriculture creates favourable microclimates and often provides habitats for wild plants and animals (Torquebiau 1992). Remote Omani oases are also an important refuge for indigenous wild plant species, such as *Epipactis veratrifolia* Boiss. et Hohen. ex Boiss. Several individuals of this endangered orchid were found flowering beside a water basin in an isolated part of the oasis Maqta. According to Patzelt (2006) this orchid can be found in moist places in cliffs and along irrigation canals at an altitude of 450–2000 m. In Oman it is threatened by habitat degradation and infrastructure development.

Acknowledgments The help of the botanist Dr. Annette Patzelt, Department of Biology, College of Science at the Sultan Qaboos University for species identification is highly appreciated. The authors are also indebted to Sultan Qaboos University in Muscat (Dr. Sulaiman Al Khanjari) and the Agricultural Service at Sayq Qataynah for the cooperation and to the Deutsche Forschungsgemeinschaft (DFG) for funding (Bu 1308/2-4). We thankfully acknowledge the patience and hospitality of the oasis farmers at Balad Seet, Maqta and Al Jabal al Akhdar.

Appendix Cultivated plants in three mountain oases in northern Oman. Nomenclature of plant species follows mainly Hanelt and Institute of Plant Genetics and Crop Plant Research (2001)

No.	Scientific name	Family	Balad Seet		Maqta		Al Jabal al Akhdar		English name
			Vernacular name	Abundance[a]	Vernacular name	Abundance[a]	Vernacular name	Abundance[a]	
Fruits									
1	*Carica papaya* L.	Caricaceae	Fifai	L	–	–	Fifai	M	Papaya
2	*Citrus aurantiifolia* (L.) Swingle	Rutaceae	Laymun	H	Laymun	M	Lumi	H	Lime
3	*Citrus aurantium* L.	Rutaceae	Narinj	L	–	–	Narinj	L	Bitter Orange
4	*Citrus limettioides* L.	Rutaceae	Safardjal	M	Safardjal	M	Safardjal	M	Sweet Lime
5	*Citrus limon* (L.) Burm. f.	Rutaceae	–	–	–	–	Laymun	L	Lemon
6	*Citrus medica* L.	Rutaceae	–	–	–	–	Shamum	L	Citron
7	*Citrus sinensis* (L.) Osbeck	Rutaceae	–	–	–	–	Burtokal	L	Orange
8	*Cordia myxa* L.	Boraginaceae	Mbou	L	Mbou	L	–	–	Sebesten Plum
9	*Ficus carica* L.	Moraceae	Tin	M	–	–	Tin	L	Fig
10	*Juglans regia* L.	Juglandaceae	–	–	–	–	Jou	M	Walnut
11	*Malus domestica* Borkh.	Rosaceae	–	–	–	–	Tufa	M	Apple Tree
12	*Mangifera indica* L.	Anacardiaceae	Ambe	L	Ambe	M	–	–	Mango
13	*Manilkara zapota* (L.) van Royen	Sapotaceae	Shiko	L	–	–	–	–	Sapodilla
14	*Morus alba* L.	Moraceae	–	–	–	–	Tut	L	White Mulberry
15	*Morus nigra* L.	Moraceae	Forsad	L	Forsad	L	–	–	Black Mulberry
16	*Musa* × *paradisiaca* L.	Musaceae	Mous	H	Mous	L	Mous	L	Banana
17	*Olea europaea* L.	Oleaceae	Seitun	L	–	–	Seitun	L	Olive Tree
18	*Opuntia ficus-indica* (L.) Mill.	Cactaceae	–	–	–	–	Tin Schokey	L	Indian Fig
19	*Opuntia vulgaris* Mill.	Cactaceae	Sabarr	L	–	–	Sabarr	L	Prickly Pear
20	*Phoenix dactylifera* L.	Palmae	Nakheel	H	Nakheel	H	Nakheel	L	Date Palm
21	*Pithecellobium dulce* (Roxb.) Benth.	Mimosaceae	Sbarr	L	–	–	–	–	Manila Tamarind
22	*Prunus armeniaca* L.	Rosaceae	–	–	–	–	Mishmish	H	Apricot
23	*Prunus domestica* L.	Rosaceae	–	–	–	–	Barkuk	L	Plum
24	*Prunus dulcis* (Mill.) D. A. Webb	Rosaceae	–	–	–	–	Lous	L	Almond Tree
25	*Prunus persica* L.	Rosaceae	Khokh	L	–	–	Khokh	H	Peach
26	*Psidium guajava* L.	Myrtaceae	Seitun	L	–	–	Seitun	L	Guava
27	*Punica granatum* L.	Punicaceae	Roman	M	Roman	M	Roman	H	Pomegranate
28	*Pyrus communis* L.	Rosaceae	–	–	–	–	Komathra	L	Pear
29	*Syzygium cuminii* (L.) Skeels	Myrtaceae	Sam	L	Sam	M	–	–	Rose Apple
30	*Terminalia catappa* L.	Combretaceae	Betham	L	–	–	–	–	Singapore Almond
31	*Vitis vinifera* L.	Vitaceae	Einab	M	Einab	M	Einab	M	Grape Vine

Appendix continued

No.	Scientific name	Family	Balad Seet		Maqta		Al Jabal al Akhdar		English name
			Vernacular name	Abundance[a]	Vernacular name	Abundance[a]	Vernacular name	Abundance[a]	
32	*Ziziphus mauritiana* Lam.	Rhamnaceae	Siddir	L	–	–	–	–	Indian Jujube
33	*Ziziphus spina-christi* (L.) Desf.	Rhamnaceae	Siddir	M	Siddir	M	Siddir	M	Christ Thorn
Vegetables									
34	*Allium cepa* L. var. *aggregantum* G. Don	Liliaceae	Bassal	H	Bassal	L	Bassal	M	Onion
35	*Beta vulgaris* L. ssp. *vulgaris* var. *cicla* L.	Chenopodiaceae	Sabanakh	M	–	–	–	–	Foliage Beet
36	*Beta vulgaris* L. ssp. *vulgaris* var. *vulgaris*	Chenopodiaceae	Banjar	M	–	–	–	–	Red Beet
37	*Brassica oleracea* L. ssp. *capitata* (L.) DC. var. *capitata* L. f. *capitata* (L.) Duch.	Cruciferae	Malfuf	H	–	–	Malfuf	L	White Cabbage
38	*Brassica rapa* L. ssp. *pekinensis* (Lour.) Hanelt	Cruciferae	Kharrdall	L	Kharrdall	L	–	–	Chinese Cabbage
39	*Canavalia ensiformis* (L.) DC.	Leguminosae	Trohe	L	–	–	–	–	Sword Bean
40	*Capsicum annuum* L.	Solanaceae	Filfil	M	Filfil	M	Filfil	M	Red Pepper
41	*Capsicum frutescens* L.	Solanaceae	–	–	Filfil	L	–	–	Chilli
42	*Cichorium intybus* L. var. *foliosum* Hegi	Compositae	Khass	M	–	–	–	–	Chicory
43	*Citrullus lanatus* (Thunb.) Matsum. et Nakai	Cucurbitaceae	–	–	Sheh	L	–	–	Water Melon
44	*Coriandrum sativum* L.	Umbelliferae	Gilgilan	H	–	–	Gilgilan	L	Coriander
45	*Cucumis sativus* L.	Cucurbitaceae	Khrear	L	–	–	–	–	Cucumber
46	*Cucurbita moschata* (Lam.) Duch. ex Poir.	Cucurbitaceae	Bobar	L	–	–	Bobar	L	Crookneck
47	*Cucurbita pepo* L. convar. *giromontiina* Greb.	Cucurbitaceae	Kusa	L	–	–	–	–	Summer Squash
48	*Daucus carota* L. ssp. *sativus* (Hoffm.) Schübl. et Mart.	Umbelliferae	Gasar	M	–	–	Zoghot	L	Carrot
49	*Eruca sativa* Mill.	Cruciferae	Djardir	M	–	–	–	–	Ruce
50	*Lactuca sativa* L. convar. *sativa* var. *capitata* L.	Compositae	Khass	H	–	–	Khass	M	Lettuce
51	*Lagenaria siceraria* (Mol.) Standl.	Cucurbitaceae	Khara	M	Khara	L	Khara	L	Bottle Gourd
52	*Lycopersicon esculentum* Mill.	Solanaceae	Tamatim	M	–	–	Tamatim	M	Tomato
53	*Petroselinum crispum* (Mill.) Nym.	Umbelliferae	Bakdunes	M	–	–	Khidf	L	Parsley
54	*Pisum sativum* L. ssp. *sativum*	Leguminosae	Gorgor	M	–	–	Gorgor	L	Pea
55	*Raphanus sativus* L. convar. *sativus*	Cruciferae	Fudjl	H	Fudjl	L	Fudjl	H	Radish
56	*Rumex vesicarius* L.	Polygonaceae	–	–	–	–	Homad	H	Bladder Dock
57	*Solanum melongena* L.	Solanaceae	Bazinjan	L	–	–	–	–	Eggplant

Appendix continued

No.	Scientific name	Family	Balad Seet		Maqta		Al Jabal al Akhdar		English name
			Vernacular name	Abundance[a]	Vernacular name	Abundance[a]	Vernacular name	Abundance[a]	
Pulses									
58	*Cajanus cajan* (L.) Huth	Leguminosae	Durian	L	–	–	–	–	Pigeon Pea
69	*Cicer arietinum* L.	Leguminosae	Donjo	H	–	–	–	–	Chick Pea
60	*Lablab purpureus* (L.) Sweet	Leguminosae	Hibil	L	–	–	Hibil	L	Hyacinth Bean
61	*Lens culinaris* Medik.	Leguminosae	Adass	L	–	–	–	–	Lentil
62	*Vicia faba* L. var. *minor* Peterm. em. Harz	Leguminosae	Baquil	H	–	–	Ful	M	Faba Bean
Tubers									
63	*Ipomoea batatas* (L.) Lam.	Convolvulaceae	Findal	M	Findal	L	Findal	M	Sweet Potato
64	*Solanum tuberosum* L.	Solanaceae	–	–	–	–	Batatas	M	Potato
Spices and condiments									
65	*Allium sativum* L. var. *sativum*	Liliaceae	Thum	H	Thum	L	Thum	H	Garlic
66	*Foeniculum vulgare* Mill. ssp. *vulgare*	Umbelliferae	Habahelua	L	–	–	–	–	Fennel
67	*Lepidium sativum* L. ssp. *sativum*	Cruciferae	–	–	Haba Hamra	M	–	–	Cress
68	*Mentha asiatica* Boriss.	Labiatae	–	–	–	–	Ghagha, Samuta	M	Horsemint
69	*Mentha* × piperita L.	Labiatae	Nanaa	H	–	–	Nanaa	L	Peppermint
70	*Ocimum basilicum* L. ssp. *basilicum*	Labiatae	Rihan	L	Rihan	L	Rihan	L	Basil
71	*Origanum majorana* L.	Labiatae	–	–	Sifsif	H	–	–	Marjoram
Cereals									
72	*Avena sativa* L.	Gramineae	Thaalabia	H	Sru	H	Mseblu	H	Oat
73	*Hordeum vulgare* L.	Gramineae	Shaer	H	Shaer	H	Shaer	H	Barley
74	*Pennisetum glaucum* L.	Gramineae	Thura	L	Haria	M	Thura	L	Pearl Millet
75	*Sorghum bicolor* (L.) Moench	Gramineae	Thura	H	Haria	M	Herbar	L	Sorghum
76	*Triticum aestivum* L.	Gramineae	Borr	H	Borr	M	Borr	L	Bread Wheat
77	*Triticum durum* Desf.	Gramineae	Nimra	H	Nimra	M	Nimra	H	Durum Wheat
78	*Triticosecale* Wittm.	Gramineae	–	–	–	–	Borr	L	Triticale
79	*Zea mays* L.	Gramineae	Mahandu	H	Mahandu	M	Khadim	H	Maize
Medicinal plants									
80	*Aloe vera* (L.) Burm.	Liliaceae	Skill	M	Sbarr	L	Suqal	M	Barbados Aloe
81	*Boswellia sacra* Flueckiger	Burseraceae	Luban	L	–	–	–	–	Olibanum
82	*Carthamus tinctorius* L.	Compositae	Shoran	L	Shoran	M	–	–	Safflower

Appendix continued

No.	Scientific name	Family	Balad Seet		Maqta		Al Jabal al Akhdar		English name
			Vernacular name	Abundance[a]	Vernacular name	Abundance[a]	Vernacular name	Abundance[a]	
83	*Datura innoxia* Miller	Solanaceae	Maraneha	M	–	–	Maraneha	M	Thorn Apple
84	*Jasminum officinale* L.	Oleaceae	Smin	M	–	–	Smin	L	Jasmine
85	*Myrtus communis* L.	Myrtaceae	Yaas	H	–	–	Yaas	H	Myrtle
86	*Ricinus communis* L.	Euphorbiaceae	Arash	M	Arash	L	Arash	M	Castor Bean
87	*Ruta chalepensis* L.	Rutaceae	Khatf	L	Sedab	L	Khidif	M	Fringed Rue
Ornamentals									
88	*Bougainvillea spectabilis* Willd.	Nyctaginaceae	Bougainvillea	L	–	–	–	–	Bougainvillea
89	*Catharanthus roseus* (L.) G. Don	Apocynaceae	Suhur	M	–	–	–	–	Madagasca Periwinkle
90	*Helianthus annuus* L.	Compositae	–	–	–	–	Abady Shams	L	Sunflower
91	*Ipomoea* sp.	Convolvulaceae	Suhur	M	–	–	–	–	Morning Glory
92	*Nerium mascatense* A. DC.	Apocynaceae	Haban	M	Haban	L	Haban	L	Oleander
93	*Plumeria alba* L.	Apocynaceae	Narjes	L	–	–	–	–	White Frangipani
94	*Ficus altissima* Blume	Moraceae	Role	L	–	–	–	–	False Banyan
95	*Rosa damascena* Mill.	Rosaceae	Ward	M	–	–	Ward[b]	H	Rose
96	*Tagetes erecta* L.	Compositae	–	–	–	–	Safran Al Shaba	L	Marigold
Fodder									
97	*Medicago sativa* L.	Leguminosae	Khatt	H	Khatt	L	Khatt	M	Alfalfa
98	*Melilotus officinalis* (L.) Pall.	Leguminosae	Safra	M	–	–	Safra	M	Yellow Sweet Clover
99	*Panicum maximum* Jacq.	Gramineae	Snoom	H	Sakarr	M	–	–	Guinea Grass
100	*Pennisetum setaceum* (Forssk.) Chiov.	Gramineae	Halfa	M	Musablou	H	Shjera	L	Fountain Grass
101	*Trigonella foenum-graecum* L.	Leguminosae	Halba	M	Halba	H	–	–	Fenugreek
102	*Vicia sativa* L.	Leguminosae	Maqronia	H	–	–	Krenat	H	Common Vetch
Others									
103	*Agave americana* L.	Agavaceae	–	–	–	–	Masat	M	Century Plant
104	*Azadirachta indica* Juss.	Meliaceae	Sherich	L	–	–	–	–	Neem Tree
105	*Gossypium arboreum* L.	Malvaceae	Kottn	L	Kottn	L	–	–	Cotton
106	*Lawsonia inermis* L.	Lythraceae	Henna	M	Henna	L	–	–	Henna
107	*Leucaena leucocephala* (Lam.) De Wit	Fabaceae	Bahr	L	–	–	Sherich	L	Leucaena

[a] Abundance of plant species found in the oasis systems: L = low, M = medium and H = high

[b] In Al Jabal al Akhdar an important technical crop for attar of rose production

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