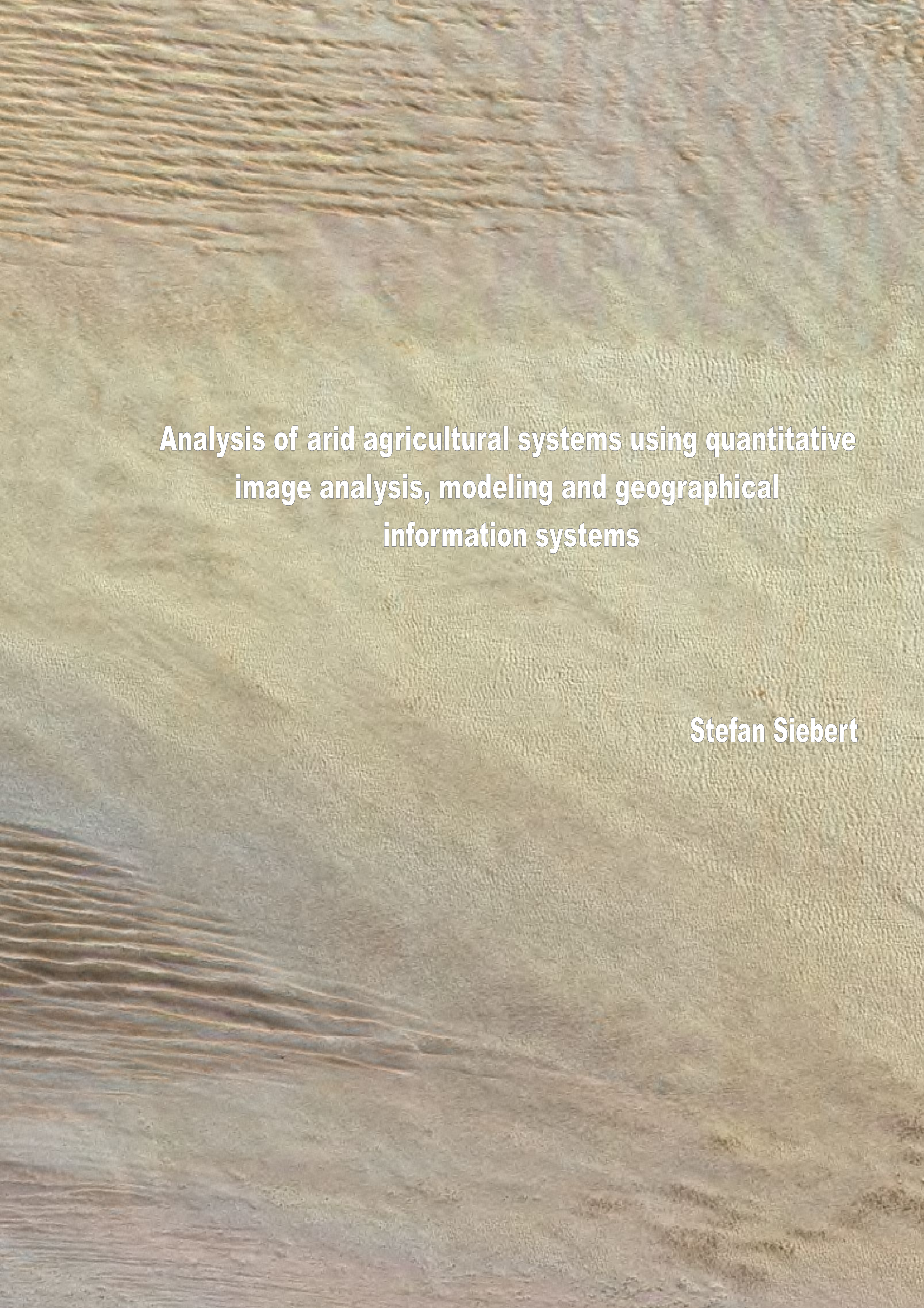

Analysis of arid agricultural systems using quantitative image analysis, modeling and geographical information systems

Stefan Siebert

Analysis of arid agricultural systems using quantitative image analysis, modeling and geographical information systems

Analyse von Agrarsystemen im ariden Klima durch quantitative Bildanalyse, Modellierung und Geographische Informationssysteme

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Stefan Siebert

ENGLISH SUMMARY

1. INTRODUCTION

Under arid climate conditions natural ecosystems as well as man-made agro-ecological systems show a specific adaptation to limited water resources. This adaptation comprises physiological, morphological, genetic, and in the case of agricultural systems, also management-related aspects.

The strong contrast between irrigated agricultural land and the sparse vegetation cover in natural ecosystems has been widely used to classify land cover and land use in arid regions by remote sensing techniques (IWMI, 2005; Leff et al., 2004; Droogers, 2002; NIRE, 2000; Ramancutty and Foley, 1998). Recently observed improvements of methodologies used in remote sensing and advancements in Geographic Information Systems (GIS) now also allow to use satellite imagery for the determination of meteorological variables such as temperature, radiation or vapor pressure and to compute net primary production of the vegetation (see for example the list of available data sets from the MODIS sensor at http://edcdaac.usgs.gov/modis/dataproducts.asp). Such applications more and more require to combine image analysis techniques and modeling. Existing remote sensing based measurements are used in models of real processes to simulate those variables that are difficult to measure. The estimate of variables that are difficult or impossible to measure (such as predictions of the future) and the reduction of costs and efforts (e.g. generation of high-resolution global data sets, calculation of evapotranspiration, climate research) are in general two of the major reasons for the development and application of models. Finally, the opportunity to use Geographic Information Systems and Global Positioning Systems (GPS) to generate, process and present geographical information in a user friendly environment led to a dynamic development of this sector and to a wide use of these methods in many disciplines. The final stage of this development are interactive map servers that even allow inexperienced users to produce individual maps. Examples are map servers of the United States Geological Survey (USGS) at http://seamless.usgs.gov/website/seamless/viewer.php or the Australian Natural Resources Atlas at http://audit.ea.gov.au/ANRA/atlas_home.cfm.

In the context of this dissertation methods and tools of quantitative image analysis, modeling and GIS were developed and applied for:

- the non-destructive dry matter estimation of *Alhagi sparsifolia* vegetation in the foreland of the Qira oasis in Northwest China (publication 1),
- mapping of land cover and land use at global, regional or local scale (publications 1, 2, 4 and 6),
- the classification of mountain oases in northern Oman according to land use, water resources and settlement type,

- the establishment of water- and nutrient balances in mountain oases of the Sultanate of Oman (publications 3 and 5),
- the calculation of the carrying capacity of two mountain oases in northern Oman to assess the sustainability of the current resource use (publications 2 and 6) and to
- establish settlement hypotheses for two mountain oases in northern Oman (publications 2 and 6).

In the following section the materials and methods used to reach these goals are described and the research sites are introduced. The main results are presented and discussed in section 3 and conclusions are given in section 4. The six already mentioned publications are part of this thesis and were placed in its appendix.

2. MATERIALS, METHODS AND RESEARCH SITES

With the exception of the work published within the Global Map of Irrigation Areas, the research summarized in this thesis was carried out on arid sites in the Northwest of the Peoples Republic of China (publication 1) and in the North of Oman (publications 2, 3, 5 and 6). In the following section these research sites are introduced.

2.1 Research sites

Sultanate of Oman

All work was conducted at the eastern edge of the Arabian Peninsula along the Hajar mountain range in the northern part of the Sultanate of Oman (Fig. 1). With an average annual precipitation of 55 mm and a potential evapotranspiration of more than 2000 mm yr^{-1} the Sultanate is effected by extremely arid climate conditions. Thus the country's agriculture depends completely on irrigation. The area equipped for irrigation was reported to be 61 550 ha in 1993, equivalent to about 0.2% of Oman's total land surface. Almost 57% of it, or 34 930 ha, is located in the Al Batinah coastal plain in the North of the country. The total area harvested was 70 930 ha in the same year. The most important crops were perennial date palm (*Phoenix dactylifera* L.) and banana (*Musa* ssp) on 43 000 ha as well as alfalfa (*Medicago sativa* L.) on 17 330 ha, vegetables (5700 ha) and cereals (4900 ha; FAO, 1997). There are different figures for the irrigation techniques used. While some reports indicate only 3730 ha to be equipped with modern sprinkler and drip irrigation techniques (FAO, 1997), other authors claim about 74% of the irrigated area to be equipped with modern techniques (Ibrahim, 1999). Although agriculture and fisheries employed about 37 % of the total labour force in 1993, they accounted for only 3.3% of the country's GDP (FAO, 1997). The predominant suppliers to Oman's economic well-being are the oil industry, trade and services.

Funded by the Deutsche Forschungsgemeinschaft (DFG), the two oasis settlements of Balad Seet (57.39° E, 23.19° N, 996 m a.s.l.) and Maqta (59.00° E, 22.83° N, 1050 m a.s.l.) and the settlements in Wadi Tiwi with Tiwi as main village (59.25° E, 22.83° N, 32 m a.s.l.) have been studied within the framework of an interdisciplinary project entitled 'Transformation Processes in Oasis Settlements of Oman'. The oasis of Balad Seet (Fig. 2a) is situated at the upper end of the Wadi Bani Awf, a watershed on the northern side of the Hajar range of the Jabal Akhdar mountains at the foot of a 1000 m high cliff and surrounded by mountains consisting of carbonates and clay-stones. The houses of today's 650 inhabitants, which are located on a rocky outcrop in the center of the oasis, are surrounded by 385 agricultural fields covering 4.6 ha and by 8.8 ha of palm groves. A large part of the agricultural land is cultivated and irrigated year-round. The inhabitants own about 200 small ruminants (sheep and goats) and about 30 cattle. Five irrigation water supply systems, called

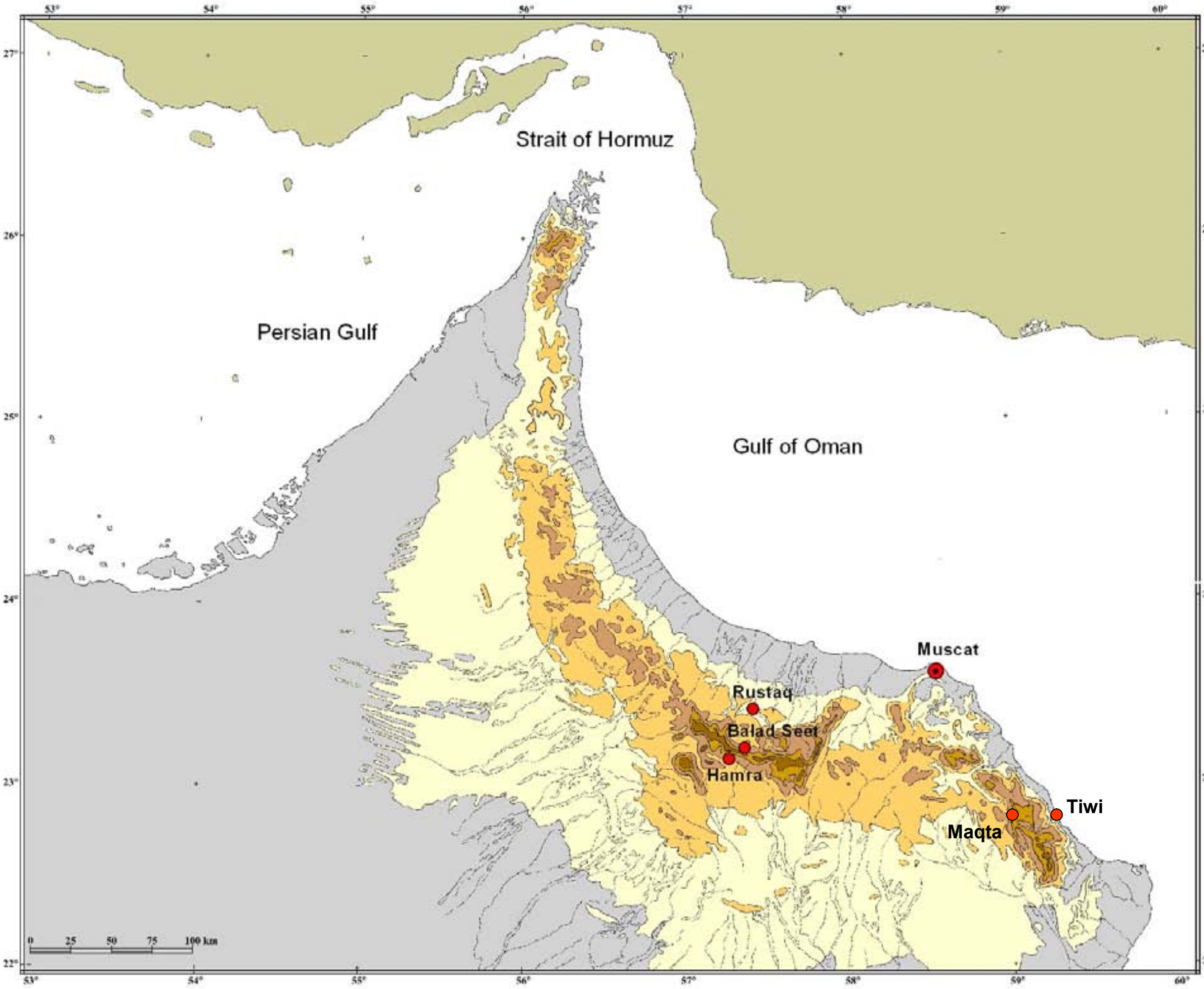

Fig. 1. Relief map of northern Oman showing the major mountain ranges, important towns and villages and the research sites of Balad Seet, Maqta and Tiwi (Fig. 1 of publication 6, modified).

aini-Aflaj, provide spring water from the surrounding mountains to the villagers (publication 6).

In contrast to the compact settlement structure found at Balad Seet, houses and agricultural land of the agro-pastoral community of Maqta, situated in Wadi Khabbah of the Jabal Bani Jabir mountains of North-central Oman (Fig. 2b), are spread within a radius of 800 m. Most of the terraced fields were not cultivated between 2000 and 2003 because the outflow of the 22 springs was mainly used to irrigate 2.9 ha of palm groves.

In contrast to the water scarcity observed at Maqta, Wadi Tiwi (Fig. 2c) is rich in water. Although the 8 km long valley bottom between the settlements of Mibam and Tiwi is almost completely cultivated with date palms and a prolonged drought occurred during the observation period between 2000 and 2003, a stable outflow of water was observed at the mouth of Wadi Tiwi into the Gulf of Oman near Tiwi. Terraced fields are rare in Wadi Tiwi where most of the agricultural land is used for palm groves (Korn et al., 2004).

An area of about 60 000 km^2 in the northern part of the Sultanate of Oman was selected to perform a remote sensing based classification of oases according to land- and water resources use and settlement type (Fig. 3). In addition to the Hajar mountain range, the selected region also covers large parts of the Batinah coastal plain.

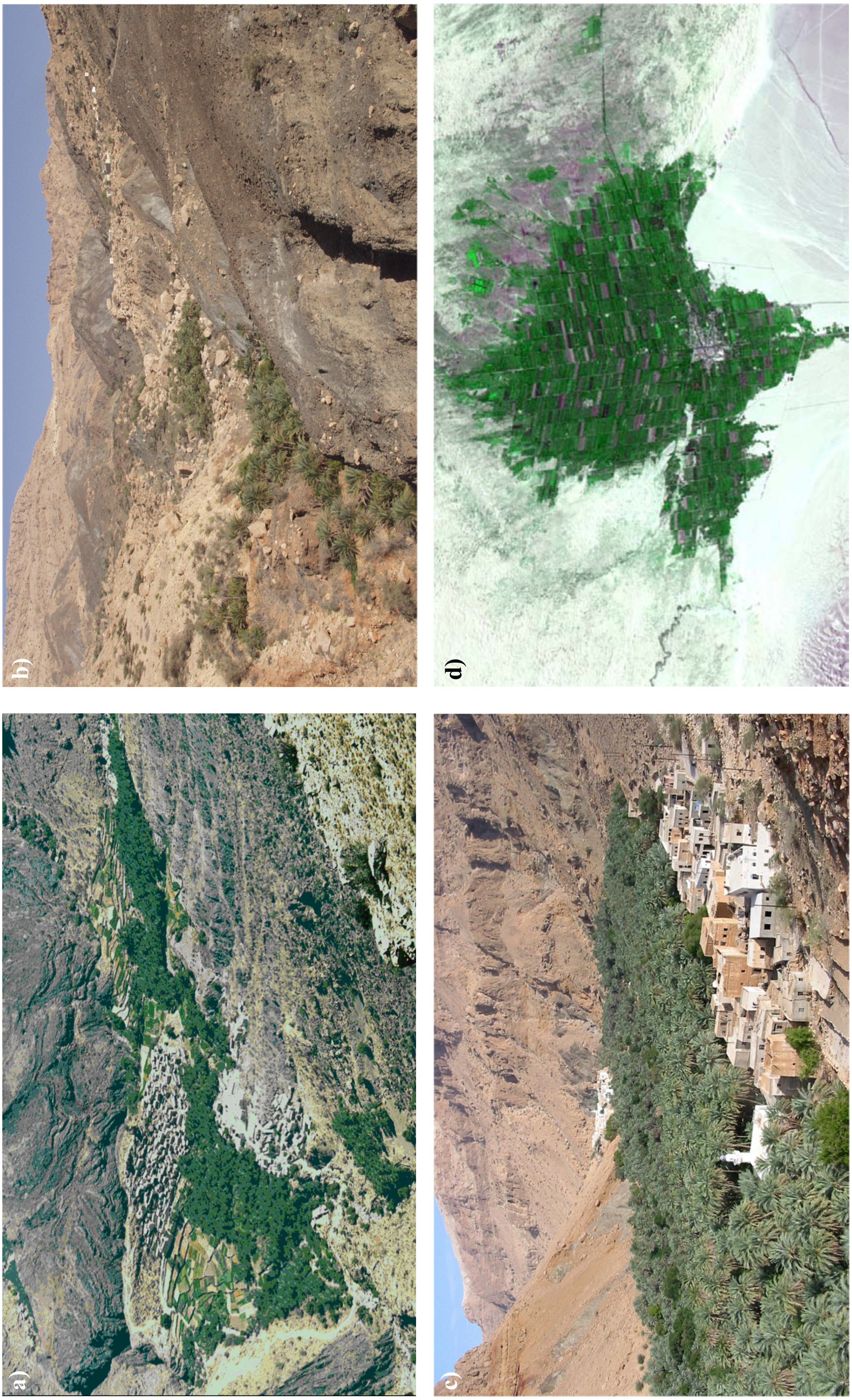

Fig 2. Photographs showing the research sites. a) Balad Seet, b) Maqta, c) Wadi Tiwi next to Harat al-Bida, d) Satellite image of Qira oasis.

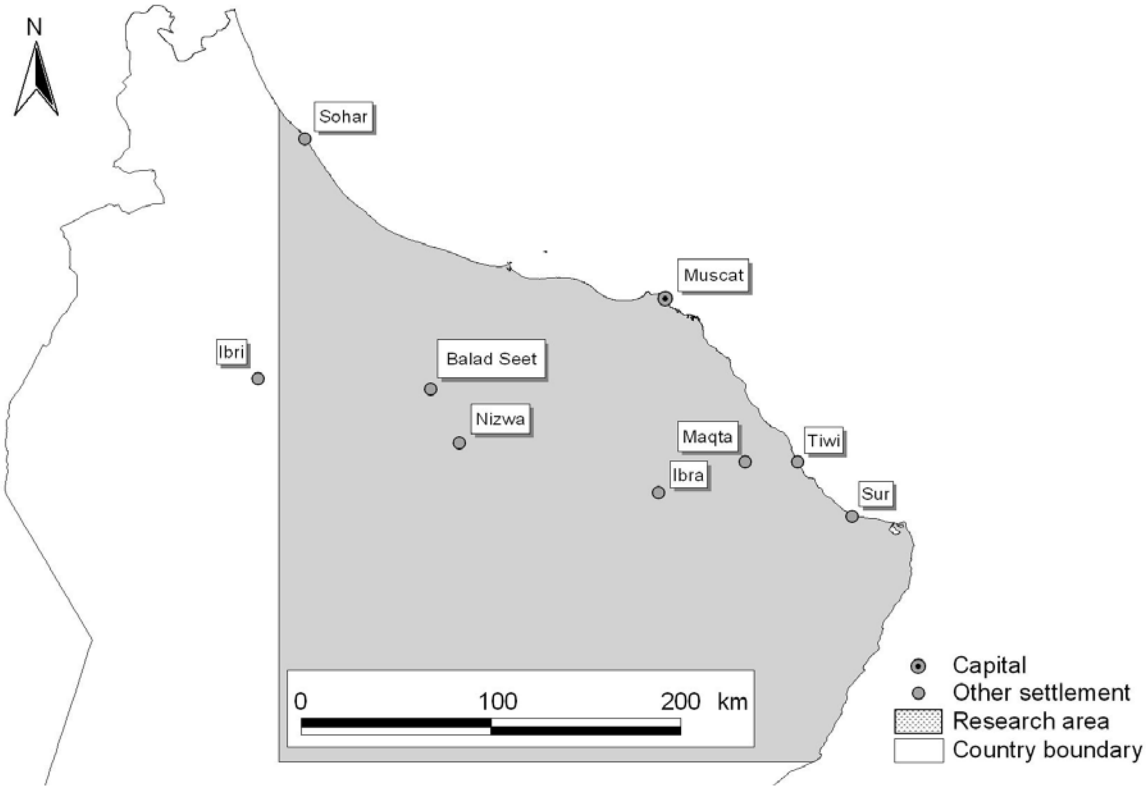

Fig. 3. Map of northern Oman showing the area selected to perform a remote sensing based classification of oases according to land- and water resources use and settlement type.

Qira oasis, Taklamakan desert, PR of China

The oasis of Qira (80.60° E, 37.01° N, 1365 m a.s.l.) is situated at the southern fringe of the Taklamakan desert in Xinjiang Autonomous Region, NW China. The climate is continental, with cold, dry winters and hot, dry summers. Mean annual temperature is 11.9 °C, annual potential evapotranspiration is approximately 2600 mm and the annual sum of precipitation is 35.1 mm (Xia et al., 1993). Plant growth thus largely depends on water from melting snow which flows down from the Kunlun mountain range in large rivers. The cultivated area of the oasis extended from about 7600 ha in 1956 to about 9000 ha in 2000 (Bruelheide et al., 2003). The oasis is surrounded by a belt of natural vegetation (*Populus euphratica, Tamarix ramosissima, Alhagi sparsifolia, Karelinia caspica, Phragmites australis*), that is used as a major source of forage, fuel and construction wood, while it is grazed by sheep, goats and camels. It also protects the oasis against shifting sands from the desert (Xia et al., 1993). In 1998 the number of inhabitants was estimated at 130 000 (Zhang et al., 2001).

2.2 Materials and methods

Dry matter estimation of Alhagi sparsifolia vegetation in the foreland of the Qira oasis

Fifty *Alhagi* shrubs were marked on the 96 x 66 m large field that was predominantly vegetated by *Alhagi sparsifolia*. True colour aerial photographs of the site were taken from a remotely controlled standard 24 mm x 36 mm reflex-camera attached to a kite (Buerkert et al., 1996; Gerard et al., 1997) at a height of ca. 250 m (Fig. 4a). The sample shrubs marked before were measured for their length, width and height, harvested, dried in a forced drought oven at 65 °C and weighted to determine total above-ground dry matter of each shrub. The harvested shrubs were marked on the image and the surface area covered by *Alhagi sparsifolia* was detected using an automated image classification (Fig. 4b). Subsequently, regression equations were established between calculated shrub canopy area of the sample shrubs and shrub dry matter. The regression equation was then applied to the other shrubs to calculate total *Alhagi sparsifolia* dry matter and dry matter density on the entire field. The results were verified in 20 test plots of 4 x 4 m size visible on the aerial photograph (Fig. 4a). The *Alhagi* shrubs growing on the verification plots were also harvested, dried and weighted. The GIS-based methodology to estimate above-ground biomass was compared to a traditional allometric approach for the accuracy of the estimate and for time requirements.

Water- and nutrient balances, carrying capacity and settlement hypotheses for the mountain oases of Balad Seet and Maqta and Wadi Tiwi in northern Oman

The work related to this part of the thesis was carried out parallel to the dissertation of Dr. Maher Nagieb in the same project. This close cooperation was reflected in an intensive exchange of data and in the joint publications 2, 3, 5 and 6. The following data, mainly collected by Dr. Nagieb, have been also used in this thesis:

- monthly measurements of spring outflow in the oases of Balad Seet and Maqta,
- data on cultivated crops, yields and fertilizer use on terraced fields in oases of Balad Seet and Maqta collected in years 2001 and 2002,
- precipitation measurements taken at Balad Seet,
- data on number, yield and growing area of date palms in the oases of Balad Seet and Maqta,
- maps of land use and infrastructure for the oases of Balad Seet and Maqta and Wadi Tiwi inclusive Digital Elevation Models (DEM) produced for the surrounding of the oases.

The establishment of water balances at the oasis level required the calculation of the evapotranspiration of field crops and date palms. Reference evapotranspiration at Balad Seet was computed according to Penman-Monteith (Allen et al., 1998) because a direct measurement was not possible in the framework of the project (publication 3). Temperature, global radiation and sunshine duration were measured using an automated weather station located at Balad Seet in intervals of 10 minutes for the period November 2002 to October 2003, while wind speed was estimated based on numerous observations made in the oasis. Global radiation and sunshine duration were measured for six intervals lasting 211 days in total while temperature was available for the entire period. For the remaining days global radiation and sunshine duration were computed by combining computed extraterrestrial radiation to a solar position calculator and a digital elevation model (Fig. 5). This approach also allowed to estimate the shading effect of the surrounding mountains on potential evapotranspiration. The calculations of potential evapotranspiration performed in the context of former studies on the carrying capacity of the oases of Balad Seet (publication 6), Maqta (publication 2) and Tiwi (Korn et al., 2004) were based on a simplified method according to Priestley and Taylor (1972) modified by Shuttleworth (Shuttleworth, 1993). To compute evapotranspiration at Maqta and Tiwi it was assumed, that the measurements of temperature and radiation as taken at Balad Seet could be also used for the other oases after correction for the different altitudes of the sites. Crop specific evapotranspiration was calculated for each single field by using the collected data on field size, land use and growing period and crop specific coefficients (Doorenbos and Pruitt, 1977; Allen et al., 1998).

The water use efficiency of the oasis of Balad Seet was computed as the ratio between total evapotranspiration in the oasis and total spring outflow measured in monthly time steps. Crop water use indices were computed as ratios between crop dry matter yields and crop evapotranspirations.

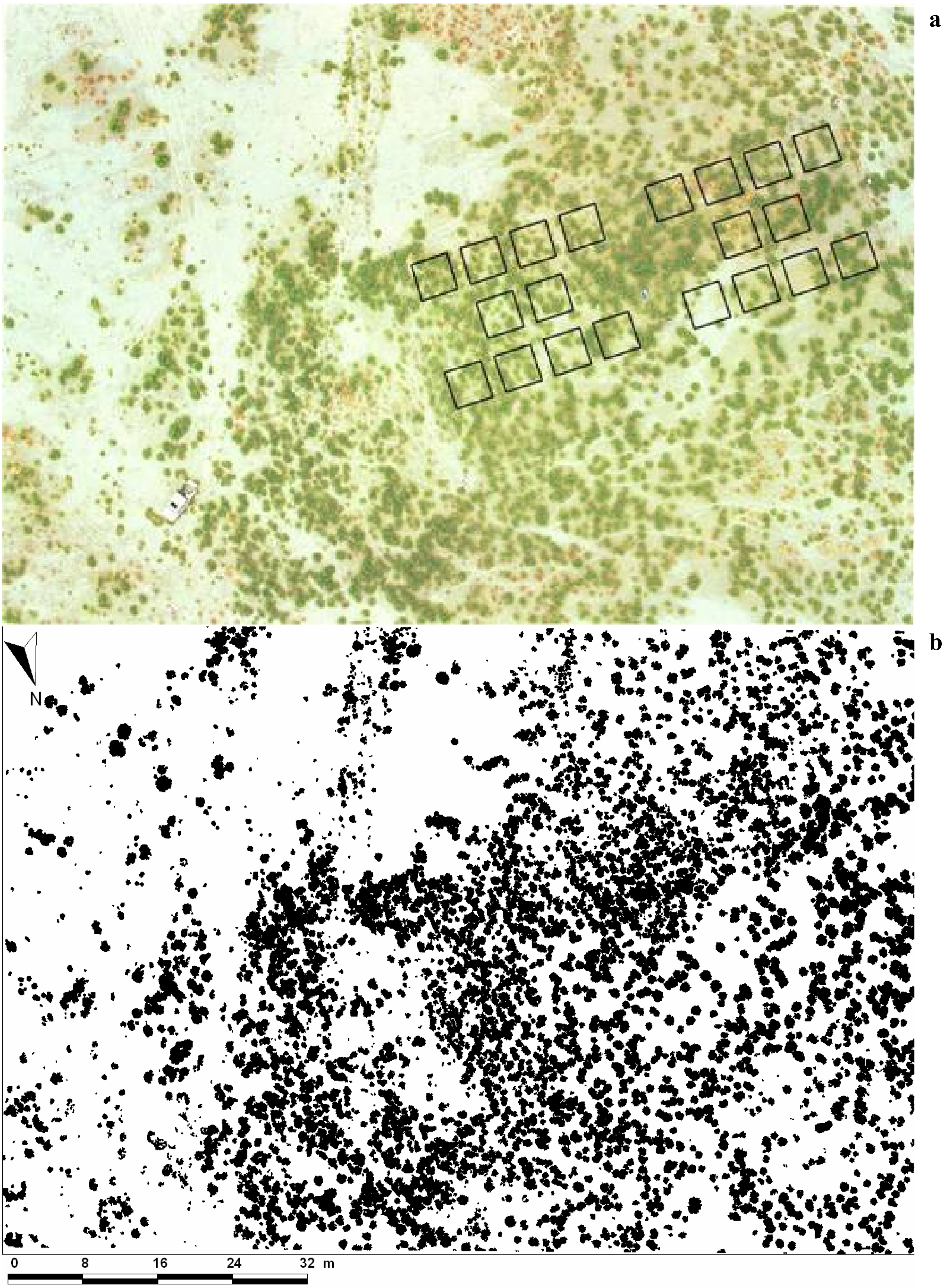

Fig. 4. a) Aerial photograph of *Alhagi sparsifolia* vegetation from ca. 250 m height with 4 x 4 m sample squares (Fig. 1a in publication 1, modified); b) Polygon layer of *Alhagi* shrubs showing the results of the classification (detected *Alhagi* vegetation appears in black, Fig. 1b in publication 1).

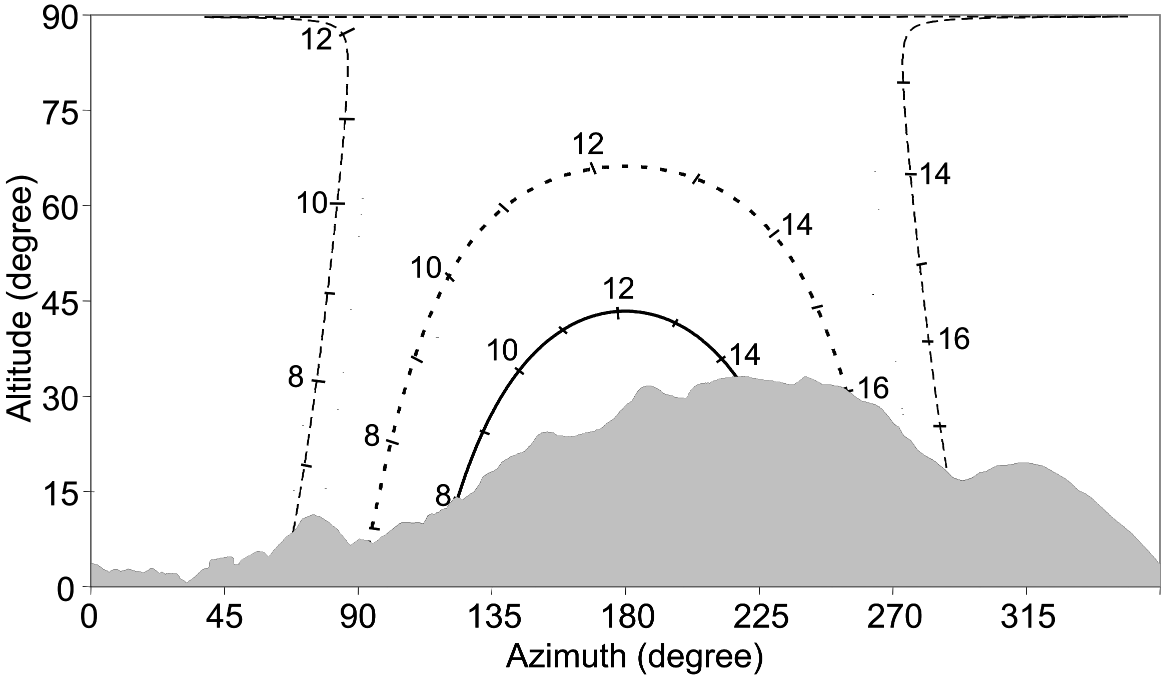

Fig. 5. Height of the mountains along the horizon and sun path on 20th of December (solid line), 20th of March (dotted line) and 20th of June (dashed line) at Balad Seet (Oman), thick marks along the sun paths indicate hours of local time, Azimuth of 0 = North (Fig. 4 in publication 3).

Carrying capacities were computed for each of the oases to estimate the potential number of people able to live of the given agricultural production assuming an optimal use of the cultivated areas and optimal use of the water resources (publications 2, 6 and Korn et al., 2004). Using a typical drought scenario balances between the energy content of the produced food and the human energy requirements were generated. The land- and water management was assumed to be optimal if it led to a maximization of energy content in the produced food. The combination of the detected carrying capacities with findings of archaeologists and architects allowed to establish a consistent settlement hypothesis for each of the three oases across their likely time of existence.

Classification of mountain oases in northern Oman according to land- and water resources use and settlement type

Satellite images taken in the period 2000 – 2004 from the 'Advanced Spaceborn Thermal Emission and Reflection Radiometer' (ASTER) on board of NASA's Terra-satellite were used to compute the Normalized Difference Vegetation Index (NDVI) based on the reflections in the red and infrared channels. The used ASTER-level 2 reflection data (AST07) have a resolution of 15 m and each ASTER scene covers an area of about 60 x 60 km. Geometric and radiometric corrections were applied by the data providers to remove atmospheric disturbances and distortions originating by the specific angles between sun, satellite and earth (Abrams et al., 2003). To georeference the images 121 reference points, which are provided for each of the satellite images (USGS, 2003), were used. The results showed, however, that this mode of georeferencing was insufficient to remove distortions in the images. Errors of 250 m and more were detected by comparing scenes taken for the same location but on different days. It was also found, that these errors varied for different locations on the same satellite image so that a simple correction by a shifting was not possible. Therefore it was decided to correct the georeference locally for squares of 4 x 4 km. One satellite image was defined to be the reference image and a program was developed that computed the errors for each single 4 x 4 km square and each satellite image relative to the reference image. The applied procedure shifted the 4 x 4 km squares up to 30 pixels (450 m) in all directions. It was assumed that georeferencing was optimized when the sum of the differences between the pixels of the square and the related pixels of the reference image was minimized.

The computed vegetation indices could vary between -1 and 1, whereby high values indicate photosynthetically active vegetation. Since the radiometric correction procedure applied by the data provider was found to be particularly unreliable for mountainous areas (Abrams et al., 2003), it was decided not to perform a common multispectral classification. Instead, the pixels of the images were classified to represent palm groves, fields or natural vegetation based on the following assumptions:

- perennial crops growing in palm groves are permanently photosynthetically active and have thus always relative high vegetation indices,
- field crops and natural vegetation have only temporarily photosynthetic activity and are thus characterized by varying vegetation indices,
- the photosynthetic activity of field crops, which is induced by irrigation, is a localized phenomenon, whereas the activity of natural vegetation, which is caused by scarce precipitation events, is a large-scale phenomenon.

It was thus necessary to compare vegetation indices for the same location but different times of the year. Subsequently, at least three different satellite images were used for each location, whereby for most positions even more than five images were available.

The results showed that the computed vegetation indices differed strongly when comparing images taken for the same vegetation type at the same place (e.g. palm groves) but different times of the year. The vegetation index for one and the same closed palm grove varied for example between 0.3 and 0.8. This indicates that the images would also need improved radiometric correction. To reduce the error caused by the imperfect radiometric correction, it was decided to scale the vegetation indices by a coefficient that was constant for all pixels of the same image. The coefficient was computed by dividing 1.0 by the average of the 30 largest NDVI-values of the entire satellite image.

The classified areas of palm groves and field crops were assigned to specific oases by using the coordinates provided by a geographic name server of the United States National Geospatial Intelligence Agency (NGA, 2004). The settlement types core oasis and scattered oasis were distinguished by the distribution of cultivated land around the oasis centers. Additionally it was assumed that the total extent of cultivated land can be used to quantify the availability of water resources and that the existence of a large fraction of perennial palm groves indicated stable water resources while a large fraction of annual field crops indicates fluctuating water resources.

Global mapping of areas equipped for irrigation

The Global Map of Irrigation Areas (GMIA) was developed by combining irrigation statistics for 10 825 sub-national statistical units (e.g. districts, provinces, basins, counties) and geo-spatial information on the location and extent of irrigation schemes (publication 4). Most of the statistical records were derived from national statistical yearbooks or provided by the library of FAO's AQUASTAT project. Geospatial information on position and extent of irrigated areas was derived by digitizing hundreds of irrigation maps available in reports of FAO, World Bank, irrigation associations or national ministries of agriculture. Additionally, information from several atlases or inventories based on remote sensing available in digital format was utilized. For most of the countries, more than one data source was used. As the relevance and reliability of the maps varied, it was necessary to decide which geospatial record should be used in a specific sub-national unit. This was realized by applying a priority level to each record. Only if the extent of all digitized irrigated areas with the highest priority level was smaller than the total irrigated area reported for the specific sub-national unit, also records with the second highest priority were considered. This distribution process was repeated down to the next lower priority level until the sum of irrigated area in the map was equal to the irrigated area in the sub-national statistics.

To estimate the map quality at the scale of countries, world regions and the globe two indicators were developed that considered the density of available information. Additionally the map was compared to irrigated areas as derived from two remote sensing based global land cover inventories.

3. RESULTS AND DISCUSSION

Dry matter estimation of Alhagi sparsifolia vegetation

Both, the traditional allometric and the GIS-based approach were suitable to estimate aboveground dry matter of *Alhagi sparsifolia* vegetation in the foreland of the Qira oasis. Non-linear regressions between shrub volume (allometric approach) or shrub canopy area (GIS-based approach) and above ground shrub dry matter showed high correlation coefficients (r^2 of 0.98 and 0.96, respectively). Using the regressions the above ground dry matter for the entire field was estimated at 857 kg (allometric approach) or 858 kg (GIS-based approach using quadratic type of regression equation). The comparison of both methods in the 20 plots of 4 x 4 m showed that the allometric approach was very reliable, whereas the GIS-based approach led to an overestimation of *Alhagi* dry matter in densely vegetated areas. However, this systematic error decreased with increasing size of the surveyed field. The initial establishment of the method required five man days for the allometric approach and 20 man days for the GIS-based approach, whereas the application of the method to a field of 1 ha size required 17 days for the allometric approach and 1.5 days for the GIS-based method (publication 1).

Water- and nutrient balances and carrying capacity for Omani mountain oases

An irrigation water use efficiency of 0.75 was computed for the oasis of Balad Seet. Crop water use index was 0.92 kg m^{-3} for wheat grain yield, 0.64 kg m^{-3} for sorghum grain and 1.85 kg m^{-3} for garlic bulbs. Potential evapotranspiration on agricultural land was 194 390 m^3 yr^{-1} with a minimum in January (10 675 m^3 $month^{-1}$) and a maximum in June (21 988 m^3 $month^{-1}$, Fig. 6). 83% of the water was used to irrigate palm groves. Removing of the shading effect of the surrounding mountains and of the effect of the high altitude increased reference evapotranspiration from 1778 mm yr^{-1} to 2393 mm yr^{-1} (publication 3).

The calculation of the natural carrying capacity for the oasis of Balad Seet showed that the available water- and land resources would allow to produce enough food for 14 people at the time of the first settlement 3000 years ago increasing to 156 people nowadays. Today's 650 oasis inhabitants thus by far exceed the computed carrying capacity and is the result of external revenues coupled to a substantial import of food (publication 6). This also applies for the oasis of Maqta whose carrying capacity was computed at 72 people while about 200 peoples are living there today (publication 2). In contrast, the computed natural carrying capacity of 1485 people for Wadi Tiwi exceeds the 695 people currently living in the wadi itself (not accounted for the inhabitants of the coastal settlement of Tiwi) (Korn et al., 2004). A substantial amount of barren fields observed in Balad Seet and in Maqta confirm farmers' claims that water is the most production limiting resource these days (Table 1).

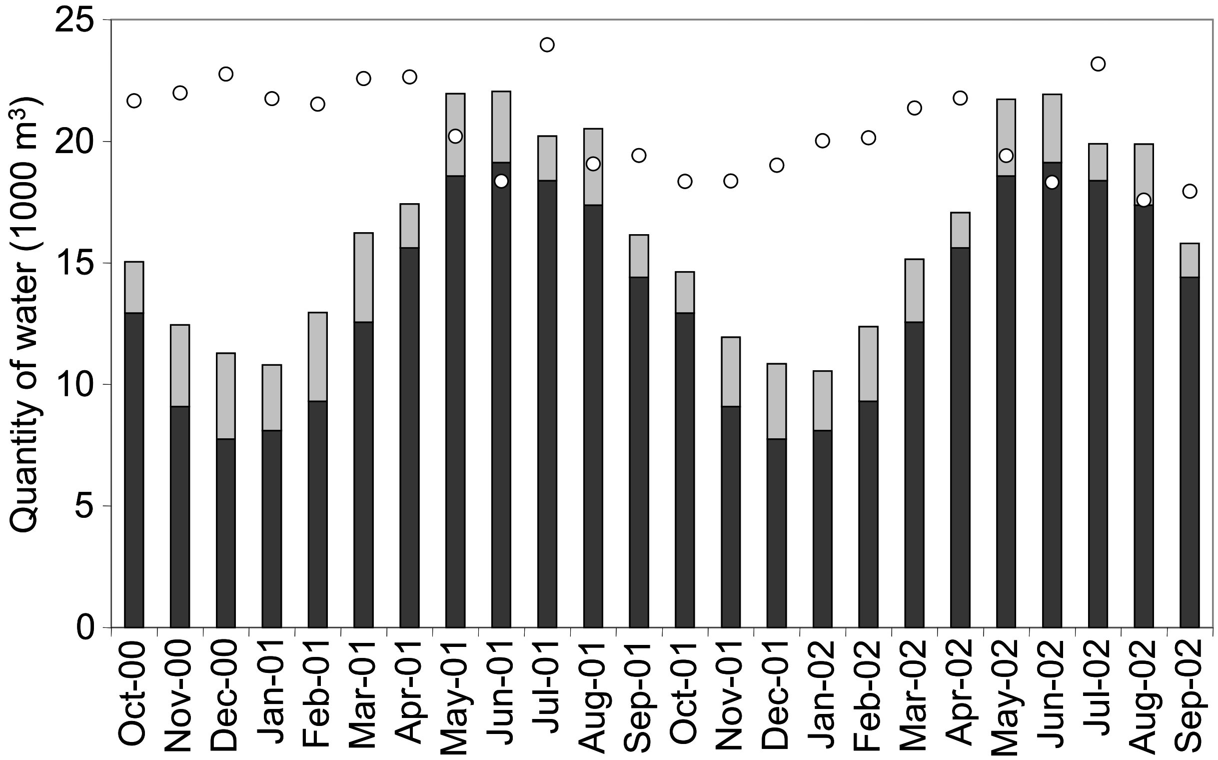

Fig. 6. Monthly fresh water resources as sum of spring outflow and precipitation (unfilled circles) and crop evapotranspiration in palm groves (black columns) and cropland (gray columns) at Balad Seet (Oman) (Fig. 7 in publication 3).

Classification of mountain oases in northern Oman according to land- and water resources use and settlement type

The results of the categorization of oases in northern Oman according to settlement type, land- and water resources were not convincing. The applicability of the developed methodology was evident for oases such as Balad Seet or Tiwi (Fig. 7) and also for many flat

Table 1. Comparison of natural resources and inhabitants in the scattered oasis of Maqta, the core oasis of Balad Seet and the water-rich valley oasis of Wadi Tiwi in northern Oman (Table 3 in publication 2).

Natural resource	Maqta	Balad Seet	Wadi Tiwi	Wadi Tiwi & Tiwi
Palm grove area (ha)	2.9	8.8	107.0	128.2
Terraced fields (ha)	1.6	4.6	0	3.3
Available water ($m^3\ d^{-1}$)	115	601	10 000	10 000
Number of inhabitants[a]	200	650	695	2884
Average agricultural area per inhabitant (m^2)	225	207	1540	456
Fraction of palm grove area	0.64	0.66	1.00	0.98
Cropping intensity[b] in 2002/2003	0.66	0.85	1.00	1.00
Available water per inhabitant ($l\ d^{-1}$)	575	925	14 388	3467

[a] Total population in 2003 comprising adults and children
[b] Agriculturally active area / total agricultural area

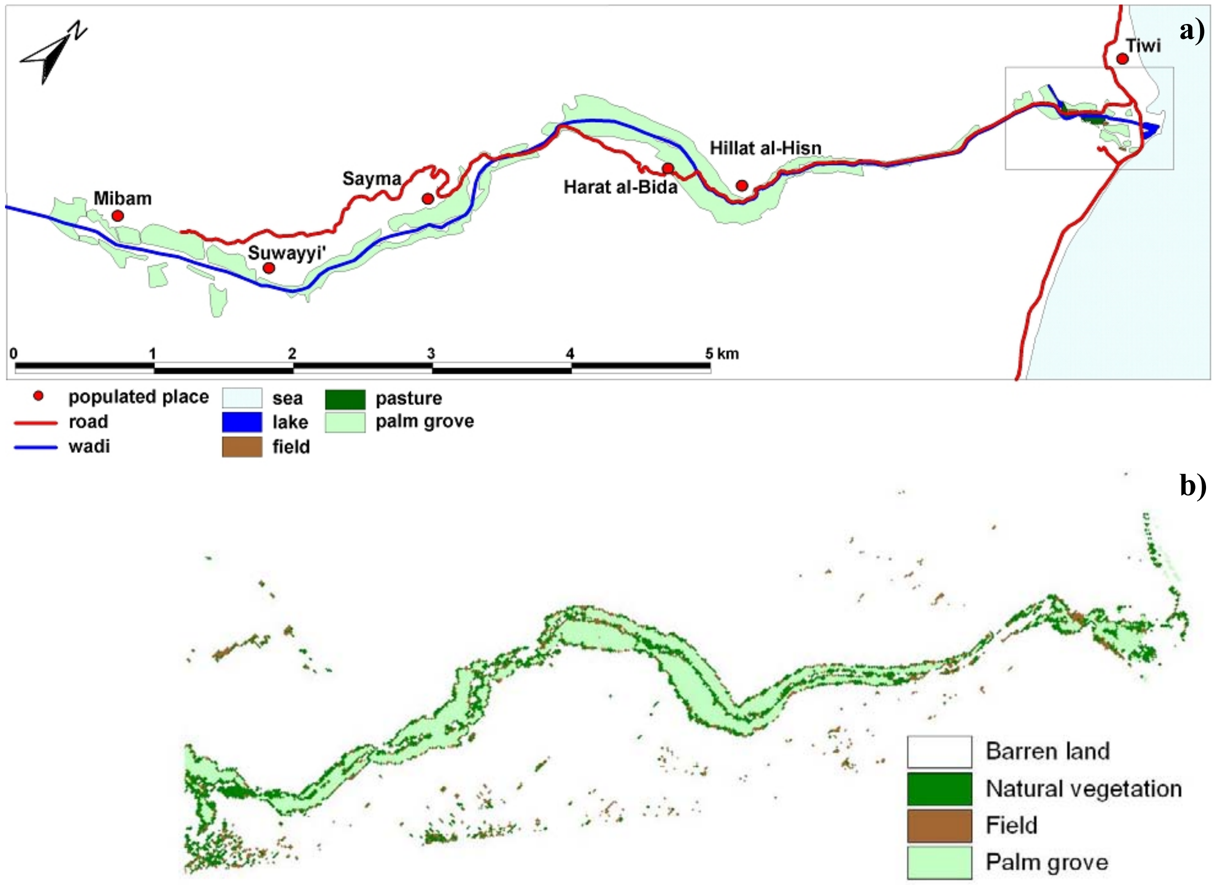

Fig. 7. Land use in the lower part of Wadi Tiwi (Oman), a) as measured and mapped by a ground based GPS-survey (Fig. 2 in Korn et al., 2004) and b) as classified using ASTER satellite imagery.

(floodplain) areas in the Batinah. The results were not satisfactory, however, for most mountainous areas. In particular the separation between field crops and palm groves and between field crops and natural vegetation was not convincing. The main reason for this unexpected result was that the used ASTER-satellite imagery was not suitable for multitemporal classification. In particular the low precision of the coordinates provided for georeferencing and the radiometric properties of the imagery made it for many regions impossible to compare images taken on different days (see also the previous section).

Global mapping of irrigated areas

The Global Map of Irrigation Areas comprised a total of 273.7 Mio ha land. About 69% of this area was located in Asia, 17% in America, 9% in Europe, 4% in Africa and 1% in Oceania. The largest contiguous areas of high irrigation density were found in North India and Pakistan along the rivers Ganges and Indus, in the Hai He, Huang He and Yangtze basins in China, along the Nile river in Egypt and Sudan, in the Mississippi-Missouri river basin and in parts of California. Other areas of high irrigation density with regional importance are located along the Snake and Columbia rivers in the north-western United States, along the western coasts of Mexico and Peru, in central Chile, in the rice growing areas along the border between Brazil and Uruguay, along the Danube and Po rivers in Europe, in the Euphrates-Tigris basin in Iraq and Turkey, the Aral sea basin, the Amu Darya and Syr Darya river basins, the Brahmaputra basin in China and Bangladesh, the Mekong delta in Vietnam, the plain around Bangkok in Thailand, the island of Java (Indonesia) and the Murray-Darling basin in Australia. Smaller irrigation areas are spread across almost all populated parts of the

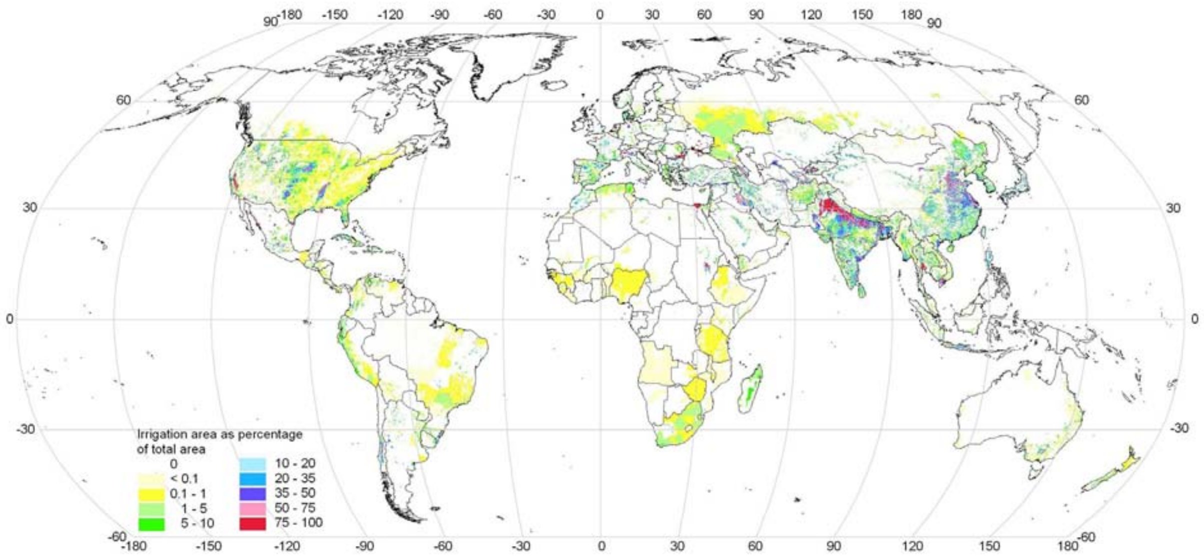

Fig. 8. Global Map of Irrigation Areas Version 3: Percentage of 5-minute grid cell area that was equipped for irrigation around the year 2000 (Robinson projection, Fig. 3 in publication 4).

world (Fig. 8). The map quality was assessed on a scale between 0 and 5 and at the global scale the quality was estimated as good (2.07). However, there are large regional differences. The map quality appeared to be very good (1.03) for North America but poor (4.00) for the Russian Federation. 81% of the total area equipped for irrigation was located in countries where the map quality was assessed to be very good or good. The use of the global land cover data bases GLCC (USGS, 2000) and GLC2000 (Joint Research Centre of the European Commission, 2003) to extract irrigated areas cannot be recommended because these data sets failed to show neither the extent nor the distribution of irrigation areas (publication 4).

A comparison of the land use data sets developed at the global, regional or local scale highlights, that beside the fact that different methods have been used to generate the data sets, the latter also have different categories, precision and constraints (Fig. 9). This largely precludes a consistent interpretation.

4. CONCLUSIONS

The determination of *Alhagi sparsifolia* above-ground dry matter by combining aerial photography and GIS can be recommended without restriction on *Alhagi* sole stands and if the area covered is bigger than 1 ha. The method can probably easily be transferred to similar plant species elsewhere as long as the plants only have a minimum of woody components.

The high water use efficiency, the high crop water use indices and the fact of the millennia-old existence of the oasis of Balad Seet are proof of a sustainable use of water- and soil resources and thus indicate a good adaptation to the harsh environment. Nevertheless it was shown that the natural resources available at Balad Seet and Maqta are not sufficient to produce enough food for the inhabitants living there today requiring substantial imports of food, fodder and fertilizers. Because flows of goods from the oasis to the surroundings are rare, the inhabitants rely on financial support from outside. The future existence of mountain oases in northern Oman therefore requires this support to be continued. Unfortunately, the framework of this study did not allow to further address this socio-economic and also political aspect.

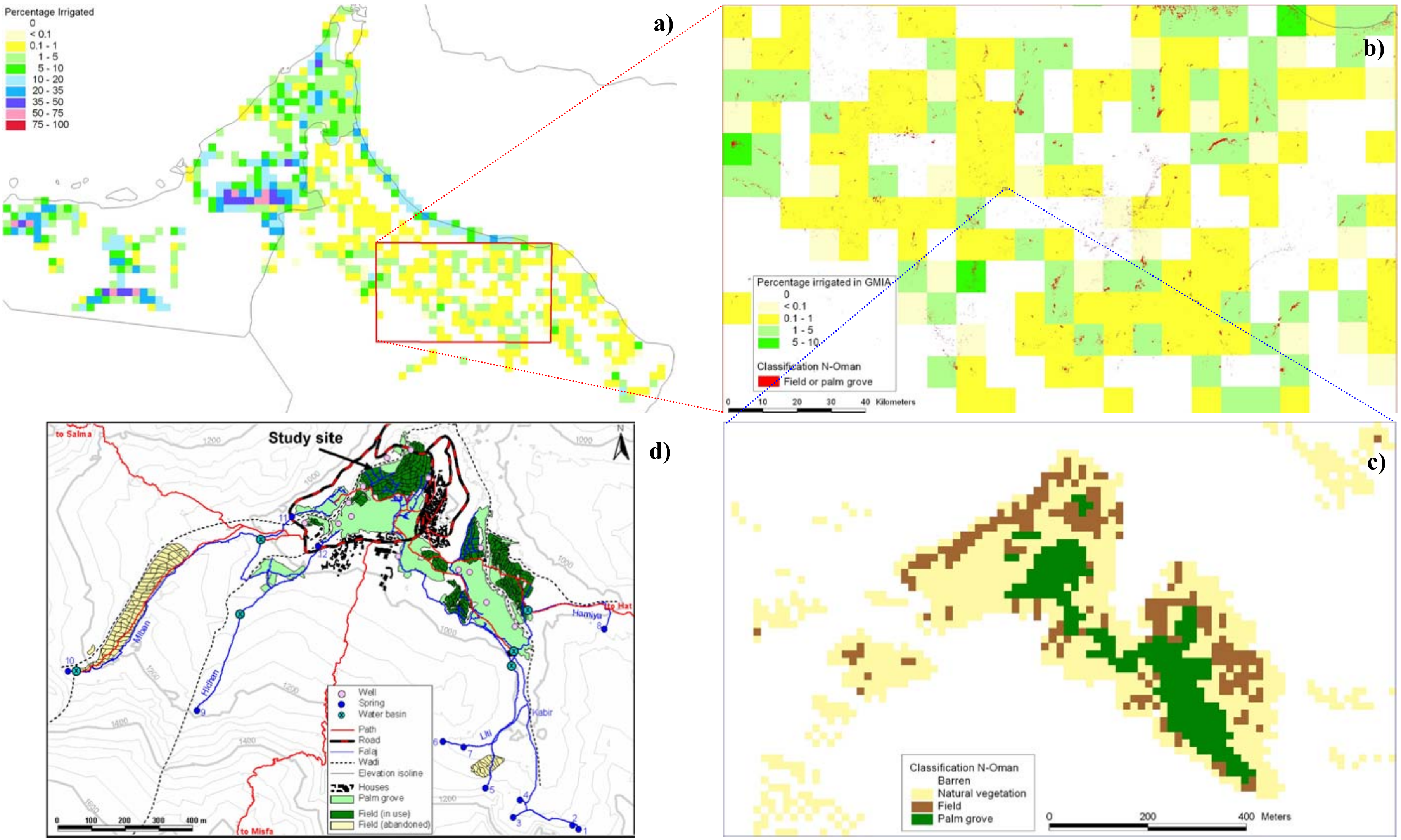

Fig 9. Land use mapping in northern Oman at different scales. a) Global Map of Irrigation Areas, N-Oman and UAE, b) Remote sensing based land use characterization for northern Oman on top of the Global Irrigation Map; c) Land use at Balad Seet as detected by the classification for northern Oman, d) Land use and infrastructure of the oasis of Balad Seet as mapped by using GPS and low altitude aerial photography.

Land use mapping at the global, regional or local scale needs different approaches. A coupling of geographical and statistical information was necessary to map irrigation areas at the global scale while a combination of aerial photography, GIS and GPS was successful to determine biomass or to map the infrastructure and land use at the local scale in Qira oasis and in oases of northern Oman. The problems and difficulties that appeared when mapping land use within the entire region of northern Oman demonstrated the high precision of satellite imagery necessary for multitemporal classifications of vegetation.

The combination of modelling, GIS, aerial photography and image analysis methods and the application of these skills and tools in an interdisciplinary research project allowed to derive additional knowledge for a better understanding of agro-ecosystems. Many fundamental hypotheses could only be addressed interdisciplinary and required an adaptation of known- or the development of new methods. Also in this context the present study represents an important method-oriented contribution to the progress of scientific knowledge.

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Analyse von Agrarsystemen im ariden Klima durch quantitative Bildanalyse, Modellierung und Geographische Informationssysteme

Stefan Siebert

DEUTSCHE ZUSAMMENFASSUNG

1. EINLEITUNG

Im ariden Klima zeichnen sich sowohl natürliche Ökosysteme als auch Agrarökosysteme durch eine starke Anpassung an die gegebene Wasserknappheit aus. Diese Anpassung ist vielfältig und umfaßt physiologische, morphologische, genetische und soweit es sich um Agrarökosysteme handelt insbesondere auch mangegementbedingte Komponenten.

Der in ariden Gebieten besonders starke Kontrast zwischen bewachsenen bewässerten Flächen und nicht oder kaum bewachsenen unbewässerten Flächen wurde in zahlreichen Studien genutzt, um landwirtschaftliche Nutzflächen unter Verwendung von Luft- und Satellitenbildern großflächig zu kartieren (IWMI, 2005; Leff et al., 2004; Droogers, 2002; NIRE, 2000; Ramancutty und Foley, 1998). Der sehr dynamische verlaufene Wissenszuwachs im Bereich Fernerkundung und Geographische Informationssysteme (GIS) hat zur Entwicklung von Methoden geführt, die es erlauben, Satellitenbilder auch standardmäßig zur Ermittlung meteorologischer Kenngrößen (Temperatur, Einstrahlung, Luftfeuchte) oder zur Ermittlung der Photosyntheseleistung des Pflanzenbestandes einzusetzen (siehe dazu auch die vom USGS bereitgestellten MODIS-Daten auf http://edcdaac.usgs.gov/modis/dataproducts.asp). Hierbei erfolgt zunehmend eine Kopplung von Bildanalyse und mathematischer Modellierung. Die hierfür eingesetzten Modelle setzen gemessene oder geschätzte Größen in einen sinnvollen Zusammenhang und erlauben es dadurch, Werte anderer, unbekannter Größen zu simulieren. Sie werden insbesondere dort eingesetzt, wo die Ermittlung gesuchter Größen durch direkte Messung entweder nicht möglich (Aussagen zu Vergangenheit und Zukunft) oder zu aufwendig wäre (Erstellung hochaufgelöster, globaler Datensätze, Ermittlung der Evapotranspiration eines Pflanzenbestandes, Klimaforschung). Die Anwendung von Geographischen Informationssystemen und Geographischen Positionssystemen (GPS) schließlich hat die Erhebung, Verarbeitung und Darstellung von Daten mit räumlicher Verteilung gegenüber traditionellen Methoden (Landvermessung mit Theodoliten, Zeichnung von Karten per Hand) revolutioniert und zu einer weiten Verbreitung dieser Methoden über Fachdisziplingrenzen hinweg geführt. Ein Ausdruck dieser Entwicklung ist die zunehmende Verbreitung geographischer Informationen in digitaler Form bis hin zu interaktiven map-servern, die auch Nutzern ohne Spezialkenntnissen die Erstellung individueller Karten ermöglicht. Als Beispiele seien hier der map-server des US-Geological Survey (http://seamless.usgs.gov/website/seamless/viewer.php) oder der Australian Natural Resources Atlas (http://audit.ea.gov.au/ANRA/atlas_home.cfm) genannt.

Im Rahmen dieser Dissertation wurden Werkzeuge der quantitativen Bildanalyse, der Modellierung sowie Geographische Informationssysteme angewandt und weiterentwickelt zur:

- Nicht-destruktiven Bestimmung der Biomassedichte von *Alhagi sparsifolia* Vegetation im Vorland der Qira Oase in Nordwest China (Publikation 1),
- Kartierung von Landbedeckung und Landnutzung auf globaler, regionaler oder lokaler Ebene (Publikationen 1, 2, 4 und 6),
- Typologisierung von Bergoasen im Norden Omans hinsichtlich Landnutzung, Wasserressourcen und Siedlungsform,
- Modellierung von Wasser- und Nährstoffbilanzen in Bergoasen des Sultanats Oman (Publikationen 3 und 5),
- Abschätzung der Nachhaltigkeit der Ressourcennutzung zweier Bergoasen des Sultanats Oman mittels Tragfähigkeitsanalysen (Publikationen 2 und 6) sowie zur
- Aufstellung von Besiedelungshypothesen für zwei Bergoasen des Sultanats Oman (Publikationen 2 und 6).

Im folgenden Abschnitt werden die verwendeten Materialien und Methoden sowie die Untersuchungsgebiete vorgestellt. Der anschließenden Beschreibung und Diskussion der wichtigsten Ergebnisse (Abschnitt 3) folgen die daraus gezogenen Schlußfolgerungen (Abschnitt 4). Die bereits erwähnten sechs Publikationen befinden sich als Bestandteil dieser Dissertationsschrift im Anhang.

2. MATERIAL, METHODEN UND UNTERSUCHUNGSGEBIETE

Die hier vorgestellten Arbeiten erfolgten, mit Ausnahme der Publikation zur Erstellung der Globalen Karte der Bewässerungsgebiete (Publikation 4), in ariden Untersuchungsgebieten im Nordwesten der Volksrepublik China (Publikation 1) sowie im Norden des Sultanats Oman (Publikationen 2, 3, 5 und 6). Bevor im Einzelnen auf die verwendeten Materialien und Methoden eingegangen wird, sollen die Untersuchungsgebiete hier zunächst kurz vorgestellt werden.

2.1 Untersuchungsgebiete

Sultanat Oman:
Das Untersuchungsgebiet in dem im Nordosten der Arabischen Halbinsel gelegenen Sultanat Oman erstreckt sich entlang des Hajar Gebirgszuges im Norden des Landes (Abb. 1). Das örtliche Klima ist geprägt durch extreme Aridität mit durchschnittlichen Jahresniederschlägen von ca. 54 mm bei einer potentiellen Evapotranspiration von mehr als 2000 mm a^{-1}. Die künstlich bewässerte, landwirtschaftlich genutzte Gesamtfläche des Landes betrug im Jahr 1993 insgesamt 61 550 ha, was etwa 0,2 % der Landesfläche entspricht. 34 930 ha davon befanden sich in der fruchtbaren Küstenebene Batinah. Die gesamte abgeerntete Fläche betrug im selben Jahr 70 930 ha. Die wichtigsten Kulturarten waren Dauerkulturen, insbesondere Datteln (*Phoenix dactylifera* L.) und Bananen (*Musa* ssp.) auf 43 000 ha sowie Luzerne (*Medicago sativa* L.) auf 17 330 ha, Gemüse (5700 ha) und Getreide (4900 ha; FAO, 1997). Über die verwendeten Bewässerungsverfahren gibt es unterschiedliche Angaben. Während die FAO davon ausgeht, daß 1993 nur auf 3730 ha Fläche Beregnungs- oder Tropfbewässerungsanlagen installiert waren (FAO, 1997), berichtet eine andere Studie, daß 74% der Gesamtbewässerungsfläche des Landes mit modernen Beregnungseinheiten ausgestattet sei (Ibrahim, 1999). Obwohl im Jahre 1993 37% der Arbeitskräfte in der Landwirtschaft oder Fischerei beschäftigt waren, konnten diese Sektoren nur 3,3% zum Bruttosozialprodukt beitragen (FAO, 1997). Der überwiegende Teil der Wertschöpfung Omans wird jedoch durch Erdölindustrie, Handel und Dienstleistungen erbracht.

Im Rahmen eines von der DFG finanzierten interdisziplinären Projektes 'Transformationsprozesse in Oasensiedlungen Omans' wurden von der agrarwissenschaftlichen Arbeitsgruppe, zu deren Ergebnissen die hier verhandelte Dissertation beiträgt, die drei Oasengebiete Balad Seet (57,39 °O, 23,19 °N, 996 m über NN), Maqta (59,00 °O, 22,83 °N, 1050 m über NN) sowie die Oasen im Wadi Tiwi mit dem Hauptort Tiwi (59,25 °O, 22,83 °N, 32 m über NN) untersucht. Die Oase Balad Seet (Abb. 2a) befindet sich am oberen Ende des Wadi Bani Awf an der Nordseite der Hajar Bergkette und ist umgeben von bis zu 1000 m hohen Steilwänden aus Kalk- und Tonstein. Das sich auf einem Hügel befindliche drei Jahrtausende alte Dorf wird von 650 Einwohnern bewohnt und ist umgeben von 8,8 ha Palmengärten und 4,6 ha Ackerland, die in ihrer Mehrzahl das ganze Jahr über intensiv bewässert werden. Die Dorfbewohner besitzen etwa 200 Schafe und Ziegen sowie etwa 30 Rinder. Fünf Bewässerungskanalsysteme, genannt Aflaj, versorgen das Dorf mit Quellwasser aus den umliegenden Bergen (Publikation 6).

Im Gegensatz zur kompakten Anordnung von Siedlung und landwirtschaftlicher Fläche in Balad Seet (Kernoase) entspricht die im Wadi Khabbah in den Jabal Bani Jabir Bergen gelegene Oase Maqta (Abb. 2b) eher dem Bild einer Streusiedlung. Sowohl Siedlungen als auch landwirtschaftliche Flächen verteilen sich auf einem Umkreis von ca. 1,6 km. Die Mehrzahl der Ackerbauterrassen konnten im Beobachtungszeitraum 2000 – 2003 nicht bestellt werden, da das Wasser der 22, meist gering schüttenden Quellen zur Bewässerung der insgesamt 2,9 ha Palmengärten benötigt wurde.

Demgegenüber ist das Wadi Tiwi (Abb. 2c) reich an Wasser. Obwohl fast der gesamte 8 km lange Verlauf des Wadis zwischen den Ortschaften Mibam und Tiwi mit Palmen bestanden ist und in den Jahren 2000 – 2003 eine mehrjährige Dürreperiode herrschte, wurde stets ein Abfluß überschüssigen Wassers an der Mündung des Wadis in den Golf von Oman bei Tiwi festgestellt (Korn et al., 2004).

Für die satellitenbildgestützte Klassifikation von Oasenstandorten bezüglich Land- und Wassernutzung sowie Siedlungsform wurde ein 60 000 km² großer Bereich im Norden Omans ausgesucht (Abb. 3). Dieser Bereich deckt neben dem Al-Hajar Gebirgszug auch weite Teile der Küstenebene Batinah ab.

Qira Oase, Taklamakanwüste, VR China:

Die Oase Qira (Abb. 2d; 80,60° O, 37,01° N, 1365 m über NN) befindet sich am Südrand der Taklamakanwüste in der autonomen Region Xinjiang im Nordwesten der Volksrepublik China. Das Klima ist kontinental mit kalten, trockenen Wintern und heißen, trockenen Sommern. Die jährliche Durchschnittstemperatur beträgt 11,9°C, die jährliche potentielle Evapotranspiration beträgt etwa 2600 mm a^{-1} und die Jahresniederschlagssumme ist 35,1 mm a^{-1} (Xia et al., 1993). Landwirtschaft und Pflanzenwachstum sind somit stark abhängig vom Schmelzwasser, daß in großen Flüssen aus der Kunlun Bergkette fließt. Die landwirtschaftliche Nutzfläche der Oase betrug im Jahr 1956 etwa 7600 ha und hat sich bis ins Jahr 2000 auf etwa 9000 ha ausgedehnt (Bruelheide et al., 2003). Die Oase ist umgeben von einem Gürtel natürlicher Vegetation (*Populus euphratica, Tamarix ramosissima, Alhagi sparsifolia, Karelinia caspica, Phragmites australis*), die als Baumatertial, Brennholz oder Futter dient und die Oase vor Treibsand aus der Wüste schützt (Xia et al., 1993). Im Jahr 1998 wurde die Bevölkerungszahl der Oase auf etwa 130 000 geschätzt (Zhang et al., 2001).

2.2 Material und Methoden

Biomasseabschätzung von Alhagi sparsifolia Vegetation im Vorland der Qira Oase

50 *Alhagi* Büsche wurden auf der etwa 96 x 66 m großen, im wesentlichen mit *Alhagi sparsifolia* bestandenen Fläche, gekennzeichnet. Mit Hilfe eines Drachens und einer ferngesteuerten Kamera (Buerkert et al., 1996; Gerard et al., 1997) wurde die Testfläche aus 250 m Höhe fotografiert (Abb. 4a). Die zuvor gekennzeichneten *Alhagi* Büsche wurden vermessen (Länge, Breite, Höhe), anschließend kurz oberhalb des Erdbodens abgeschnitten, in einem Ofen bei 65°C bis zur Gewichtskonstanz getrocknet und gewogen. Die abgeernteten

Büsche wurden auf dem erwähnten Luftbild markiert und die von *Alhagi* bedeckte Grundfläche durch eine Bildklassifikation ermittelt (Abb. 4b). Die durch eine Regressionsanalyse zwischen ermittelter Buschfläche und Buschtrockenmasse für die 50 Testbüsche ermittelte Schätzgleichung wurde dann auf die gesamte, von dem Luftbild abgedeckte Fläche angewandt und die Trockenmasseverteilung sowie die Gesamttrockenmasse ermittelt. Zur Verifikation der Ergebnisse wurden 20 abgesteckte Testflächen der Größe 4 x 4 m herangezogen, die auf dem zu analysierenden Luftbild deutlich kenntlich waren. Deren *Alhagi* Büsche wurden ebenfalls geerntet, getrocknet und gewogen. Dieser luftbildbasierte Ansatz zur Biomasseabschätzung wurde mit einem parallel durchgeführten, traditionellen (allometrischen) Verfahren hinsichtlich der Güte der Schätzung und hinsichtlich des Zeitaufwandes verglichen.

Wasser- und Nährstoffbilanzen, Tragfähigkeitsanalysen und Besiedelungshypothesen für die Bergoasen Balad Seet und Maqta sowie das Wadi Tiwi im Norden Omans

Da die hier vorgestellte Dissertation parallel, aber etwas zeitlich versetzt, zu der im August 2004 abgeschlossenen Dissertation von Maher Nagieb im selben Forschungsprojekt stattfand, bestand ein Austausch an erhobenen Daten und gewonnenen Erkenntnissen. Dies fand seinen Ausdruck auch in den gemeinsam erstellten Publikationen 2, 3, 5 und 6. Die folgenden, im wesentlichen von Maher Nagieb erhobenen Daten, wurden im Rahmen dieser Dissertation ebenfalls verwendet:

- Daten zu den monatlichen Quellausflußmessungen in den Oasen Balad Seet und Maqta,
- Daten zu den angebauten Kulturen und Erträgen auf den Ackerbauterrassen in den Oasen Balad Seet und Maqta für die Jahre 2001 und 2002,
- Daten zu den gemessenen Niederschlägen in der Oase Balad Seet,
- Daten zu Zahl, Ertrag und Anbaufläche von Dattelpalmen in den Oasen Balad Seet und Maqta,
- Karten zur Landnutzung und Infrastruktur für die Oasen Balad Seet, Maqta sowie das Wadi Tiwi einschließlich digitaler Höhenmodelle.

Die Aufstellung von Wasserbilanzen auf dem Oasenniveau erforderte die Ermittlung der Evapotranspiration der angebauten Kulturen. Die Ermittlung der Referenzevapotranspiration in der Oase Balad Seet erfolgte durch Modellierung nach Penman-Monteith (Allen et al., 1998), da eine direkte Messung dieser Größe vor Ort im Rahmen des DFG-Projektes nicht durchführbar war (Publikation 3). Als meteorologische Ausgangsgrößen wurden Daten zu Temperatur, Globalstrahlung und Sonnenscheindauer mit einer vollautomatischen Wetterstation vor Ort von November 2002 bis Oktober 2003 in Intervallen von 10 Minuten gemessen, während die Windgeschwindigkeit aus zahlreichen Beobachtungen geschätzt wurde. Während die Temperatur für den gesamten Zeitraum vollständig gemessen wurde, konnten Globalstrahlung und Sonnenscheindauer nur für 6 Intervalle von insgesamt 211 Tagen bestimmt werden. Für die restlichen Tage wurden Globalstrahlung und Sonnenscheindauer unter Verwendung eines Digitalen Höhenmodells und eines Modells zur Sonnenstandsberechnung simuliert (Abb. 5). Dieser Ansatz erlaubte es auch, die Auswirkung der Beschattung durch die umliegenden Berge sowie die Auswirkung der Höhenlage der Oase auf die potentielle Evapotranspiration zu quantifizieren. Die in früheren Publikationen zur Berechnung der Tragfähigkeit der Oasen Balad Seet (Publikation 6), Maqta (Publikation 2) und Tiwi (Korn et al., 2004) nötigen Berechnungen der potentiellen Evapotranspiration erfolgten unter Verwendung eines vereinfachten Ansatzes nach Priestley and Taylor (1972), modifiziert nach Shuttleworth (Shuttleworth, 1993). Die Abschätzung der Evapotranspiration in der Oase Maqta sowie im Wadi Tiwi erfolgte auf der Grundlage der in Balad Seet gemessenen höhenkorrigierten meteorologischen Werte für die Temperatur und

Globalstrahlung. Die Evapotranspiration der Nutzpflanzen auf dem Feldniveau wurde durch Anwendung kulturspezifischer Koeffizienten (Doorenbos und Pruitt, 1977; Allen et al., 1998) und unter Verwendung der vorhandenen Daten zu Feldgrößen, Anbauzeiten und angebauten Kulturen bestimmt.

Die Wassernutzungseffizienz für die Oase Balad Seet wurde als Koeffizient zwischen der errechneten Evapotranspiration der Gesamtoase und den monatlich gemessenen Quellausflüssen ermittelt. Die Wasserproduktivitäten ergaben sich als Koeffizient von im Rahmen des Gesamtprojektes ermitteltem Ernteertrag und Wasserverbrauch.

Um abzuschätzen, wieviele Menschen in jeder der untersuchten Oasen unter optimaler Nutzung der vorhandenen Anbauflächen für Ackerkulturen und Palmen und unter optimaler Nutzung der vorhandenen Wasserressourcen autark ernährt werden können, wurden Tragfähigkeitsanalysen durchgeführt (Publikationen 2, 6 sowie Korn et al., 2004). Zur Berechnung wurde eine Bilanz zwischen der in der in Trockenperioden produzierten Nahrung enthaltenen Energiemenge einerseits sowie der vom Menschen durchschnittlich benötigten Energiemenge andererseits erstellt. Es wurde eine Wasser- und Landressourcennutzung angenommen, die zu einer Maximierung der in den Ernteprodukten enthaltenen Nahrungsenergiemenge führt. Die Kombination der so ermittelten Tragfähigkeiten der beschriebenen Oasen und das in interdisziplinären Studien mit Historikern, Architekten und Archäologen erworbene Wissen zur Nutzung der Oaseninfrastruktur in der Vergangenheit ermöglichte die Aufstellung von in sich schlüssig erscheinenden Besiedelungshypothesen (Publikationen 2, 6 sowie Korn et al., 2004).

Typologisierung von Bergoasen im Norden Omans hinsichtlich Landnutzung, Wasserressourcen und Siedlungsform

Vom 'Advanced Spaceborne Thermal Emission and Reflection Radiometer' (ASTER) im Zeitraum 2000-2004 erstellte Satellitenaufnahmen wurden verwendet, um für jedes Bild und jeden Bildpunkt den normalisierten Vegetationsindex (NDVI) aus den Reflektionswerten im roten und infraroten Spektralbereich zu berechnen. Die verwendeten ASTER-Level 2 Oberflächenreflektionsdaten (AST07) haben eine Auflösung von 15 m und jedes Satellitenbild deckt einen Bereich von etwa 60 x 60 km ab. Die Bilder wurden standardmäßig radiometrisch korrigiert, um atmosphärische Störungen und Störungen durch die unterschiedlichen Stellung von Satellit und Sonne zur Erde zu beseitigen (Abrams et al., 2003). Zur Georeferenzierung werden 121 Georeferenzpunkte genutzt, die zu jedem Satellitenbild angegeben werden (USGS, 2003).

Der Vegetationsindex kann Werte zwischen –1 und 1 annehmen, wobei hohe Werte photosynthetisch aktive Vegetation anzeigen (Kumar und Monteith, 1981). Da die bei der Erstellung der Satellitenbilder angewandten radiometrischen Korrekturverfahren bei Geländeformationen mit großen Reliefunterschieden nicht zuverlässig sind (Abrams et al., 2003), wurde wegen des zu erwartenden Datenfehlers von der gewöhnlichen Multispektralanalyse abgesehen. Die Klassifizierung des Bildes in Dauerkultur- (Palmengärten), Ackerbau- und sonstige Flächen beruhte dabei auf folgenden Annahmen:

- Dauerkulturen sind ganzjährig photosynthetisch aktiv und haben daher immer einen relativ hohen Vegetationsindex.
- Pflanzen im Ackerbau sowie natürliche Vegetation sind nur temporär aktiv.
- Die durch künstliche Bewässerung bedingte photosynthetische Aktivität von Pflanzen im Ackerbau ist immer ein kleinräumiges, lokales Phänomen während die photosynthetische Aktivität von natürlicher Vegetation nach Regenereignissen ein großräumiges Phänomen darstellt.

Nach erfolgter Klassifikation wurden die durch Bildklassifikation ermittelten Oasenflächen Städten und Dörfern im Nordoman zugeordnet, wobei die von der US-amerikanischen National Geospatial-Intelligence Agency (NGA) bereitgestellten geographischen Ortskoordinaten Verwendung fanden (NGA, 2004). Zur Einteilung der Oasen in Kern- und Streuoasen wurde die Verteilung der Anbauflächen landwirtschaftlicher Kulturen im Umfeld der Oasenzentren berücksichtigt. Zur Abschätzung der Wasserressourcen wurde des weiteren angenommen, daß die insgesamt in den Oasen verfügbaren Wasserressourcen proportional zur genutzten Anbaufläche sind, wobei ein hoher Anteil von Dauerkulturen auf stetig verfügbare Wasserressourcen hinweist, während ein hoher Anteil von Kulturen im Ackerbau als eine Anpassung an variierende Wasserressourcen angesehen wurde.

Globale Kartierung der landwirtschaftlichen Bewässerungsgebiete

Zur Erstellung der globalen Karte der Bewässerungsgebiete wurden Statistiken zur bewässerten Fläche für 10 825 subnationale statistische Einheiten (z.B. Distrikte, Bundesstaaten, Provinzen) mit geographischen Informationen zur Lage von Bewässerungsgebieten kombiniert (Publikation 4). Die geographischen Informationen zur Lage der Bewässerungsgebiete wurden durch aus digitalisierten und georeferenzierten Karten oder aus existierenden digitalen Datensätzen entnommen und für viele Ländern im ariden Klima mittels Mosaiken aus Landsat Satellitenbildern (Earth Satellite Corporation, http://glcfapp.umiacs.umd.edu:8080) verifiziert. Da für die meisten Gebiete der Erde mehrere Bewässerungskarten verfügbar waren, wurde jedem geographischen Datensatz ein Prioritätsniveau zugeordnet. Diese Prioritätskennzahl stellte sicher, das bei der Kombination mit den subnationalen statistischen Angaben jene Datensätze vorrangig verwendet wurden, die als am verlässigsten eingestuft wurden.

Zur Validierung der globalen Bewässerungskarte wurden zwei Qualitätsindikatoren entwickelt und kombiniert, die die Dichte der verfügbaren subnationalen Statistiken zu einem und die Dichte der geographischen Datensätze zur Position der Bewässerungsgebiete zum anderen berücksichtigen. Desweiteren wurde die Globale Karte der Bewässerungsgebiete mit bewässerten Flächen verglichen, die aus zwei digitalen, globalen Landbedeckungskarten berechnet wurden.

3. ERGEBNISSE

Biomasseabschätzung von Alhagi sparsifolia Vegetation im Vorland der Qira Oase

Sowohl der allometrische als auch der luftbildbasierte Ansatz erwiesen sich als gut geeignet zur Biomasseschätzung der *Alhagi* Vegetation im Vorland der Qira Oase in NW-China. Hohe Korrelationen (r^2 = 0.98 bzw. r^2 = 0.96) wurden erreicht zwischen Buschvolumen (allometrische Ansatz) bzw. Buschquerschnitt (luftbildbasierter Ansatz) und Buschtrockenmasse der 50 destruktiv geernteten *Alhagi*-Büsche, wobei jeweils nichtlineare Schätzgleichungen angewandt wurden. Die Gesamttrockenmasse für das gesamte Feld wurde auf 857 kg (allometrischer Ansatz) bzw. 858 kg (luftbildbasierter Ansatz mit quadratischer Schätzgleichung) berechnet. Der Vergleich beider Verfahren in den 4 x 4 m Validierungsflächen zeigte, daß das allometrische Verfahren überall gute Ergebnisse lieferte während das luftbildbasierte Verfahren dazu neigte, die Trockenmasse auf dicht bestandenen Flächen (ineinandergewachsene Büsche) zu überschätzen. Dieser systematische Effekt verringerte sich aber bei Vergrößerung der Probefläche. Der Zeitbedarf zur Ermittlung der Schätzgleichungen betrug fünf Tage beim allometrischen Ansatz und 20 Tage beim luftbildbasierten Ansatz, während zur Anwendung der Methode auf ein 1 ha großes Feld 17 Tage beim allometrischen Ansatz und 1,5 Tage beim luftbildbasierten Ansatz nötig waren.

Wasser- und Nährstoffbilanzen und Tragfähigkeitsanalysen für die Bergoasen Balad Seet und Maqta sowie das Wadi Tiwi im Norden Omans

Für die Oase Balad Seet wurde eine Wassernutzungseffizienz von 0.75 und Wasserproduktivitäten bezogen auf Korntrockenmasse von 0.92 kg m^{-3} für Weizen, 0.64 kg m^{-3} für Sorghum und 1.85 kg m^{-3} für Knoblauchknollen ermittelt. Die Evapotranspiration auf den landwirtschaftlich genutzten Flächen betrug 194 390 m^3 a^{-1} mit einem Minimum von 10 675 m^3 pro Monat im Januar und einem Maximum von 21 988 m^3 pro Monat im Juni, wobei 83% des Wassers für die Bewässerung der Palmengärten benötigt wurde (Abb. 6). Nach Herausrechnen des Schatteneffektes der umliegenden Berge und des Effektes der Höhenlage erhöhte sich die Referenzevapotranspiration von 1778 mm a^{-1} auf 2393 mm a^{-1}.

Die Ermittlung der Tragfähigkeit der Oase Balad Seet ergab, daß sich die Anzahl von Menschen, die potentiell mittels der verfügbaren Land- und Wasserressourcen ernährt werden können, von 14 zur Zeit der wahrscheinlichen Gründung der Oasensiedlung vor etwa 3000 Jahren auf heute 156 erhöht hat. Dennoch liegt die Zahl der heute in der Oase lebenden Bevölkerung mit 650 weit darüber. Dies gilt ebenso für die Oase Maqta, deren heutige endogene Tragfähigkeit auf 72 Personen geschätzt wurde, deren tatsächliche Bevölkerungszahl aber etwa 200 beträgt. Demgegenüber würde die berechnete Tragfähigkeit der Oasen im Wadi Tiwi (zusammen 1485 erwachsene Personen) gut ausreichen, um die 695 im Wadi selbst lebenden Einwohner zu ernähren (Einwohner des Küstenortes Tiwi nicht berücksichtigt) (Korn et al., 2004). Da es sowohl in Balad Seet als auch in Maqta brachliegende Flächen gibt, ist als entscheidender Faktor für die unterschiedliche Tragfähigkeit der Oasen die Verfügbarkeit der Ressource Wasser anzusehen (Tab. 1).

Typologisierung von Bergoasen im Norden Omans hinsichtlich Landnutzung, Wasserressourcen und Siedlungsform

Die Typologisierung der Oasen im Nordoman bezüglich Siedlungstyp, Landnutzung und verfügbaren Wasserressourcen konnte bis zum jetzigen Zeitpunkt nicht zufriedenstellend gelöst werden. Die Eignung der angewandten Methodik konnte zwar lokal gezeigt werden (Abb. 7). Auch die Landnutzung im Flachland ist recht gut abgebildet. Allerdings waren die Ergebnisse der Satellitenbildklassifizierung für viele Bergregionen nicht überzeugend. Insbesondere die Unterscheidung zwischen Ackerbau und Palmengärten, aber auch zwischen Ackerbau und natürlicher Vegetation verlief häufig unbefriedigend. Der Hauptgrund dafür ist in der geringen Eignung der verfügbaren ASTER-Satellitenbilder zu suchen. So ist die Georeferenzierung der Bilder mit Ungenauigkeiten von bis zu 250 m unzureichend. Desweiteren ist die radiometrische Korrektur der Satellitenbilder offensichtlich mangelhaft. So wurden für ein- und dieselben, geschlossenen Palmengärten als Ergebnis Vegetationsindizes zwischen 0.3 und 0.8 berechnet. Somit ist die Differenz dieser Indizes für ein- und denselben Landnutzungstyp aber zwei verschiedene Satellitenbilder oft größer, als die Differenz zwischen verschiedenen Landnutzungstypen (Palmengarten, Ackerbau, natürliche Vegetation) innerhalb eines Satellitenbildes selbst. Einer Lösung des Problems durch Verwendung von Orthobildern mit guten radiometrischen Eigenschaften und hoher Bildauflösung steht im Moment hauptsächlich der hohe finanzielle Aufwand zum Erwerb dieses Materials entgegen.

Globale Kartierung der landwirtschaftlichen Bewässerungsgebiete

Die globale Karte der landwirtschaftlichen Bewässerungsgebiete zeigte insgesamt 273,7 Mio ha Bewässerungsfläche, davon liegen 69% in Asien, 17% in Amerika, 9% in Europa, 4% in Afrika und 1% in Ozeanien. Die größten zusammenhängenden Flächen mit hoher Bewässerungsdichte wurden in Nordindien und Pakistan entlang der Flüsse Ganges und

Indus, in den Einzugsgebieten des Hai He, Huang He und Yangtze in China, entlang des Nils in Ägypten und Sudan, im Mississippi-Missouri Einzugsgebiet und in Kalifornien festgestellt. Kleinere Bewässerungsflächen finden sich in fast allen bevölkerten Regionen der Erde (Abb. 8). Die Qualität der Karte wurde in einem Benotungssystem zwischen 0 und 5 mit insgesamt 2.07 als gut bewertet, allerdings mit Unterschieden auf regionaler Ebene zwischen 1.03 für Nordamerika und 4.00 für Rußland. 81% der bewässerten Flächen befinden sich in Ländern, für die die Kartenqualität als sehr gut oder gut eingeschätzt wurde. Eine Verwendung der globalen Landbedeckungskarten GLCC (USGS, 2000) und GLC2000 (Joint Research Centre of the European Commission, 2003) zur Bestimmung der Bewässerungsflächen kann nicht empfohlen werden, da diese Datensätze weder Ausdehnung noch Verteilung bewässerter Flächen angemessen abbilden können.

4. SCHLUSSFOLGERUNGEN

Eine nicht-destruktive Bestimmung der Trockenmasse von *Alhagi sparsifolia* Vegetation mittels Kombination von Luftbildfotographie und GIS kann vorbehaltlos empfohlen werden wenn kaum andere Pflanzenarten auf der Fläche wachsen und die Versuchsfläche größer als 1 ha ist. Die Möglichkeit der Übertragung der Methode auf ähnliche Vegetationsarten gilt als wahrscheinlich, solange keine verholzten Pflanzenteile gebildet werden.

Die für die Oase Balad Seet festgestellte hohe Wassernutzungseffizienz und die hohen Wasserproduktivitäten sowie die seit Jahrhunderten erfolgende Ackerterrassennutzung deuten auf eine nachhaltige Nutzung der Ressourcen Wasser und Boden sowie auf eine gute Anpassung der Oase an die gegebenen Standortbedingungen hin. Dennoch konnte für die Oasen Balad Seet und Maqta nachgewiesen werden, daß die vorhandenen Ressourcen nicht ausreichen, um die heute dort lebende Bevölkerung zu ernähren. Fehlende Land-, Wasser- und Nährstoffressourcen werden durch Einfuhr von Nahrungs-, Dünge- und Futtermitteln ausgeglichen. Da dem kein nennenswerter Warenstrom aus der Oase heraus ins Umland entgegensteht, ist die Oasenbevölkerung auf finanzielle Unterstützung von außerhalb angewiesen. Für das Überleben der Bergoasen im Norden Omans wird somit von großer Bedeutung sein, ob die Grundlagen dieser finanziellen Unterstützung dauerhaft sind. Dieser ökonomisch-politische Aspekt konnte im Rahmen dieser Dissertation nicht untersucht werden.

Eine Landnutzungskartierung auf der globalen, regionalen oder lokalen Ebene erfordert ganz unterschiedliche Vorgehensweisen. Während für die globale Kartierung von Bewässerungsflächen eine Kopplung von Geodaten mit statistischen Informationen notwendig war, wurde bei den kleinräumigen Untersuchungen in der chinesischen Qira Oase sowie den omanischen Bergoasen eine erfolgreiche Kombination von Luftbildfotographie, GIS und GPS zur Biomassebestimmung bzw. Kartierung der Oasen eingesetzt. Die bei der Typisierung von Bergoasen in der Region Nordoman aufgetretenen Schwierigkeiten weisen auf die hohen Anforderungen an die Qualität von Satellitenbildaufnahmen bei multitemporalen Bildklassifizierungen hin.

Durch die Verbindung von Methoden der Modellierung mit geographischen Informationssystemen sowie Methoden der Luftbildgewinnung und Bildauswertung und die Anwendung dieser Kenntnisse und Fähigkeiten in einem multidisziplinären Projektzusammenhang konnten zusätzliche Erkenntnisse gewonnen werden. Zahlreiche grundlegende Fragestellungen konnten nur interdisziplinär beantwortet werden und erforderten eine Anpassung bereits bekannter oder die Entwicklung neuer

Untersuchungsmethoden. Vor diesem Hintergrund stellt diese Studie auch einen standortsunabhängigen Beitrag zum wissenschaftlichen Erkenntnisfortschritt dar.

ÜBERBLICK ZUM EIGENEN BEITRAG

Die vorliegende kumulative Dissertation enthält sechs eigenständige Publikationen, zu denen der Verfasser der Arbeit einen wesentlichen Beitrag als Haupt- oder Koautor geleistet hat. Da bei gemeinsamen Veröffentlichungen nicht immer exakt zwischen den Beiträgen der einzelnen Autoren unterschieden werden kann, wird im Folgenden ein Überblick über den Eigenanteil an den Beiträgen gegeben.

Publikation 1: *S. Siebert, D. Gries, X. Zhang, M. Runge, A. Buerkert (2004): Non-destructive dry matter estimation of Alhagi sparsifolia vegetation in a desert oasis of Northwest China. Journal of Vegetation Science 15: 365-372.*

Beitrag Doktorand: Zentraler Anteil an Konzeption sowie vollständige Entwicklung des GIS-basierten Ansatzes zur Biomassebestimmung, Vergleich beider Verfahren

Beitrag Koautoren: Durchführung des allometrischen Ansatzes zur Biomassebestimmung, Überarbeitung des Manuskriptes

Publikation 2: *S. Siebert, J. Häser, M. Nagieb, L. Korn, A. Buerkert (2005): Agricultural, architectural and archaeological evidence for the role and ecological adaptation of a scattered mountain oasis in Oman. Journal of Arid Environments 62: 177-197.*

Beitrag Doktorand: Zentraler Anteil an Konzeption, Entwicklung der Methodik und Durchführung der Berechnungen zur Tragfähigkeitsbestimmung der Oase, wesentliche Beiträge zur Kartierung der Oase und zum Aufbau des GIS

Beitrag Koautoren: Projektleitung, wesentliche Beiträge zur Kartierung der Oase, Erhebung von Umfragedaten, Durchführung der Untersuchungen zur Architektur der Oasenbauwerke, Messung der Quellausflüsse, Durchführung der archäologischen Untersuchungen, wesentliche Beiträge zum Manuskript

Publikation 3: *S. Siebert, M. Nagieb, A. Buerkert: Climate and irrigation water use of a mountain oasis in northern Oman. Water Resources Research (eingereicht).*

Beitrag Doktorand: Zentraler Anteil an Konzeption, Entwicklung der Methodik und Durchführung und vollständige Beschreibung aller Berechnungen und der Modellierung, wesentliche Beiträge zur Kartierung der Oase und zum Aufbau des GIS

Beitrag Koautoren: Projektleitung, Erhebung von Umfragedaten zur Landnutzung und Erträgen, Messung der Quellausflüsse, Durchsicht des Manuskriptes

Publikation 4: *S. Siebert, P. Döll, J. Hoogeveen, J.-M. Faures, K. Frenken, S. Feick (2005): Development and validation of the Global Map of Irrigation Areas. Hydrology and Earth System Sciences 9: 535-547.*

Beitrag Doktorand: Vollständige Entwicklung der Methodik und Aufbau des GIS, Datenintegration, Erstellung der globalen Karte, Entwicklung der Methodik zur Validierung des Datensatzes

Beitrag Koautoren: Projektleitung, Aufbereitung und Bereitstellung von subnationalen Statistiken, Bereitstellung und Hilfe bei der Digitalisierung von Kartenmaterial, Durchsicht des Manuskriptes

Publikation 5: *A. Buerkert, M. Nagieb, S. Siebert, I. Khan, A. Al-Maskri (2005): Nutrient cycling and field-based partial nutrient balances in two mountain oases of Oman. Field Crops Research 94: 149-164.*

Beitrag Doktorand: Wesentliche Beiträge zur Kartierung der Oasen und zum Aufbau des GIS, wesentliche Beiträge zur Datenaufbereitung, Durchsicht des Manuskriptes

Beitrag Erst- und Koautoren: Projektleitung, Erhebung von Umfragedaten zur Landnutzung, zu den Erträgen und zum Düngemitteleinsatz, wesentliche Beiträge zur Kartierung der Oasen, Analyse von Pflanzen- und Dungproben, wesentlicher Beitrag zur Errechnung der Bilanzen, Verfassen des Manuskriptes

Publikation 6: *M. Nagieb, S. Siebert, E. Luedeling, A. Buerkert, J. Häser (2004): Settlement history of a mountain oasis in northern Oman – evidence from land-use and archaeological studies. Die Erde 135: 81-106.*

Beitrag Doktorand: Wesentliche Beiträge zur Kartierung der Oase und zum Aufbau des GIS sowie zur Methodik der Tragfähigkeitsberechnungen, Erstellung der GIS-basierten Abbildungen, Rezension des Manuskriptes

Beitrag Erst- und Koautoren: Projektleitung, wesentliche Beiträge zur Kartierung der Oase und zum Aufbau des GIS, Untersuchungen zur Archäologie und Historie der Oase, Verfassen des Manuskriptes

ERKLÄRUNG

Hiermit erkläre ich, daß ich die vorliegende Dissertation selbstständig angefertigt und mich anderer Hilfsmittel als der in ihr angegebenen nicht bedient habe, insbesondere, daß aus Schriften keine Entlehnungen, soweit sie in der Dissertation nicht ausdrücklich als solche mit Angabe der betreffenden Schrift bezeichnet sind, vorgenommen wurden.

Frankfurt (Main) im November 2005,

Stefan Siebert.

Journal of Vegetation Science 15: 365-372, 2004

1

Non-destructive dry matter estimation of *Alhagi sparsifolia* vegetation in a desert oasis of Northwest China

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ABSTRACT

Naturally-growing *Alhagi sparsifolia* shrubs are a major animal feed for small ruminants in the vast foreland of river oases in the Taklamakan desert of Northwest China. The determination of the total above-ground dry matter, further referred to as above-ground biomass (AGB), of shrubs at the field scale is time-consuming and only non-destructive techniques would allow repeated measurements of the same individual over time. To develop and test such techniques two different approaches were chosen. At first shrub AGB was estimated by manual ground measurements (called "allometric approach") of length, width and height of 50 sample shrubs. Subsequently regression equations were established between calculated shrub canopy volume and shrub AGB (r^2 = 0.96). This equation was used to calculate AGB from manual ground measurements in 20 sample plots within the *Alhagi* field.

Secondly, colour aerial photography coupled with the use of a Geographic Information System (called "GIS approach") was tested as an alternative method. To this end a picture was taken from a kite at about 250 m height. First and second order polynomial regressions between AGB data of the 50 individual shrubs and their respective canopy area allowed to automatically calculate the AGB of all remaining shrubs covered by the photograph (r^2 = 0.92 to 0.96). The use of non-linear AGB regression equations required an automatised separation of shrubs growing solitary or in clumps. Separation criteria were the size and shape of shrub canopies.

Finally both methods were compared in 20 plots of 4 x 4 m. The results showed that the allometric approach was very reliable, whereas the GIS-based approach led to overestimation of *Alhagi* dry matter in densely vegetated areas. However, this systematic error decreased with increasing size of the surveyed area. This reflected the fact that biomass density per unit canopy area of densely growing shrub clumps was lower than the biomass density of solitary shrubs. Future research in this field should focus on improvements of AGB estimates in areas of high shrub density.

1 INTRODUCTION

River oases at the southern fringe of the Taklamakan desert in Xinjiang, NW China, the second largest desert in the world, are surrounded by a belt of indigenous vegetation that functions as a shelter against drifting sand. This function is indispensable for the oases, as

NW winds prevail (Xia et al., 1993) and constantly transport silt from the desert towards the oases. The foreland vegetation is also an important component of the agricultural system of the oases because it is a major source of forage, fuel and construction wood, while it is grazed by sheep, goats and camels.

The protective function of the foreland vegetation is threatened by increasing overuse due to rapid population growth, and by an increasing use of water for irrigation of cropland in the oases where production is being intensified. The consequence is that large foreland areas are completely free of vegetation leading to sand encroachment of the agricultural land.

The effective protection of the foreland vegetation as an economic resource and a protective vegetation belt for the oasis cropland requires a quantitative understanding of its ecological resilience, in particular with respect to the amount of plant biomass that can be sustainably extracted each year. In the past research has focused on oasis cropland and virtually nothing is known about the effects of periodic cutting or grazing of the foreland vegetation on its productivity.

Within the framework of a broader study (Thomas et al., 2000) the work described here aims at developing and comparing non-destructive methods to determine Above-ground biomass (AGB) per unit area (biomass density) and annual biomass production of the foreland vegetation in August, the time of maximum AGB accumulation in the course of the annual growing period. The study focused on pure stands of *Alhagi sparsifolia*, a spiny, 1 m tall perennial herb of the *Fabaceae* which is unequally distributed in the foreland of the oases. Due to its high concentration of raw protein, it is a particularly valuable fodder for small ruminants and as such of particular importance for winter feeding of the large herds of the local farmers.

In principle the AGB of such shrubs can be estimated non-destructively either by ‘allometric regressions’ which are based on the basal area or the calculated crown volume (Nikolaev and Baimyradov, 1987; Uso et al., 1997). Alternatively, true colour or infrared aerial images analysed within a Geographic Information System (‘GIS-approach’) can be used (Aparicio et al., 2000; Li et al., 1998). The usage of true colour photographs to estimate AGB is based on mapping the canopy greenness (Moraghan, 1998; Blackmer and Schepers, 1996). Studies in the West African Sahel showed that it was also possible to derive AGB of solitary *Guiera senegalensis* from the shrub canopy size determined on high resolution aerial images (Gerard and Buerkert, 1999).

2 DATA AND METHODS

2.1 Study site

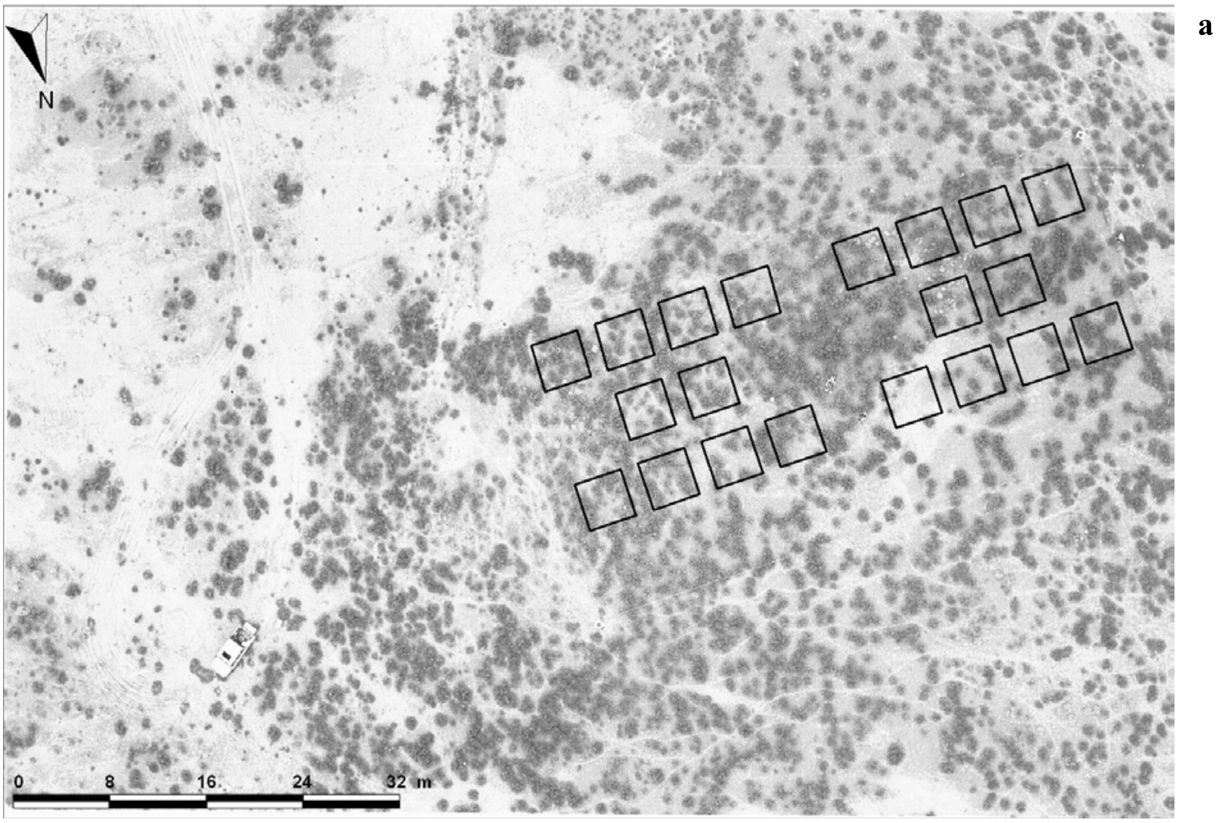
The study was carried out near the desert research station of the Chinese Academy of Science in Cele (Qira) oasis (37° 01' N, 80° 48' E, 1365 m a.s.l.) at the southern fringe of the Taklamakan desert in Xinjiang Autonomous Region, NW China. The climate is continental, with cold, dry winters and hot, dry summers. Mean annual temperature is 11.9 °C, annual potential evaporation is approximately 2600 mm and the annual sum of precipitation is 35.1 mm (Xia et al., 1993). Plant growth thus largely depends on water from melting snow which comes down from the Kunlun mountain range in large rivers. The experimental site comprised a naturally grown piece of foreland vegetation of 96 m x 66 m dominated by heterogeneously distributed *Alhagi sparsifolia* stands (Fig. 1). 20 test plots of size 4 m by 4 m are located on densely vegetated parts of this field.

2.2 Aerial photography

The lack of cold storage at the project site prevented the use of infrared films. Therefore true colour aerial photographs of the site were taken in August 2000 from a kite at a height of ca. 250 m (Fig. 1a). Attached to the kite was a remotely controlled standard 24 mm x 36 mm reflex-camera (Nikon F 601) equipped with a 50 mm lens and loaded with a Kodak 100 ISO colour negative film (Buerkert et al., 1996; Gerard et al., 1997). To avoid shaded areas on the photograph, all images were taken near midday. Because a differential global positioning system (DGPS) was not available, the images could not be geo-referenced. However, the photograph chosen for analysis covered four ground control points with known distances in-between. This allowed to compute the ground size of an image pixel.

2.3 Destructive harvest of sample shrubs

After taking the photograph in August 2000, 50 shrubs were marked on the image, measured for their largest and corresponding perpendicular diameters as well as for maximum shrub height and then harvested. Subsequent drying in a forced drought oven at 65 °C allowed the determination of total above-ground dry matter of each shrub. A total of 37 shrubs were measured, harvested and dried in the same manner in 1999, but no aerial photograph was taken.



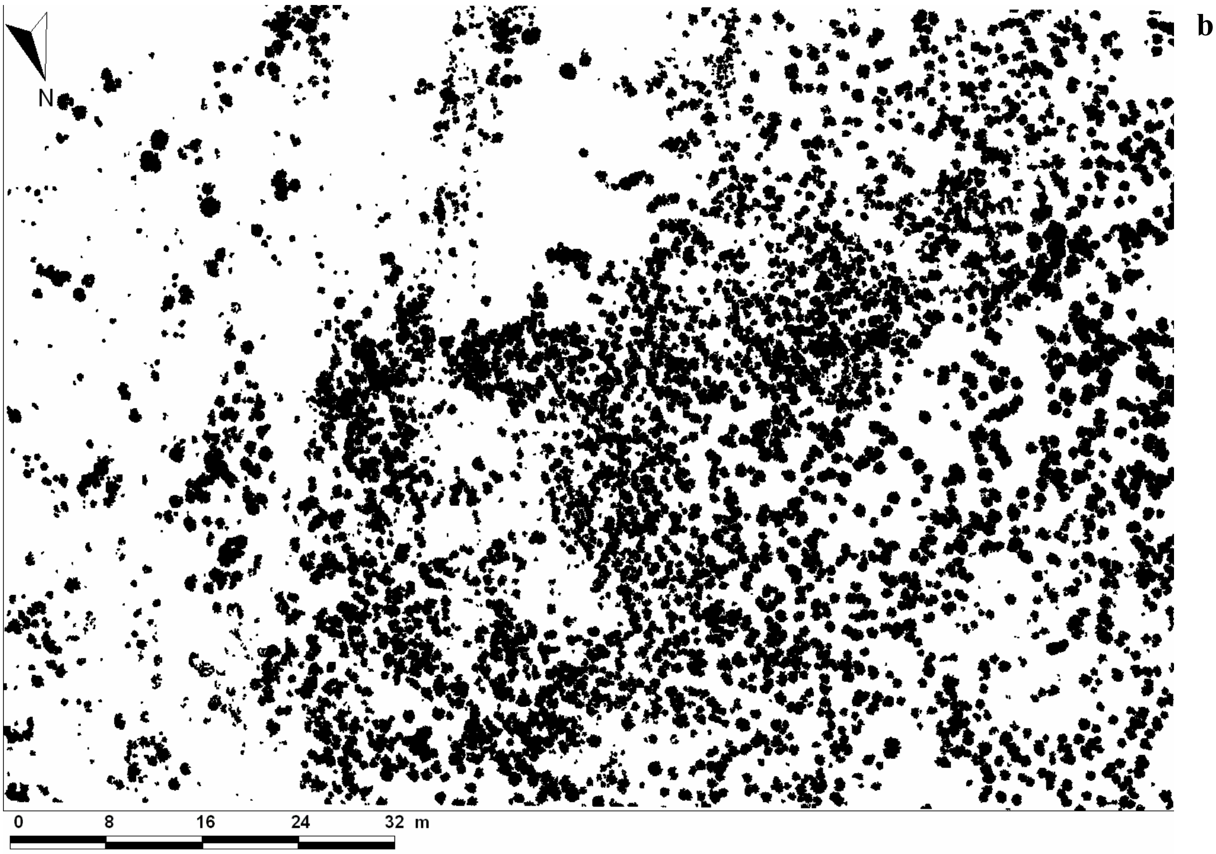


Fig. 1. **a.** Aerial photograph of *Alhagi sparsifolia* vegetation from ca. 250 m height with sample squares (above); **b.** polygon layer of *Alhagi* shrubs showing the results of a classification effort (below). Qira oasis, NW China.

2.4 Image processing

Initial efforts to extract shrub area from the photograph with standard classification methods or clustering failed because the colour of the shrub surfaces on the photograph was not uniform (Fig. 1a). The bush surface comprised a patchy pattern from light green to almost black tones. Therefore in a first step the red, green and blue channels of the image were classified within the 0-255 colour tone range. It was assumed that pixels represented *Alhagi* vegetation if the value of the blue band was below 120 and in addition the value of the green band was larger than the value of the red band.

To define single shrubs, the raster map was converted into a vector map by conglomerating neighbouring *Alhagi* pixels. Thereby more than 70 000 single polygons were created in the 96 m x 66 m field. Most of them were of a very small size and represented shadow areas within the shrubs (holes) or green reflections of the soil. To eliminate these, polygons with an area of less than 10 pixels (ca. 69 cm²) were deleted. This led to a reduction of polygons to 2209 (Fig. 1b). Because many of the shrubs were growing closely together, in some areas it was not possible to distinguish single shrubs, which led to the creation of a network of connected shrub units subsequently referred to as ‘clumps’.

2.5 Establishment of regression equations

Allometric approach

To optimize the allometric regression approach the following parameters were varied: (1) the mathematical model (linear, power or polynomial), (2) the data transformation (with or without transformation to natural logarithm) and (3) the method of determining the shrub volume or shrub projection area (two-dimensional: circle, ellipse and rectangle; three-dimensional: sphere, sphere cap and cube). Regressions were tested for significance ($p \leq 0.05$) by analysis of variance (ANOVA) and equation parameters by *t*-tests. Normal distribution of data was checked using the Kolmogorov-Smirnov test and was assumed if P for H_1 was > 0.05. Without transformation, residuals of shrub volumes were not normally distributed, therefore all volume data were transformed to their natural logarithm and linear equations were fitted using least-squares procedures. Correction factors (*CF*) for the bias introduced by logarithmic transformation were calculated according to Sprugel (1983) as:

$$CF = \exp\left(0.5 SEE^2\right) \quad (1)$$

with *SEE* = standard error of the estimate. Homogeneity of variances was tested using the Levene Median test ($p > 0.05$). To test for autocorrelation of residuals, the Durbin-Watson coefficient was calculated (Anon., 2000). Equations with a coefficient between 1.5 and 2.5 were accepted. All r^2 values reported are adjusted for degrees of freedom of their respective sums of squares. SigmaPlot 2000 software (SPSS Science, Chicago, USA) was used for statistics.

GIS-based approach

Regression analyses between total dry matter of the 50 sample shrubs and the canopy area of these shrubs as derived from the aerial photograph led to linear and nonlinear regression equations. A zero intercept was assumed because the computed intercept was negative. The use of a negative intercept would lead to a slightly better fit of the regression estimate (r^2 = 0.928 compared to 0.919 in the linear estimate) but also to negative AGB for small shrubs (< 0.048 m^2 in the linear estimate) which makes no practical sense.

For solitary shrubs a non-linear type of regression equation might be particularly useful because shrub height, which could not be detected from the aerial photograph, grows with shrub length and width. However, the nonlinear regression equation for solitary shrubs should not be used for shrub clumps, because the height of shrub clumps appeared to be limited and only loosely related to the total canopy area of the clump. To also establish a regression equation for shrub clumps, 31 clumps were split by hand into 100 single bushes. These clumps were selected because their shape allowed easy identification and separation of individual component shrubs.

Subsequently, the dry matter of these single parts was computed using the non-linear equation for solitary shrubs and thereafter the AGB of the individual clump parts was summed up to compute the AGB of the shrub clump. This was based on the assumption that bush AGB of split clumps could be computed from the (non-linear) regression equation for solitary shrubs. A linear equation was established to predict the AGB of these 31 clumps based on their computed total canopy area (Fig. 2). Subsequently, this equation was used to estimate the AGB of the other shrub clumps.

This procedure helped to avoid the splitting of all shrub clumps into single shrubs. For most of the clumps the true number of single shrubs could not be detected, neither by hand nor automatically. However, it was still necessary to distinguish between solitary shrubs and shrub clumps. An algorithm was developed which separated shrub clumps according to size and shape of the canopy area. A shrub was assumed to be a 'solitary shrub', if its canopy area

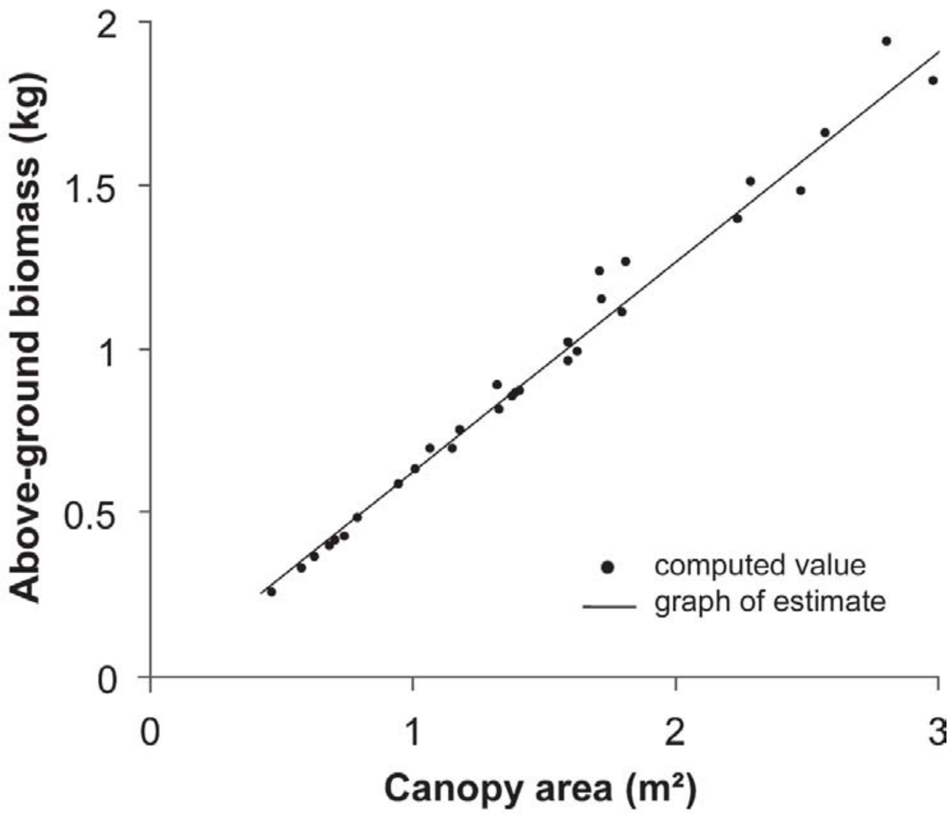


Fig. 2. Computed above ground biomass of *Alhagi sparsifolia* clumps and graph of estimate for shrub clumps at Qira oasis, NW China.

Fig. 3. Detail of the shrub polygon layer showing automatically detected solitary shrubs (dark grey coloured) and shrub clumps (light grey coloured) of *Alhagi sparsifolia* at Qira oasis, NW China.

was less than 150 pixels (ca. 0.1 m²) and a 'clump' if its canopy area was larger than 2500 pixels (ca. 1.7 m²). For canopies between these margins, the classification took also the shape of the shrub into account. Solitary shrubs tended to be compacter than shrub clumps (Fig. 3). To use this finding for further analysis a compactness indicator c was established by dividing the canopy area by the area of a circle comprising the shape. This method was first applied to compare the compactness of several European countries (Selkirk, 1982). To distinguish solitary and connected shrubs (Fig. 3) a set of mathematically defined rules was used (Table 1). The rules were defined and optimized in a trial and error approach. Compared to other methods of shape approximation (Safar et al., 2000) this approach was easy to apply, needed low computational resources and when using area expressed in m² rather than in pixels it was rotation- and scale-independent.

2.6 Verification of regression equations

To test the reliability of the regression equations, these were tested with the 20 sample plots as well as for the entire 96 m x 66 m field and the thereby computed AGB values were compared. For the allometric estimates it was assumed, that shrubs belonged to a specific sample plot if their stem was located within the plot, although parts of the shrub crown might have grown outside the plot. For the GIS-based method it was impossible to exactly locate the stem position. Therefore it was decided to cut shrub canopy areas at the borderlines of the plots.

Table 1. Decision tree to distinguish between solitary shrubs of *Alhagi sparsifolia* and shrub clumps at Qira oasis, NW China.

Shape condition	Size condition	Decision
$c < 0.4$	size < 150 pixels (≈ 0.1 m²)	solitary shrub
	size ≥ 150 pixels (≈ 0.1 m²)	clump
$0.4 \leq c < 0.5$	size < 800 pixels (≈ 0.55 m²)	solitary shrub
	size ≥ 800 pixels (≈ 0.55 m²)	clump
$0.5 \leq c \leq 0.6$	size ≤ 2000 pixels (≈ 1.38 m²)	solitary shrub
	size > 2000 pixels (≈ 1.38 m²)	clump
$c > 0.6$	size ≤ 2500 pixels (≈ 1.73 m²)	solitary shrub
	size > 2500 pixels (≈ 1.73 m²)	clump

To estimate the shrub AGB on the entire 96 m x 66 m field with the allometric approach, a regression equation between shrub density and biomass density was established that was based on the data from the 20 sample plots. This equation was applied to the entire field by using a GIS-based estimate for the total number of shrubs, so that the measurement of diameters and height for each of the shrubs could be avoided.

3 RESULTS

3.1 Regression equations for the harvested shrubs

The allometric approach and the GIS-based approach were both suitable to estimate the AGB of the harvested sample shrubs (Table 2). For the allometric approach AGB was closely correlated with shrub volume calculated as a sphere, with mean of shrub length, width and height as parameters. The regressions were statistically significant ($p \leq 0.001$) and met the requirements for regression analysis with respect to normal distribution, homogeneity of variances and autocorrelation of residuals. The slopes and offsets of the allometric regression equations for 1999 and 2000 were not significantly different using tests at $p \leq 0.05$. Therefore even dry weights of shrubs harvested in 2000 could be well predicted by the 1999 regression equation (Fig. 4, Table 2). Also in the GIS-based approach shrub AGB was highly correlated with the canopy area as detected from the aerial photograph (Fig. 5, Table 2).

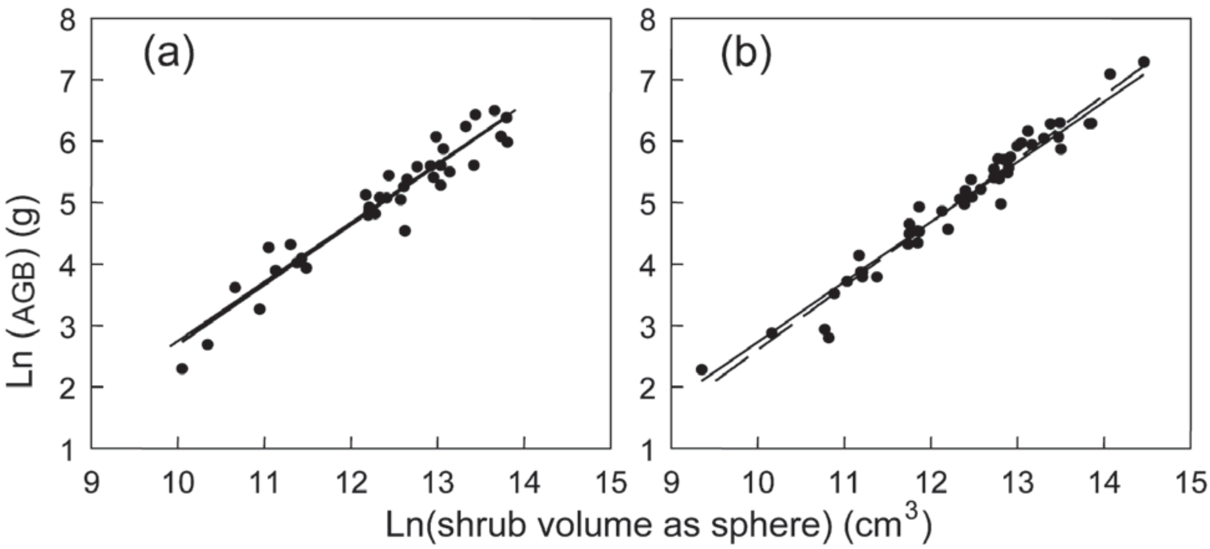


Fig. 4. **a.** Relationship between *Alhagi sparsifolia* shrub volume and their above-ground biomass (AGB) in August 1999 at Qira oasis, NW China; ● measured values; – linear regression equation, $r^2 = 0.92$, $p \leq 0.0001$; **b.** same as above but harvested in August 2000; $r^2 = 0.96$, $p \leq 0.0001$; dry weights of shrubs harvested in 2000 predicted by the 1999 regression equation.

Table 2. Results of regression analysis between harvested above-ground biomass (AGB) of *Alhagi* shrubs and the canopy area computed from the aerial photograph (GIS-based approach) or shrub volume (allometric approach) at Qira oasis, NW China.

	Harvested shrubs	Estimate A	Estimate B	Estimate C	Estimate D	Estimate F
Description	50 harvested sample shrubs in year 2000	Function fitted to volume and AGB of shrubs harvested in 2000, allometric	Function fitted to volume and AGB of shrubs harvested in 1999, allometric	Linear function fitted to crown area and AGB of shrubs harvested in 2000, GIS-based	Non-linear function fitted to crown area and AGB of (solitary) shrubs harvested in 2000, GIS-based	Linear function fitted to canopy area and AGB of 31 shrub clumps, GIS-based
Type of regression equation	---	ln (AGB) = a*ln(Volume)+b	ln (AGB) = a*ln(Volume)+b	AGB = a*Area	AGB = a*Area² + b*Area	AGB = a*Area
Units	---	g (AGB) and cm^3 (Volume)	g (AGB) and cm^3 (Volume)	kg (AGB) and m² (Area)	kg (AGB) and m² (Area)	kg (AGB) and m² (Area)
Parameters	---	a = 1.0349 b = -7.7455 CF = 1.0257	a = 0.9753 b = -7.0649 CF = 1.045	a = 0.7395	a = 0.2684 b = 0.4944	a = 0.6343
r^2 adj.	---	0.96	0.92	0.92	0.96	0.98
AGB range within the shrub samples (g)	10 - 1458	7 - 1397	8-1186	5 - 1142	3 - 1403	257 - 1939
Standard deviation (g)	273	261	224	244	275	457
Total AGB (g)	12 589	12 624	11 570	13 441	12 188	28 277

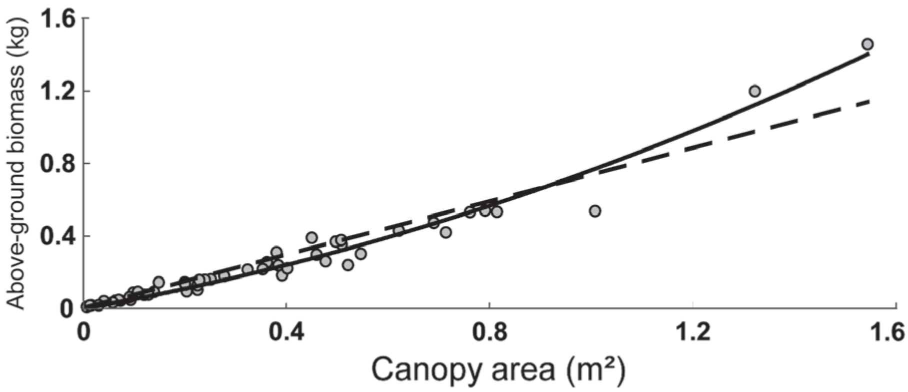


Fig. 5. Relationship between *Alhagi sparsifolia* canopy area (derived from the aerial photograph) and shrub above-ground biomass; measured; – quadratic regression equation; - -linear regression equation. Qira oasis, NW China.

3.2 Above-ground biomass of the sample squares

With the allometric approach an AGB of 52 kg was calculated for the 422 shrubs of the 20 sample plots. Average shrub density in the 20 sample squares was 1.32 ind. m^{-2} with a range from 0.3 to 2.6 ind. m^{-2}. Individual shrub AGB was between 71 and 376 g, and biomass density varied between 79 and 261 g m^{-2}. Average biomass density of the 20 sample squares was 163 ± 9 g m^{-2} (Table 3). Mean shrub AGB was inversely correlated with shrub density (Fig. 6a). This partly compensated for the effect of shrub density (g m^{-2}) on biomass density (g m^{-2}), so that biomass density was only weakly (but significantly) correlated to shrub density (Fig. 6b) according to:

$$\textit{Biomass density} = 40.4 * \textit{Shrub density} + 109.3 \qquad (2)$$

with adjusted r^2 = 0.37 and P = 0.003. Using the GIS-based regression equations and the detected canopy areas of the shrubs AGB values of 73 kg (for the non-linear estimate) and 86 kg (for the linear estimate) were computed. About 86% of the biomass was growing in shrub clumps.

3.3 Above-ground biomass of the entire field

On the aerial photograph 1649 solitary bushes, covering a total area of 310 m^2 and 560 shrub clumps, covering a total area of 1044 m^2 were detected. Based on the average number of 4.33 shrubs per shrub clump for the 4 m x 4 m sample squares (Table 4) the total number of shrubs on the aerial photograph was estimated as 4.33 * 560 + 1649 = 4076 shrubs. Shrub density in the 96 m x 66 m field therefore was 0.643 ind. m^{-2} and biomass density was estimated

Table 3. Shrub density, above-ground biomass and aboveground biomass density of *Alhagi sparsifolia* in the sample squares at Qira oasis, NW China (means ± *se*, $n = 20$).

	Shrub density (ind. m^{-2})	AGB (g)	AGB (g m^{-2})
Mean	1.32 ± 0.13	150.1 ± 16.9	163 ± 9
Minimum	0.3	71	79
Maximum	2.6	376	261

Table 4. Estimation of average number of shrubs per clump from ground and GIS counts in sample squares of *Alhagi sparsifolia* at Qira oasis, NW China.

	Solitary shrubs	Shrub clumps
Total number of shrubs (manual ground count)	422	-
GIS estimate	110	71
Shrubs in clumps	312	
Shrubs per clump = 312 / 71 = 4.33		

according to Eq. 2 as 135.3 g m^{-2}. Using this biomass density, the shrub AGB of the entire field was estimated as 0.1353 kg m^{-2} * 6336 m^2 = 857 kg. Using the GIS-based approach AGB values of 858 kg (for the non-linear estimate) and 1001 kg (for the linear estimate) were calculated. Irrespective of the type of equation shrub clumps comprised 77% of the shrub AGB of the field.

3.4 Time requirement

The initial establishment of the method required 5 man days for the allometric approach and 20 man days for the GIS-based approach. However, given that both approaches with their respective equations are now established and most likely can be reused, the future timerequirements for the estimation of *Alhagi* AGB should be substantially smaller for GIS-based estimates compared with allometric measurements (Table 5).

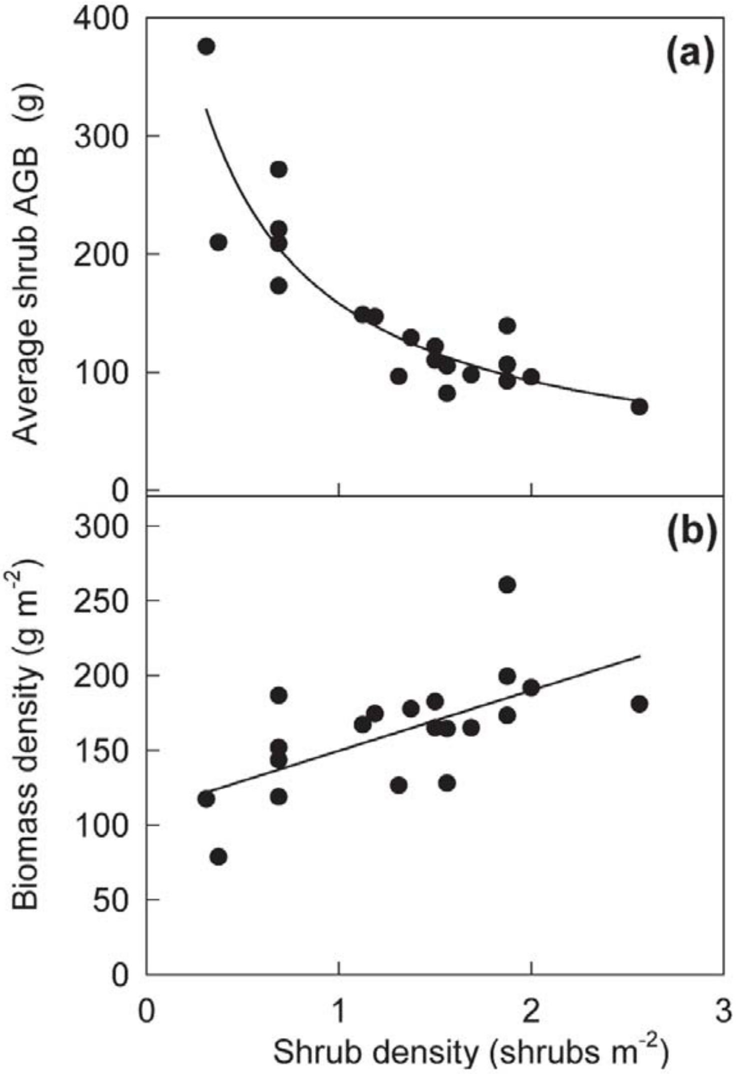


Fig. 6. Relationship between shrub density and average shrub weight of *Alhagi sparsifolia* in twenty 4 m x 4 m sample plots at Qira oasis, NW China. Adjusted r^2 of hyperbolic equation = 0.79, $p \leq 0.05$ **(a)**; Relationship between shrub density and biomass density; adjusted r^2 = 0.37, p = 0.003 **(b)**.

4 DISCUSSION

The high correlation of the different estimates of shrub AGB with true dry matter is encouraging. Because shrub clumps comprised over 77% of the AGB in the sample area, future research should be focused on these densely vegetated areas. Most of the 50 sample shrubs harvested in 2000 were solitary shrubs, whereas the 37 sample shrubs harvested in 1999 were representative for the 20 sample squares and therefore most of them were parts of shrub clumps.

The use of GIS-based regression equations requires the ability to distinguish between solitary shrubs and shrub clumps. In the linear regression equation, which does not distinguish

Table 5. Time requirement for biomass estimates of *Alhagi sparsifolia* at Qira oasis, NW China.

Ground based allometric estimate		GIS-based aerial photography	
Establishment of the regression equation			
Establishment of sample squares	1 d	Establishment of sample squares	1 d
Measurement of shrub dimensions (473 shrubs)	2 d	Measurement of shrub dimensions (473 shrubs)	2 d
Sample preparation, data evaluation	2 d	Taking of the aerial photograph, digititizing of the photograph, image classification	1 d
		Developing of an algorithm to separate clumps, data processing	16 d
Total time required	5 d	Total time required	20 d
Application on a field of size 1 ha			
Measurement of shrub dimensions †	16 d	Taking of two aerial photographs, establishment of ground control points	0.5 d
Data evaluation	1 d	Digitizing, data processing	1 d
Total time required	17 d	Total time required	1.5 d

† assuming a density of 6400 shrubs ha^{-1} and manual measurements of 800 shrubs $(2\ man\ days)^{-1}$

Table 6. Comparison of ground-based and GIS-based detected above-ground biomass (AGB) and canopy areas of sample shrubs of *Alhagi sparsifolia* at Qira oasis, NW China.

	Allometric AGB estimate (kg)	GIS-based AGB estimate linear (kg)	GIS-based AGB estimate linear (kg)	Crown projection area (m^2)[1]	Canopy area detected by GIS (m^2)	Average shrub crown projection area (m^2)	Biomass density[2] (kg m^{-2})
50 shrubs harvested in 2000	12.6	13.4	12.2	36.7	18.2	0.65	0.34
Shrubs in 20 sample squares	52.1	85.6	73.3	161.2	115.8	0.33	0.32
Shrubs in eastern 10 sample squares	26.0	47.1	40.0	81.2	63.7	0.28	0.32
Shrubs in western 10 sample squares	26.1	38.5	33.3	80.0	52.1	0.41	0.33

[1] computed as an ellipse using measured length and width of the shrubs; [2] related to crown projection area

between shrub types, the slope was 0.74. However, in the regression equation for clumps, established by splitting clumps into single shrubs and summing up the AGB derived from the non-linear estimate, the slope was only 0.63 (Table 2). Nevertheless, even the application of this clump specific estimate led to an overestimation of AGB in the densely vegetated sample squares (Table 6). This overestimation was largest in areas in which the average crown projection area of the shrubs was small. This is usually the case in the clumps where the space to extent the twigs horizontally is limited. The biomass density derived from the crown projection (allometric approach) remained nearly constant (Table 6). This leads to the assumption, that differences between allometrically determined crown projection areas vs. GIS-determined canopy areas may explain the different dry matter estimates. In principle the GIS-determined canopy area should be smaller than the computed crown projection area (Fig. 7). The GIS-determined canopy area of the sample shrub in Fig. 7 was always the same, whereas the sum of the allometrically computed crown projection areas depended on the number of shrubs in the clump (Fig. 7b-d).

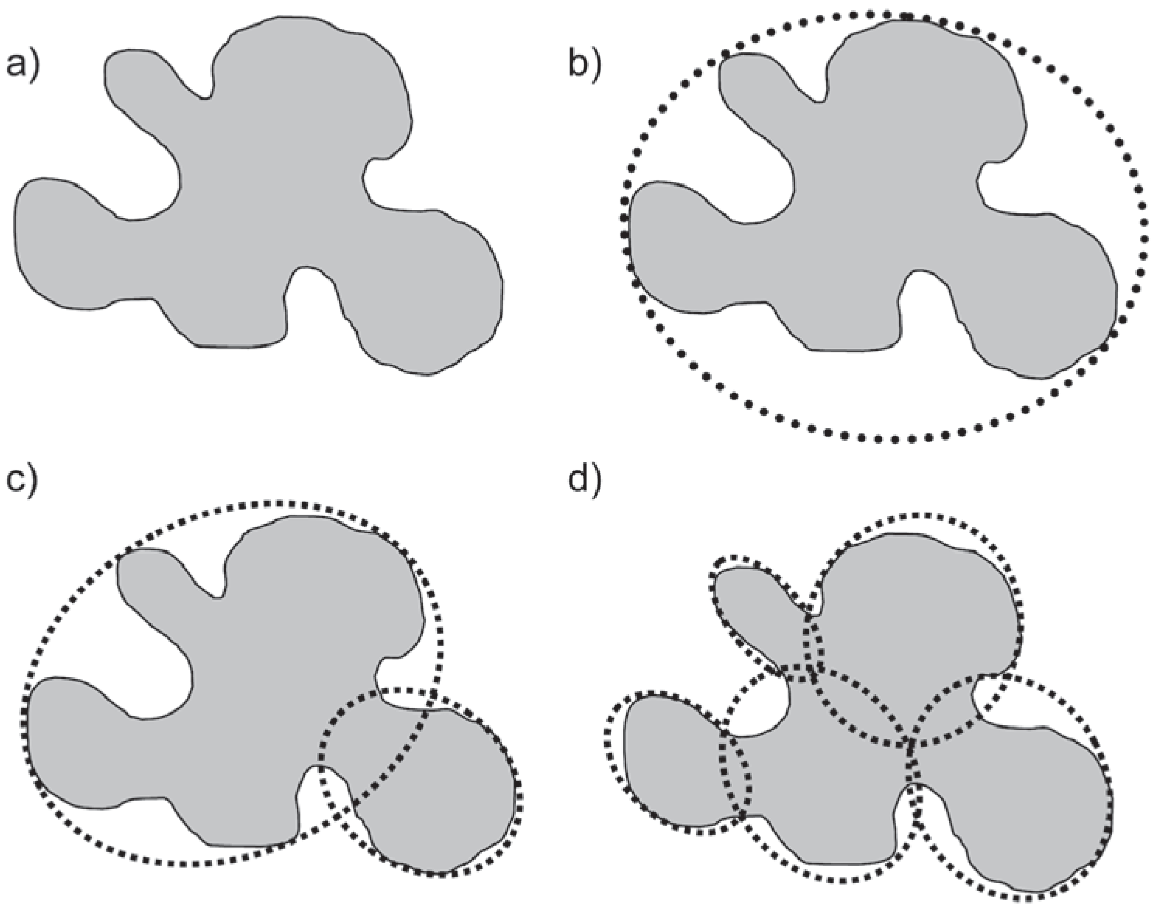


Fig. 7. Differences between GIS-detected shrub canopy area (gray colored) and computed crown projection area (dotted outline), assuming that the shrub consists of a solitary shrub (b), that the shrub consists of a clump of two (c) or five (d) shrubs. Qira oasis, NW China.

Assuming that the ratio between biomass density and crown projection area remained similar (Table 6), it is possible to explain why the biomass density related to the GIS-detected canopy area should be smaller in shrub clumps and densely vegetated areas compared with solitary shrubs. This also explains the overestimation of biomass in the sample squares determined with the GIS-approach and the robustness of the allometric approach. Based on these findings the use of non-linear regression equations in the GIS-based approach is recommended as it takes into account that the biomass density in shrub clumps is lower than in single shrubs. The close agreement between the non-linear GIS-based estimate and the allometric estimate at the field level indicated, that errors of the GIS-based estimate should substantially decrease with increasing field size.

Strong edge effects for the AGB determination in sample squares may be expected because the sample square size of 4 m x 4 m was relatively small in comparison to the individual shrub projection area. These edge effects affected the GIS-based and allometric approaches differently (see Material and Methods section).

The time requirement for the GIS-based AGB estimation depends much on the height from which the aerial photograph is taken and the corresponding quality of the image whereby image quality is a function of resolution (scale) and shading. The useful image resolution also depends on the optical properties of camera equipment, film material and film-scanning device. Therefore larger camera heights may be compensated up to a certain limit (film grain resolution) by a higher scanning resolution. Taking photographs from a higher altitude would allow to keep the scale constant to avoid effects like changing pixel variances (Cao and Lam, 1997) and clumping (Laurini and Thompson, 1999). Shading depends on sun elevation and thus the length of the daily monitoring period around midday.

Further research may be needed to optimize this technique for application in larger areas of interest. As such the methodology should work particularly well in environments with sparse vegetation coverage and dominated by a single photo-synthetically active plant species.

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Agricultural, architectural and archaeological evidence for the role and ecological adaptation of a scattered mountain oasis in Oman

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ABSTRACT

The recent discovery of the monumental 5000 years old tower tombs on top of the up to 1850 m high Shir plateau has raised numerous questions about the economic and infrastructural basis of the agro-pastoral-piscicultural society which likely has constructed them. The scattered oasis settlement of Maqta, situated just below the towers in a rugged desert environment has therefore been studied from 2001 to 2003 to understand its prehistoric and present role along the ancient trade route which connected the inner-Omani Sharqiya across the southern Hajar mountains with the ocean port of Tiwi. Maqta consists of a central area with 59 buildings and 12 scattered temporary settlements comprising a total of about 200 semi-nomadic inhabitants and next to 900 sheep and goats. The 22 small springs with a flow rate between 5 and 1212 l h^{-1} are watering 16 terrace systems totaling 4.5 ha of which 2.9 ha are planted to date palms (*Phoenix dactylifera* L.), 0.4 ha to wheat landraces (*Triticum durum* and *Triticum aestivum*) during the cooler winter months, 0.4 ha are left fallow and 0.8 ha are abandoned. During a pronounced drought period from 2001 to 2003, the springs' flow rate declined between 38% and 72%. Most of the recent buildings of the central housing area were found empty or used as temporary stores by the agro-pastoral population watching their flocks on the surrounding dry mountains. There is no indication that there ever was a settlement older than the present one. A number of Hafit (3100–2700 BC) and Umm an-Nar (2700–2000 BC) tombs just above the central housing area and further along one of the trade routes to the coast are the only indication of an old pastoral land use in Maqta territory where oasis agriculture may have entered only well after 1000 AD. With this little evidence of existence during the 3rd millennium BC, Maqta is unlikely to have played any major role favoring the construction of the nearby monumental Shir tower tombs other than providing water for herders and their flocks, early migrant traders or tower tomb constructors.

1 INTRODUCTION

The Jabal Bani Jabir in the southern Hajar mountain range of northern Oman represents one of the driest climates on earth with a potential evapotranspiration of more than 2500 mm and an average annual precipitation of less than 75 mm. Whereas a companion paper describes the current status and development history of oasis agriculture in a typical composite settlement of the northern Hajar mountains (Nagieb et al., 2004), this study focuses on the ecological adaptation of a scattered agro-pastoral oasis further south. This area is topographically important as the up to 1850 m high Shir plateau divides the coastal zone of the Arabian Sea from the inner-Omani Sharqiya. The extended Shir plateau is also the origin of four major drainage systems, Wadi Tiwi and Wadi Shab to the East, Wadi Bani Khalid to the South, and Wadi Khabbah to the north-west. Given the lower water availability on the western side of the Jabal Bani Jabir compared to their water-rich eastern side (Korn et al., 2004), terraced land is very scarce in the former area. Besides, perennial cultivation of date palm (*Phoenix dactylifera* L.), annual crop production plays a less important role on the eastern side. Similar to the northern Hajar range, the irrigation infrastructure needed for any agricultural production in this area is based on aini-aflaj (sing. falaj) systems, referring to canals that convey water from a spring at the foot of a mountain to agricultural fields. Settlements typically consist of either only semi-nomadic pastoralists or an agro-pastoral community cultivating a number of small and widely scattered terrace systems with a field size between 2 and 160 m^2. Most of these are squeezed between cliffs into rugged mountain escarpments and headed each by a tiny spring. Below the spring, four types of agricultural production are positioned like onion skins. The most water demanding date palms are immediately adjacent to the spring or a water collection basin. These are followed by fields planted to Omani wheat landraces (*Triticum durum* and *Triticum aestivum*; Al-Maskri et al., 2003) during the cooler winter months and left fallow the rest of the year, fields which are used for fodder production and finally terraced fallow plots which are only cropped in years of abundant rainfall. Except for date palms no cultivation occurs during the hot summer months.

Archaeologically important in this region are the so-called ‘tower tombs’ on the top of the Shir plateau (Fig. 1 and Photo 1). They were discovered from the air in 1977, presented to the public in 1991 by Paolo Costa (Yule and Weisgerber, 1996) and published for the first time by Yule (1992). In 1995, these tombs were examined more thoroughly by Yule and Weisgerber (1996, 1998). A total of 59 tombs were registered in an area of several square kilometers and three of them were excavated. Five different building types of tombs were observed which all resembled in form and manner of building graves of the Hafit or Umm an-Nar period (3100–2000 BC; Table 1). However, no finds were discovered to confirm this date. Instead, some pottery sherds were found which were dated to the early Iron Age (1100–600 BC) probably belonging to secondary burials.

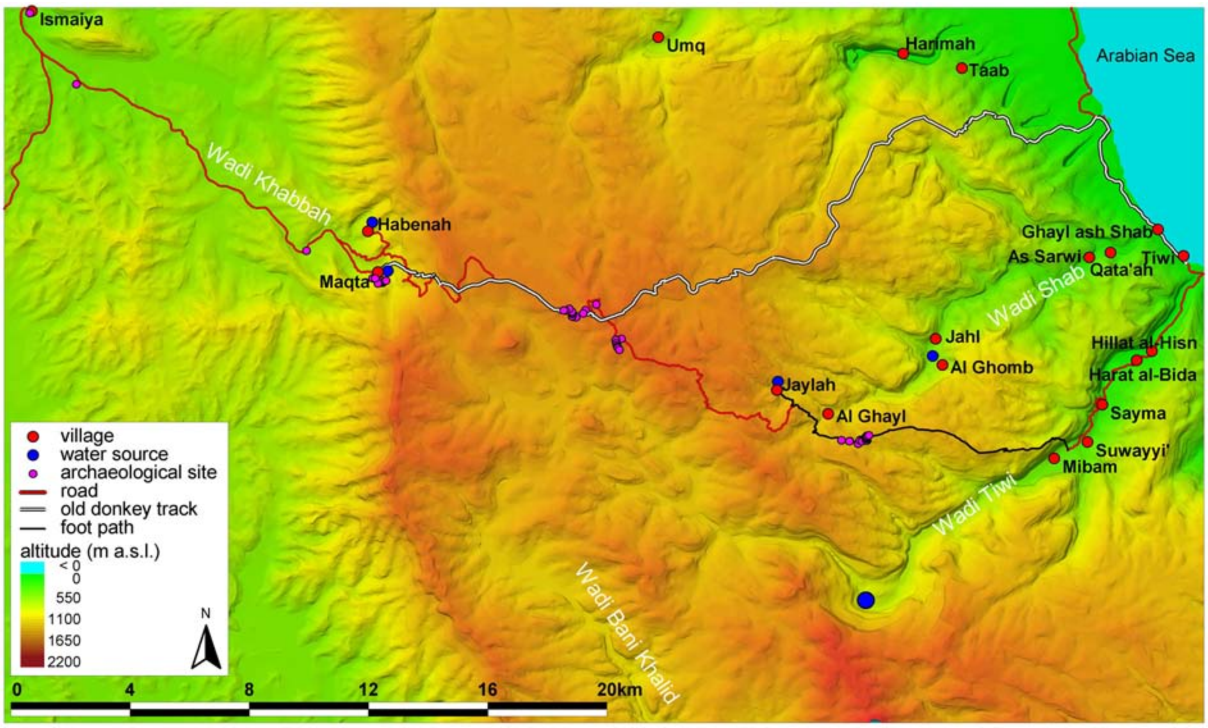

Fig. 1. Three-dimensional map of the study area reaching from the Arabian Sea in the east across the Jabal Bani Jabir mountains of central Oman to the Wadi Khabbah in the West.

Photo 1. Tower tomb Sh1 on the Shir plateau.

Table 1. Archaeological and historic time periods in Oman.

Time period	Duration
Hafit	3100–2700 BC[a]
Umm an-Nar	2700–2000 BC
Wadi Suq	2000–1300 BC
Iron Age I	1300–1100 BC
Iron Age II	1100–600 BC
Iron Age III	600–300 BC
Late Iron Age (Samad)	300 BC–630 AD[b]
Early Islamic	630–1055 AD
Middle Islamic	1055–1500 AD
Late Islamic	1500–1970 AD
Recent	1970–today

[a] Before the birth of Christ.
[b] After the birth of Christ.

In search for a settlement, which belongs to the tombs on the Shir plateau, the mountain oasis of Maqta (Fig. 1) was first surveyed by Yule and Weisgerber (1998) in 1995. During a one day visit they discovered several Hafit tombs (Maqt1, Maqt2), two tombs of unknown date (Maqt3), a 30 m long wall (Maqt4), that was interpreted as an Iron Age fortification, as well as several Iron Age hut tombs and some Umm an-Nar houses (Maqt5) in the sedimentation depression above the settlement of Maqta (Fig. 2).

Following Wadi Khabbah into the direction of the inland, the same group of archaeologists discovered several triliths (Sha1, Sha3), stone alignments of unknown function, and several Hafit-type tombs (Sha2, Sha5, Sha8) at the village of ash-Shariq (Fig. 1). A sherd of a typical bottle of the Samad period (300–900 BC) showed that this area was also used in that period. Not far from ash-Shariq is the oasis of Suma'iyah where the most prominent archaeological site is an early Iron Age (1100–600 BC) fortress on topof the Qarn Suwaich (Ism1). The ruins of houses on artificial terraces are still visible and a lot of very coarse domestic pottery is scattered between them. Some Hafit-type tombs (Ism2) are also visible on the mountain crest ending at the edge of the fortress.

Most archaeological investigations north of the Shir plateau are focused on the coast (Biagi, 1988; Ibrahim and ElMahi, 2000). Only a single survey between ash-Shab and Tiwi as well as in Wadi Tiwi so far considered the hinterland and the likely connection between coast and inland (Fig. 1; Häser and Schreiber, 2003; Schreiber and Häser, 2004; Korn et al., 2004). This survey provided evidence for a continuous occupation of Tiwi from the 5th millennium

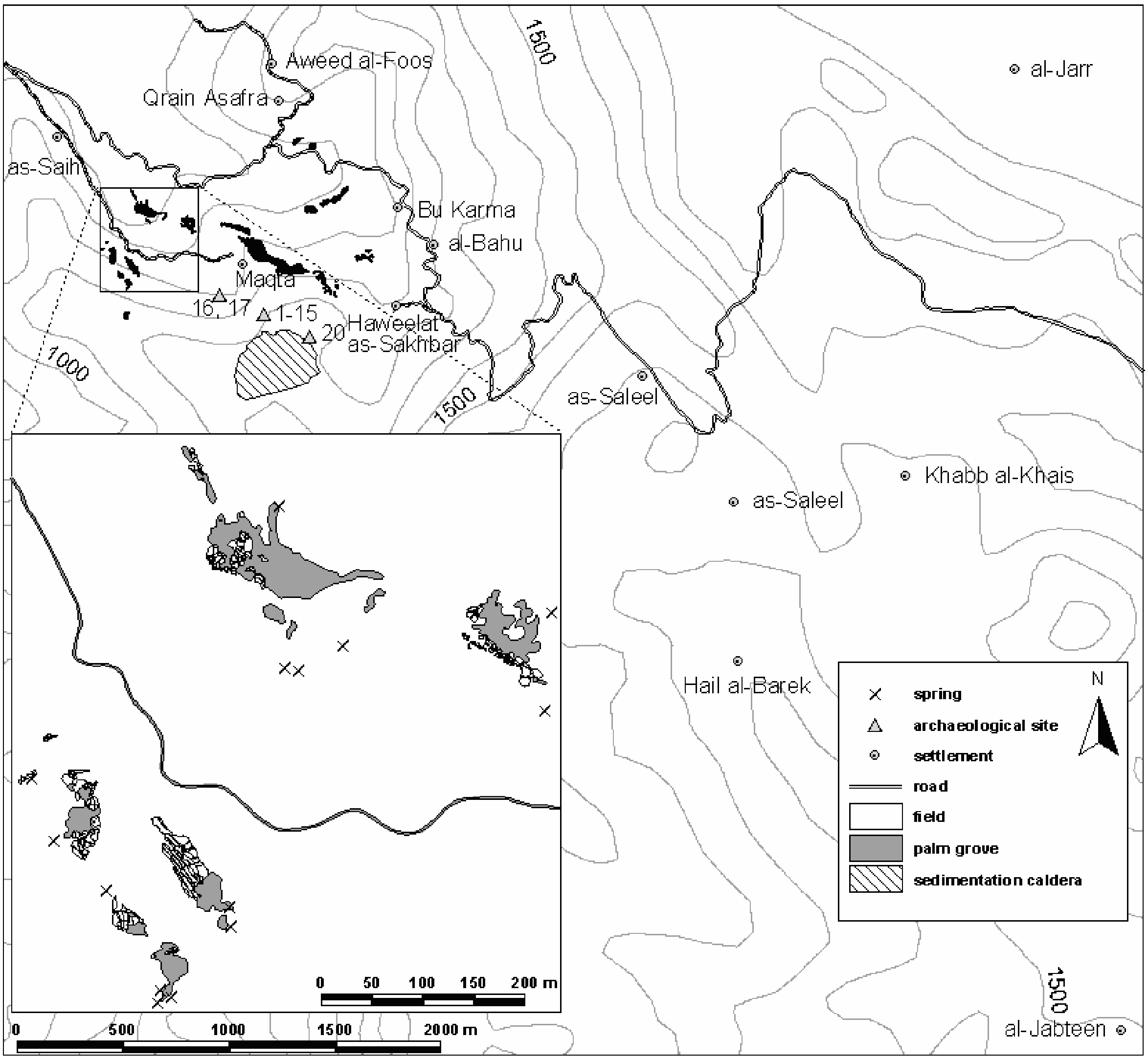

Fig. 2. GIS-based map of the Maqta territory in Oman with the terrace systems, the central housing area, the dispersed settlements, the natural grazing basin and the major archaeological sites.

BC to modern times, whereas Wadi Tiwi was only settled from the 9th/10th century AD to modern times. Nevertheless, the position of Hafit-type tombs on very prominent places along the coast and at the entrance to Wadi Tiwi suggested that they served as markers for inland routes which might have been in existence by the late 4th/early 3rd millennium BC.

This interdisciplinary study between agricultural scientists, archaeologists and orientalists had several goals. Firstly to analyze the agricultural structure of one of the scattered agro-pastoral settlements in the Jabal Bani Jabir as a function of topography and water availability. Secondly to describe the composition of the central housing area and to develop a likely settlement history based on the available archaeological finds. In a larger context this study thirdly aimed at a partial understanding of the role mountain oases in northern Oman may have played as an economic and cultural link between coastal and inland areas.

2 METHODOLOGY

2.1 Experimental area and bio-physical measurements

The study area comprised the agro-pastoral, communal territory of Maqta village in the Wadi Khabbah of the Jabal Bani Jabir mountains of central Oman. This territory is divided into a central village area (59.00° E, 22.83° N; 1050 m a.s.l.) with 73 houses, an agricultural area comprising 16 small terrace systems and 12 scattered temporary settlements within the vast rocky grazing area and inhabited by an agropastoral population which identifies itself as inhabitants of Maqta. The methods used for the agricultural part of the study closely followed those described by Nagieb et al. (2004). First, the topography of the rugged surrounding mountains was digitized from Russian military maps (1:100 000, Joint Stock Company SK-IMPEX, Moscow, Russia) with 40-m altitude lines. Subsequently, all major features governing the territory of Maqta were mapped using a differential Global Positioning System (GPS; Trimble Pathfinder, Sunnyvale, CA, USA) with decimeter precision. Those features comprised the position of all major villages between Maqta and the coastal town of Tiwi, the modern dirt road connecting most villages and the two major, traditional trade routes to the coastal zone of Tiwi and the position of springs on the Jabal Bani Jabir between the Wadi Khabbah and the Arabian Sea. For the territory of Maqta settlements, the terraces systems with their total of 22 springs, the position of date palms (separately for young and adult individuals) and the size of wheat fields cultivated in early 2002 and 2003 were mapped. The position of a major sedimentation depression above Maqta (1160 m a.s.l.; Photo 2) of 500 m x 300 m in size was also entered. It comprised at its northern bench a number of major archaeological features such as tombs and at the eastern end an ancient falaj. The basis of this falaj contained some charcoal that was used for ^{14}C-dating using accelerated mass spectrometry at the Leibniz Laboratory of Age Determination and Isotope Research in Kiel, Germany.

To estimate the agricultural production of the oasis, grain yield and total dry matter of wheat were measured in 10 representative fields and multiplied by the area harvested. Total date palm yield was estimated through farmers’ records for individual trees and multiplied by the total number of adult date palms.

To obtain the amount of water available over time between March 2001 and March 2003, repeated outflow measurements of all springs were taken with a hand operated barrel system. During the entire period no measurable rainfall occurred. The regular occurrence of such droughts in Oman has been confirmed by farmers' oral records and the 110-year weather records from Seeb Airport in Muscat (FAO, 2001). In November 2002 and January 2003, selected springs were also sampled to determine the approximate age of the stored water using its tritium/^{3}helium ratio and concentration of the anthropogenic trace gases sulphurhexafluoride and chlor-fluorcarbohydrates according to methods described in detail by Aeschbach-Hertig et al. (1998) and Beyerle et al. (1999). The purpose of these water measurements in the context of this paper was to compare the 'elasticity' of water flow during the extended period of drought to data from the Balad Seet oasis in the Northern Hajar range. This comparison was meant to provide some indication of the degree of water scarcity one might expect during drought periods and help to explain the likely adaptation strategies to this constraint by the agro-pastoral community. In October 2002, a soil pit was dug into one of the typical terrace soils cropped to wheat and a lacquer peel technique (modified after Hähnel, 1961) was used to prepare a profile (Photo 3).

2.2 Estimation of agricultural production and carrying capacity

In contrast to a similar study in the Northern Oman mountains (Nagieb et al., 2004), only a simplified analysis of the ecological carrying capacity of the Maqta territory was conducted.

Photo 2. Sedimentation depression above Maqta from the North. The white arrow indicates the location of the soil profile taken for pollen analysis.

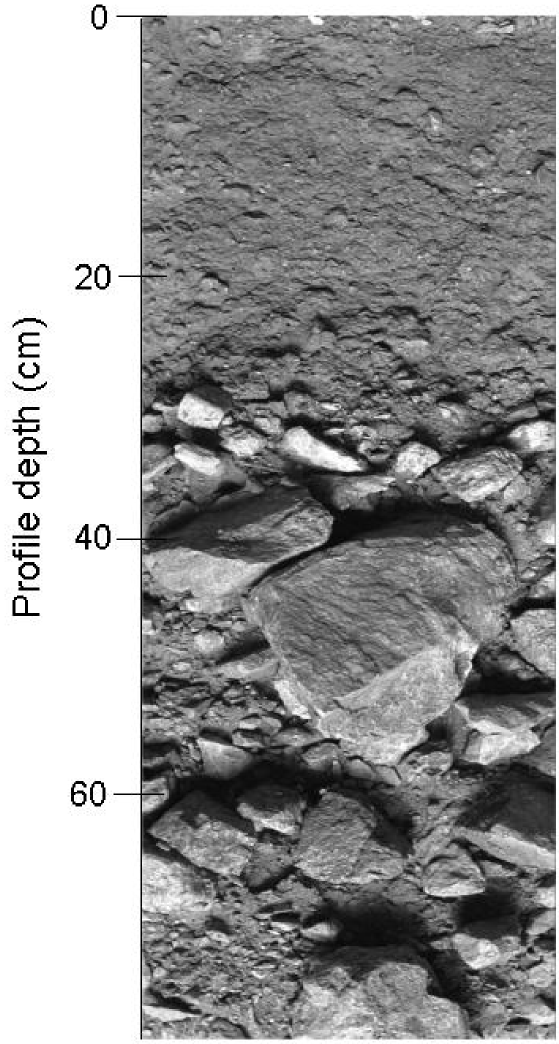

Photo 3. Profile of a typical man-made terrace soil at Maqta (Oman).

Since the road construction in 1985, major amounts of drinking water for humans and animals as well as fodder grasses are being transported regularly into the area. This and government allowances paid to the semi-pastoral farmers living in the Maqta territory has led to a rise of the carrying capacity far beyond that determined by the ecological resource base. The estimation of the traditional ecological carrying capacity was based on a typical drought scenario when the available water is concentrated on the date palm groves and therefore no annual crops are cultivated. Similar to the approach described by Nagieb et al. (2004), the underlying assumptions of the analysis were:

(1) The water outflow of the springs in the Maqta territory during prolonged drought periods is similar to the one measured during 2001–2003.

(2) Date yields and energy levels from today's local palms genotypes are similar to those prior to 1970. Present-day date yield of 25 kg DM tree^{-1} year^{-1} are in close agreement with data reported from Oman prior to modernization (FAO, 2003).

(3) Goats and sheep are fed entirely by natural grazing of the mountain pastures and the meat harvested from the flock is similar to today's conditions.

(4) The energy contained in the dates and meat can be taken from the literature (George, 1987).

To compare the agro-ecological conditions of Maqta territory to those elsewhere in northern Oman, its palm grove area, total size of terraced fields, number of inhabitants and the available water was compared to those of the core oasis of Balad Seet in the northern Hajar mountains and to Wadi Tiwi on the eastern side of the Jabal Bani Jabir.

2.3 Architectural data

The built substance of the central housing area of Maqta was recorded with balloon-based aerial photographs (Buerkert et al., 1996) followed by a ground survey. The vertical images were used to draw a preliminary ground plan of the village that was verified on the ground house by house. Subsequently, the preliminary map was refined by detailed control measures. Notes on building conditions, access, functions and current use of buildings were taken. Additional information on the functions of buildings was gathered through informal interviews with inhabitants.

2.4 Archaeological setting

Given the scattered nature of the settlements, the overall poor find situation and the time available, all data were collected in two one-day surveys conducted by foot. The survey in the surroundings of Maqta was based on aerial photographs (OM81-73-110-190 and OM81-73-110-191 at the scale 1:20 000) taken in 1981 by the National Survey Authority of Oman. The positions of all identified archaeological sites were registered by GPS. The tombs at the edge of the sedimentation depression above Maqta were photographed from a height of about 100 m using the same balloon technique. Also, a group of newly discovered tombs between Mibam and Jaylah was registered, examined and photographed. The already mentioned tombs on the Shir plateau were not the subject of the survey since these have already been described in detail by Yule and Weisgerber (1998). However, they were visited several times to allow typological comparisons. All finds of pottery sherds were classified by ware type, shape and dimension. Subsequently, the sherds were dated according to an existing pottery typology.

3 RESULTS

3.1 Traditional trading infrastructure, bio-physical setting and agricultural carrying capacity

According to local oral records, the probably millenia-old, 40 km long and fully developed donkey trade route from Maqta to Tiwi (Fig. 1) was not only used to regularly exchange wheat from the Sharqiya against dried fish for everyday consumption from the coast but also to import large quantities of dried anchovies (*Engraulidae*). These were reportedly applied as a phosphorus (P) fertilizer annually at a rate of 1–2 kg dry matter per palm tree which at an assumed P concentration of 35 g kg^{-1} would correspond to about 53 g P per year and thus be equivalent to the P uptake of 80 kg dates. The equally ancient footpath between Jaylah and Mibam in contrast seems to have served as a shortcut for personal visits and the transport of minor goods between the extended families divided by the Jabal Bani Jabir mountain range. A recent evidence of these old family ties is the fact that Habaynah, the village next to Maqta on the western side of the Jabal Bani Jabir mountains administratively belongs to the coastal area of Fins on the eastern side of the mountain range north of Tiwi.

In March 2003, the village territory of Maqta comprised approximately 200 agropastoral inhabitants distributed in the central housing area and the 12 scattered settlements. Of the total of 4.5 ha terraced land, 2.9 ha were planted to date palms, in part with an understory production of fodder grasses, 0.4 ha to wheat of the Walidi landrace (Al-Maskri et al., 2003), 0.4 ha were left fallow and 0.8 ha were abandoned. At this moment the outflow of the different springs varied between 5 and 1212 l h^{-1} compared to 18 l h^{-1} (-72%) and 1928 l h^{-1} (-38%) for the same springs two years earlier. The two years of drought had clearly affected the small springs much more than the big ones. During the same period, total spring outflow declined by 46% from 9.0 to 4.8 m^3 h^{-1}, which corresponds to a 2% decline per month (Fig. 4). Water age in the measured springs ranged between 2 and 8 years (Luedeling et al., unpublished). As a response to increasing water scarcity, the total area planted to wheat at Maqta declined from 0.4 ha in early 2001 to less than 0.3 ha two years later (Figs. 3 and 4). As the drought progressed in January and February 2003 even many of the planted plots could not be irrigated to maturity but were harvested just after booting as green fodder (Photo 4).

Across all terrace systems, grain yield of wheat varied from 2.4 to 3.5 t ha^{-1} with a simultaneous total dry matter production of 11.4 to 12.3 t ha^{-1} and little variation as a consequence of decreased water availability. Date yield on the 947 adult palms ranged between 10 and 50 kg per adult tree and manure addition between 10–40 kg per tree for palm groves and 10–15 t ha^{-1} for wheat fields.

Inspection of the vegetation depression after a 20-mm rainfall in April 2003 revealed a strong germination of fodder grasses and a regular pattern of spontaneously growing indigo (*Indigofera tinctoria* L.) on about 0.25 ha whose leaves according to farmers records were used locally as a medical tea and sold as a natural dye. The radiocarbon dating suggested a falaj age of 425 ± 30 years B.P., but it remains unclear whether the falaj was constructed or renovated at this time.

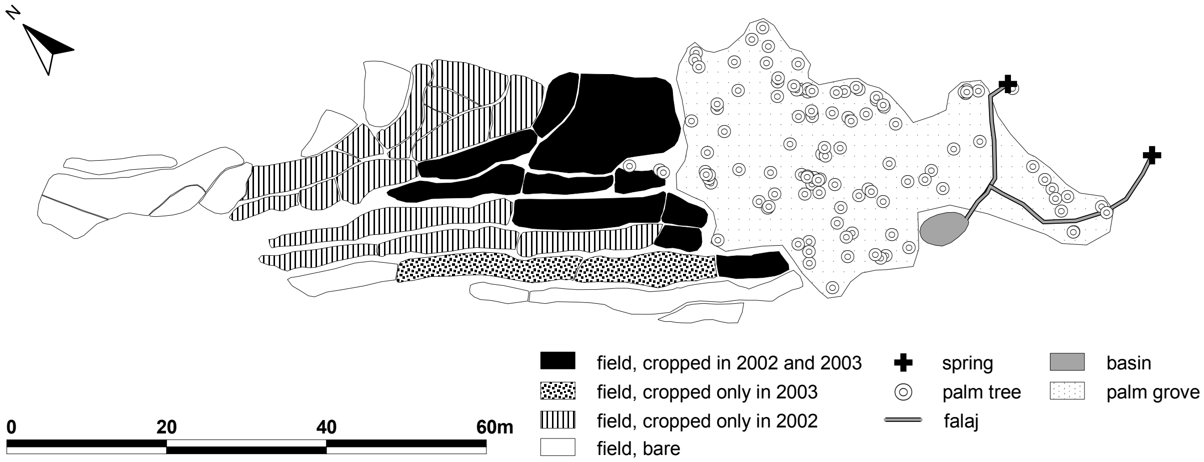

Fig. 3. Map of a typical terrace system (see also Photo 4) of Maqta (Oman) with the spring, position of date palms and the cultivated wheat fields in March 2001 and March 2003 after 2 years of pronounced drought.

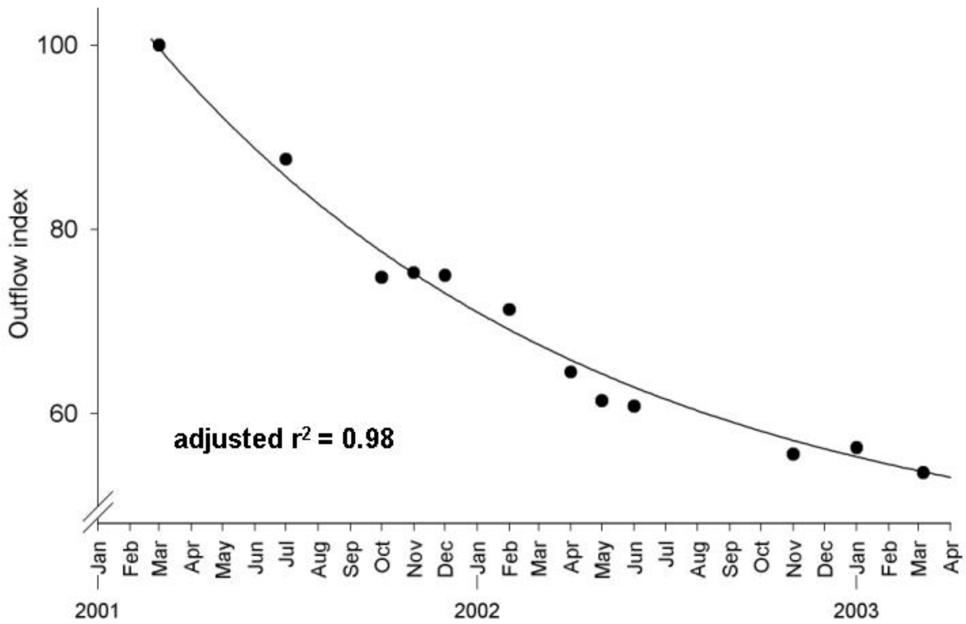

Fig. 4. Total outflow of the 22 springs at Maqta relative to the onset of the measurement period in March 2001. No rainfall was recorded for the 24-month measurement period.

Photo 4. Terrace system at Maqta, Oman (see also Fig. 3) with date palms near the spring (left) and fields planted to winter wheat further right. After a two-year drought, half of the land has been left fallow due to water scarcity. The white arrow indicates a wheat plot which due to water scarcity was cut prematurely as fodder.

Table 2. Estimated carrying capacity of the scattered mountain oasis of Maqta (Oman) during a drought period[a].

Agricultural resources and their use	
Number of adult date palms	947
Average date palm yield (kg (tree x yr) $^{-1}$)	25
Total date harvest (kg yr^{-1})	23 675
Energy content dates (kJ kg^{-1})	6530
Total energy from dates (MJ)	154 750
Energy demand per inhabitant (kJ (head x day) $^{-1}$)	7 530
Number of adult inhabitants living from dates	*56*
Number of small ruminants[b]	900
Fraction of animals slaughtered per year	0.4
Energy content meat (kJ kg^{-1})	8360
Meat per slaughtered animal (kg $head^{-1}$)	15
Total energy from meat (MJ yr^{-1})	45 140
Number of adult inhabitants living from meat	*16*

[a] During a pronounced drought period all water is used to irrigate the palm groves and no annual crops are cultivated.
[b] Number of goats and sheep kept with current levels of feed supplementation in the Maqta territory. The number of heads under traditional animal husbandry without such levels of external inputs is unknown but should have been substantially lower.

The calculations of the ecological carrying capacity of the Maqta territory prior to the advent of modern external subsidies indicated that the equivalent of a maximum of 72 adults may have been able to live there from agriculture. For these date production was energy wise much more important than herding on the marginal pastures (Table 2). The comparison of the

Table 3. Comparison of natural resources and inhabitants in the scattered oasis of Maqta, the core oasis of Balad Seet and the water-rich valley oasis of Wadi Tiwi in Northern Oman.

Natural resource	Maqta	Balad Seet	Wadi Tiwi	Wadi Tiwi & Tiwi
Palm grove area (ha)	2.9	8.8	107.0	128.2
Terraced fields (ha)	1.6	4.6	0	3.3
Available water ($m^3\ d^{-1}$)	115	601	10 000	10 000
Number of inhabitants[a]	200	650	695	2884
Average agricultural area per inhabitant (m^2)	225	207	1540	456
Fraction of palm grove area	0.64	0.66	1.00	0.98
Cropping intensity[b] in 2002/2003	0.66	0.85	1.00	1.00
Available water per inhabitant ($l\ d^{-1}$)	575	925	14 388	3467

[a] Total population in 2003 comprising adults and children
[b] Agriculturally active area / total agricultural area

natural resources of Maqta with the core oasis of Balad Seet and Wadi Tiwi confirmed the marginal status of the former. It was governed by a per capita water availability which at Maqta was only 4% and an agricultural area that was only 15% of that at Wadi Tiwi (Table 3). At a similar amount of agricultural land per inhabitant, Balad Seet had almost twice as much water as Maqta.

3.2 Architectural structure

The central housing area of Maqta has a rather unified structure with respect to coherence of the built area, building types and building techniques. However, there are clear differentiations in each category that allow consistent conclusions about the recent development of the settlement. The overall situation of Maqta within a mountain slope facing north-west implies a rise in ground level of about 10m from the open square where the road from Suma'iyah terminates (Fig. 5, between 1 and 2), to the eastern end of the village (24). Some houses are built on a level some meters further up (30–37). The steepest parts of the ascent, marked by the steps between (9) and (18), and south of (6) and (7), form the ramp to the terrace on which the core of the village is placed (Photo 5). The area adjacent to the village to the north, still flat but strewn with large rocks, is occupied by near-circular animal pens.

A clear differentiation can be made between the clustered houses in the eastern part, and the loose structure in the western half of the built area of Maqta. The agglutination of single room units to larger structures with a relatively closed front seems to be typical of the traditional core of the village. Passages between the structures are usually narrow; open spaces between the buildings are rare and not larger than 8 m x 8 m. Access to some rooms is apparently only possible through others. As a contrast, buildings in the western part of Maqta are clearly separated from each other and widely spaced. Larger houses have a walled courtyard from which each room is directly accessible.

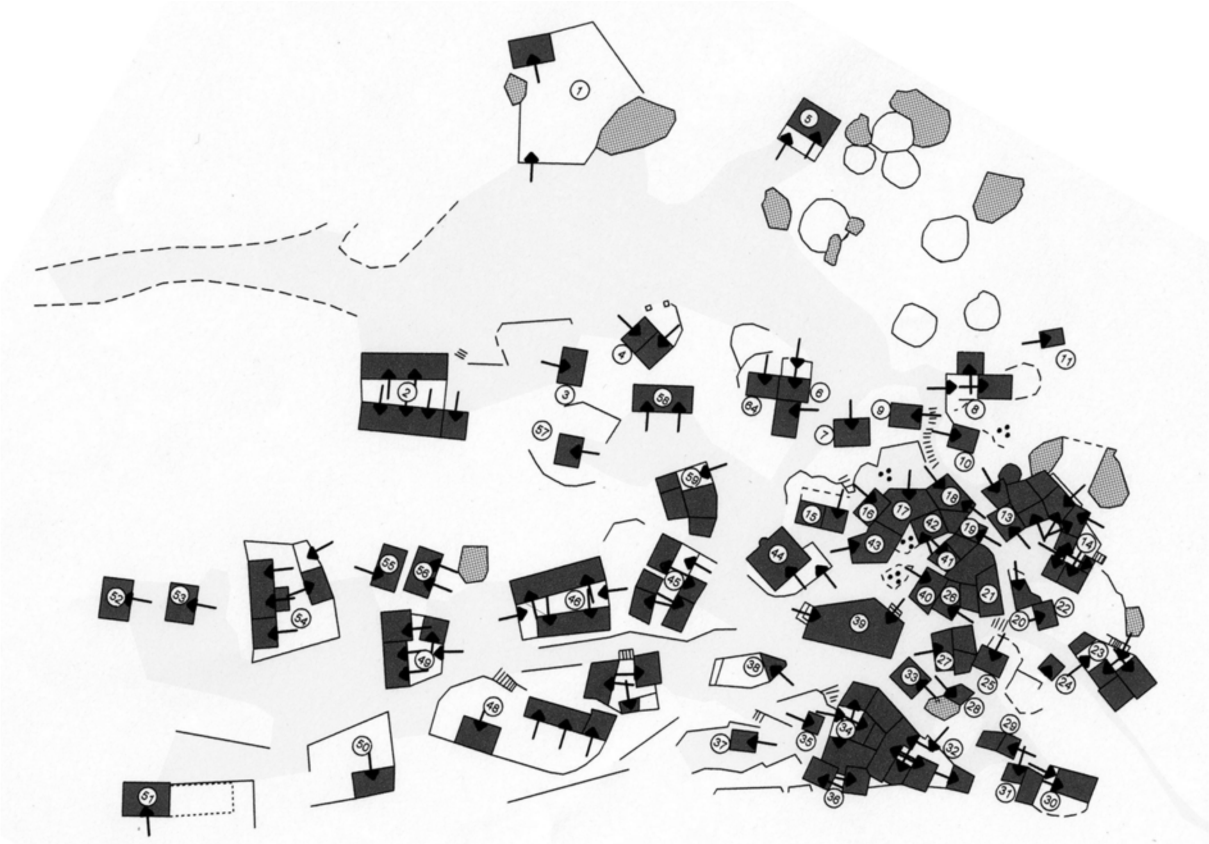

Fig. 5. General plan of the central housing area of Maqta (Oman) with arrows indicating the access to the respective building.

Photo 5. Eastern half of the central housing area of Maqta from NW.

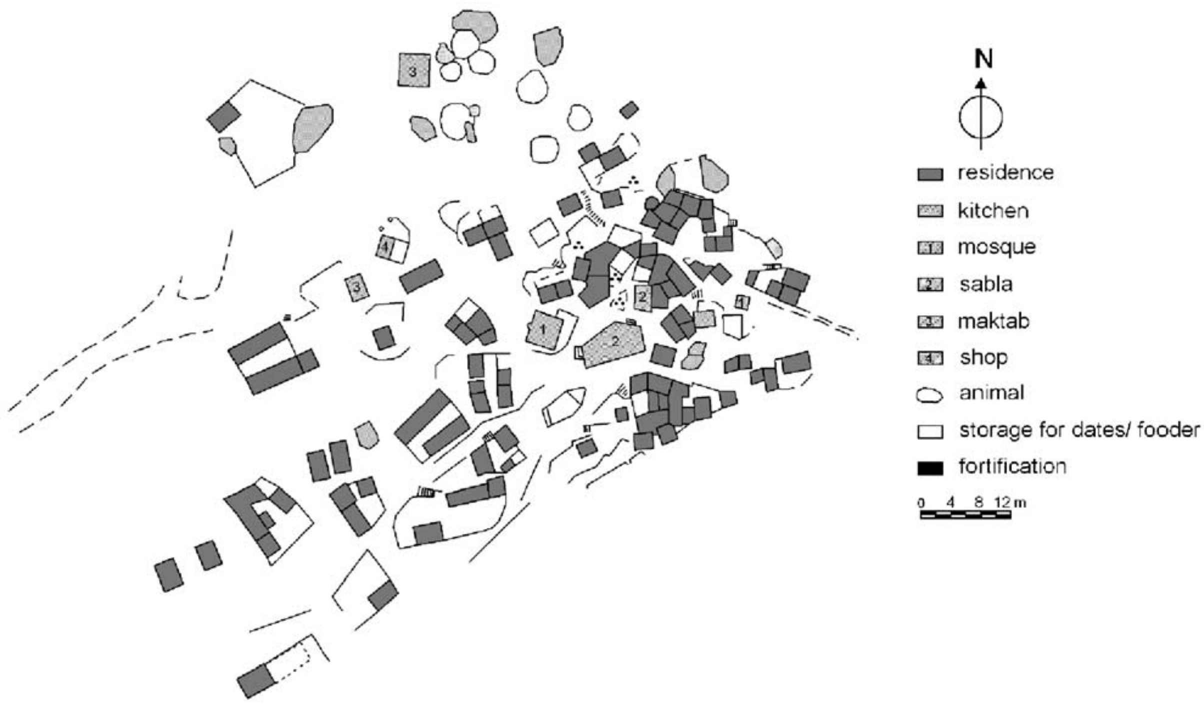

Fig. 6. Plan showing the functions of buildings in the central housing area of Maqta, Oman.

While the majority of houses is built on a rectangular plan—the model structure is a single room with the door as the sole opening in the longer side—some houses in the eastern part of Maqta are built on an irregular plan, due to their clustering in a restricted area. Walls are built of rubble and mortar, slightly battered, and in some cases plastered and whitewashed. All buildings are single-storey. A cornice made of a horizontal layer of flat stones prevents the water from seeping down the walls. The flat roofs are constructed with beams and layers of mud and pebbles. Cement mortar and cement plastering can be observed on recent buildings, particularly in the western half of the village, whereas no cinder blocks were found yet.

The eastern part of Maqta shows a certain functional variety (Fig. 6). Here, the two mosques of the village are located. A small masjid (24) marks the entrance of the path from the east, whereas the main mosque (44) occupies a central position, easily accessible from both parts of the village, and next to the roofed place for receptions and gatherings of the men (sabla, 39). The closed winter sabla (40) is located on the same square. Further to the north, a watchtower emerges from a cluster of houses (13), offering a view on both paths leading up or down the valley. Some of the rooms of the central cluster (as well as some freestanding buildings) are used as storerooms for dates. No external features mark them off from the residential rooms next door; they could very well have been built as dwellings and then turned

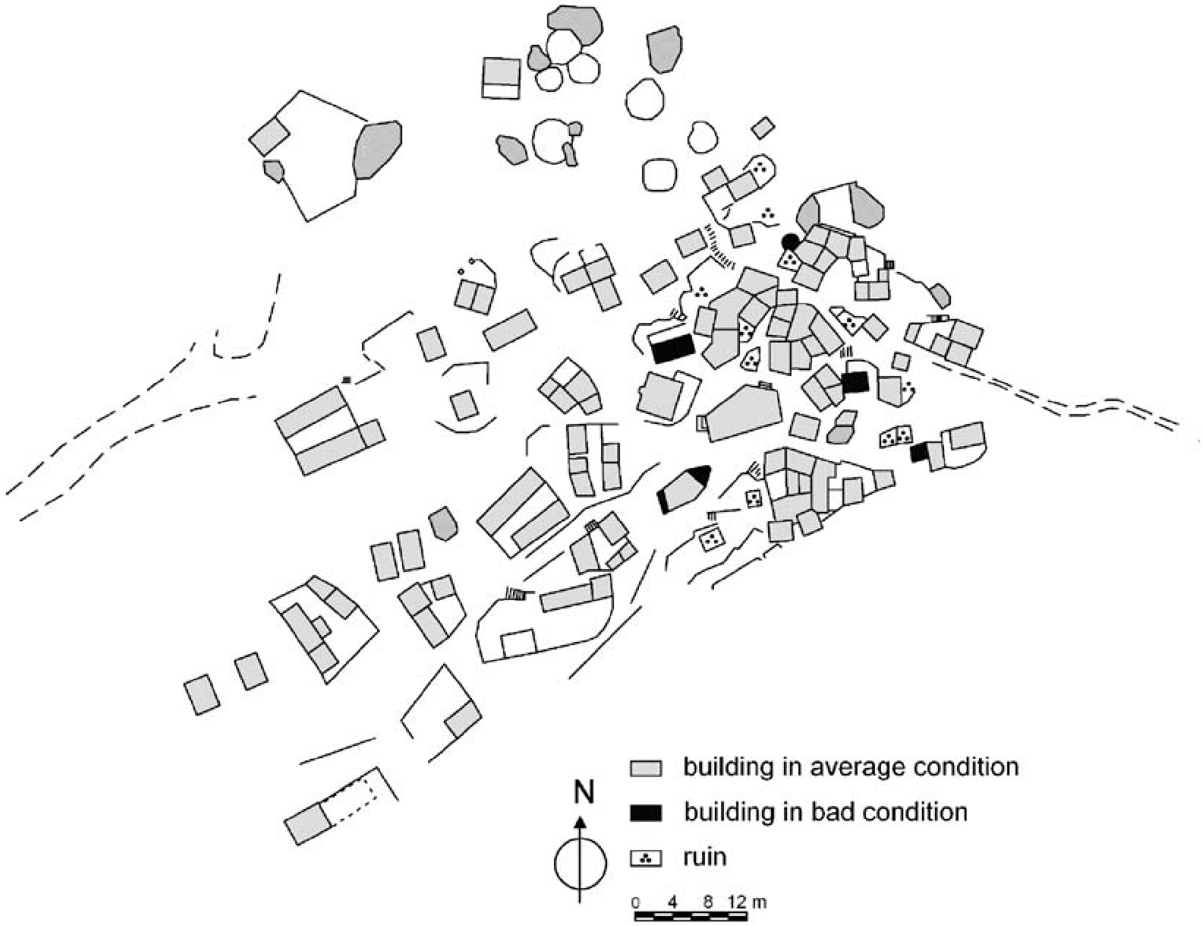

Fig. 7. Plan showing the building conditions of the central housing area of Maqta, Oman.

into their present function in the recent expansive phase of the village. Other buildings are unoccupied and in a state of decay; some are even completely ruined (Fig. 7).

On the wide square which forms the entrance to Maqta from the direction of Suma'iyah, two buildings (3 and 5) are identified as school (maktab) and the teacher's residence, reportedly built by a private foundation. A shop on the square (4) is presently unoccupied. The general impression of emptiness or depopulation in Maqta is explained by the fact that about half of the houses belong to shepherds who dwell in the mountains for days and weeks.

3.3 Archaeological setting

The survey in the surroundings of Maqta did not provide evidence of any settlement older than the existing one. In particular, no traces of the early Iron Age fortress dated by Yule and Weisgerber (1998) without any pottery finds were detected. However, there were numerous remains of burial places from different periods. Two Hafit-type tombs (Maq16 and Maq17), even without finds clearly recognizable by their outstanding position and their building technique, were detected on the slope at the south side of the road at the entrance to the central housing area of Maqta. They are probably identical to Maqt1 of the survey by Yule and Weisgerber (1998). Another Hafit-type tomb (Maq18) is visible on the southern crest of the sedimentation depression above the central housing area of Maqta.

Just below the Hafit tombs at the edge of the depression, there are also some Umm an-Nar tombs (Photo 6) which were described as houses from the same period (Maqt5) by Yule and Weisgerber (1998). The round building Maq3 is constructed with large boulders and an entrance to the south-west. In the center of the building traces of a compartment wall running north-east–south-west are visible which indicates that this building was a tomb rather than a house. The same is true for Maq14 which presumably originally had several chambers. Its southern part is heavily destroyed and it is possible that it was used for burials during later time periods. The constructions Maq4–Maq6, and Maq8 are ringwalls with inserted or attached walls. Due to the pottery found in their surroundings it is very probable that they were originally Umm an-Nar tombs and later used for secondary burials. In the Islamic period they may have been used as foundations for houses. A small Islamic cemetery (Maq2) is situated about 50 m south of the prehistoric tombs. An oval tomb of a double wall of stones and an inner filling of small stones is located between the Islamic graves (Maq1). Such tombs appear frequently on Islamic cemeteries to emphasize the position of a high ranking person. However, on the cemetery there were scattered several early Iron Age sherds which may point to its interpretation as an early Iron Age tomb. Inside the modern settlement no prehistoric or early and middle Islamic pottery was found. Even on the rubbish dump—a very promising location for archaeological finds in most of the Omani oases—no prehistoric pottery was identified.

In spring 2003 about 20 km south-east of Maqta along the traditional footpath between Jaylah and Mibam 15 new Hafit-type tombs (Jay1–8, Jay12, Jay13, Jay15–19, Jay21) were discovered (Photo 7), however, there are likely more in the surroundings. The largest one, Jay6, has a diameter of 7.5 m and a height of 2.5 m. Jay16 is the best preserved one with only one cap stone missing. It measures 4.9 m in diameter and 2.5 m in height. The other tombs are more or less dilapidated with some being used for later burials. Two very demolished cist graves or wolf traps were also found (Jay14, Jay22). Close to construction Jay14 a sherd of the late Iron Age (300 BC–900 AD) was discovered which might prove the use of one or more of these buildings during that period. Jay9–Jay11 were round constructions with a

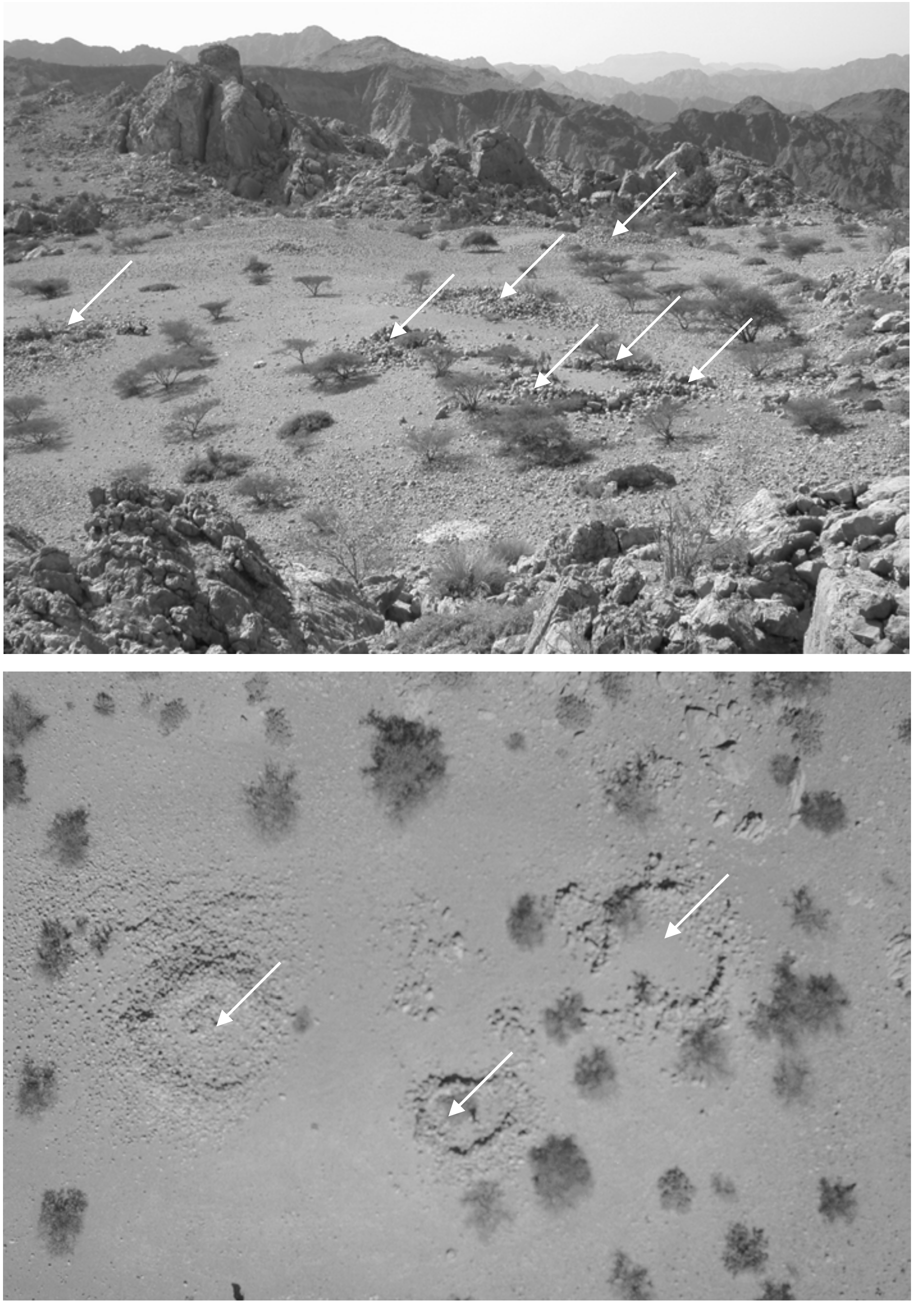

Photo 6. Dilapidated and re-used Umm an-Nar tombs (marked by white arrows) in the sedimentation depression above the oasis of Maqta (above). Aerial view of the dilapidated and re-used Umm an-Nar tombs (marked by white arrows) in the sedimentation caldera above the oasis of Maqta (below).

this assumption. Jay20 is a 1.2 m high construction built of a double-corbelled wall of which the upper part is not closed. Probably, this was also a Hafit tomb, and the outer walls were robbed. A small Islamic cemetery is situated close to Jay7. Reportedly, there also are tombs on the mountain crest above Jaylah; however, their type and position could not be examined. Finally, a series of Hafit-type tombs are situated on prominent locations along Wadi Khabbah that connect the Shir plateau with the inland oasis of ash-Shariq and Suma’iyah.

4 DISCUSSION

4.1 Bio-physical setting and agricultural adaptation

The extensive network of trade routes probably originating at the ancient, major town of Ibra in the inner-Omani Sharqiya, passing through Suma'iyah and crossing the steep Jab al Bani Jabir towards the port of Tiwi via Maqta underlines the important role the latter village had for inter-ecoregional trade in both directions. This is also reflected by the tribal ties which the inhabitants of Maqta claim to have with the coast rather than the Sharqiya. Beyond that the genetic structure of the traditional wheat germplasm (*T. durum*, *T. aestivum* and *T. dicoccon*) collected within the Maqta territory and the lower Wadi Khabbah area seems to bear testimony of ancient trade relationships with the Middle East, central Asia and the Indian subcontinent (Al-Maskri et al., 2003; Hammer et al., 2004; Zhang et al., unpublished). In this context Omani mountain oases, even as marginal as Maqta, could well have played the role of hidden refugia for regional gene fluxes that came with trade goods along the coast of the Arabian Sea.

Maqta's role on this trade route was most likely built on its precious supply of water which, however, was much less abundant than that determined in Wadi Tiwi on the eastern side of the Shir plateau (Korn et al., 2004) or in oasis systems of the Wadi Bani Awf a watershed on the northern side of the Hajar range of the Jabal Akhdar mountains (Nagieb et al., 2004). The latter systems not only had a larger but also a more consistent flow of spring water during the same drought period which, as indicated by a higher water age, was most likely caused by a larger size of the reservoir in the calcareous bedrock.

Given the scarcity of water in the extremely rugged environment, the agro-pastoral inhabitants of the Maqta territory had to use even minor springs with a flow rate between 5 and 20 l h^{-1} dug into small escarpments around which only a few terraces could be built. The ecological setting and the related need for a high reliance on seminomadic herding of small ruminants led to a 'scattered type' rather than a 'core type' of settlement and to the combined cultivation of date palms with wheat. The comparative studies in water-rich environments such as in Wadi Tiwi or the Wadi Bani Awf (Table 3; Korn et al., 2004; Nagieb et al., 2004) provide evidence for the severeness of water scarcity at Maqta even within Oman. In a wider sense, the data also indicate that the more predictable the water availability, the more farmers can rely on perennial date palm cultivation or the combination of date palms and winter plus summer crops. For the inhabitants of Maqta instead, the area dedicated to wheat each year was a function of the springs' flow rate at the onset of the season in fall and the rainfall obtained during the subsequent winter. The data collected in the context of this study show that poor winter rainfall leads to a progressive conversion of wheat fields into areas used for green fodder. First physiological trials under controlled conditions indicated a surprisingly large drought tolerance of the wheat landrace used. This was expressed by its, compared to material from Mongolia and Pakistan, pronounced ability to resume shoot growth once the drought stress is relieved. Wheat yields at Maqta were about half of those measured at Balad Seet which reflects besides the effects of water scarcity mainly the consequences of the very shallow soils (Photo 3) compared to a profile depth of up to 1.3 m at Balad Seet. For both sites, however, sustainable agricultural production requires the availability of high quality irrigation water from springs, the maintenance of low salt levels in the soil profile by appropriate leaching and the regular application of animal manure to offset the high turnover of organic carbon (Luedeling et al., 2005; Wichern et al., 2004). The apparently recent efforts of production intensification on the sedimentation depression by temporary irrigation and subsequent cultivation of indigo correspond to the recent development of the housing area. They may thus reflect relatively modern efforts of the agropastoralists of the Maqta territory to avoid the consequences of living in a very marginal environment by increasing their income from a flexible mode of agriculture rather than relying on only their herds. The rather late—compared to other oases in northern Oman—introduction of oasis agriculture around Maqta was also indicated by the results of radiocarbon-dated pollen diagrams obtained from the sedimentation depression above the central housing area. According to these the occurrence of *P. dactylifera* pollen started only sometime after 1500 AD (Urban and Buerkert, unpublished). Interestingly, this was only little before, as shown by the radiocarbon dating of its sarooj cement, the falaj in the sedimentation depression was built, suggesting an intensification of irrigation agriculture.

4.2 Architecture

The structure of the village as well as the distribution of building types clearly indicate that the eastern part of Maqta's central housing area is the traditional core from which the village has grown. Differences in building type and construction technique provide evidence that the western half of the village is of relatively recent date. The area west of the old core offers free space with a relatively low slope, which can be easily terraced through retaining walls. A few houses at the eastern margin of the village (23, 30, 31) are also of recent construction and seem to form an eastern extension of the settlement on the few spots on the steep slope where buildings can be established. Apparently, expansion to hitherto little used ground has made it possible for some inhabitants of Maqta to leave the central housing area. This might explain the rededication of centrally located houses as storage buildings. A future expansion of this area would only be practicable to the west, but will be generally hampered by the rugged topography.

4.3 Archaeology

The results of the survey in the surroundings of Maqta strongly suggest that there was no permanent settlement in the village territory until the late Islamic period. This likely reflects the relative unreliability of the spring outflow in an environment with reportedly up to 7 years of drought.

This distinguishes the scattered oasis of Maqta considerably from the core oasis of Balad Seet in the northern Hajar mountains where the springs provided abundant water even after a prolonged period of drought and where thus likely the cause for a continued settlement since the early Iron Age (1000–600 BC) (Häser, 2000, 2003; Nagieb et al., 2004).

Nevertheless Maqta was, together with Habaynah, Jaylah and Al Ghayl, one of the very few places on the Shir plateau where water was available year-round. This should have been attractive to pastoralists at least since the late 4th or early 3rd millennium BC. An additional reason which may have made the Maqta territory attractive to a semi-nomadic population was the sedimentation depression above the central housing area which as in modern times has provided decent grazing conditions to small ruminants and donkeys for a few weeks after one of the scarce but heavy rainfall events. Even though the scarceness of tombs in its proximity indicates, that Maqta remained an inhospitable environment.

It is thus unlikely that Maqta has played a major role as an oasis settlement for a sedentary or larger pastoral population during the 3rd millennium BC when the famous tower tombs and the Hafit-type tombs were built on top of the Shir plateau and as indicated by the few climate records available for this period the vegetation was very much alike today's (Urban and Buerkert, unpublished). These structures could be markers for main trading routes between the coast and the inland. This interpretation is strengthened by the recently discovered tombs at Tiwi, those between Mibam and Jaylah and those at Jaylah itself. They find their counterparts on the south-eastern side of the Hajar mountains along Wadi Khabbah, at Suma'iyah and at Ibra.

These occurrences of Hafit-type tombs along major routes is not singular in this region but a recurrent phenomenon all over the Arabian Peninsula. This shows that the Hafit-type tombs on the Shir plateau are part of a network and as such are not that exceptional as postulated when they were first discovered. Nevertheless, the tower tombs have to been regarded as rather special, since for the time being they have no real comparison. Additionally to their use as graves and possibly as signs for trading and pastoral routes, they could well have been monumental markers indicating the occurrence of four water-rich wadis in a xeric environment. However, until a complete ground survey of the surrounding mountains has been completed, this function will remain somewhat speculative as it is more likely to discover tower tombs near settlements or trade routes than elsewhere. A former ritual function of these tombs for people living in the catchment area of the wadis cannot be excluded either.

5 CONCLUSIONS

As a scattered agro-pastoral settlement with a recently built central housing area, a large number of tiny terrace systems cultivated with date palms and a flexible area of wheat irrigated for a few months, the Maqta territory represents an extreme case of human adaptation to a xeric mountain environment in Northern Oman. Compared to other oasis systems in the Hajar range, at Maqta agriculture based on the use of aini-aflaj-conveyed spring water may have been developed only after 1500 AD and thus be relatively recent. Nevertheless, the permanent availability of spring water in this life-threatening desert should always have made Maqta an important resting place for nomads and their herds. As such, its existence also must have been instrumental in developing the millennia-old network of trade and pastoral routes from the Omani coast to the inland which gave rise to the tower tombs on top of the Shir plateau whose mysterious, possibly multiple role remains to be unravelled.

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Water Resources Research: submitted

3

Climate and irrigation water use of a mountain oasis in northern Oman

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ABSTRACT

The apparent sustainability of the millennia-old mountain oases of northern Oman has recently received considerable attention. However, little is known about crop growth and water use efficiency of these systems. To fill this gap evapotranspiration and water use indices were modeled for nine field crops and date palm (*Phoenix dactylifera* L.) at Balad Seet, a typical oasis in the Northern Omani Hajar range, whose agricultural area is composed of 8.8 ha of palm groves with 2690 date palms and 4.6 ha of land under field crops. Climatic data were derived from a weather station located in the oasis. The use of a digital elevation model (DEM) allowed estimating the shading effect of the surrounding mountains on evapotranspiration. When removing the site-specific effects of altitude and shading by surrounding mountains, reference evapotranspiration increased from 1778 mm yr^{-1} to 2393 mm yr^{-1}. Total crop water requirements of the oasis were modeled at 194 190 m^3 yr^{-1} while measured available water resources from spring outflow and precipitation amounted to 245 668 m^3 yr^{-1}. An irrigation water use efficiency of 0.75 at the oasis level provides evidence for an efficient water use of these ancient land use systems.

1 INTRODUCTION

In 2002, the cultivated area in the Sultanate of Oman only amounted to 73 500 ha, representing about 2.4% of the total geographical area of the country. Of these about 42 000 ha produced fruits (mainly dates, *Phoenix dactylifera* L.), while the remaining area was used to grow vegetables, the fodder crops Rhodes grass (*Chloris gayana*) and alfalfa (*Medicago sativa* L.) and a range of other field crops (Ministry of National Economy, 2004). At an average annual rainfall of about 100 mm yr^{-1} with extremes of 300 mm yr^{-1} in the northern mountains and 55 mm yr^{-1} in the central part of Oman (Shahalam, 2001) and a potential evapotranspiration rate of more than 2000 mm yr^{-1} (FAO, 2001a) the country's agriculture depends completely on irrigation. The large climatic water deficit on agricultural land and the increase of cultivated area from about 20 000 ha in 1961 (FAO, 2005) to over 70 000 ha since the beginning of the 1990s (Ministry of National Economy, 2004) led to an increased consumption of irrigation water which represents about 94% of the total water use of the country (FAO, 1997). Several authors claim that at the country level water use now exceeds the long-term recharge (Omezzine et al., 1998; Al-Ajmi and Abdel-Rahman, 2001; FAO, 1997). Consequences are a decline of ground water tables and saline water intrusion into aquifers of the Batinah and Salalah costal plains (Omezzine et al., 1998; Victor and Al-Farsi, 2001; Weyhenmeyer et al., 2002).

The reported salinity problems, particularly in the intensively cropped Batinah coastal plain, and the ongoing rapid change and development of the country (Peterson, 2004) stimulated scientists and government to study the water sector in more detail, in particular the balance between water availability and consumption to ensure a more sustainable use of the country's water resources (Abdel-Rahman and Abdel-Magid, 1993; Omezzine et al., 1998; Al-Ismaily and Probert, 1998; Al-Ajmi and Abdel-Rahman, 2001). While an increasing part of domestic and industrial water demand can be satisfied by water produced in desalination plants and while treated waste water can be used to water trees along the roads (FAO, 1997), agricultural water use in the Batinah district depends on pumping of groundwater from wells (Al-Ismaily and Probert, 1998). Total water consumption in this district was estimated at 766 Mio m^3 yr^{-1} and thus 190 Mio m^3 yr^{-1} larger than the groundwater recharge (Ministry of Water Resources, 1993). Ground water recharge could be increased by establishing additional recharge dams, which lower surface runoff after the rare flood events and allow about 75 – 80% of the captured volume to enter the groundwater body (Al-Ajmi and Abdel-Rahman, 2001). There also still is large potential to increase agricultural water use efficiency (Al-Lawati and Esechie, 2002; Omezzine and Zaibet, 1998). Another option to save water may be to reduce the cultivated area in the Batinah plain and to replace the corresponding irrigation water demand by 'virtual water' imported via food trade (Hoekstra et al., 2005).

In contrast to modern day's water resources overuse in the coastal plain, land use in traditional Omani mountain oases has been considered sustainable given their millennia-old existence (Nagieb et al., 2004). In mountain oases, only a minor proportion of the water supply comes from wells, whereas the major part is provided by channel systems called Aflaj (singular Falaj). Three main types of Aflaj can be distinguished (Al-Ismaily and Probert, 1998): Dawudi Aflaj are fed from a mother well from which tunnels convey the water to the surface and finally to the fields. In the Ghayli Aflaj system water is taken from the sediments of a wadi (valley), captured in depressions and transported in channels to the point of use. Finally Ayni Aflaj are directly fed from springs. Common to these systems is that their water flow is natural and once established, does not need any direct energy input (Shahalam, 2001). The system is thus self-regulating and avoids an overuse of the water body (Al-Ismaily and Probert, 1998). More than 4000 Aflaj exist in the Sultanate of Oman supplying about 33% of the country's water demand (Shahalam, 2001).

The functioning of Aflaj systems, its organization and the scheduling of water distribution is well documented (Al-Ghafri et al., 2001; Shahalam, 2001; Al-Marshudi, 2001; Abdel-Rahman and Omezzine, 1996; Wilkinson, 1977). However, little is known about irrigation water use efficiency in traditional mountain oases. The average efficiency of surface irrigation methods as used in the Aflaj-driven mountain oases was estimated at 60% by Oman's Ministry of Agriculture and Fisheries (MAF), whereas the efficiency of modern irrigation methods reportedly reaches 85%. Therefore the ministry supports the conversion of the traditional systems to modern irrigation methods by subsidies (Al-Ajmi and Abdel-Rahman, 2001). However, in his study of irrigation demand / supply ratios of six farm plots under traditional flood irrigation at Falaj Hageer in Wadi Bani Kharus Norman et al. (1997) found efficiencies between 0.60 and 0.98 with a mean of 0.79.

In view of this contrasting information about the water use efficiencies of traditional oasis agriculture in Oman, the objective of this study was to model crop water requirements for the oasis of Balad Seet and to compute irrigation water use efficiency by comparing modelled crop evapotranspiration to measured water use. To this end the effect of site-specific conditions such as altitude and topography on crop evapotranspiration needed quantification.

2 MATERIALS AND METHODS

2.1 Study site

The research was carried out at the mountain oasis of Balad Seet (23.19° N; 57.39° E; 996 m a.s.l.) situated at the upper end of the Wadi Bani Awf, a watershed on the northern side of the Hajar range of the Jabal Akhdar mountains. The oasis is situated at the foot of a 1000 m high cliff and surrounded by mountains consisting of highly permeable carbonates (dolomites and limestones of the Mahi formation) resting over impermeable, red-greyish-green silt- and clay-stones of the Muaydin formation (Photo 1). The siltstones have very little fracture porosity and act therefore as an aquifuge, whereas the carbonates above are highly fractured and karstic allowing groundwater to be stored, to migrate over long distances and to enter the surface via many different springs located along the boundary of these two rock formations (Nagieb et al., 2004).

The outflow of 12 springs is collected by five Ayni-Aflaj systems (Luedeling et al., 2005) and is transported to 385 agricultural fields covering 4.6 ha and to 2690 date palms (*Phoenix dactylifera* L.) growing on an additional 8.8 ha of terraced land intercropped with some lime (*Citrus aurantiifolia* [Christm. et Panz.] Swingle) and a few banana (*Musa* spp.)

Photo 1. The project site at Balad Seet, Wadi Bani Awf, Sultanat of Oman.

plants. About 1.9 ha of the palm groves are sown to understory grasses (Buerkert et al., 2005). Fields and palm groves surround the houses of the 650 inhabitants, which are located on a rocky outcrop in the center of the oasis (Fig. 1). Compared to more marginal oases, in which settlement and fields are more dispersed given the occurrence of smaller and less reliable water bodies, Balad Seet can therefore be characterized as a typical core oasis (Nagieb et al., 2004). Cultivated plants are perennial alfalfa (*Medicago sativa* L.) and annual crops such as traditional wheat landraces (*Triticum aestivum* L. and *Triticum durum*; Al-Maskri et al., 2003), sorghum (*Sorghum bicolor* Moench s. l.), barley (*Hordeum vulgare* L. s. l.), oat (*Avena sativa* L.), maize (*Zea mays* L.), garlic (*Allium sativum* L.), onion (*Allium cepa* L.) and coriander (*Coriandrum sativum* L.). These are planted in complex summer-winter crop rotation systems (Fig. 2). Wheat, garlic, onion and coriander are grown for human consumption and partially sold as cash crops on the market while the other cereals are used to feed up to 200 small ruminants (sheep and goat). Maize, oat and barley are harvested immature, while sorghum is harvested as both grain and green fodder (Nagieb et al., 2004). Barley, oat, onion and garlic are grown during the winter season, whereas sorghum is cultivated only during the hot summer season. Maize and coriander are grown in both summer and winter (Fig. 2, Table 1). The cultivated area varies over the year as a large portion of the field crop area is left fallow during summer (Table 1).

The agricultural land consists of Irragric Anthrosols (FAO, 2001b) of 0.4–1.3 m depth with 9–14% clay content. These soils are well drained because of a gravel layer below 1.3 m. Plant available water capacity of the topsoil is about 19% compared to 13% and 13.5% at 0.25 and 0.60 m depth. The soil's organic carbon (C_{org}) content is with 3.7% at 0-0.15 m depth and 3% at 0.15-0.45 m depth very high (Luedeling et al., 2005). This is a consequence of annual manure applications of up to 12 t ha^{-1} (Buerkert et al., 2005). In general the deeper soils are to be found on cropland whereas palms are growing on more shallow soils (Nagieb et al., 2004).

The predominant part of the oasis's water demand is met by the 12 springs. Only a minor part (estimated at 9 % annually) is provided by motor pumps from 14 wells that have been dug into the wadi sediments. However, during the prolonged drought between 2001 and 2003 most of these wells fell dry (Nagieb et al., 2004). The domestic water demand of the inhabitants is largely met by a well below the terraces while the Falaj water is used for basin-based flood irrigation. The average size of the basins is about 1.7 m^2 on cropland and up to 30 m^2 in palm yards. The average length of an irrigation cycle amounts to 18 days during the winter season and to 9 days in summer (Nagieb et al., 2004).

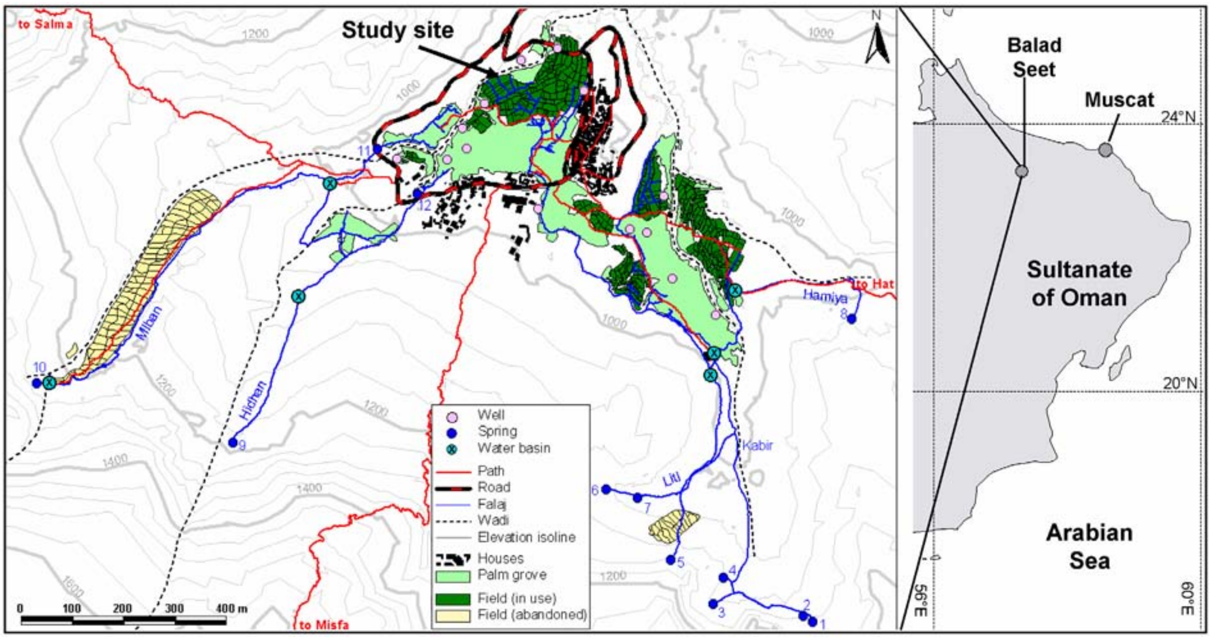

Fig. 1. GIS-based map with the agricultural features and archaeological sites of the mountain oasis of Balad Seet, Oman (Luedeling et al., 2005).

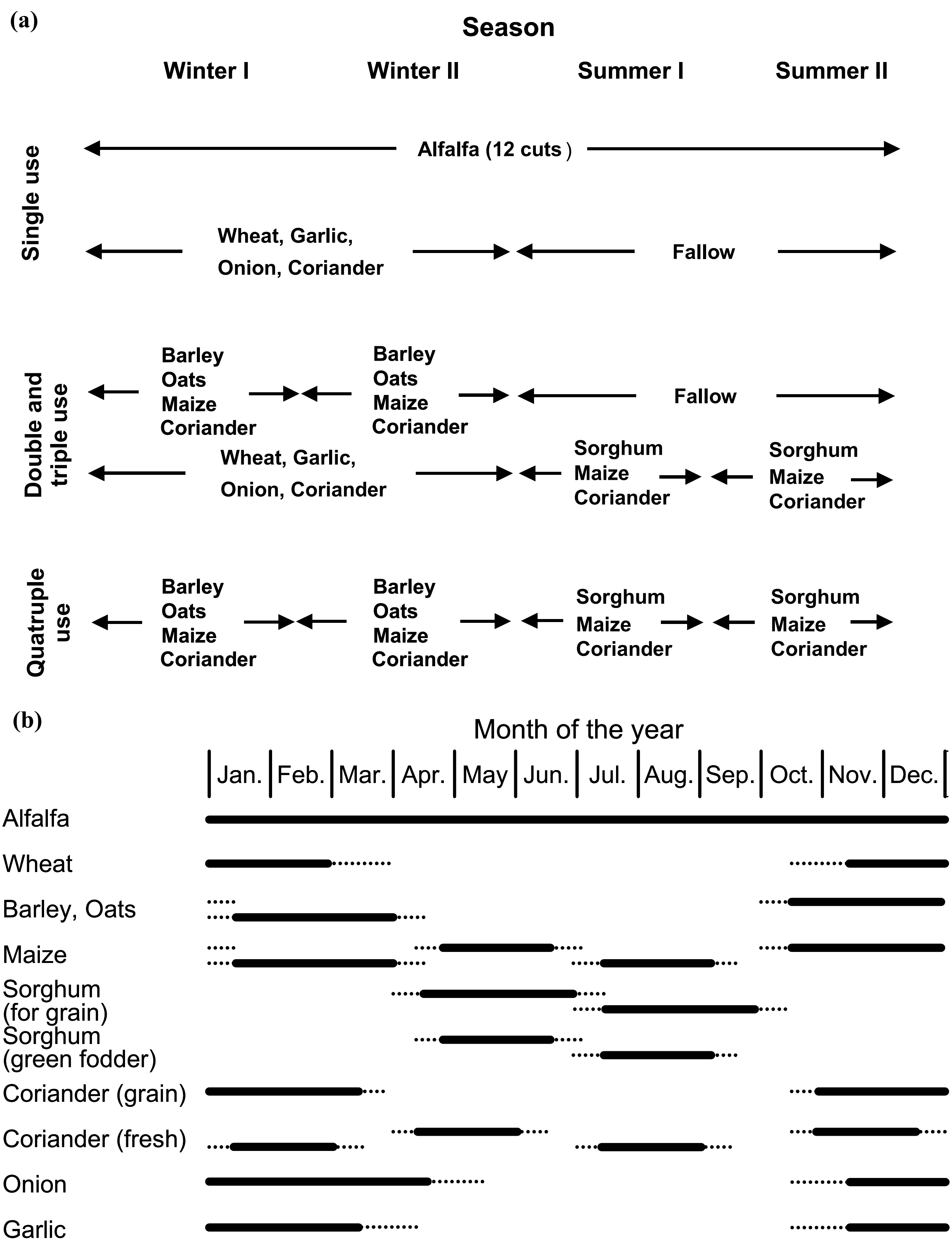

Fig. 2. Cropping calendar on fields at Balad Seet (Oman), (a) cropping pattern, (b) length of growing season, solid line: fields are cropped in general, dotted line: only some fields are cropped.

2.2 Irrigation water use efficiency ($IWUE$)

Many indices to assess water use performance have been used which are summarized by Purcell and Currey (2003). Such indices describe the conversion of available water resources into crop yield at different stages of plant growth and thus quantify the proportion of productive water use to unproductive losses. In this study irrigation water use efficiency is computed as the ratio of actual water demand and the applied amount of irrigation water (Norman et al., 1998):

$$IWUE = \frac{(ET_a - P_e - \Delta S)}{I_s} \qquad (1)$$

where $IWUE$ is the irrigation water use efficiency, ET_a is the actual evapotranspiration (mm), P_e is the effective precipitation (mm), ΔS is the change in root zone moisture (mm) and I_s is the irrigation water supply (mm).

All presented terms refer averages for a two-year measurement period between October 2000 and October 2002. Because of the low amount of rain per precipitation event (max. 40 mm) and because surface runoff is to be excluded given the existence of irrigation basins, it was assumed that all precipitation is effective. Change in root zone moisture (ΔS) was neglected because the calculations were performed for the oasis as a whole over the two-year period and differences of the soil moisture balance in specific plots were therefore assumed to level out. Irrigation water supply (I_s) was estimated as the sum of water flows in the five Aflaj systems. Measurements of Falaj flows were taken at monthly intervals with a hand-operated barrel system (Nagieb et al., 2004). Actual evapotranspiration was assumed to be equal to potential crop evapotranspiration (ET_c) in all months with water surplus ($ET_c \leq I_s + P_e$) but reduced to the given water supply ($I_s + P_e$) in months with water deficit ($ET_c > I_s + P_e$). Potential crop evapotranspiration was computed in daily time steps as:

$$ET_c = k_c ET_0 \qquad (2)$$

where ET_0 is the reference crop evapotranspiration (mm) and k_c represent crop coefficients that depend on crop type and development stage. Crop coefficient curves for four growth stages (initial stage, crop development, mid-season and late season) were developed according to the single crop coefficient approach (Allen et al., 1998). The crop coefficients (Table 2)

Table 1. Cropping areas in growing seasons 2000/2001 and 2001/2002 (ha), total cultivated and fallow area (ha) and cropping intensity on fields at Balad Seet (Oman).

Crop	Cropping areas in growing season 2000/2001 (ha)				Cropping areas in growing season 2001/2002 (ha)			
	Winter I	Winter II	Summer I	Summer II	Winter I	Winter II	Summer I	Summer II
Alfalfa	0.42	0.42	0.37	0.37	0.33	0.33	0.32	0.35
Barley	0.61	0.52	0.00	0.00	0.62	0.49	0.00	0.00
Coriander	0.22	0.18	0.19	0.16	0.09	0.13	0.17	0.23
Garlic	0.83	0.83	0.00	0.00	0.66	0.66	0.00	0.00
Maize	0.38	0.34	0.14	0.15	0.16	0.10	0.05	0.04
Oat	0.66	0.65	0.00	0.00	0.47	0.42	0.00	0.00
Onion	0.18	0.18	0.00	0.00	0.11	0.11	0.00	0.00
Sorghum	0.00	0.00	1.06	0.99	0.00	0.00	1.11	0.73
Wheat	0.61	0.61	0.00	0.00	0.96	0.96	0.00	0.00
Cultivated	3.91	3.72	1.76	1.67	3.41	3.20	1.65	1.35
Bare	0.72	0.92	2.87	2.97	1.23	1.44	2.98	3.29
Cropping intensity	0.84	0.80	0.38	0.36	0.74	0.69	0.36	0.29

Table 2. Length of initial growing period (L_{ini}), crop development period (L_{dev}), mid-season period (L_{mid}), late season period (L_{late}) and total length of growing period (L_{tot}) in days, crop coefficients for initial period (Kc_{ini}), mid season (Kc_{mid}), end season (Kc_{end}) and average crop coefficient over the growing season (Kc_{avg}) for crops at Balad Seet (Oman).

Crop	Length of growing period (d)					Crop coefficients (-)			
	L_{ini}	L_{dev}	L_{mid}	L_{late}	L_{tot}	Kc_{ini}	Kc_{mid}	Kc_{end} [1]	Kc_{avg}
Alfalfa	5	10	10	5	30	0.40	1.20	1.15	0.93
Wheat	20	25	60	30	135	0.35	1.15	0.40	0.87
Barley	15	25	50	0	90	0.35	1.15	n.a.	0.91
Oat	15	25	50	0	90	0.35	1.15	n.a.	0.91
Maize (winter)	20	30	40	0	90	0.35	1.15	n.a.	0.84
Maize (summer)	15	30	25	0	70	0.35	1.15	n.a.	0.81
Sorghum (for grain)	15	25	30	20	90	0.35	1.10	0.55	0.81
Sorghum (green fodder)	15	30	25	0	70	0.35	1.10	n.a.	0.78
Coriander (for grain)	15	30	45	45	150	0.50	1.10	0.30	0.75
Coriander (green)	15	25	20	0	60	0.50	1.10	n.a.	0.83
Onion	20	30	90	45	185	0.70	1.05	0.20	0.88
Garlic	20	30	80	20	150	0.70	1.00	0.70	0.91

[1]: late season is not applicable for crops that are harvested immature

were adjusted to match the observed management and climate conditions using the recommendations given by Allen et al. (1998). The length of the four crop development stages (Table 2) was chosen according to site-specific field observations. Within the initial stage, crop coefficients were constant at the level of $K_{C\ ini}$. During crop development, crop coefficients increased at constant daily rates to the level given by $K_{C\ mid}$. In the mid-season period, crop coefficients were constant at the level of $K_{C\ mid}$ and in the late season stage, crop coefficients were assumed to decrease in constant steps to the value given by $K_{C\ end}$. By using the crop calendar (Fig. 2) and records of the crops grown on the fields in the winter and summer seasons of 2000/2001 and 2001/2002 (Buerkert et al., 2005), the crop coefficient curves were applied to the 385 individual fields. The start of the growing seasons (Table 3) could not be recorded for all fields and was therefore defined according to the following criteria:

a) The start of the growing season is within the range given in Table 3.

b) Farmers who cultivate more than one field should harvest or prepare at the most one field per day to minimize labor peaks.

2.3 Reference crop evapotranspiration (ET_0)

Reference crop evapotranspiration was computed in daily time steps according to the FAO Penman-Monteith method (Allen et al., 1998) as:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{900}{T + 273} u(e_s - e_a)}{\Delta + \gamma(1 + 0.34u)} \tag{3}$$

where ET_0 stands for the reference evapotranspiration (mm day^{-1}), R_n the net radiation at the crop surface (MJ m^{-2} day^{-1}), G the soil heat flux density (MJ m^{-2} day^{-1}), T the mean daily air temperature (°C), u the wind speed at 2 m height (m s^{-1}), e_s the saturation vapour pressure (kPa), e_a the actual vapour pressure (kPa), Δ the slope of the vapour pressure curve (kPa °C^{-1}) and γ a psychrometric constant (kPa °C^{-1}). Since the calculations were performed in daily time steps, soil heat flux density (G) was assumed to be negligibly low compared to R_n (Allen et al., 1998) and was therefore set to 0.

Table 3. Start of growing seasons for non-perennial crops at Balad Seet (Oman).

Crop	Start of growing season
Barley, Oat	01 Oct. – 16 Oct. and 01 Jan. – 15 Jan.
Coriander (for grain)	15 Oct. – 29 Oct.
Coriander (green)	15 Oct. – 29 Oct., 01 Jan. – 15 Jan., 01 Apr. – 15 Apr. and 30 Jun. – 14 Jul.
Garlic, Onion, Wheat	15 Oct. – 14 Nov.
Maize	01 Oct. – 16 Oct., 01 Jan. – 15 Jan., 11 Apr. – 25 Apr. and 30 Jun. – 14 Jul.
Sorghum (for grain)	01 Apr. – 15 Apr. and 30 Jun. – 14 Jul.
Sorghum (green fodder)	11 Apr. – 25 Apr. and 30 Jun. – 14 Jul.

2.4 Climatic data

The calculation of ET_0 according to the FAO Penman-Monteith method requires measurements of air temperature (daily minimum, maximum and average), solar radiation, humidity and wind speed. Air temperature was measured with thermocouples in a cultivated alfalfa field using a combined setup which recorded soil moisture by capacitance probes (Decagon Devices Inc., Pullman, Washington, USA) and soil temperature and air temperature by thermocouples. All measurements were collected in 30–minute intervals and stored with a Campbell CR10 (Campbell Scientific Inc., Logan, Utah, USA) data logger. For each day the minimum and maximum temperature was derived and the average of the 48 values computed. Measurements were taken between October 2002 and October 2003 and assumed to be also representative of the previous cropping seasons. Relative humidity and dew point temperature were measured in 10-minute intervals using a small weather station (Weather Station III, O. Feger, Traunstein, Germany). An analysis of the data showed that maximum humidity was for many summer days below 70 %, which was confirmed by measurements taken with an independent climate logger (Technika, Phoenix, AZ, USA). This indicated a deviation from reference conditions, most probably caused by the aridity of the site and the small size of the oasis. As recommended by Allen et al. (1998) the measurements were discarded and instead actual vapor pressure (e_a) was computed as:

$$e_a = 0.6108 \exp\left(\frac{17.27 T_{dew}}{T_{dew} + 237.3}\right) \tag{4}$$

assuming that $T_{dew} = T_{\min} - 2$ where T_{dew} stands for the dew point temperature (°C) and $T_{\min}$ for the daily minimum temperature (°C).

Based on the observation that there was no or only very light wind on the large majority of days in the oasis, wind speed was assumed to be constant at 1 m s^{-1}. Solar radiation was measured during four selected time periods (25 Nov. 2002 – 21 Dec. 2002, 04 Jan. 2003 – 01 May 2003, 18 Jun. 2003 – 06 Jul. 2003, 18 Aug. 2003 – 04 Oct. 2003) with a pyranometer in 10-minute intervals using the small weather station. The cumulative length of all measurement periods was 211 days. Daily sunshine (in minutes) was recorded by the same weather station using the radiation records and a threshold value of 120 W m^{-2} for bright sunshine. Missing data of global radiation and daily sunshine were modeled using a digital elevation model (DEM) based on digitized Russian military maps (Buerkert et al., 2005). The position of the sun at the sky was computed for each minute in the simulation period according to Szokolay (1996) and Carruthers et al. (1990) as applied by the solar position calculator of Square One research PTY LTD (http://www.squ1.com/index.php?http://www.squ1.com/solar/solar-position.html). The use of the DEM allowed computing the height of the mountains along the horizon as it appears for a viewer located at the weather station. Subsequently daily potential sunshine (n_{DEM}) was calculated as the length of the period when the sun was above the mountains. Daily actual sunshine was calculated by applying a coefficient that represents the influence of cloudiness as:

$$n_{act} = c_n n_{DEM} \tag{5}$$

where n_{act} is the actual duration of sunshine (min d^{-1}), c_n the cloudiness coefficient, n_{DEM} the potential duration of sunshine (length of period when the sun is above the mountains along the horizon in min d^{-1}). The coefficient c_n was computed by linear interpolation between the related coefficients as calculated during the measurement periods (Table 4).

Solar radiation was modeled in a similar way. During the period, when the sun is above the mountains along the horizon, solar radiation on a clear sky day (R_{S0}) was computed according to Allen (1996) as:

$$R_{S0(a)} = \sum_{m=1}^{1440} R_a \exp\left(\frac{-0.0018P}{K_t \sin\phi}\right) \tag{6}$$

where $R_{S0(a)}$ is the short wave radiation on a clear-sky day with the sun above the mountains (MJ m^{-2} d^{-1}) [$R_{S0(a)}$ = 0 if the sun is behind the mountains along the horizon, m the minute of the day ($1 \le m \le 1440$)], R_a the extraterrestrial radiation (MJ m^{-2} min^{-1}), P the atmospheric pressure (kPa), ϕ the angle of the sun above the horizon (rad) and K_t the turbidity coefficient (kPa rad^{-1}) which was set to 1.0 for clean air.

The solar radiation on a clear sky day for the period when the sun is above the horizon ($\phi > 0$) but behind the mountains ($R_{S0(b)}$) was computed by assuming that the average incoming solar radiation during this period in the early morning and the late afternoon was 25 W m^{-2} and that any increase or decrease of solar radiation was linear during this period (Fig. 3). Total daily solar radiation (R_S) was then computed by applying the coefficient c_S (Table 4) to the sum of both solar radiations computed before as:

$$R_S = c_S (R_{S0(a)} + R_{S0(b)}) \tag{7}$$

where R_S is the short wave or solar radiation (MJ m^{-2} d^{-1}), c_S represents the influence of cloudiness or turbid air and $R_{S0(b)}$ stands for the short wave radiation on a clear-sky day with the sun above the horizon but behind the mountains (MJ m^{-2} d^{-1}). The radiation and sunshine values recorded or simulated for the period November 2002 – November 2003 were assumed to be also representative also for the period October 2000 to October 2002.

Daily precipitation was recorded at Balad Seet between July 2001 and July 2004, of which monthly averages were used to calculate water use efficiency (equation 1).

2.5 Crop water use indices

Crop water use indices were computed for eight field crops and date palms as:

$$CWUI = \frac{Y}{ET_c} \tag{8}$$

Table 4. Average coefficients for cloudiness or turbidity used in calculations of daily sunshine duration (c_n) and incoming solar radiation (c_s) as computed from measurements or interpolated for periods without measurements at Balad Seet (Oman).

Month	Number of measurement days	Coefficients as derived from measurements		Coefficients computed for periods without measurements	
		c_n	c_s	c_n	c_s
January	28	1.065	0.958	1.067	0.986
February	28	1.024	0.950	n.a.	n.a.
March	31	0.986	0.882	n.a.	n.a.
April	29	0.975	0.917	0.975	0.921
May	1	0.984	0.984	0.983	0.908
June	13	0.969	0.851	0.976	0.874
July	6	0.981	0.834	0.969	0.847
August	14	0.987	0.848	0.979	0.838
September	30	0.992	0.838	n.a.	n.a.
October	4	1.000	0.961	1.033	0.934
November	6	1.022	1.049	1.053	0.943
December	21	1.102	0.966	1.081	1.011

where $CWUI$ denotes the crop water use index (kg m^{-3}), Y the dry matter economic crop yield (kg) and ET_c the crop evapotranspiration (m^3). The above-ground dry matter of crops was recorded for the four seasons (winter I and II, summer I and II) and the two growing seasons 2000/2001 and 2001/2002 following the procedure described by Buerkert et al. (2005).

2.6 Effects of altitude and topography on potential evapotranspiration

The objective of this approach was to estimate potential evapotranspiration in a fictive oasis at the same geographical location but without the surrounding mountains and at mean sea level. For this purpose altitude a.s.l. was set to 0 m, measured average temperatures were increased by 6.5 °C based on an altitudinal temperature gradient of 0.65 °C per 100 m altitude. Average daily maximum temperature was only increased by 2 °C because an increase of 6.5 °C would lead to average maximum temperatures larger than 50 °C that were not reported for any place on the entire Arabian Peninsula. The lower increase of maximum temperatures was balanced out by an increase of average daily minimum temperatures by 11 °C. Daily sunshine duration was set to monthly values as reported by Jervase et al. (2003) for the town of Rustaq (23.41° N; 57.42° E; 322 m a.s.l.) which is located just 25 km north of Balad Seet. Solar radiation was

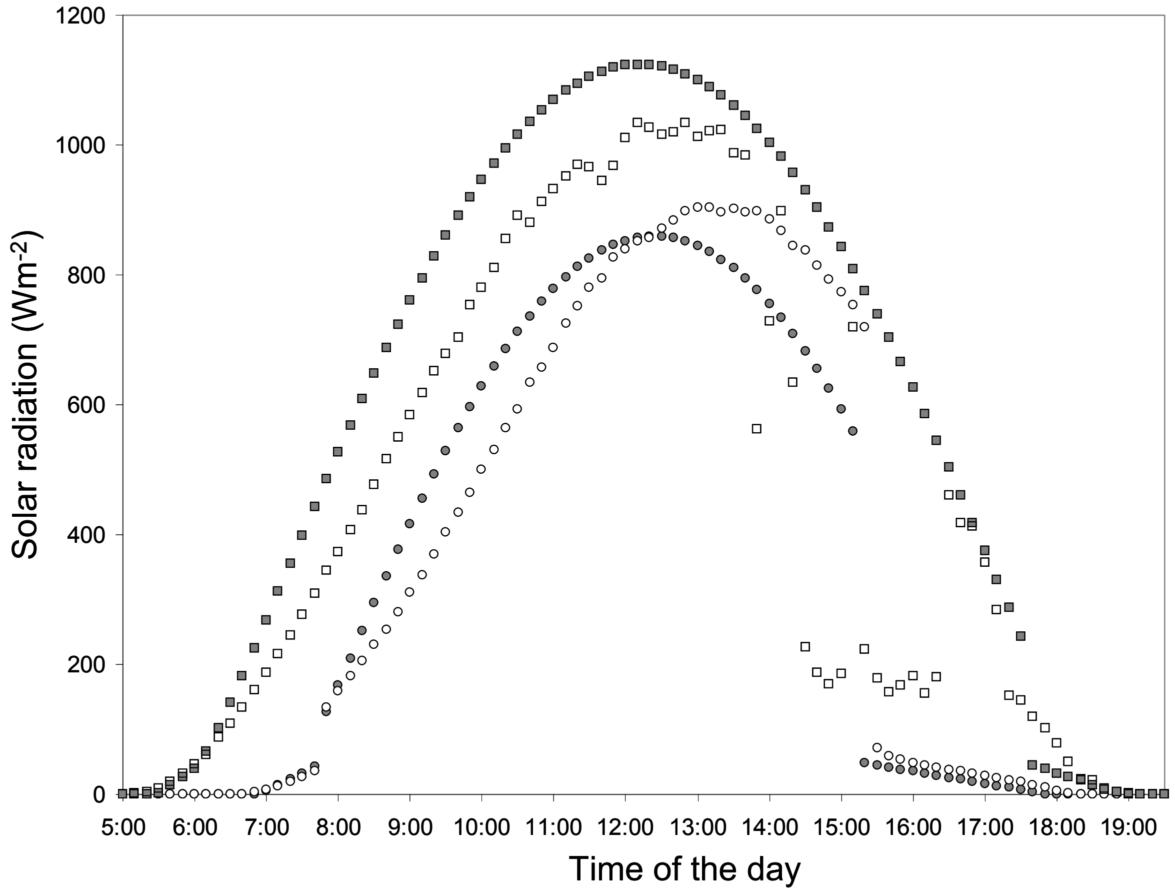

Fig. 3. Measured solar radiation (unfilled symbols) versus simulated clear sky solar radiation (filled symbols) on 1st of February 2003 (circles) and 20th of June 2003 (squares) at Balad Seet (Oman).

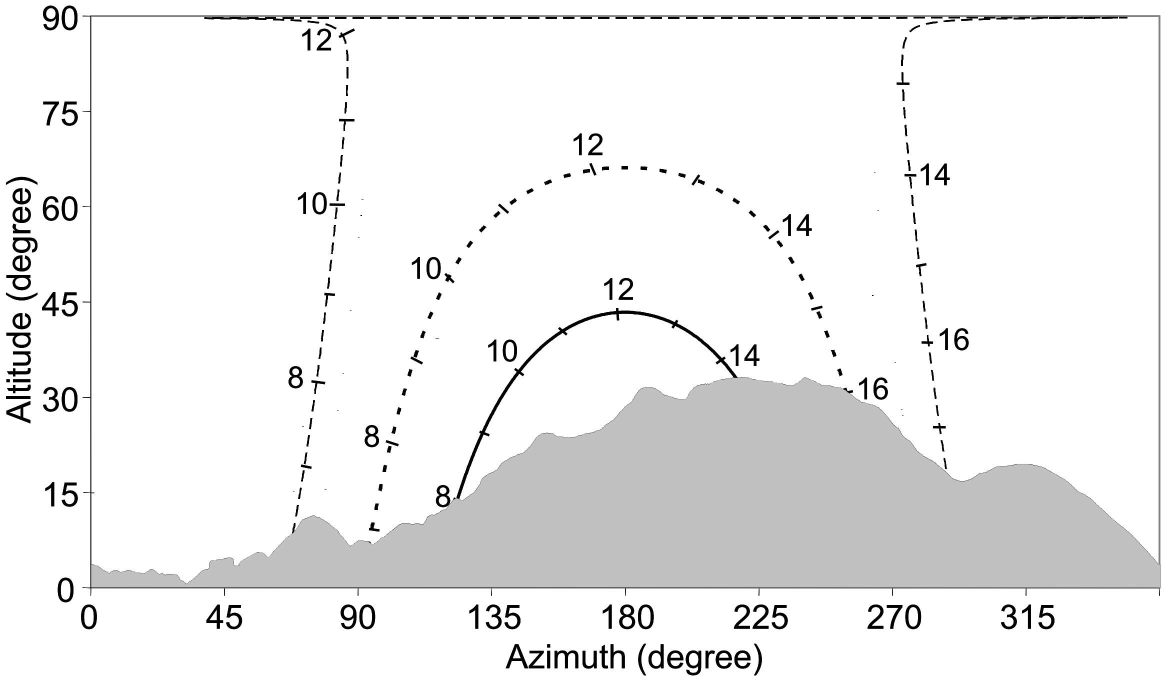

Fig. 4. Height of the mountains along the horizon and sun path on 20th of December (solid line), 20th of March (dotted line) and 20th of June (dashed line) at Balad Seet (Oman), thick marks along the sun paths indicate hours of local time, Azimuth of 0 = North.

increased in the months of December – February to averages measured at Seeb International Airport near Muscat to reduce the shadow effect of the mountains. In all other months, solar radiation measured at Balad Seet was larger than the values measured at Muscat and was therefore not changed. Wind speed was increased to monthly averages as recorded for July 2004 – February 2005 at Rustaq (http://www.wunderground.com/global/stations/41253.html). Wind speed for the months March – June was computed by increasing wind speed as measured in February at Rustaq each month by 0.1 m s^{-1}. A stepwise increase of wind speed in this season was reported previously for other weather stations located in Oman (Sulaiman et al., 2002).

3 RESULTS

3.1 Climatic data

Average temperature during the one year-measurement period was 25.8 °C. Average daily maximum temperature was 34.9 °C while the average daily minimum was 17.5 °C. January was the coldest month and June the hottest one (Table 5). Average annual precipitation over the 4-year measurement period was 94.5 mm. Most of the rain fell in July with 40.1 mm, which indicates the influence of the Indian Ocean monsoon (Burns et al., 2002). During winter time (November – February) only very little precipitation was recorded.

A large variation of sunshine duration and solar radiation between summer and winter season was found (Table 5), which reflects a combined effect of site-specific topography and solar geometry. In December the sun was above the mountains along the horizon for about 6 hours and for about 11 hours in June (Fig. 4). The shading effect of the mountains around Balad Seet had a much larger influence on the sunshine duration than on solar radiation (Figs. 5 and 6). The potential sunshine duration at the given latitude was computed to last 640 min d^{-1} in December and 800 min d^{-1} in June while the potential solar radiation on clear-sky days amounted to 17 MJ m^{-2} d^{-1} in December and 32 MJ m^{-2} d^{-1} in June. Including the shading effect of the mountains decreased potential sunshine duration to 380 min d^{-1} in December and 680 min d^{-1} in June, while potential solar radiation decreased to 14.5 MJ m^{-2} d^{-1} in December and to 31.2 MJ m^{-2} d^{-1} in June (Figs. 5 and 6). The reduction of sunshine and solar radiation by cloudiness, however, seemed to be higher in summer than in winter (see coefficients in Table 4).

Table 5. Monthly averages of daily maximum temperature (T_{max}), daily minimum temperature (T_{min}), daily average temperature (T_{avg}), daily sunshine duration (n) and daily solar radiation (R_s), monthly sum of effective precipitation (P_e) at Balad Seet (Oman).

Month	T_{max} (°C)	T_{min} (°C)	T_{avg} (°C)	n (min d^{-1})	R_S (MJ m^{-2} d^{-1})	P_e (mm)
January	26.3	8.8	16.3	436.4	15.1	0.0
February	29.0	12.5	20.4	484.5	18.8	1.2
March	31.0	15.2	23.5	533.6	21.6	12.2
April	35.6	16.4	25.9	585.8	26.2	22.2
May	39.5	19.9	29.9	634.4	28.0	4.2
June	44.0	23.9	33.9	659.1	27.1	0.0
July	40.1	25.8	32.3	643.2	26.1	40.1
August	40.3	23.7	31.8	610.9	24.8	2.3
September	38.2	21.2	29.8	566.1	22.0	8.9
October	36.5	17.1	26.5	515.7	20.4	0.5
November	30.3	14.1	21.1	457.4	16.6	2.9
December	27.2	11.2	17.9	423.6	14.2	0.0
Annual average[1]	34.9	17.5	25.8	546.2	21.7	94.5

[1]: In case of precipitation the annual sum is reported

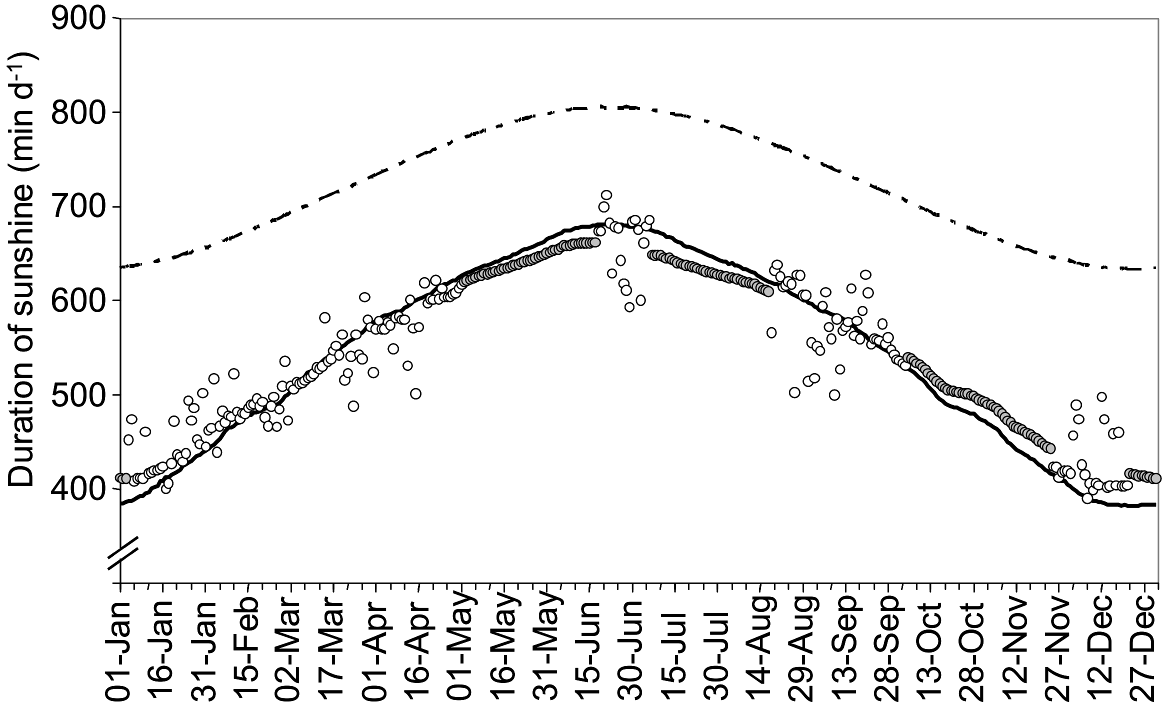

Fig. 5. Daily duration of sunshine at Balad Seet (Oman); dot-dashed line: potential astrological sunshine duration (sun altitude > 0°), solid line: potential local sunshine duration (sun above the mountains along the horizon), unfilled dots: measured sunshine duration, filled dots: sunshine duration interpolated for periods without measurements.

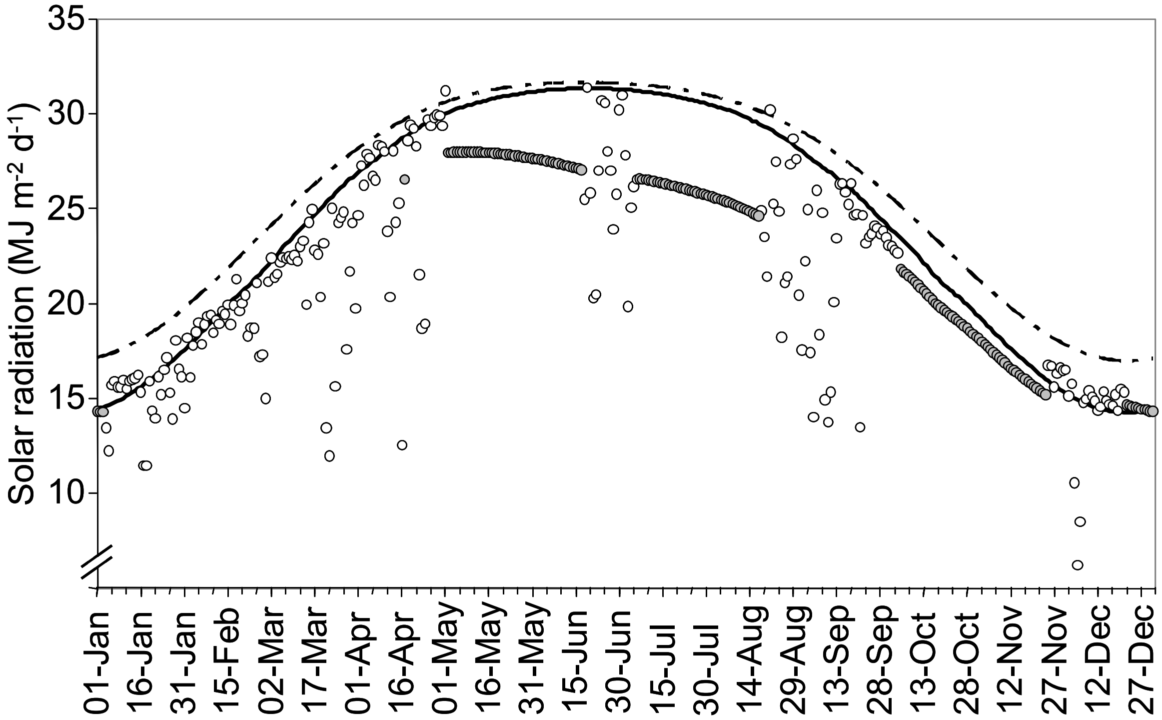

Fig. 6. Daily incoming solar (short-wave) radiation at Balad Seet (Oman); dot-dashed line: potential astrological solar radiation on a clear-sky day, solid line: potential local solar radiation on a clear-sky day (shadowing effect of mountains along the horizon considered), unfilled dots: measured solar radiation, filled dots: solar radiation interpolated for periods without measurements.

3.2 Evapotranspiration

Annual reference evapotranspiration (ET_0) was 1778 mm yr^{-1} in the two years simulated. Monthly reference evapotranspiration was highest for June with 208 mm while reference evapotranspiration appears to be lowest in December with 84 mm (Table 6).

Total annual crop evapotranspiration in palm groves accounted for about 84% of the total evapotranspiration on agricultural land (Table 6). Because of the perennial cultivation in palm groves, the seasonal variation of crop evapotranspiration was similar to that of the reference evapotranspiration. Therefore evapotranspiration was largest in the hot summer season (May – August) and lowest in the cooler winter season (November – February).

In contrast to the situation in palm groves, seasonal evapotranspiration is more balanced on cropland (Table 6). So total crop evapotranspiration in winter (October – March) was 17 355 m^3 yr^{-1} and was thus even higher than evapotranspiration computed for the period April – September (13 838 m^3 yr^{-1}). This reflects the higher cropping intensity in the winter compared to the summer season (Table 1). The highest total evapotranspiration was computed for sorghum (8216 m^3 yr^{-1}) and alfalfa (5939 m^3 yr^{-1}).

3.3 Irrigation water use efficiency (*IWUE*)

Irrigation water use efficiency for the entire oasis was 0.75 during the two year period from October 2000 to September 2002. Actual evapotranspiration (ET_a) was 373 623 m^3 and thus somewhat lower than the potential evapotranspiration of 388 780 m^3. Total precipitation on agricultural land was 25 390 m^3 and irrigation water supply from the Aflaj (I_s) was 465 946 m^3 with, however, large seasonal differences. While in the winter season about half of the used irrigation water did not seem to be needed by the plants, there was a small water deficit computed for some months in the summer season (Fig. 7).

3.4 Water use indices

Crop water use index was 0.92 kg m^{-3} for wheat grain yield, 0.64 kg m^{-3} for sorghum grain and 1.85 kg m^{-3} for garlic bulbs (Table 7). Crop water use indices for total dry matter (TDM) ranged between 1.88 kg m^{-3} for oat and 4.27 kg m^{-3} for maize. For wheat and sorghum differences between both types of indices were particularly large (Table 7). Crop water use index in palm groves was 0.17 kg m^{-3} for dates and 2.74 kg m^{-3} for harvested understory fodder.

Table 6. Reference evapotranspiration (ET_0) in mm month^{-1} and crop specific evapotranspiration in m^3 month^{-1} for alfalfa, wheat, barley, oats, maize, sorghum, coriander, onion and garlic, for cropland total, palm groves and total agricultural land as average of the two year simulation period at Balad Seet (Oman).

Month	ET_0 (mm month^{-1})	Potential evapotranspiration (m^3 month^{-1})											
		Alfalfa	Wheat	Barley	Oat	Maize	Sorghum	Coriander	Onion	Garlic	Cropland	Palm-groves	Total
January	88	316	795	211	230	86	0	150	134	656	2577	8097	10 675
February	101	352	653	540	580	207	0	115	154	749	3350	9309	12 659
March	137	478	78	783	839	346	0	13	160	432	3129	12 555	15 684
April	170	536	0	112	97	82	640	111	52	1	1631	15 609	17 240
May	202	648	0	0	0	171	2096	360	0	0	3275	18 569	21 843
June	208	664	0	0	0	144	1991	63	0	0	2862	19 126	21 988
July	200	663	0	0	0	74	778	158	0	0	1673	18 373	20 046
August	189	639	0	0	0	179	1648	357	0	0	2823	17 373	20 196
Septembe	157	526	0	0	0	55	974	19	0	0	1574	14 401	15 975
October	141	479	127	356	313	129	89	28	71	301	1893	12 939	14 831
November	99	346	458	652	592	246	0	102	119	582	3097	9093	12 190
December	84	295	746	581	537	256	0	145	128	622	3309	7753	11 062
Annual	1778	5939	2857	3235	3189	1974	8216	1621	818	3344	31 193	163 197	194 390

Table 7. Crop evapotranspiration, dry matter yield and crop water use indices for alfalfa, wheat, barley, oat, maize, sorghum and garlic over the two year period at Balad Seet (Oman).

Crop	ET_c (m^3)	Total dry matter yield (kg)		Crop water use index (kg m^{-3})	
		Grain[a]	Above-ground dry matter	Grain[a]	Above-ground dry matter
Alfalfa	11 878	[b]	19 750	[b]	1.66
Wheat	5713	5264	22 791	0.92	3.99
Barley	6470	[b]	13 206	[b]	2.04
Oat	6379	[b]	11 965	[b]	1.88
Maize	1976	[b]	8429	[b]	4.27
Sorghum[c]	12 174	7766	45 265	0.64	3.72
Garlic	6687	12 390	16 680	1.85	2.49

[a] Dry bulbs in case of garlic
[b] Only vegetative parts were harvested as animal fodder
[c] Only sorghum for grain production considered

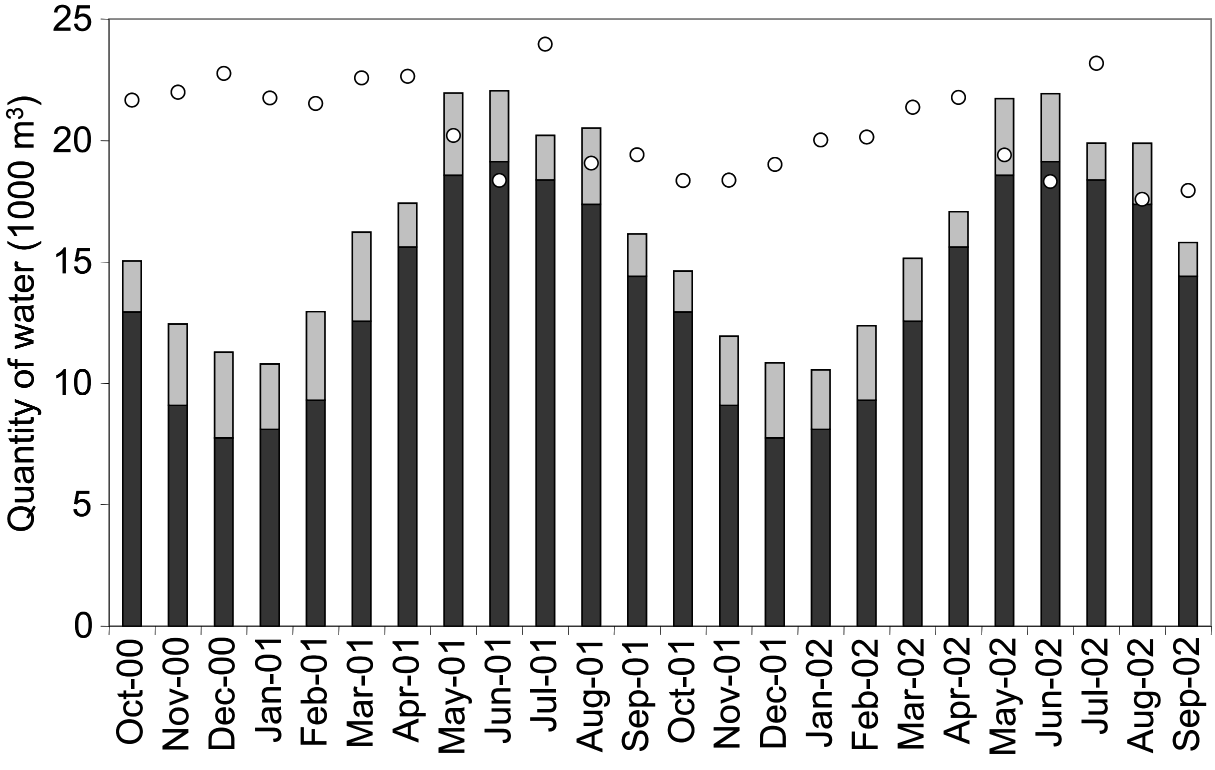

Fig. 7. Fresh water resources as sum of spring outflow and precipitation (unfilled circles) and crop evapotranspiration in palm groves (black columns) and cropland (gray columns) at Balad Seet (Oman).

3.5 Effect of altitude and topography on potential evapotranspiration

When simulating climate conditions of the fictive oasis at the same position but at mean sea level and without surrounding mountains, reference evapotranspiration increased by 35% from 1778 mm yr^{-1} to 2393 mm yr^{-1} (Table 8).

Table 8. Monthly averages of daily maximum temperature (T_{max}), daily minimum temperature (T_{min}), daily average temperature (T_{avg}), daily sunshine duration (n), daily solar radiation (R_s), wind speed (u) and daily reference evapotranspiration (ET_0) at Balad Seet (Oman) after removing shadowing effects of mountains and surface cooling effect by the high elevation of the site.

Month	T_{max} (°C)	T_{min} (°C)	T_{avg} (°C)	n (hours d^{-1})	R_S (MJ m^{-2} d^{-1})	u (m s^{-1})	ET_0 ($mm\ d^{-1}$)
January	32.8	15.3	22.8	8.5	15.3	1.43	3.86
February	35.5	19.0	26.9	8.6	18.8	1.76	4.99
March	37.5	21.7	30.0	9.0	21.6	1.86	5.86
April	42.1	22.9	32.4	9.7	26.1	1.96	7.61
May	46.0	26.4	36.4	10.5	27.9	2.06	8.74
June	50.5	30.4	40.4	10.8	27.0	2.16	9.50
July	46.6	32.3	38.8	10.6	26.1	2.28	8.61
August	46.8	30.2	38.3	10.3	24.8	1.97	8.06
September	44.7	27.7	36.3	10.0	21.9	1.97	7.11
October	43.0	23.6	33.0	9.6	20.3	1.69	6.18
November	36.8	20.6	27.6	9.3	16.9	1.44	4.43
December	33.7	17.7	24.4	8.7	14.6	1.38	3.67
Annual	41.4	24.0	32.3	9.6	21.8	1.83	6.56

4 DISCUSSION

4.1 Methodology and data

The modeling of evapotranspiration, crop water use indices and irrigation water use efficiency as conducted in this study bears several sources of uncertainty. First, the scarcity of data required their combination across different time periods assuming that the measured values were representative to be used across years. It is nevertheless obvious that these climate data do not represent the conditions in any specific year very well. A second source of uncertainty is that radiation and sunshine measurements were not available for a complete year and missing values therefore had to be modeled. Also, it was impossible to compare the measured or modeled values to measurements taken in similar locations, as all the registered long-term measurement stations in the Sultanate of Oman are close to the coastline and at least 100 km away from Balad Seet. Nevertheless, a comparison of measured or assumed values for temperature and wind speed at Balad Seet to values reported by a newly established weather station at Rustaq indicates that the former values are reliable. Radiation measurements were found to be higher than at other weather stations of Oman (FAO, 2001a; Dorvlo and Ampratwum, 1998; Al-Hinai and Al-Alawi, 1995).

Any straightforward calculation of actual evapotranspiration from potential evapotranspiration (Sect. 2.2) represents a very simplified approach. Usually modeling of actual evapotranspiration requires at least measurements of the actual soil water status (Doorenbos and Kassam, 1979) or the measurement of plant parameters like sap flow (Smith and Allen, 1996) or stomatal responses (Jarvis, 1976). However, some observations indicate that for our case the simplified version may be acceptable. First of all, the high nutritional status of the crops at Balad Seet (Buerkert et al., 2005) suggests that evapotranspiration might be at its full potential, if enough water was available. As surface runoff on the terraced soils can be excluded, water losses in the fields only occur by drainage into deep soil layers. The first assumption that has to be verified is that $ET_a = ET_0$ in times when more water is available than is usable by plants. This holds generally during winter time (Fig. 7). Assuming an average plant extractable water capacity of 16 vol% (Luedeling et al., 2005), a maximum evapotranspiration of 100 mm month^{-1} during winter time (Table 5) and a length of the irrigation cycle of 18 days, an effective soil depth of 37.5 cm would be needed to store enough water. This soil depth is given almost everywhere in the oasis. The other assumption is that all applied irrigation water is extracted by the plants in periods of water scarcity, which appear to be limited to summer time. Assuming a minimum effective soil depth of 40 cm, about 64 mm of applied water can be stored in the soil. Assuming a water application of max. 20 000 m^3 per month (Fig. 7), about 10.5 ha cultivated land (8.8 ha palm groves and 1.7 ha cropland) and a length of the irrigation cycle of 9 days during summer time, the mean application rate would be 55.5 mm. Thus the assumption that there are no leaching losses during summer might hold.

The coefficients c_n and c_s used to compute actual sunshine duration (equation 5) or actual solar radiation (equation 7) should be smaller than 1 because potential sunshine duration and potential solar radiation computed when considering the shadow effect of the mountains should be further decreased by effects of cloudiness, fog or dust. However, in wintertime these coefficients were computed to be larger than 1 (Table 4). The measurements taken in this period also showed that measured sunshine duration and radiation (Figs. 5 and 6) are often larger than the respective computed potential values. This indicates problems with the precision of the used digital elevation model. Indeed numerous altitude measurements taken by differential GPS south of Balad Seet confirmed differences of up to 100 m between measured elevation and altitude derived from the DEM (Luedeling, unpublished). Therefore coefficients c_n and c_s not only represent corrections for cloudiness or turbid air but also corrections of the used DEM. As a consequence, these coefficients could not be used to calculate the effects of altitude and topography on evapotranspiration (Sect. 2.6).

4.2 Assessment of results

The computed annual reference evapotranspiration of 1778 mm yr^{-1} was much lower than evapotranspiration computed for other locations in northern Oman. Scientists at FAO computed the reference evapotranspiration for Muscat at 2287 mm yr^{-1}, for Sohar at 2604 mm yr^{-1} and for Sur at 2314 mm yr^{-1} (FAO, 2001b). The lower reference evapotranspiration given by our model is clearly an effect of the local climate as driven by the high altitude of the site and the shadow effect of the surrounding mountains. Annual evapotranspiration computed after removing these effects was 2393 mm yr^{-1} and thus very close to the values reported for Muscat and Sur.

The irrigation water use efficiency (*IWUE*) of 0.75 for the entire oasis was surprisingly close to the *IWUE* at Falaj Hageer reported by Norman et al. (1998). The high values at both locations indicate that water use efficiency in traditional Omani mountain oases might be much higher than previously assumed, although farmers use surface irrigation methods. A high *IWUE*, the location of the oasis close to the springs and the reduced reference evapotranspiration show the adaptation of the oasis system to the harsh environmental conditions.

The results of this study also indicate, that *IWUE* could be even larger than 0.75 if more cropland was cultivated during winter. The plants needed only about 60 % of the available water resources for evapotranspiration (Fig. 7). Numerous abandoned fields at Balad Seet and the records of the farmers give evidence that in the past there was more cropland in use (Nagieb et al., 2004).

Average annual evapotranspiration in palm groves (18 545 m^3 ha^{-1} yr^{-1}) was larger than that of cropland (6781 m^3 ha^{-1} yr^{-1}), because palm groves are growing also in the hot summer season whereas large parts of the cropland areas are left fallow during this period. As Norman et al. (1998) already described, arable cropland is only being used to cultivate non-perennial field crops when there is excess water. Therefore the use of different portions of the available cropland in different times of the year allows the oasis inhabitants to adapt their use of irrigation water to the available flow of the springs. As a consequence, the ratio of cropland to palm groves could be used as an indicator to quantify the amount and variation of spring flows in other traditional mountain oases. Evapotranspiration computed for palm groves only could be expected to represent the long-term minimum spring flow, whereas maximum evapotranspiration on total agricultural land might reflect usable spring flow in years following a strong rainfall event. According to the oral records of the farmers at Balad Seet such a strong rain event, which leads to a recharge of the groundwater reservoir occurs on average every six years. The last strong rain event was reported for 1997. In a typical drought period precipitation spring flow was computed to decline at a rate of about 3 % per month (Nagieb et al., 2004). By using the average evapotranspiration for the period June – August the expected minimum spring flow at Balad Seet was estimated at 609 m^3 d^{-1}, while the expected maximum usable spring outflow was as high as 843 m^3 d^{-1}. The observed variation in spring outflow between October 2000 and September 2002 ranged from a maximum of 734 m^3 d^{-1} in December 2000 to 558 m^3 d^{-1} in September 2002. This means that water supply to the plants would be below the optimum in hot summer months without monsoon-driven precipitation.

Results of other studies performed in Wadi Tiwi (Korn et al., 2004) or Wadi Khabbah (Siebert et al., 2005) support the hypothesis that a low cropland / palm groves area ratio indicates the existence of water rich oases or oases with stable water flows, whereas a high ratio indicates a large inter-annual variability of given water resources. However, more research is certainly needed to verify this observation.

The computed crop water use index (*CWUI*) for wheat grain yield is with 0.92 kg m^{-3} lower than the median of 412 experiments collected from 28 different sources all over the world by Zwart and Bastiaanssen (2004), which was reported to be 1.02 kg m^{-3}. However, the latter values refer to air-dry grain yields, whereas in this study the values refer to total dry matter. *CWUI* for wheat would be 1.02 kg m^{-3} at Balad Seet if it was based on air-dry grain yield.

For forage crops *CWUI*s were higher than respective values measured by Al-Lawati and Esechie (2002) for maize (2.24 kg m^{-3}) and Rhodes grass (0.91 kg m^{-3}) in the Batinah region near Muscat. At Balad Seet *CWUI*s amounted to 4.27 kg m^{-3} for maize, to 1.66 kg m^{-3} for alfalfa, to 1.88 kg m^{-3} for oats and to 2.04 kg m^{-3} for barley which may have several reasons. The trial at the research station near Muscat was carried out only during winter as in the Batinah region commonly crops are only grown in the winter season to save irrigation water. However, maize and Rhodes grass are C_4-crops and could therefore be more productive during summer season. At Balad Seet maize was grown in the winter and in the summer season. Another reason may be that compared to the use of modern short stature varieties in the Batinah, farmers at Balad Seet used local landraces with a much lower harvest index (see the ratio of grain yield and above-ground biomass harvest for wheat and sorghum in Table 7).

Unfortunately, there are no comparative crop water use indices for sorghum, dates and garlic grown under Omani conditions. However, yields for sorghum and dates at Balad Seet are close to the country's averages as reported by FAO (2005) and Omezzine et al. (1998). Due to the lower evapotranspiration at Balad Seet compared to the country's average evapotranspiration, it may be expected that *CWUI*-values for these crops are also higher at Balad Seet than for the average of the country.

5 CONCLUSIONS

The data indicate that altitude and shading by mountains have a large effect on crop evapotranspiration. Therefore, a combination of high resolution land use data and digital elevation models would be needed to model irrigation water requirements for larger regions or the entire country of Oman.

The measurements of climatic data taken at Balad Seet indicate that climate conditions in the interior of Oman differ considerably from values measured by the registered long-term measurement stations along the coastline. To reduce the uncertainty of modeling studies of water use in the interior of the Arabian Peninsula, it would thus be necessary to also establish long-term climate stations in regions distant from the coastline.

The observed high water use efficiency, the apparent sustainability of land and water use, the comparatively little competition for water by other users and the wealth of cultural heritage to be preserved call for a more systematic support of Aflaj agriculture in remote mountain oases of Oman. This may require a reassessment of prevailing public policies which focus on the agricultural systems of the country's coastal plain.

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4

Development and validation of the Global Map of Irrigation Areas

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ABSTRACT

A new version of a digital global map of irrigation areas was developed by combining irrigation statistics for 10 825 sub-national statistical units and geo-spatial information on the location and extent of irrigation schemes. The map shows the percentage of each 5 arc minute by 5 arc minute cell that was equipped for irrigation around the year 2000. It is thus an important data set for global studies related to water and land use. This paper describes the data set and the mapping methodology and gives, for the first time, an estimate of the map quality at the scale of countries, world regions and the globe. Two indicators of map quality were developed for this purpose, and the map was compared to irrigated areas as derived from two remote sensing based global land cover inventories.

1 INTRODUCTION

Agriculture is by far the largest water-use sector, accounting for about 70 percent of all water withdrawn worldwide from rivers and aquifers for agricultural, domestic and industrial purposes (Shiklomanov, 2000). In many developing countries more than 90 percent of the water withdrawals are for irrigation (FAO AQUASTAT-database, http://www.fao.org/ag/agl/aglw/aquastat/main/index.stm, 2005). In arid regions, irrigation is the prerequisite for crop production. In semi-arid and humid areas, irrigation serves to increase yields, to attenuate the effects of droughts or, in the case of rice production, to minimize weed growth. Average yields are generally higher under irrigated conditions as compared to rainfed agriculture (Bruinsma, 2003). In the United States, for example, average crop yields of irrigated farms exceeded, in 2003, the corresponding yields of dryland farms by 15% for soybeans, 30% for maize, 99% for barley, and by 118% for wheat (Veneman et al., 2004). Although globally only 18% of the cultivated area is irrigated (FAO, 2005a), 40% of the global food production comes from irrigated agriculture (UNCSD, 1997). Both the water scarcity caused by using large amounts of water in irrigated agriculture and the importance of irrigation for crop production and food security induced several studies to quantify the different elements of the global water balance in space and time (e.g. Vörösmarty et al., 2000; Oki et al., 2001; Alcamo et al., 2003; FAO, 2005b). Others focused on the importance of irrigated food production in general (Faures et al., 2002; Wood et al., 2000), on the impact of irrigated agriculture on global (or regional) climate (Boucher et al., 2004; De Rosnay et al.,

2003) or on the impact of climate change and climate variability on global irrigation water requirements (Döll, 2002).

All these studies depend on data on the distribution and extent of irrigated areas in the world. The first digital global map (or rather data set) of irrigated areas was published in 1999 (Döll and Siebert, 2000). It showed the areal fraction of 0.5 arc degrees by 0.5 arc degree grid cells that was equipped for irrigation in the 1990s. Since then, the map has been updated several times and the map resolution has increased to 5 arc minutes by 5 arc minutes. A new mapping methodology was developed (Siebert and Döll, 2001) and this methodology was applied to all countries by using information collected in the framework of FAO's AQUASTAT program (http://www.fao.org/ag/agl/aglw/aquastat/main/index.stm). A documentation of the source data used in these updates as well as the most recent version of the Global Map of Irrigation Areas is available at the web page of the mapping project (http://www.fao.org/ag/agl/aglw/aquastat/irrigationmap/index.stm).

In this paper we present the most recent version 3.0 of the Global Map of Irrigation Areas, which shows the fraction of 5 arc minutes by 5 arc minutes cells that was equipped for irrigation around the year 2000. To our knowledge, this is the only global data set of irrigated areas that is not primarily based on remote sensing information. We describe the mapping methodology (Sect. 2) and then we present the mapping results (Sect. 3). The focus of this paper is on an assessment of the map quality which is based on two indicators of map quality and a comparison to irrigated areas as identified in global and continental land cover maps that are based on remote sensing (Sect. 4). Finally, we draw conclusions with respect to the recommended use of the data set (Sect. 5).

2 DATA AND METHODS

The global map of irrigation areas was developed by combining sub-national irrigation statistics with geospatial information on the position and extent of irrigation schemes to compute the fraction of 5 arc minute cells that was equipped for irrigation, which is called irrigation density (Fig. 1). In the following, we provide a concise description of the mapping methodology. A detailed description is given in Siebert and Döll (2001).

Irrigation statistics for 10 825 sub-national units (e.g. districts, counties, provinces, governorates, river basins), from national census surveys and from reports available at FAO, World Bank and other international organizations, were used to develop the most recent map irrigation. Due to several reasons (e.g. crop rotation, water shortage, damage of infrastructure)

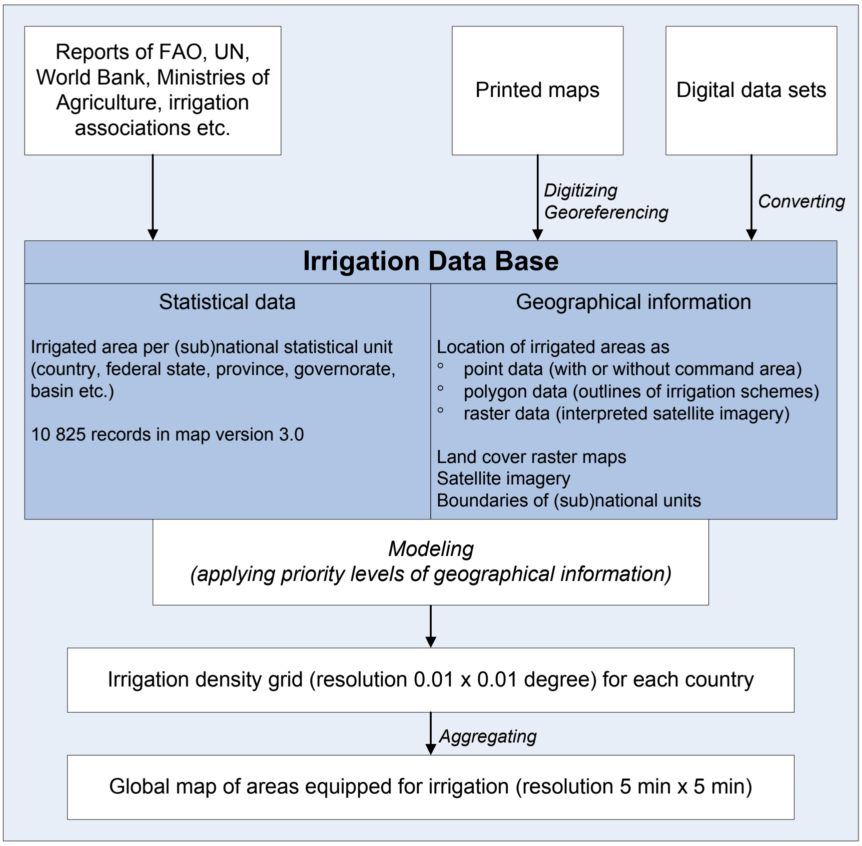

Fig. 1. Scheme of mapping methodology used to develop the Global Map of Irrigation Areas.

the area actually irrigated maybe significantly lower than the area equipped for irrigation. However, some countries report the area that was actually irrigated in the year of the census. Statistics for the year closest to 2000 were used if statistics for more than one year have been available. For countries, where the irrigation statistics reported by the FAO AQUASTAT database were assumed to be more representative, the collected sub-national statistics were scaled so that the sum of the irrigated area equals the area equipped for irrigation as given by AQUASTAT at the country level.

In order to distribute irrigated area within the sub-national units, geospatial information on position and extent of irrigated areas was derived by digitizing hundreds of irrigation maps available in reports of FAO, World Bank, irrigation associations or national ministries of agriculture. Additionally, information from several atlases or inventories based on remote sensing available in digital format was utilized. For most of the countries, more than one data source was used. As the relevance and reliability of the maps varies, it was necessary to decide which geospatial record should be used in a specific sub-national unit. This was realized by applying a priority level to each record. Only if the extent of all digitized irrigated areas with the highest priority level was smaller than the total irrigated area reported for the specific sub-national unit, also records with the second highest priority were considered. This distribution process was repeated down to the next lower priority level until the sum of irrigated area in the map was equal to the irrigated area in the sub-national statistics. Several different criteria have been used to assign priorities to geospatial information, for example:

- the scale and publishing date of the maps
- the type of map (simple sketch or drawing to scale)
- how the background information for the maps was collected (by ground based mapping, survey or via remote sensing)
- if only the position or also the extent of the irrigation schemes was provided.

In many sub-national units, lack of geospatial information on irrigation made is necessary to use indirect information to infer areas within the sub-national unit where irrigation is probable. Such information includes areas where the main irrigated crops are grown, or cultivated areas in very arid regions. For arid regions, remote sensing data were additionally used to verify the available maps. If no direct or indirect information about the spatial distribution of irrigation within a sub-national unit was available, irrigated area was distributed according to a global land cover data set (USGS, 2000) to all areas classified as: "Dryland Cropland and Pasture", "Irrigated Cropland and Pasture", "Cropland / Grassland Mosaic", "Cropland / Woodland Mosaic", "Grassland", "Shrubland", "Mixed Shrubland / Grassland", "Savanna", "Herbaceous Wetland" or "Wooded Wetland".

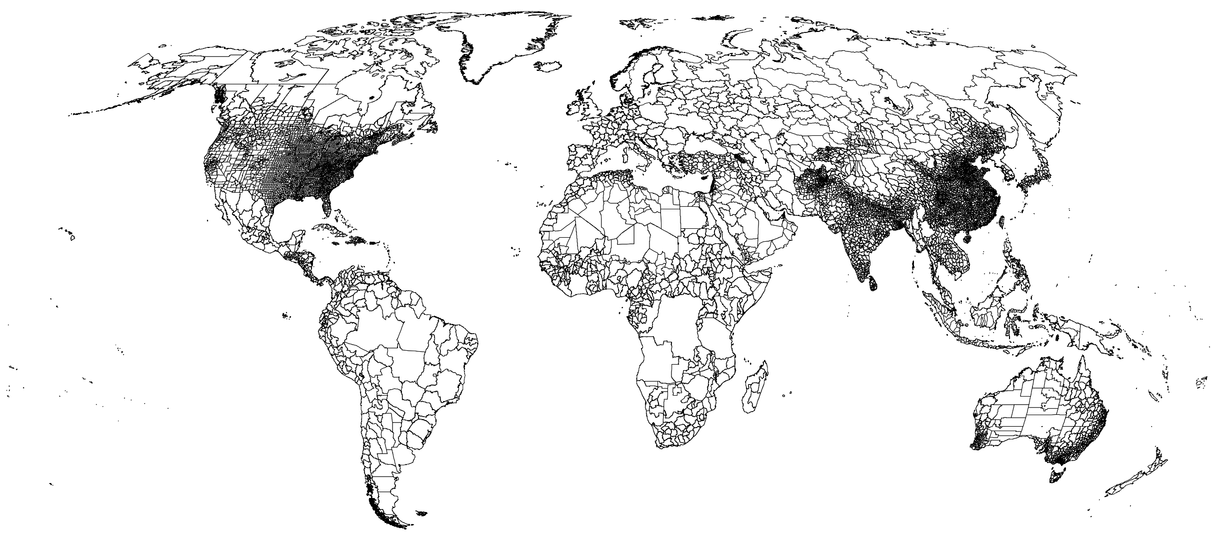

Fig. 2. Location and extent of the 10 825 sub-national units with information on area equipped for irrigation (or areas actually irrigated) that was used to develop the Global Map of Irrigation Areas Version 3 (Robinson projection).

3 RESULTS

The total area equipped for irrigation in map version 3 of the Global Map of Irrigation Areas is 273.7 Mio ha (Table 1). About 69% of the total irrigated area is located in Asia, 17% in America, 9% in Europe, 4% in Africa and 1% in Oceania. The largest values of irrigated area on the country level are those for India (57.3 Mio ha), China (53.8 Mio ha) and the United States (27.9 Mio ha) (Table A1). More than 20% of the cultivated area are equipped for irrigation in the following world regions: South Asia (37.6%), Central Asia (34.9%), Near East (30.6%) and Northern Africa (20.5%). In Western Africa and Greenland, the cultivated areas are almost completely rainfed (Table 1).

The largest contiguous areas of high irrigation density are found in North India and Pakistan along the rivers Ganges and Indus, in the Hai He, Huang He and Yangtze basins in China, along the Nile river in Egypt and Sudan, in the Mississippi-Missouri river basin and in parts of California. Other areas of high irrigation density with regional importance are located along the Snake and Columbia rivers in the northwestern United States, along the western coasts of Mexico and Peru, in central Chile, in the rice growing areas along the border

Table 1. Number of countries (n_{cnt}), area equipped for irrigation ($area_{irri}$), percentage of cultivated area equipped for irrigation ($irri_{perc}$), average area of the sub-national units ($area_{admav}$) and average area of the sub-national units weighted by irrigation density ($area_{admw}$) for the entire world and 19 world regions

Region	n_{cnt}	$area_{irri}$ (ha)	$irri_{perc}$ (%)	$area_{admav}$ (ha)	$area_{admw}$ (ha) (*IND_A*)
North America	2	28 698 918	12.4	512 287	243 101
Central America	32	7 859 309	18.3	971 195	938 242
South America	14	10 102 130	8.1	9 065 021	2 744 775
Northern Africa	5	5 804 793	20.5	3 860 121	448 374
Western Africa	24	1 005 495	1.1	4 939 529	2 520 777
Eastern Africa	13	3 546 276	7.5	4 404 625	1 918 066
Southern Africa	11	1 880 337	4.6	7 445 113	3 408 977
Western Europe	15	2 131 807	6.9	7 387 722	4 385 796
Eastern Europe	18	7 556 000	8.1	11 745 784	13 696 554
Southern Europe	9	10 022 456	18.0	2 222 626	2 635 819
Russian Federation	1	4 878 000	3.9	19 234 888	5 028 884
Near East	16	18 839 608	30.6	2 075 844	834 586
Central Asia	9	14 854 955	34.9	1 045 886	323 565
East Asia	7	59 875 193	19.4	457 947	161 378
South Asia	7	77 236 998	37.6	523 047	395 817
South-East Asia	11	16 793 335	17.7	1 603 949	681 205
Oceania	26	2 637 835	4.7	623 907	147 544
Greenland	1	0	0.0	214 464 485	n.a.
World	221	273 723 445	16.3	1 241 912	330 249

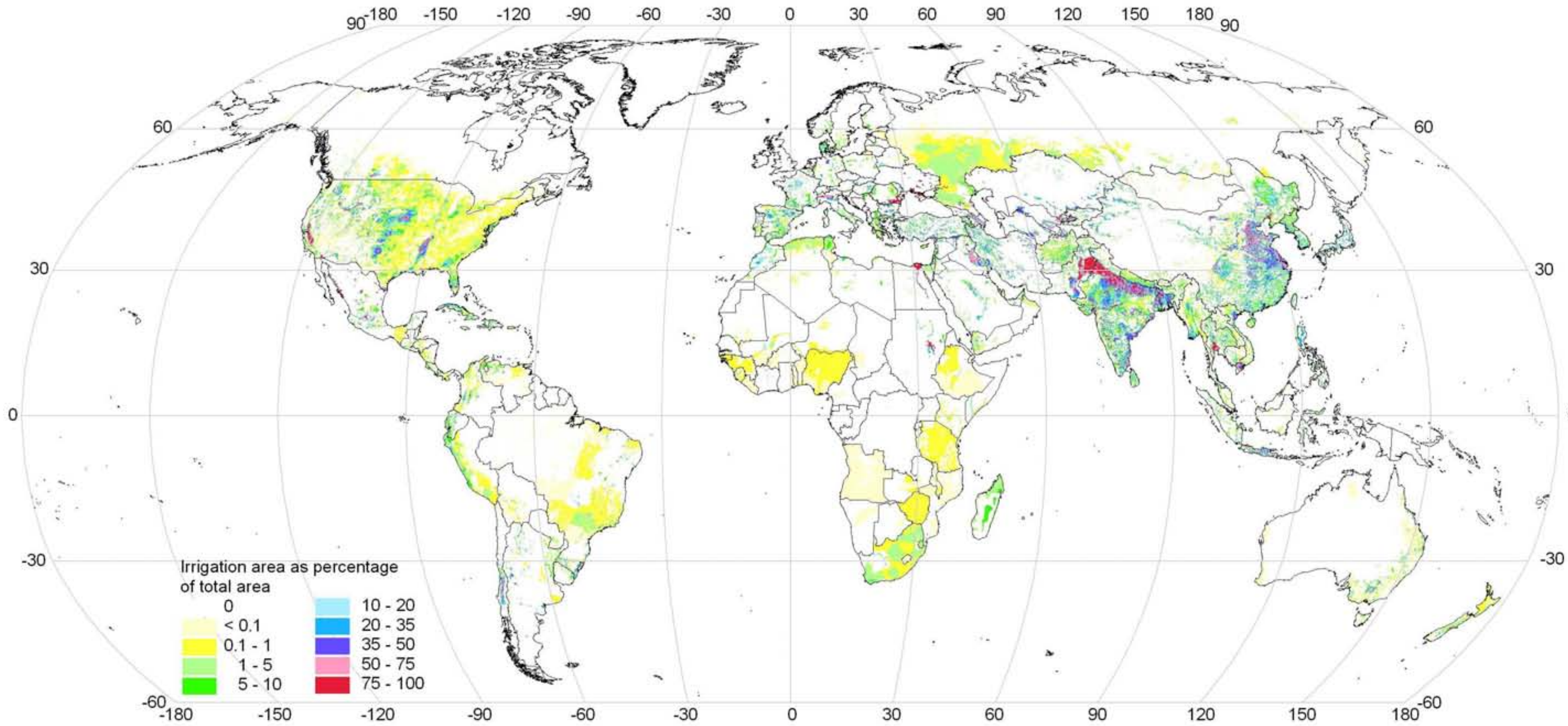

Fig. 3. Global Map of Irrigation Areas Version 3: Percentage of 5-minute grid cell area that was equipped for irrigation around the year 2000 (Robinson projection).

between Brazil and Uruguay, along the Danube and Po rivers in Europe, in the Euphrates-Tigris basin in Iraq and Turkey, the Aral sea basin, the Amu Darya and Syr Darya river basins, the Brahmaputra basin in China and Bangladesh, the Mekong delta in Vietnam, the plain around Bangkok in Thailand, the island of Java (Indonesia) and the Murray-Darling basin in Australia. Smaller irrigation areas are spread across almost all populated parts of the world (Fig. 3).

4 ASSESSMENT OF MAP QUALITY

A common method to assess the quality of a macro-scale data set is to compare it with independent smaller-scale information at selected locations and then to draw conclusions with respect to the quality at these locations and in general. Here, however, all data on irrigated areas known to the authors (at appropriate scales) were used to compile the map itself and could thus not be used for a quality assessment. Besides, any generalization would not be possible, as the map quality is different in each individual sub-national unit depending on the data sources used in the specific case. Instead, to assess the quality of the Global Map of Irrigation Areas, two indicators were computed that take into account the geospatial information density (Sect. 4.1), and the map was compared to the irrigated areas of two global land cover inventories that are based on remote sensing (Sect. 4.2).

4.1 Indicators of map quality

Because of the mapping methodology (see Sect. 2), the quality of the mapping product is strongly influenced by the density and reliability of the used information. Thus the map quality differs from country to country and even within countries.

Two country-specific indicators were developed to quantify the density of information used as input data sources: indicator A (*IND_A*) represents the density of the used sub-national irrigation statistics while indicator B (*IND_B*) represents the density of the available geospatial records on position and extent of irrigated areas. Marks derived from the two indicators were combined to obtain a mark for the overall map quality for each country (Table A1).

While the density of information could be assessed, it was in general not possible to estimate the reliability of the data sources. Some local studies show that there may be large differences between census-based sub-national irrigation statistics and the extent of areas equipped for irrigation observed in reality. Döll and Hauschild (2002), for example, presented best guess estimates of local experts for area equipped for irrigation in the two semi-arid Brazilian states of Piauí and Ceará that were 28% (Piauí) and 45% (Ceará) lower than the corresponding results of the Brazilian agricultural census. The reliability of geo-spatial data on location and extent of irrigation schemes may be also uncertain. It is well known, for example, that many of the former irrigation schemes in Eastern Europe and the former Soviet Union do not exist anymore. But lack of information made it impossible to verify the available data on the global scale systematically. However, the overall map quality mark was downgraded for a country when it was found that sub-national statistics coming from different sources disagreed, when statistics were found to be incomplete or when geo-spatial information was found to be out of date.

4.1.1 Indicator for the density of sub-national irrigation statistics (IND_A)

A possible indicator for the density of sub-national irrigation statistics is the arithmetic mean of the size of the sub-national units. However, there are some countries where irrigation is concentrated in some small sub-national units while in other very large sub-national units of the same country there is no or very little irrigation. One of these countries is Canada, with a lot of irrigation in some small census divisions in southern Alberta and no irrigation at all in several very large census divisions in the northern part. To avoid that large sub-national units without significant irrigation have a negative impact on the indicator, the size of each sub-national statistical unit is weighted by the irrigation density in the sub-national unit relative to the irrigation density in the entire region (country, world region or global), and

$$IND\_A_{reg} = \frac{area_{reg}}{\sum_{adm=1}^{n} (irridens_{adm} / irridens_{reg})} \tag{1}$$

with

$$irridens_{adm} = \frac{irarea_{adm}}{area_{adm}} \tag{2}$$

where IND_A_{reg} is the average weighted size of the sub-national units in region *reg* (ha), $area_{reg}$ is the surface area of region *reg* (ha), $irridens_{adm}$ is the irrigation density in sub-national unit *adm* (-), $irridens_{reg}$ is the irrigation density in region *reg* (-), *n* is the number of sub-national units in region *reg*, $irarea_{adm}$ is the irrigated area in sub-national unit *adm* (ha) and $area_{adm}$ is the surface area in sub-national unit *adm* (ha). Simplifying Eq. 1 results in

$$IND\_A_{reg} = \frac{irarea_{reg}}{\sum_{adm=1}^{n} irridens_{adm}} \quad (3)$$

where $irarea_{reg}$ is the total irrigated area in region *reg* (ha).

IND_A would be equal the arithmetic mean of the size of sub-national units in a region if the irrigation density would be the same in all sub-national units of the region. If all irrigated area would be concentrated in only one sub-national unit, *IND_A* would be equal to the size of this sub-national unit. *IND_A* would be lower than the arithmetic mean of the size of the sub-national units if the irrigation density is higher in small sub-national units than in the larger sub-national units.

A comparison of the arithmetic mean of the size of sub-national units ($area_{admav}$) and IND_A on the country level (Table A1) or per region (Table 1) shows that *IND_A* is smaller in most cases. This indicates that the density of irrigation statistics is higher in areas where irrigation is important (areas of high irrigation density). However, there are also exceptional cases, e.g. the countries of Azerbaijan, Cameroon, Fiji (Table A1) or the regions of Eastern and Southern Europe (Table 1).

4.1.2 Indicator for the density of geo-spatial records (IND_B)

The second indicator (*IND_B*) was developed to give an estimate on the density of geospatial information used to assign irrigated area to specific cells within the sub-national units. *IND_B* was computed as the fraction of irrigated area that could be assigned to specific grid cells by using geospatial records on the position and extent of known irrigation projects.

4.1.3 Mark for the overall map quality at the country level

Depending on the computed indicator values, the marks excellent, very good, good, fair, poor or very poor were given to each country for both of the indicators *IND_A* and *IND_B* (Table 2). A mark for the overall quality was given assuming that the types of information that are reflected by the two indicators can replace each other. Thus, in general, the mark for the overall map quality was set to the better of the two marks given according to *IND_A* and *IND_B* (Table A1). If, for example, the location and extent of almost all irrigation projects in a country is known then the overall quality of the map should be excellent independently from the mark given according to the weighted size of sub-national units. On the other hand, if the size of the sub-national statistical units is very small (in an extreme case smaller than the map resolution of 5 arc minutes), the overall quality of the map should also be excellent even if there are no geo-spatial records on the position of irrigation schemes within the sub-national units available.

In 64 out of 211 countries, however, the mark for the overall map quality was downgraded because there were doubts regarding the reliability of the used information (Table A1). One example is Cyprus. Based on the average weighted size of the sub-national units of 81 702 ha the mark for *IND_A* is excellent. The mark given according to *IND_B* is good, because an inventory of public irrigation schemes was available. The overall quality mark is set to good and not to excellent, because of lack of information for the Turkish part of the island. Another example is China, where the marks according to both of the indicators are very good. However, the overall map quality is estimated as good only, because there are doubts regarding the quality of information published in the statistical yearbooks (Heilig, 1999) and due to inconsistencies between irrigated areas derived from a land use atlas and the statistics published in the corresponding statistical yearbook. There are 27 countries where the overall map quality is estimated as very good but also 9 countries with a very poor map quality (all of the latter are located in Africa or Europe).

4.1.4 Mark for the overall map quality at the global level and in world regions

Marks for the overall mapping quality in world regions or at global scale were computed by combining the marks for the overall quality of the map at country level and the irrigated area in the corresponding countries (Table A1) as:

$$m_{reg} = \frac{irarea_{v\_good} + 2 * irarea_{good} + 3 * irarea_{fair} + 4 * irarea_{poor} + 5 * irarea_{v\_poor}}{irarea_{reg}} \quad (4)$$

where m_{reg} is the overall quality of irrigation map in region *reg*, $irarea_{v\_good}$, $irarea_{good}$, $irarea_{fair}$, $irarea_{poor}$ and $irarea_{v\_poor}$ represent the irrigated area of all countries in a region *reg* with very good, good, fair, poor or very poor map quality (ha) and $irarea_{reg}$ is the irrigated area in region *reg* (ha).

At the level of world regions, map quality in North America (overall mark 1.03), Oceania (1.44), Central Asia (1.63), South-East Asia (1.87) and South Asia (1.94) is best. Western Africa (3.39), Southern Africa (3.85), Western Europe (3.97) and the Russian Federation (4.00) have the worst map quality. At the global scale, the overall map quality is good (2.05). About 50 Mio ha of areas equipped for irrigation are located in countries where map quality is estimated to be very good, 171 Mio ha in countries with good map quality, 43 Mio ha in countries with fair map quality, 9 Mio ha in countries with poor map quality and 0.7 Mio ha in countries with very poor map quality. Consequently about 81% of the total irrigated area of the world is located in countries where the map quality is assessed to be very good or good (Table 3).

Table 2. Assignment of marks dependent on the quantities of the map quality indicators for the weighted average size of sub-national statistical units (*IND_A*) and the percentage of irrigated area assigned to grid cells by using geospatial records on position and extent of known irrigation schemes (*IND_B*)

Mark	Indicator *IND_A* (ha)	Indicator *IND_B* (%)
Excellent	< 100 000	90 - 100
Very good	100 000 – 250 000	70 - 90
Good	250 000 – 500 000	50 - 70
Fair	500 000 – 1 000 000	25 - 50
Poor	1 000 000 – 3 000 000	10 - 25
Very poor	> 3 000 000	< 10

Table 3. Sum of area equipped for irrigation in countries with very good ($irarea_{v\_good}$), good ($irarea_{good}$), fair ($irarea_{fair}$), poor ($irarea_{poor}$) and very poor ($irarea_{v\_poor}$) map quality and resulting final mark for map quality for the entire world and 19 world regions

Region	$irarea_{v\_good}$ (ha)	$irarea_{good}$ (ha)	$irarea_{fair}$ (ha)	$irarea_{poor}$ (ha)	$irarea_{v\_poor}$ (ha)	Final mark
North America	27 913 872	785 046	0	0	0	1.03
Central America	65 608	539 542	7 251 160	3000	0	2.92
South America	0	2 231 334	7 752 616	118 180	0	2.79
Northern Africa	0	3 606 150	2 198 643	0	0	2.38
Western Africa	0	113 799	405 546	466 935	19 215	3.39
Eastern Africa	17 630	1 981 720	1 158 017	360 785	28 124	2.55
Southern Africa	0	150 857	47 781	1 606 699	75 000	3.85
Western Europe	0	0	602 120	989 687	540 000	3.97
Eastern Europe	340 000	307 000	6 618 000	282 000	9000	2.91
Southern Europe	0	3 900 456	6 122 000	0	0	2.61
Russian Federation	0	0	0	4 878 000	0	4.00
Near East	403 645	14 834 051	3 601 912	0	0	2.17
Central Asia	7 708 097	4 991 658	2 155 200	0	0	1.63
East Asia	525 528	57 832 365	1 517 300	0	0	2.02
South Asia	4 958 127	72 278 871	0	0	0	1.94
South-East Asia	5 565 415	7 821 600	3 406 320	0	0	1.87
Oceania	2 056 580	372	580 882	0	0	1.44
Greenland	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
World	49 554 503	171 374 820	43 417 497	8 705 286	671 339	2.05

More than 20% of the cultivated area is equipped for irrigation in Northern Africa, Near East, Central Asia and South Asia (Table 1). The overall map quality mark in these regions is best in Central Asia (1.63) and worst in Northern Africa (2.38) (Table 3). The overall map quality mark for these four regions is 1.96. 93% of the total irrigated area in this region is located in countries where map quality is assessed to be very good or good. Therefore it can be stated that the map quality is better than average for regions where irrigation is important.

The weighted arithmetic mean of the size of sub-national units at the global scale is 330 249 ha. This is close to the size of one 0.5 degree grid cell at the equator. This indicates, that the use of the map can be recommended in general for global or regional studies at this resolution. The overall quality of the map at the global scale (2.05) indicates, that the use of the map can also be recommended for global studies performed on the map resolution of 5 arc minutes. For studies performed on the country or regional scale, we recommend the use of the Global Map of Irrigation Areas only if the overall map quality was estimated as very good (Table A1) or better than 2.5 (Table 3).

4.2 Comparison to global land cover data sets

To further assess the quality of the Global Map of Irrigation Areas, it was compared to results of global land cover classifications based on remote sensing which distinguish in their classification irrigated and rainfed agriculture at the global scale (Global Land Cover Characterization GLCC, USGS, 2000) or at least for some world regions (Global Land Cover 2000 database GLC2000, European Commission, Joint Research Centre, 2003). Both data sets have a resolution of 1 km by 1 km. Please note that they were not developed with the focus on mapping irrigated areas, and that the land cover class irrigated agriculture is only one of many others.

GLCC was derived from 1-km Advanced Very High Resolution Radiometer (AVHRR) 10-day composites spanning a 12-month period (April 1992 - March 1993). In addition, other key geographic data such as digital elevation data, ecoregions interpretations, and country or regional-level vegetation and land cover maps have been used in the classification. The methodology used to develop GLCC is described in Loveland et al. (2000). Dataset and documentation are available at http://lpdaac.usgs.gov/glcc/glcc.asp.

GLC2000 was developed by using 14 months of daily 1-km resolution satellite data acquired over the whole globe by the VEGETATION instrument on-board the SPOT 4 satellite and delivered as multi-channel daily mosaics. The monitoring period was from 1

November 1999 to 31 December 2000. Irrigated and rainfed agriculture was distinguished in the regional products for Africa, Europe, South Asia and South-East Asia only. Dataset and documentation are available at http://www-gvm.jrc.it/glc2000/defaultGLC2000.htm.

The area classified as irrigated in these data sets was summarized for each country and compared to the corresponding irrigation statistics as used for the Global Map of Irrigation Areas (Table A1). The two remote sensing based data sets detected the area that was actually irrigated during the monitoring period while the statistics used to develop the Global Map of Irrigation Areas depict, for most countries, the area equipped for irrigation, which includes all areas having irrigation infrastructure. Therefore it can be expected that the irrigated areas of the remote sensing products are somewhat smaller than the values of the irrigation statistics. However, the result of the comparison shows that there is hardly any agreement between the statistical data and the irrigated areas of GLCC and GLC2000 even on the country level. The difference between irrigated areas from the statistics and from remote sensing was smaller than 20% for only seven countries in the case of GLCC, and for only three countries in the case of GLC2000. Additionally there is also hardly any agreement between the two land cover data sets (Table A1). Certainly, census based statistics may have a high degree of uncertainty, depending often on the importance of irrigation for a country. However, the large discrepancies in the most countries do indicate that the estimates of the extent of irrigated areas as derived from the land cover classification are not very reliable.

A second comparison was performed at the scale of 5 arc minutes. The cells of the two land cover classifications were aggregated to the 5 arc minutes resolution, and the percentage of each 5 minute cell that is irrigated was computed (Figs. 4 and 5). The comparison of the Global Map of Irrigation Areas (Fig. 3) to GLCC shows that the best agreement exists in Egypt, Western China and North America (although the many irrigation areas along the Mississippi and the scattered small scale irrigation in the Eastern US are missing in GLCC). In all other regions there are large discrepancies. For example most of the important irrigation areas in the Ganges and Indus basins are missing in GLCC. Instead, large parts in South-East India appear to be irrigated. Most of the irrigation schemes in Africa, Europe, South America, Australia and on the Arabian Peninsula are missing in GLCC, while other areas in Myanmar, Thailand and Eastern China are irrigated very densely. The agreement between the Global Map of Irrigation Areas and GLC2000 is good for the Nile basin and parts of South Asia (Myanmar, Thailand, Vietnam, upper Indus and upper Ganges basins). In all the other regions there are large discrepancies. The irrigated areas in many parts of Africa, Europe and South-East Asia are missing in GLC2000, while irrigation density in India is mostly very high.

Not only with respect to the country values but also with respect to the spatial distribution of irrigated areas within countries, there is also very little agreement between the two land cover classifications themselves (Figs. 4 and 5).

There are several reasons why the remote sensing based global land cover inventories failed to classify irrigated areas in many regions. First of all, the methodology used in the land cover classifications leads to the detection of the main land cover type for each grid cell, which would be irrigated agriculture if irrigation density is more than 50%, and something else if irrigation density is lower. Therefore, the land cover classification maps tend to overestimate irrigation density in the main irrigation areas as compared to the Global Map of Irrigation Areas, and on the other hand many of the smaller irrigation areas are missing. Second, a successful detection of irrigated areas in more humid regions requires a lot of background knowledge on cropping practices, weather, soil conditions and agricultural management, which is not available on the global scale at the required resolution. The results of the land cover classifications are better in arid regions if the irrigation schemes are large enough. The irrigated areas along the Nile River or at the fringe of the Taklamakan desert in Western China are detected very well while many of the oases on the Arabian Peninsula or in Northern Africa are classified as scrubland or grassland because they are much smaller than the resolution of the used satellite imagery.

Please remember that the methodology used in the land cover classification was not developed with the focus on irrigated areas. A methodology for remote sensing based global irrigation mapping was developed by researchers at the International Water Management Institute (IWMI). The methodology is actually being used in an ongoing global irrigation mapping project (see http://www.iwmidsp.org/iwmi/info/research.asp).

5 CONCLUSIONS

The quality of the Global Map of Irrigation Areas, which was compiled by combining sub-national irrigation statistics for 10 825 statistical units with geo-spatial information on the location and extent of irrigation schemes, differs strong between countries and world regions, depending on the density and reliability of the used data sources. The overall map quality of version 3 of the global irrigation map is estimated as good. Improvements of the irrigation map are in particular necessary for the continents of Africa and Europe and for the Russian Federation.

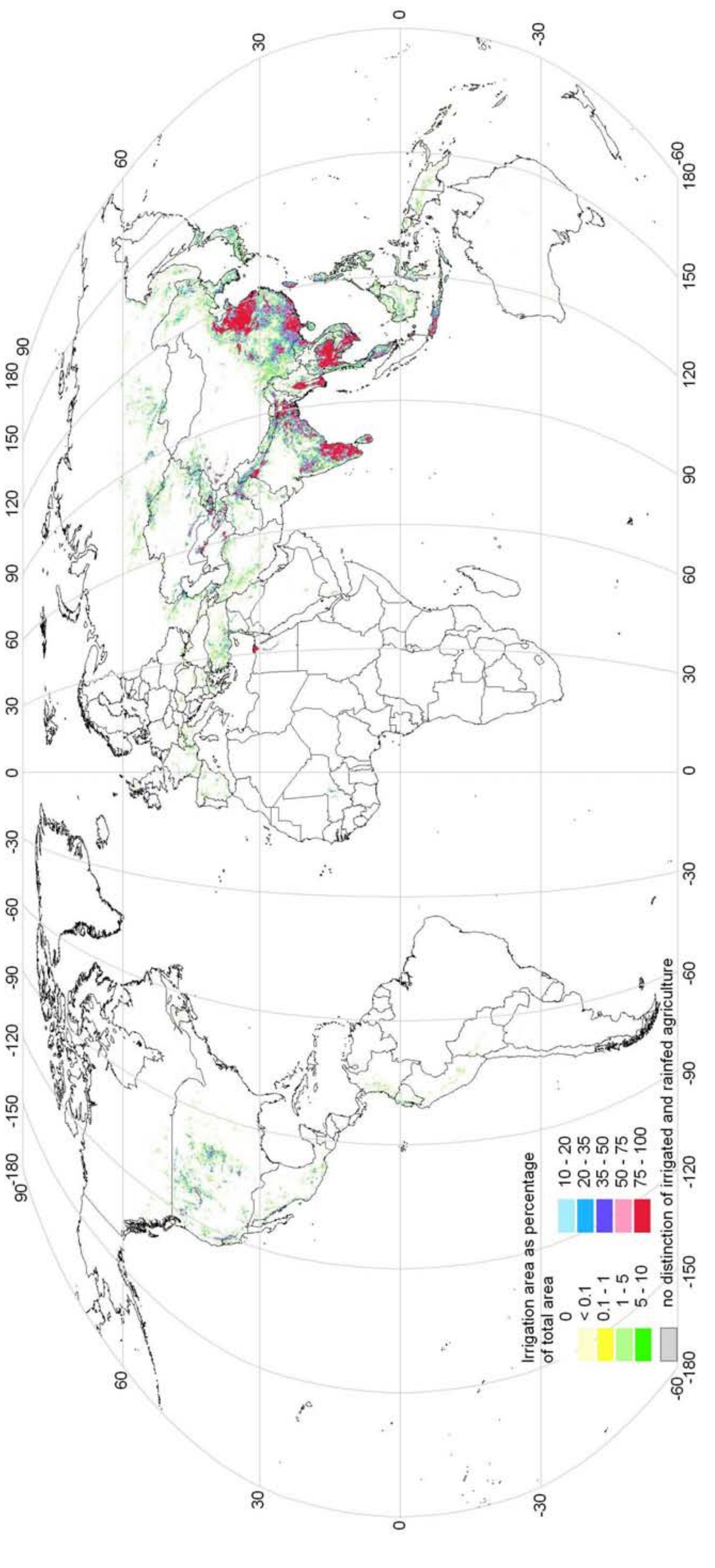

Fig. 4. Percentage of 5-minute grid cell area that was classified as irrigated agriculture in the GLCC (in Robinson projection).

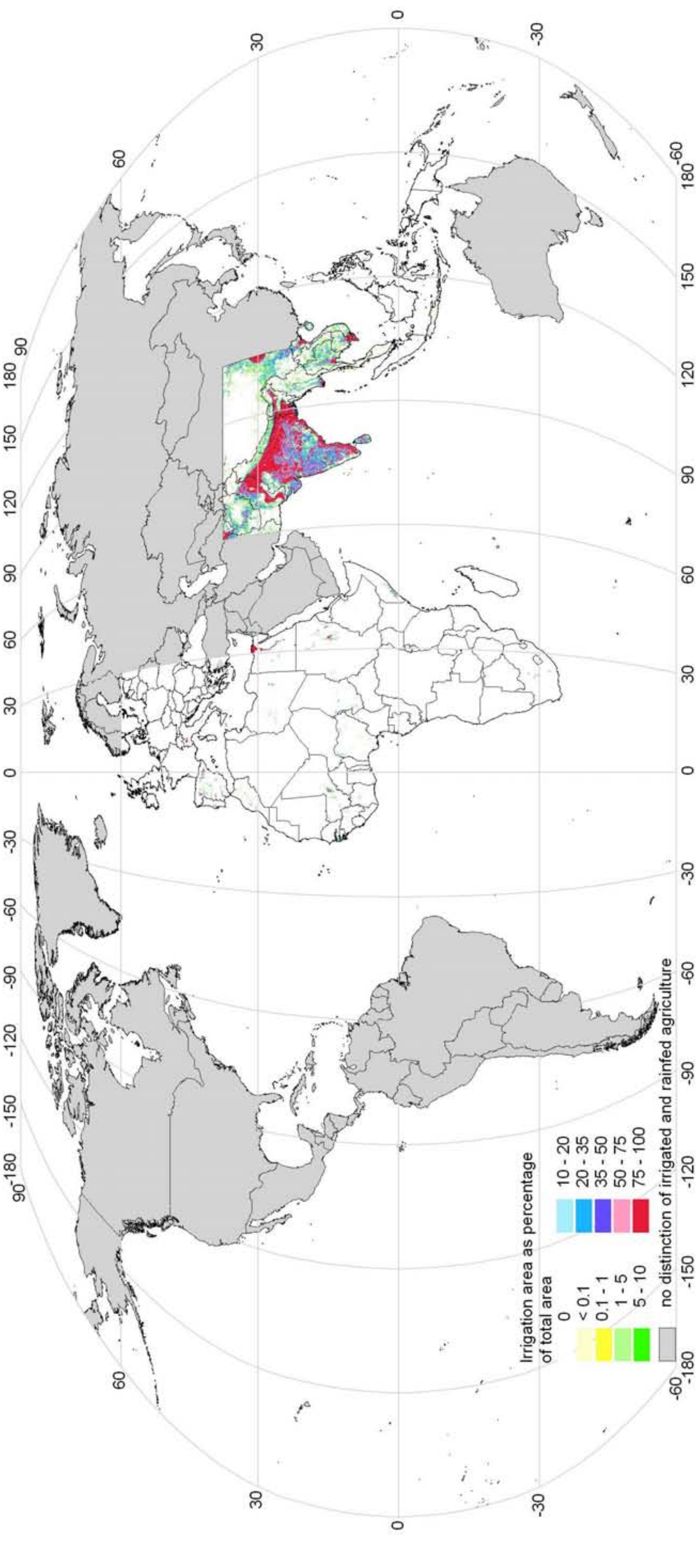

Fig. 5. Percentage of 5-minute grid cell area that was classified as irrigated agriculture in the GLC2000 data set (Robinson projection).

The quality of the map allows to recommend the use of the data set for global studies or for studies focusing on the world regions of North America, Northern Africa, Near East, Central Asia, East Asia, South Asia, South-East Asia or Oceania. Additionally the map quality was estimated as very good for 27 countries so that the use of the Global Irrigation Map for studies performed for these countries can also be recommended if there is a lack of similar country specific data sets and if the map resolution of 5 arc minutes is sufficient.

The comparison to two global land cover inventories indicates that these data sets should not be used to extract irrigated areas. The main advantage of the Global Map of Irrigation Areas is that the total area equipped for irrigation in any of the sub-national units is equal to the irrigated area as reported by census-based statistics. This is important for many applications of the map, e.g. for the calculation of irrigation water use. The mapping methodology allows to easily incorporate new information and thus to benefit from advancements made by national census and mapping authorities.

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APPENDIX

Table A1. Assessment of map quality for countries. Number of sub-national units (n_{adm}), area equipped for irrigation ($area_{irri}$), average area of the sub-national units ($area_{admav}$), average area of the sub-national units weighted by irrigation density (*IND_A*), map quality based on indicators A and B (considering the weighted average size of sub-national units and the availability of geospatial records to distribute irrigated areas within sub-national units, respectively), overall map quality, and irrigated area in the Global Land Cover Characterization (USGS, 2000) data set GLCC, and irrigated area in the Global Land Cover 2000 data set GLC2000 (European Commission, Joint Research Centre, 2003) (GLC2000), for all countries where irrigation was reported.

Country	Region	n_{adm}	$area_{irr}$ (ha)	$area_{admav}$ (ha)	*IND_A* (ha)	Map quality			Irrigated area in other datasets (ha)	
						Based on indicator A	Based on indicator B	**overall**	GLCC	GLC2000
Afghanistan	Central Asia	329	3 199 070	195 012	100 129	very good	good	**very good**	1 556 249	6 251 633
Albania	Eastern Europe	1	340 000	2 869 803	2 869 803	poor	very good	**very good**	19 055	0
Algeria	Northern Africa	48	555 500	4 832 921	356 678	good	poor	**fair**	0	1 385
Andorra	Southern Europe	1	150	46 040	46 040	excellent	good	**good**	1 075	0
Angola	Southern Africa	1	75 000	125 157 722	125 157 722	very poor	very poor	**very poor**	0	0
Antigua and Barbuda	Central America	1	130	54 524	54 524	excellent	very poor	**good**	0	n.a.
Argentina	South America	24	1 437 275	11 580 985	10 013 677	very poor	good	**fair**	1 554	n.a.
Armenia	Central Asia	39	286 027	75 942	53 342	excellent	good	**very good**	14 107	n.a.
Australia	Oceania	1322	2 056 580	582 328	116 419	very good	good	**very good**	26 270	n.a.
Austria	Western Europe	1	46 000	8 363 819	8 363 819	very poor	fair	**fair**	5 883	0
Azerbaijan	Central Asia	7	1 453 318	1 231 120	2 078 392	poor	good	**good**	712 368	n.a.
Bahrain	Near East	9	4 060	6 925	3 774	excellent	very good	**very good**	0	n.a.
Bangladesh	South Asia	64	3 751 045	213 733	202 300	very good	good	**very good**	7 466 244	10 339 672
Barbados	Central America	1	1 000	44 964	44 964	excellent	good	**very good**	0	n.a.
Belarus	Eastern Europe	1	115 000	17 650 795	17 650 795	very poor	poor	**poor**	419	n.a.
Belgium	Western Europe	1	40 000	3 046 628	3 046 628	very poor	poor	**poor**	6 761	0
Belize	Central America	1	3 000	2 229 079	2 229 079	poor	fair	**poor**	0	n.a.
Benin	Western Africa	6	10 236	1 933 320	966 604	fair	good	**fair**	0	15 121
Bhutan	South Asia	20	38 734	198 897	159 021	very good	very good	**very good**	63 698	214 268
Bolivia	South America	10	128 240	10 877 707	6 741 935	very poor	good	**fair**	31 583	n.a.
Bosnia Herzegovina	Eastern Europe	1	2 000	5 034 643	5 034 643	very poor	very poor	**very poor**	3 158	0
Botswana	Southern Africa	6	1 381	9 659 377	712 669	fair	fair	**fair**	0	0

Country	Region	n_{adm}	$area_{irr}$ (ha)	$area_{admav}$ (ha)	IND_A (ha)	Map quality			Irrigated area in other datasets (ha)	
						Based on indicator A	Based on indicator B	**overall**	GLCC	GLC2000
Brazil	South America	30	2 656 284	28 355 229	18 399 822	very poor	fair	**fair**	0	n.a.
Brunei	South-East Asia	1	1 000	590 083	590 083	fair	fair	**fair**	41 513	0
Bulgaria	Eastern Europe	1	800 000	11 034 060	11 034 060	very poor	fair	**fair**	86 372	0
Burkina Faso	Western Africa	10	24 331	2 757 477	2 723 515	poor	fair	**fair**	1 337	28 945
Burundi	Eastern Africa	8	14 400	338 353	24 229	excellent	very poor	**good**	0	0
Cambodia	South-East Asia	21	284 172	867 100	537 055	fair	very good	**very good**	7 346 838	1 887 695
Cameroon	Western Africa	36	20 970	1 300 415	1 739 517	poor	very good	**fair**	0	65 537
Canada	North America	270	785 046	3 664 480	693 806	fair	good	**good**	189 254	n.a.
Cape Verde	Western Africa	1	2 779	404 523	404 523	good	very poor	**fair**	0	0
Central African Republic	Western Africa	24	135	2 595 067	8 845 312	very poor	excellent	**good**	0	0
Chad	Western Africa	11	14 020	11 585 520	2 872 441	poor	very good	**good**	0	130 753
Chile	South America	13	1 900 000	5 801 591	2 547 695	poor	good	**good**	0	n.a.
China	East Asia	2414	53 823 000	387 005	149 312	very good	very good	**good**	110 027 672	n.a.
Colombia	South America	33	900 000	3 463 207	2 127 824	poor	fair	**fair**	305 919	n.a.
Comoros	Eastern Africa	4	130	48 447	23 839	excellent	excellent	**very good**	0	0
Congo, Dem. Rep.	Western Africa	1	10 500	233 798 683	233 798 683	very poor	very good	**good**	0	0
Congo, Rep	Western Africa	2	217	17 158 886	590 730	fair	very poor	**poor**	0	0
Costa Rica	Central America	8	103 084	642 259	944 203	fair	fair	**fair**	0	n.a.
Cote D'Ivoire	Western Africa	1	72 750	32 316 231	32 316 231	very poor	good	**fair**	0	27 326
Croatia	Eastern Europe	1	3 000	5 675 863	5 675 863	very poor	very poor	**very poor**	3 224	0
Cuba	Central America	15	870 319	734 561	774 494	fair	poor	**fair**	0	n.a.
Cyprus	Near East	9	55 813	102 795	81 702	excellent	good	**good**	9 427	0
Czech Republic	Eastern Europe	1	24 000	7 868 122	7 868 122	very poor	poor	**poor**	55	0
Denmark	Western Europe	1	476 000	4 260 345	4 260 345	very poor	very poor	**very poor**	243	0
Djibouti	Eastern Africa	5	407	434 531	173 210	very good	very poor	**fair**	0	0
Dominican Republic	Central America	31	269 710	156 667	186 440	very good	good	**good**	0	n.a.
East Timor	South-East Asia	1	14 000	1 290 097	1 290 097	poor	fair	**fair**	141 290	0
Ecuador	South America	22	863 370	1 168 061	914 831	fair	fair	**fair**	714 920	n.a.
Egypt	Northern Africa	26	3 245 650	3 785 072	366 380	good	good	**good**	1 961 473	3 208 725
El Salvador	Central America	1	44 993	2 051 927	2 051 927	poor	very good	**good**	0	n.a.

Country	Region	n_{adm}	$area_{irr}$ (ha)	$area_{admav}$ (ha)	*IND_A* (ha)	Map quality			Irrigated area in other datasets (ha)	
						Based on indicator A	Based on indicator B	**overall**	GLCC	GLC2000
Eritrea	Eastern Africa	1	28 124	12 175 259	12 175 259	very poor	poor	**very poor**	0	4 621
Estonia	Eastern Europe	1	4 000	4 325 320	4 325 320	very poor	very poor	**very poor**	263	0
Ethiopia	Eastern Africa	9	160 785	12 584 053	10 197 682	very poor	fair	**poor**	0	14 895
Fiji	Oceania	2	3 000	967 209	1 838 800	poor	fair	**fair**	0	n.a.
Finland	Western Europe	1	64 000	31 286 011	31 286 011	very poor	very poor	**very poor**	1 039	n.a.
France	Southern Europe	22	2 000 000	2 490 354	2 743 917	poor	fair	**fair**	291 147	0
French Guyana	South America	1	2 000	8 362 955	8 362 955	very poor	fair	**fair**	0	n.a.
Gabon	Western Africa	26	4 450	1 021 554	1 476 439	poor	good	**fair**	0	0
Gambia	Western Africa	3	1 670	358 586	390 843	good	fair	**good**	0	71 670
Georgia	Central Asia	1	300 000	6 979 779	6 979 779	very poor	fair	**fair**	43 961	n.a.
Germany	Western Europe	15	531 120	2 370 523	3 076 418	very poor	fair	**fair**	16 555	0
Ghana	Western Africa	9	6 374	2 663 105	861 620	fair	very good	**good**	0	1 555
Greece	Southern Europe	1	1 422 000	13 212 760	13 212 760	very poor	fair	**fair**	297 326	647 003
Grenada	Central America	1	219	41 508	41 508	excellent	poor	**good**	0	n.a.
Guadeloupe	Central America	1	2 000	177 668	177 668	very good	good	**very good**	0	n.a.
Guam	Oceania	1	312	55 038	55 038	excellent	very poor	**good**	0	n.a.
Guatemala	Central America	22	129 803	494 303	375 233	good	good	**good**	0	n.a.
Guinea	Western Africa	23	92 880	1 068 124	1 537 311	poor	poor	**poor**	0	42 205
Guinea Bissau	Western Africa	1	17 115	3 370 176	3 370 176	very poor	very poor	**very poor**	0	108 149
Guyana	South America	10	150 134	2 112 413	432 368	good	fair	**good**	0	n.a.
Haiti	Central America	9	91 502	303 796	396 653	good	good	**good**	0	n.a.
Honduras	Central America	18	73 210	622 137	431 031	good	fair	**fair**	84	n.a.
Hungary	Eastern Europe	1	210 000	9 274 395	9 274 395	very poor	fair	**fair**	26 277	0
India	South Asia	555	57 291 407	577 832	418 698	good	good	**good**	64 989 028	152 440 746
Indonesia	South-East Asia	89	4 459 000	2 133 773	929 478	fair	good	**good**	11 630 619	516 156
Iran	Near East	25	6 913 800	6 488 740	4 599 816	very poor	good	**good**	1 908 232	n.a.
Iraq	Near East	18	3 525 000	2 399 113	1 218 600	poor	fair	**fair**	166 202	n.a.
Israel	Near East	33	183 408	67 738	31 251	excellent	good	**very good**	35 035	n.a.
Italy	Southern Europe	20	2 698 000	1 506 391	1 811 753	poor	fair	**fair**	239 901	344 425
Jamaica	Central America	14	25 214	79 097	110 296	very good	good	**very good**	0	n.a.
Japan	East Asia	47	3 129 000	794 798	702 829	fair	good	**good**	3 238 580	n.a.

Country	Region	n_{adm}	$area_{irr}$ (ha)	$area_{admav}$ (ha)	*IND_A* (ha)	Map quality			Irrigated area in other datasets (ha)	
						Based on indicator A	Based on indicator B	**overall**	GLCC	GLC2000
Jordan	Near East	8	76 912	1 126 990	294 032	good	fair	**fair**	362	n.a.
Kazakhstan	Central Asia	19	1 855 200	14 145 120	12 729 831	very poor	good	**fair**	5 263 375	n.a.
Kenya	Eastern Africa	8	66 610	7 308 011	1 382 698	poor	good	**fair**	0	0
Korea, Dem. Rep.	East Asia	1	1 460 000	12 244 011	12 244 011	very poor	good	**fair**	1 321 814	n.a.
Korea, Republic	East Asia	15	880 365	659 376	395 459	good	fair	**good**	1 682 588	n.a.
Kuwait	Near East	6	6 968	288 451	680 602	fair	very good	**very good**	0	n.a.
Kyrgyzstan	Central Asia	41	1 075 040	486 307	286 062	good	good	**good**	1 252 028	n.a.
Laos	South-East Asia	18	295 535	1 281 555	1 013 132	poor	very good	**very good**	1 579 030	660 757
Latvia	Eastern Europe	1	20 000	6 431 369	6 431 369	very poor	poor	**poor**	0	0
Lebanon	Near East	26	117 113	39 722	50 242	excellent	fair	**very good**	22 771	n.a.
Lesotho	Southern Africa	1	2 722	3 049 045	3 049 045	very poor	fair	**poor**	0	0
Liberia	Western Africa	1	2 100	9 612 261	9 612 261	very poor	very poor	**very poor**	0	0
Libya	Northern Africa	25	360 500	6 477 352	432 994	good	good	**good**	0	143 525
Lithuania	Eastern Europe	1	9 000	6 459 028	6 459 028	very poor	poor	**poor**	0	0
Macedonia	Eastern Europe	1	55 000	2 541 962	2 541 962	poor	poor	**poor**	14 873	0
Madagascar	Eastern Africa	6	1 087 000	9 868 007	8 236 266	very poor	fair	**fair**	0	0
Malawi	Southern Africa	10	28 000	1 185 072	490 930	good	good	**good**	0	0
Malaysia	South-East Asia	14	362 600	2 365 595	567 143	fair	good	**good**	5 617 450	135 570
Mali	Western Africa	34	191 470	3 689 200	3 241 291	very poor	fair	**fair**	326 681	653 718
Malta	Southern Europe	1	2 000	40 055	40 055	excellent	very poor	**fair**	0	0
Martinique	Central America	1	3 000	115 445	115 445	very good	fair	**good**	0	n.a.
Mauritania	Western Africa	13	49 200	8 026 288	4 147 985	very poor	good	**fair**	1 323	51 061
Mauritius	Eastern Africa	1	17 500	183 361	183 361	very good	good	**very good**	0	0
Mexico	Central America	32	6 104 956	6 121 135	4 072 214	very poor	fair	**fair**	1 956 154	n.a.
Moldova Rep.	Eastern Europe	1	307 000	3 388 941	3 388 941	very poor	very good	**good**	3 987	n.a.
Mongolia	East Asia	18	57 300	8 678 282	7 070 172	very poor	good	**fair**	138 701	n.a.
Morocco	Northern Africa	27	1 258 200	2 493 714	2 336 883	poor	good	**fair**	0	92 040
Mozambique	Southern Africa	10	116 715	7 880 772	5 426 595	very poor	very good	**good**	0	0
Myanmar	South-East Asia	14	1 841 320	4 783 485	3 921 831	very poor	fair	**fair**	13 091 993	3 582 744
Namibia	Southern Africa	10	6 142	8 246 880	7 608 665	very poor	good	**good**	0	0
Nepal	South Asia	75	1 168 349	196 349	143 668	very good	good	**very good**	2 067 770	2 463 348

Country	Region	n_{adm}	$area_{irr}$ (ha)	$area_{admav}$ (ha)	IND_A (ha)	Map quality			Irrigated area in other datasets (ha)	
						Based on indicator A	Based on indicator B	**overall**	GLCC	GLC2000
Netherlands	Western Europe	1	565 000	3 478 820	3 478 820	very poor	fair	**poor**	5 418	0
New Zealand	Oceania	16	577 882	1 679 748	2 996 306	poor	fair	**fair**	0	n.a.
Nicaragua	Central America	19	61 365	673 557	427 918	good	fair	**fair**	6 364	n.a.
Niger	Western Africa	8	66 480	14 845 330	2 353 231	poor	fair	**poor**	0	109 218
Nigeria	Western Africa	9	300 350	10 144 308	12 469 784	very poor	poor	**poor**	0	167 607
Northern Marianna Islands	Oceania	4	60	7 843	4 708	excellent	very poor	**good**	3 233	n.a.
Norway	Western Europe	1	127 000	31 435 582	31 435 582	very poor	poor	**poor**	1 053	n.a.
Oman	Near East	8	72 630	3 917 788	1 322 773	poor	very good	**very good**	123 569	n.a.
Pakistan	South Asia	112	14 417 464	771 245	490 643	good	good	**good**	3 393 750	25 964 976
Palestine	Near East	17	19 466	36 577	11 530	excellent	good	**very good**	0	n.a.
Panama	Central America	10	34 626	749 726	669 811	fair	poor	**fair**	595	n.a.
Paraguay	South America	1	67 000	40 033 587	40 033 587	very poor	poor	**poor**	0	n.a.
Peru	South America	25	1 195 228	5 186 247	2 540 813	poor	fair	**fair**	116 131	n.a.
Philippines	South-East Asia	12	1 550 000	2 476 588	2 420 277	poor	fair	**fair**	3 668 113	17 486
Poland	Eastern Europe	1	100 000	31 074 704	31 074 704	very poor	fair	**fair**	2 179	0
Portugal	Southern Europe	7	632 000	1 303 693	1 435 741	poor	good	**good**	17 812	100 129
Puerto Rico	Central America	79	37 079	11 348	12 715	excellent	fair	**very good**	0	n.a.
Qatar	Near East	1	12 520	1 125 261	1 125 261	poor	good	**good**	0	n.a.
Reunion	Eastern Africa	1	12 000	250 925	250 925	good	very poor	**good**	0	8 827
Romania	Eastern Europe	1	2 880 000	23 715 940	23 715 940	very poor	fair	**fair**	39 938	0
Russian Federation	Russian Federation	88	4 878 000	19 234 888	5 028 884	very poor	poor	**poor**	6 180 020	n.a.
Rwanda	Eastern Africa	1	4 000	2 531 838	2 531 838	poor	good	**fair**	0	0
Sao Tome and Principe	Western Africa	1	9 700	96 663	96 663	excellent	very poor	**good**	0	0
Saudi Arabia	Near East	14	1 730 767	13 785 211	5 964 304	very poor	good	**good**	42 172	n.a.
Senegal	Western Africa	4	71 400	4 932 187	1 995 968	poor	good	**good**	0	283 781
Serbia and Montenegro	Eastern Europe	1	57 000	10 247 622	10 247 622	very poor	poor	**poor**	4 944	0
Sierra Leone	Western Africa	5	29 360	1 448 465	2 475 078	poor	good	**fair**	0	2 224
Slovakia	Eastern Europe	1	174 000	4 889 727	4 889 727	very poor	fair	**fair**	2 036	0
Slovenia	Eastern Europe	1	2 000	2 024 675	2 024 675	poor	poor	**poor**	2 963	0

Country	Region	n_{adm}	$area_{irr}$ (ha)	$area_{admav}$ (ha)	*IND_A* (ha)	Map quality			Irrigated area in other datasets (ha)	
						Based on indicator A	Based on indicator B	**overall**	GLCC	GLC2000
Somalia	Eastern Africa	17	200 000	3 738 850	3 939 119	very poor	fair	**poor**	0	521 289
South Africa	Southern Africa	45	1 270 000	2 716 145	3 074 240	very poor	fair	**poor**	0	143 529
Spain	Southern Europe	17	3 268 306	2 968 187	3 323 641	very poor	good	**good**	349 598	1 332 525
Sri Lanka	South Asia	26	570 000	256 983	285 239	good	good	**good**	2 301 825	2 257 224
St. Kitts and Nevis	Central America	1	18	29 556	29 556	excellent	fair	**very good**	0	n.a.
St. Lucia	Central America	1	297	63 905	63 905	excellent	good	**very good**	0	n.a.
Sudan	Eastern Africa	62	1 946 200	4 052 908	2 286 757	poor	very good	**good**	0	944 060
Suriname	South America	1	51 180	14 674 639	14 674 639	very poor	poor	**poor**	0	n.a.
Swaziland	Southern Africa	1	67 400	1 732 063	1 732 063	poor	very poor	**poor**	0	0
Sweden	Western Europe	1	115 000	44 775 499	44 775 499	very poor	poor	**poor**	8 011	n.a.
Switzerland	Western Europe	1	25 000	4 058 894	4 058 894	very poor	fair	**fair**	28 105	0
Syria	Near East	13	1 266 900	1 433 681	1 022 356	poor	good	**good**	184 991	n.a.
Taiwan, Province of China	East Asia	23	525 528	158 178	140 295	very good	very good	**very good**	1 765 431	n.a.
Tajikistan	Central Asia	2	719 200	7 090 702	3 150 233	very poor	good	**good**	1 021 262	n.a.
Tanzania	Southern Africa	1	150 000	94 549 369	94 549 369	very poor	poor	**poor**	0	0
Thailand	South-East Asia	76	4 985 708	680 171	377 064	good	very good	**very good**	26 609 734	6 630 135
Togo	Western Africa	1	7 008	5 726 793	5 726 793	very poor	fair	**poor**	0	680
Trinidad and Tobago	Central America	1	3 600	504 986	504 986	fair	fair	**fair**	0	n.a.
Tunisia	Northern Africa	23	384 943	673 995	332 076	good	fair	**fair**	0	0
Turkey	Near East	73	4 185 910	1 069 316	1 099 341	poor	good	**good**	2 004 936	453 243
Turkmenistan	Central Asia	5	1 744 100	9 779 032	8 841 162	very poor	very good	**good**	2 383 627	n.a.
Uganda	Eastern Africa	11	9 120	2 203 246	5 007 171	very poor	very good	**good**	0	0
Ukraine	Eastern Europe	1	2 454 000	56 917 149	56 917 149	very poor	fair	**fair**	73 986	n.a.
United Arab Emirates	Near East	8	280 341	984 729	645 184	fair	good	**good**	78	n.a.
United Kingdom	Western Europe	1	142 687	24 408 258	24 408 258	very poor	fair	**poor**	58 709	0
United States of America	North America	3506	27 913 872	269 534	238 739	very good	good	**very good**	10 719 481	n.a.
Uruguay	South America	1	181 200	17 703 613	17 703 613	very poor	good	**good**	0	n.a.
US Virgin Islands	Central America	2	185	18 007	20 972	excellent	very poor	**good**	0	n.a.

Country	Region	n_{adm}	$area_{irr}$ (ha)	$area_{admav}$ (ha)	*IND_A* (ha)	Map quality			Irrigated area in other datasets (ha)	
						Based on indicator A	Based on indicator B	**overall**	GLCC	GLC2000
Uzbekistan	Central Asia	13	4 223 000	3 264 072	1 197 314	poor	very good	**very good**	5 210 733	n.a.
Venezuela	South America	24	570 219	3 800 359	1 332 888	poor	fair	**fair**	9 988	n.a.
Vietnam	South-East Asia	32	3 000 000	1 027 496	740 739	fair	good	**good**	10 747 900	8 192 239
Yemen	Near East	19	388 000	2 352 871	920 210	fair	good	**good**	83 407	n.a.
Zambia	Southern Africa	7	46 400	10 773 311	3 797 335	very poor	fair	**fair**	0	0
Zimbabwe	Southern Africa	1	116 577	39 184 102	39 184 102	very poor	poor	**poor**	0	0
	World	10 825	273 723 445	1 241 912	330 249	n.a.	n.a.	n.a.	325 636 618	n.a.

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Nutrient cycling and field-based partial nutrient balances in two mountain oases of Oman

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ABSTRACT

Little is known about nutrient fluxes as a criterion to assess the sustainability of traditional irrigation agriculture in eastern Arabia. In this study GIS-based field research on terraced cropland and groves of date palm (*Phoenix dactylifera* L.) was conducted over two years in two mountain oases of northern Oman to determine their role as hypothesized sinks for nitrogen (N), phosphorus (P) and potassium (K). At Balad Seet 55% of the 385 fields received annual inputs of 100–500 kg N ha^{-1} and 26% received 500–1400 kg N ha^{-1}. No N was applied to 19% of the fields which were under fallow. Phosphorus was applied annually at 1–90 kg ha^{-1} on 46% of the fields, whereas 27% received 90–210 kg ha^{-1}. No K was applied to 27% of the fields, 32% received 1–300 kg K ha^{-1}, and the remaining fields received up to 1400 kg ha^{-1}. At Maqta N-inputs were 61–277 kg ha^{-1} in palm groves and 112–225 kg ha^{-1} in wheat (*Triticum* spp.) fields, respective P inputs were 9–40 and 14–29 kg ha^{-1}, and K inputs were 98–421 and 113–227 kg ha^{-1}. For cropland, partial oasis balances (comprising inputs of manure, mineral fertilizers, N_2-fixation and irrigation water, and outputs of harvested products) were similar for both oases, with per hectare surpluses of 131 kg N, 37 kg P, and 84 kg K at Balad Seet and of 136 kg N, 16 kg P and 66 kg K at Maqta. This was despite the fact that N_2-fixation by alfalfa (*Medicago sativa* L.), estimated at up to 480 kg ha^{-1} yr^{-1} with an average total dry matter of 22 t ha^{-1}, contributed to the cropland N-balance only at the former site. Respective palm grove surpluses, in contrast were with 303 kg N, 38 kg P, and 173 kg K ha^{-1} much higher at Balad Seet than with 84 kg N, 14 kg P, and 91 kg K ha^{-1} at Maqta. The data show that both oases presently are large sinks for nutrients. Potential gaseous and leaching losses could at least partly be controlled by a decrease in nutrient input intensity and careful incorporation of manure.

1 INTRODUCTION

In recent years the determination of carbon (C) and nutrient fluxes in agro-ecosystems has received increasing attention by agricultural scientists worldwide as it seems to offer a way of objectively assessing a system’s sustainability and the potential side-effects of management on the environment at different scales. Much of the initial work was triggered by Dutch scientists working on low-input cropping systems in Africa (Baijukya and de Steenhuijsen Piters, 1998; Wijnhoud et al., 2003). Driven by concerns about the impact of human management on soil fertility leading to a perceived large scale soil depletion and degradation or farmers' indigenous productivity management strategies (Harris, 1998), bio-physical modeling tools such as NUTMON were used to monitor data on both the input and output side of nutrient balances at the field, district, and country level (Smaling et al., 1993, 1996; Smaling and Fresco, 1993; Stoorvogel and Smaling, 1994; de Jaeger et al., 1998ab; van den Bosch et al., 1998ab).

Simultaneously, European and American scientists, driven by concerns about greenhouse gas emissions in temperate agro-ecosystems and in intensively managed Asian rice, developed new methods to reliably estimate nitrogen (N) and C losses to the atmosphere and to monitor the effects of management changes on nutrient fluxes (Ko and Kang, 2000; Wang and Adachi, 2000; Wassmann et al., 2000; Xu et al., 2000; Butterbach-Bahl et al., 2001). Depending on the aim and scale of the research, either full or partial balances were used. Full balances comprised measurements or estimates of inputs such as mineral fertilizers, manure, N_2-fixation by leguminous crops and free living micro-organisms, nutrient acquisition from deeper soil layers, human faeces, irrigation water, and dry and wet atmospheric deposition. Outputs included removed yields, erosion, atmospheric emissions, and leaching losses. Partial balances, in contrast, assumed that variables such as atmospheric deposition, gaseous emissions, or leaching losses are either too difficult to measure or to model at the required resolution or are negligible in size compared to the other variables.

Whereas most published work focuses on rainfed or irrigated agriculture with relatively simple cropping systems, little information is available on nutrient fluxes in more complex, small scale crop rotations such as practiced in intensively irrigated desert oasis systems of eastern Arabia. To fill this gap of knowledge, this study reports data from two ancient oases in the mountains of northern Oman, where the large C turnover on intensively manured soils with low C:N ratios has been the subject of earlier work (Wichern et al., 2004ab). Our underlying hypothesis was that one of the decisive causes of the productivity of the oasis agriculture under study was their role as sinks for nutrients, leading to large positive partial balances of N, phosphorus (P), and potassium (K).

2 MATERIALS AND METHODS

2.1 Description of the agroecosystems

The study area comprised two contrasting spring-fed oases in the al-Hajar mountains of Oman. Despite being at the upper end of large watersheds, both have no regular runoff, but irrigation combined with occasional torrential rainfalls in winter can lead to rapid leaching and flash floods that rush through the barren wadis. The agro-ecological setting and physical structure of the oases were as follows:

Balad Seet (23.19° N, 57.39° E; 950 to 1020 m asl; 0 to 240 mm of total average annual precipitation) is situated in a small valley at the upper end of the Wadi Bani Awf watershed in the Jabal Akhdar range. It is a typical 'core oasis' with a central settlement on a rocky outcrop at the upper end of six surrounding terrace systems (Fig. 1; Nagieb et al., 2004). The 385 agricultural fields are situated on terraced Irragric Anthrosols (FAO, 2001) of 0.4 to 1.3 m profile depth with 9-14% clay and an organic C concentration of 3.7% at 0-0.15 m and of 3% at 0.15-0.45 m (Luedeling et al., 2004). These fields totaled 4.6 ha to which 2690 date palms (*Phoenix dactylifera* L.) comprising 16 varieties interplanted with some lime (*Citrus aurantiifolia* [Christm. et Panz.] Swingle) and a few banana (*Musa* spp.) plants have to be added, which together cover an additional 8.8 ha of terraced land. About 1.9 ha of the palm groves were sown to understory grasses, which were cut three times per year and fed to goat and sheep as a feed supplement. Of the total number of date palms 58% were bearing fruit during the 24 months of study from October 2000 to October 2002. The main cultivated plants were perennial alfalfa (*Medicago sativa* L.) and annual crops such as traditional wheat landraces (*Triticum aestivum* L. and *Triticum durum*; Al-Maskri et al., 2003), sorghum (*Sorghum bicolor* Moench s. l.), barley (*Hordeum vulgare* L. s. l.), oat (*Avena sativa* L.), garlic (*Allium sativum* L.) and onion (*Allium cepa* L.). These were planted in complex

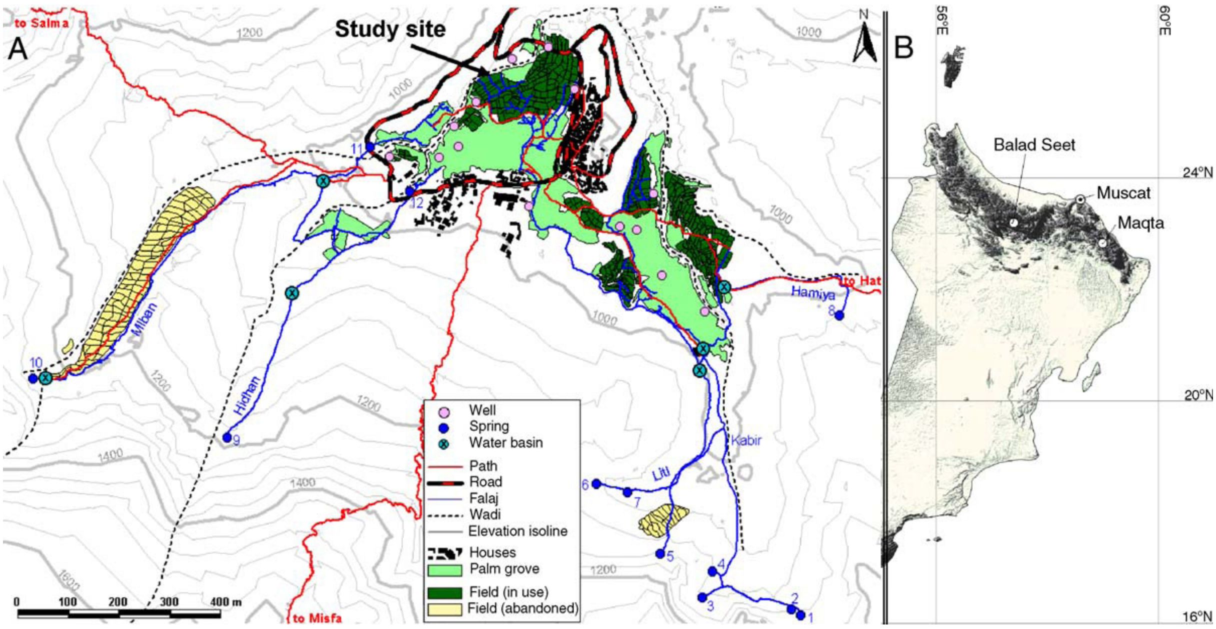

Fig. 1. GIS-based map with the main features of the 'core oasis' of Balad Seet, Oman (left) and position of the two mountain oases under study (right). The arrow indicates the field where the ^{15}N experiment was conducted to quantify N_2-fixation of alfalfa.

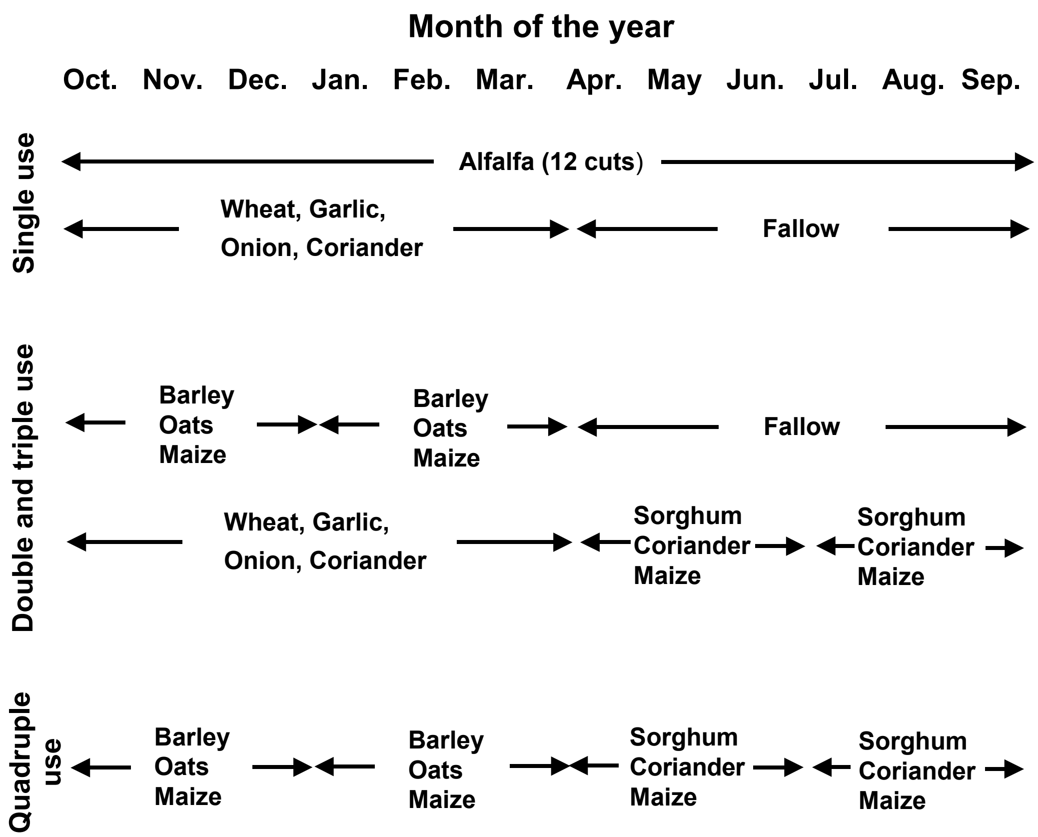

Fig. 2. Cropping sequences on terraced fields at Balad Seet, Oman.

summer-winter crop rotation systems (Fig. 2). The village's 650 inhabitants, exceeding several times the assumed traditional agricultural carrying capacity of the oasis (Nagieb et al., 2004), were distributed in 80 households. Recent studies (Nagieb et al., 2004) indicated that the settlement history of this oasis may date back as far as to the 2nd millenium BC. This likely reflects the ideal ecological conditions provided by an abundant and relatively stable water supply from twelve springs originating at the foot of a 1000 m high calcareous cliff (Luedeling et al., 2004). Depending on rainfall conditions, the total flow of the springs varied between 20 and 30 m^3 h^{-1} during the study period. An elaborate spring irrigation system (sing. Falaj, pl. aflaj in Arabic) conveys the water to the cropland and the palm groves.

Maqta, at the upper end of the widely open Wadi Khabbah in the Jabal Bani Jabir mountains, in contrast, is a typical 'scattered oasis' with a central village area (59.00 °E, 22.83 °N; 1,050 m asl) of 73 houses and 12 widely dispersed temporary settlements in a vast rocky grazing area (Fig. 3; Siebert et al., 2004). In 2001 the total agro-pastoral population of this territorial unit numbered about 200. The 5.2 ha terraced agricultural area of interest for this study were divided into 130 fields on 17 terrace systems, in which terrace size ranged from 32 to 22 200 m^2 (Fig. 4). Palm groves totaled 3.6 ha with 2128 trees of which 937 were

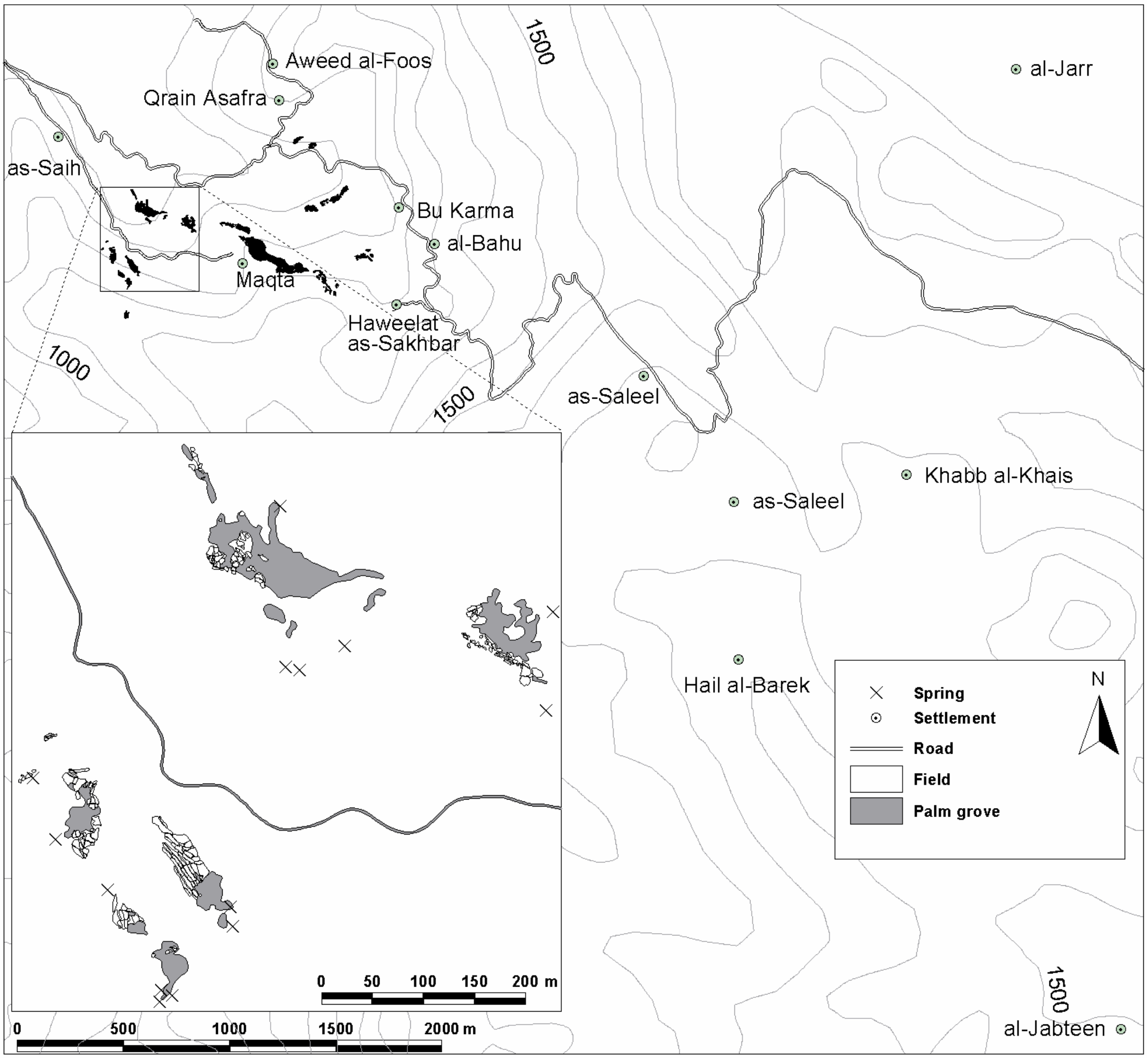

Fig. 3. GIS-based map of the Maqta territory in Oman with the terrace systems, the central housing area, the dispersed settlements, the natural grazing basin, major archaeological sites and altitude lines (Siebert et al., 2005).

productive. On 1.2 ha of the palm groves fodder grasses were grown, cut as in Balad Seet three times a year, and fed to goat and sheep. Additionally there were 0.4 ha of wheat of the Walidi landrace (Al-Maskri et al., 2003) growing on 10 of the 17 terrace systems, plus 0.4 ha of fallow, and 0.8 ha of abandoned land. The total flow of the 22 springs was between 4.8 and 9.0 m^3 h^{-1} during the 12-month measurement period of this study (February 2001 to March 2002). In the hot summer water was applied to the palm groves only.

At both oases all agronomically relevant measurements were based on the initial establishment of a three-dimensional digital map established within a Geographical Information System (GIS) in April 2000. Low altitude aerial photography (Buerkert et al., 1996) and ground-truth data collected with a differential Global Positioning System (GPS;

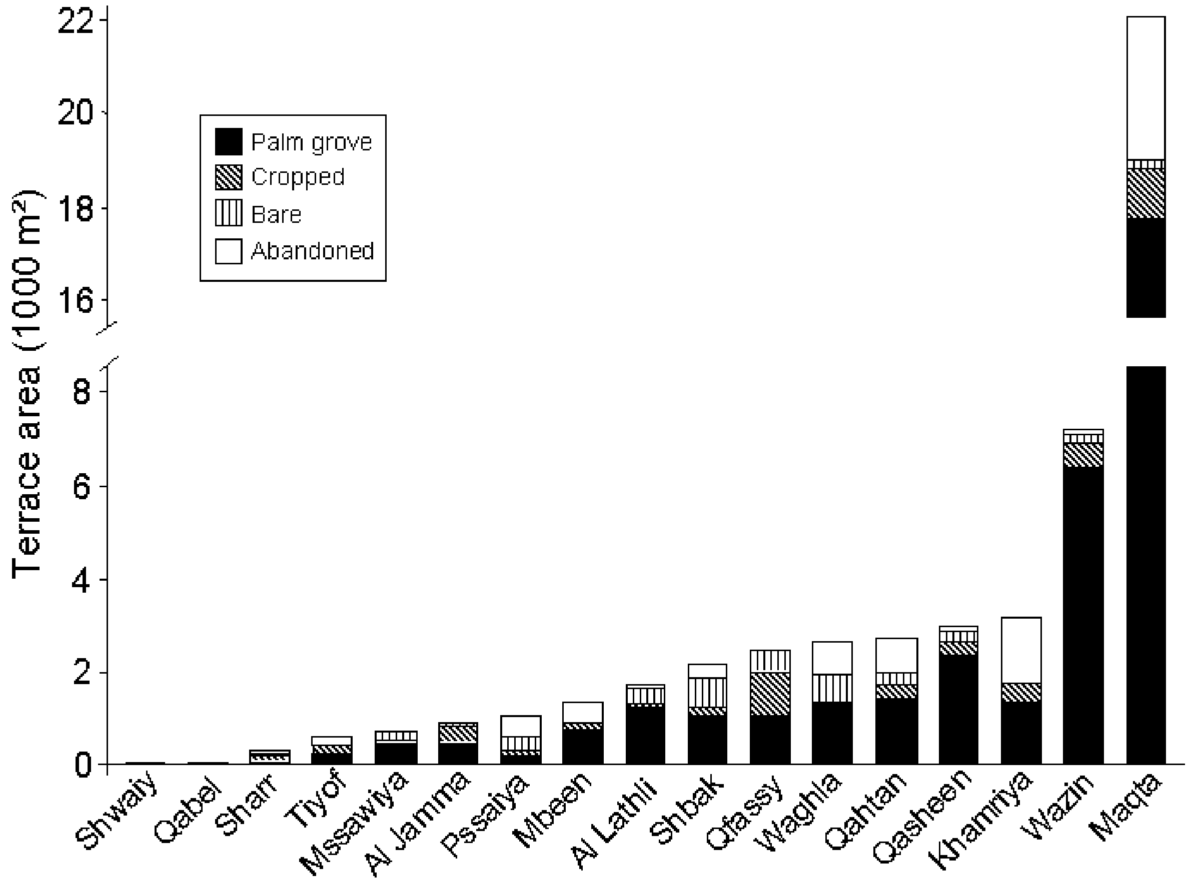

Fig. 4. Size and land use of the 17 terrace systems at the 'scattered' oasis of Maqta, Oman.

Trimble Pathfinder, Sunnyvale, CA, USA) at decimeter precision were used to record important features governing the agricultural system of the oasis such as water basins, main irrigation channels, the contours of the terraces, roads, and foot paths. Also the variety and age class (young versus fruit bearing) of each palm tree were noted. The precise size of individual fields and their cropping sequence as well as the data about the heavily fertilized date palms was needed for the establishment of partial nutrient balances.

2.2 Outputs (nutrient exports)

For crops and dates the calculation of nutrient exports was based on the amounts of N, P and K that were removed with the harvested dry matter from an individual field during the respective measurement periods. Nutrients removed with harvested under-story fodder grasses were estimated based on two representative samples from Balad Seet and one sample from Maqta. At neither site were nutrient losses by leaching, denitrification and volatilization, nor N gains from atmospheric deposition and non-symbiotic N_2-fixation accounted for.

Balad Seet. For yield measurements, four representative reference fields were selected for each of the eight crops grown in the different rotation systems of the oasis. These reference fields were classified into four yield classes (low, medium, high, very high) and harvested. Depending on the crop grown total biomass or straw and grain yields were determined after sun drying to weight constancy on all 32 fields. Subsequently, the yields of the remaining fields were estimated based on those of the reference fields (yield classes). To calculate above-ground nutrient uptake, the estimated yield of each individual plot was multiplied by the respective concentrations of total nitrogen (N), phosphorus (P) and potassium (K) in the reference plot of the corresponding yield class. Total N was determined with a N-Analyzer (FP-328 LECO, Mi, USA) with standards being included every 15 samples, P colorimetrically (Hitachi U-2000 spectrophotometer, Japan) according to the vanado-molybdate method (Gericke and Kurmies, 1952), and K by flame photometry (Instrument Laboratory 543, CA, USA).

To estimate the date yields for the 1685 individual fertile trees of Balad Seet, a single representative palm grove with 171 fruit bearing palms was used as a reference. First, the fresh weight of the dates on each tree of the grove was estimated with the help of their owners based on the number and size of the date bundles. Subsequently, the fresh yields of all other trees in the oasis were estimated according to the average yield determined for each variety grown in the reference grove. Samples of 14 date varieties were freeze-dried and their N, P and K concentration determined as above and total nutrient uptake in the dry matter calculated.

Maqta. In each of the small 10 terrace systems cultivated with wheat, one single field was chosen at random for measurement of grain and straw yield and for determination of N, P and K concentrations. The amounts of N, P and K accumulated annually in growing palm leaves and trunk parts were estimated based on data from the literature (IFA, 2004). These assume that adult trees with about 70 kg edible dates yr^{-1} produce a vegetative biomass of 50 kg dry matter with concentrations of 8.6 g N kg^{-1}, 1 g P kg^{-1} and 30 g K kg^{-1}. As P and K accumulated in the vegetative biomass is over time effectively recycled through ash from the eventually burned tissue in both oasis settings, only N losses are relevant for the calculation of partial nutrient balances. For Balad Seet such N losses were estimated at about 215 g N per fruit bearing tree with 35 kg of dates and at 54 g per young tree. At Maqta N losses in the burned palm tree tissue were adjusted for the lower date yields of this site and were thereby estimated at 60 g N per fruit bearing tree with 10 kg of dates and at 15 g per young tree.

2.3 Inputs

Balad Seet. Nutrient inputs to crops consisted of a widely varying mixture of air-dried manure compost comprised of about one-half from goat and sheep manure and about one-half from cattle manure complemented by applications of the synthetic fertilizers NPK (15-15-15) and urea (46-0-0). Manure was typically hand-applied in units of full jute bags for which an average content weight was determined based on 10 filled sample bags. Manure composition was determined twice during the measurement period by taking 12 and 8 samples, respectively from different bags and analyzing them individually for N, P, and K concentrations as above. For subsequent calculations of field-based nutrient budgets median values of the twenty measurements were used.

Nutrients applied through synthetic fertilizers to each crop were measured by a detailed survey of each farm household, field visits and a verification survey of the total number of urea and NPK fertilizer bags purchased annually by the villagers. Biological N_2-fixation in alfalfa was estimated from a 18-months long factorial ^{15}N study conducted at Balad Seet (^{15}N was applied twice at 15.1 g $(NH_4)_2SO_4$ enriched with 10% ^{15}N) with wheat as a test crop revealed N_2-fixation rates (dNfa) of 69-85% in alfalfa at a shoot N concentration of 29 g kg^{-1} (Nagieb, 2004). Based on these results an average N_2-fixation rate (Ndfa) of 75% was used to estimate the contribution of symbiotically fixed N in the harvested shoot dry matter. It was further estimated that the amount of symbiotically fixed N stored in the roots and released or recycled in the rhizosphere amounted to about 1/3 of the above ground N. From this it was assumed that total N_2-fixation of the crop corresponded to the entire amount of N removed with harvested alfalfa shoots. In the balance calculations N uptake with the harvested alfalfa was accounted for once as export and once as input (fixation). The effect of N_2-fixation on partial balances appeared thus indirectly in the manure component into which all alfalfa fed to animals was finally converted.

Maqta. The only source of nutrient inputs was goat and sheep manure, as neither synthetic fertilizers nor N_2-fixing alfalfa were used.

At both sites also the amounts of N, P and K in the night soil produced from human faeces and applied to palm trees in irregular intervals were considered. As recording of human faeces was a culturally sensitive issue, no actual data could be taken in either oasis and data from the literature for the total daily nutrient excretion of adults in Thailand had to be used instead (7.8 g N, 1.7 g P and 2.3 g K per person; Schouw et al., 2002). At Balad Seet, of the 632 inhabitants living in the oasis 367 were adults with an age of ≥15 and counted with a relative weight factor of 1, 168 were adolescents and counted with a weight factor of 0.75, and 97 were children ≤5 years old and counted with a weight factor of 0.33. At Maqta, in contrast, only 25 of the 200 inhabitants living in the vast agro-pastoral territory took shifts watering the terraces and may thus have actively contributed their faeces to the nutrient inputs. Of those 14 were adults and 11 adolescents.

The last recorded input variable was the nutrient contribution through irrigation water. Its N, P, and K concentration was determined several times for the major falaj-systems at Balad Seet and once for the important springs at Maqta. Data were weighted for the respective spring flows and multiplied by the total amount of water applied during the respective 12- and 24-month measurement periods.

2.4 Analysis of nutrient fluxes

Balad Seet. All nutrient outputs (in all harvested products) and inputs (in manure, synthetic fertilizers, irrigation water and human faeces, as well as the amount of N_2-fixed by alfalfa) measured for crops and date palms over the 24-month study period were recorded and subsequent partial balance sheets computed at the level of individual fields and for the oasis as a whole.

Maqta. Given its much more scattered structure, the basis for recorded parameters and computed partial balances were the 17 individual terrace systems and the oasis as a whole. As no synthetic fertilizers or alfalfa were used in this oasis, all input calculations were based on the amounts of manure applied annually to date palms and wheat fields.

For crops, field-based (Balad Seet) or terrace-based (Maqta) average annual N, P, and K inputs were plotted as absolute quantities (frequency distributions) for several input classes whose size differed for the nutrients. To examine whether these input distributions depended on field size, the displayed plots at Balad Seet differentiated between fields of <72, 72-138, and >138 m^2. These classes were chosen based on the frequency distribution of all field sizes. Subsequently field- or terrace-based partial nutrient balances were computed. For date palms input and output fluxes were summarized at the oasis level (Balad Seet) or displayed for each terrace separately (Maqta).

At both sites oasis partial balances were set up to show aggregated inputs, outputs, and partial balances according to the type of land use (cropland versus palm groves) on a per hectare basis and for the oasis as a whole.

3 RESULTS

3.1 Annual crop yields, nutrient concentrations and nutrient exports

At Balad Seet cereal yields averaged 2980 kg ha^{-1} for wheat grain. Respective total dry matter (TDM) yields of fodder barley and fodder oats were 5420 and 5370 kg ha^{-1}, and TDM of maize was 5490 kg ha^{-1}. There was an overall crop yield difference between years, with the 2000/2001 season having higher yields than 2001/2002 (Table 1). With 12 cuts per year, average annual alfalfa TDM amounted to 22 520 kg ha^{-1}. At Maqta wheat yields were 2210 kg ha^{-1}, much lower than at Balad Seet. The same was true for the nutrient concentrations in wheat (Tables 2 and 3).

Table 1. Air-dried shoot yields (kg ha^{-1}) for four yield classes of the major crops grown at the core oasis of Balad Seet (Oman) in the 2000/2001 and the 2001/2002 cropping seasons.

	Straw				Grain			
Crop / Class	Low	Medium	High	Very high	Low	Medium	High	Very high
2000/2001								
Wheat	11 070	11 250	11 880	11 970	2610	2700	3060	3150
Barley	5490	6300	6570	7020	[a]	[a]	[a]	[a]
Sorghum	11 440	12 760	13 200	14 960	2250	2250	2790	3240
Maize	5670	6480	6660	6940	[a]	[a]	[a]	[a]
Oat	5730	6090	6730	6910	[a]	[a]	[a]	[a]
Alfalfa[b]	1820	1910	2360	2450	[a]	[a]	[a]	[a]
Garlic[c]	1890	2060	2150	3270	5180[c]	5340[c]	5770[c]	9940[c]
Coriander	3400	3500	4000	4400	[a]	[a]	[a]	[a]
2001/2002								
Wheat	6300	8100	10 800	11970	2020	2880	3600	3780
Barley	3600	4050	4500	5850	[a]	[a]	[a]	[a]
Sorghum	11 700	12 600	13 500	15 300	2160	2250	2790	3060
Maize	2880	4500	4950	5850	[a]	[a]	[a]	[a]
Oat	3640	3820	4550	5460	[a]	[a]	[a]	[a]
Alfalfa[b]	910	1460	1640	2460	[a]	[a]	[a]	[a]
Garlic[c]	1720	2150	2580	3440	4680[c]	5460[c]	7020[c]	10 140[c]
Coriander	2250	2520	2880	3420	[a]	[a]	[a]	[a]

[a] Only vegetative parts were harvested as animal fodder
[b] Yields refer to a single cut, there typically were 12 cuts per year
[c] Dry bulbs

Table 2. Air-dried straw and grain yields (kg ha^{-1}) of the Walidi wheat landrace and concentrations (g kg^{-1}) of nitrogen (N), phosphorus (P) and potassium (K) for different yield classes (terrace level) at the scattered oasis of Maqta (Oman) in the 2001/2002 season.

	------------ Wheat straw -----------------				------------ Wheat Grain ---------------			
Class	Low	Medium	High	Very high	Low	Medium	High	Very high
Dry matter	6580	8460	8460	9400	1800	2070	2250	2700
N	2.3	3.1	3.3	3.8	16.2	16.5	18.3	15.4
P	0.4	0.4	0.3	0.5	2.8	2.5	2.6	2.8
K	18.9	11.9	13.1	19.5	3.4	3.1	3.0	3.3

3.2 Nutrient inputs and partial balances

Balad Seet. During the 2-year measurement period, 55% of the 385 fields received total annual N inputs of 100-500 kg N ha^{-1}, 25% received 500-1400 kg N ha^{-1}, and 11% did not receive N. Annual P applications of up to 90 kg P ha^{-1} were applied on 46% of the fields, whereas 27% received 90-210 kg P ha^{-1}, and the same percentage received no P. Similarly to P no K was applied on 27% of the fields, whereas 32% received 1-300 kg K ha^{-1}, and the remaining fields received up to 1400 kg K ha^{-1} (Fig. 5). The distribution of all three nutrients tended to be slightly skewed at the upper end meaning that very large fields tended to receive higher input intensities than small ones. The majority of the input distribution curve, however, appeared to be unaffected by field size (Fig. 5). Bi-annual partial balances of N were positive on 82%, of P on 79%, and of K on 63% of the fields (Fig. 6). Nutrient concentrations in irrigation water were 0.57 mg N l^{-1}, 0.30 mg P l^{-1}, and 1.0 mg K l^{-1}.

Maqta. Palm groves clearly dominated the cultivated land on all but the Qfassy terrace system and large proportions of their land was temporarily uncultivated (bare) and abandoned (Fig. 4). Manure application led to N-inputs from 61–277 kg N ha^{-1} in palm groves and from 112–225 kg N ha^{-1} in wheat fields, to P inputs from 9–40 kg P ha^{-1} in palms and 14–29 kg P ha^{-1} in wheat, and to K inputs from 98–421 kg K ha^{-1} in palms and 113–227 kg K ha^{-1} in wheat (Fig. 7). With the exception of the tiny and poorly fertilized Shwaiy system, which did not contain wheat fields, differences in overall input intensity between terraces were with correlation coefficients (r) of 0.48 for fields and 0.47 for palm groves unrelated to their size (Fig. 7). However, on the smaller terrace systems palm groves tended to receive higher input intensities than wheat fields, but the reverse was true on the largest systems, particularly for N and P.

Table 3. Concentrations of nitrogen (N), phosphorus (P) and potassium (K) for four yield classes of the major crops grown at the core oasis of Balad Seet (Oman) in the 2000/2001 season. All data are in g kg^{-1} dry matter.

	Straw												Grain[a]											
Class	Low			Medium			High			Very high			Low			Medium			High			Very high		
Crop / Nutrient	N	P	K	N	P	K	N	P	K	N	P	K	N	P	K	N	P	K	N	P	K	N	P	K
Wheat	3.8	0.2	19	3.7	0.2	18	2.3	0.2	13	2.7	0.2	12	20.7	2.6	5	18.2	3.3	5	19.8	3.1	4	18.8	3.1	5
Barley	27.9	3.9	25	18.5	1.3	11	31.4	1.7	11	23.9	3.9	25	a	a	a	a	a	a	a	a	a	a	a	a
Sorghum	8.9	1.6	9	8.8	2.6	12	9.5	1.6	18	nd	nd	nd	21.3	4.6	5	22.5	4.6	5	21.2	4.6	5	nd	nd	nd
Maize	23.9	2.5	27	24.5	2.8	29	18.8	1.9	27	21.1	1.9	27	a	a	a	a	a	a	a	a	a	a	a	a
Oat	27.8	3.2	25	21.4	2.8	29	19.6	2.8	30	20.0	3.0	30	a	a	a	a	a	a	a	a	a	a	a	a
Alfalfa	27.0	1.8	9	27.8	1.8	8	34.2	2.0	17	25.8	2.0	17	a	a	a	a	a	a	a	a	a	a	a	a
Garlic[b]	17.6	1.8	26	12.1	1.2	36	17.6	2.4	22	10.7	2.6	20	18.0	1.0	5	16.0	1.4	6	17.0	1.5	6	14.0	1.6	4
Coriander	27.5	3.6	42	28.6	3.8	36	38.8	3.6	28	36.7	3.6	24	a	a	a	a	a	a	a	a	a	a	a	a

[a]: Only vegetative parts were harvested as animal fodder

[b]: Dry bulbs

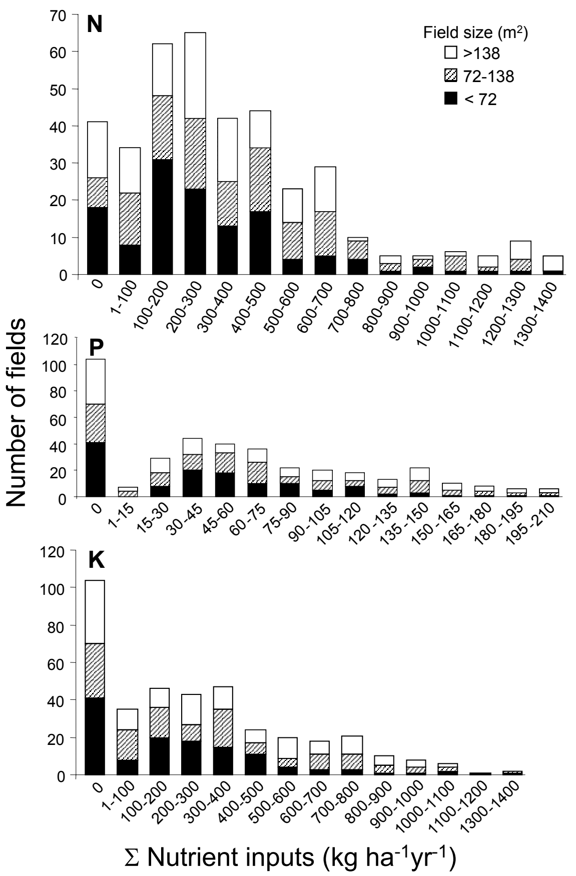

Fig. 5. Annual amounts of nitrogen (N), phosphorus (P) and potassium (K) applied as animal manure or synthetic fertilizers to the three different field size classes at the 'core oasis' of Balad Seet, Oman, from 2001 to 2002. Columns show absolute frequencies in their respective input classes and comprise all 385 fields of the oasis system.

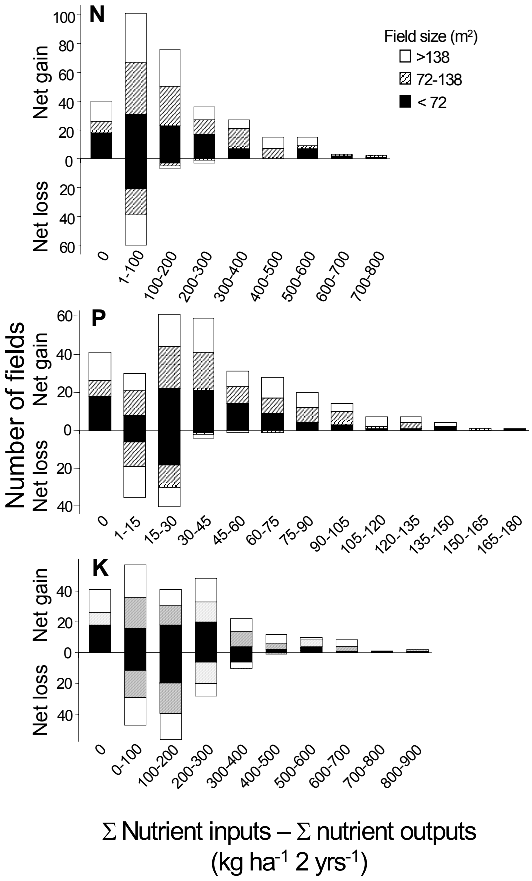

Fig. 6. Bi-annual partial balances (inputs minus outputs) of nitrogen (N), phosphorus (P) and potassium (K) on the three different field size classes at the 'core oasis' of Balad Seet, Oman, from 2001 to 2002. Columns show absolute frequencies in their respective input classes and comprise all 385 fields of the oasis system.

Partial nutrient balances were strongly positive regardless of terrace use in all systems, except for K in wheat fields at Al Lathli and Shbak (Fig. 8). For the 12-month measurement period nutrient gains were 47–222 kg N ha^{-1}, 7–34 kg P ha^{-1} and 79–266 kg K ha^{-1} in palm groves and 63–157 kg N ha^{-1}, 7–19 kg P ha^{-1}, and -13–85 kg K ha^{-1} in wheat fields (Fig. 8). Nutrient concentrations in the irrigation water were 0.49 mg N l^{-1}, 0.010 mg P l^{-1}, and 2.50 mg K l^{-1}.

3.3 Annual partial nutrient balances at the oasis level

Balad Seet. Input intensities far exceeded outputs for N, P and K on cropland but also on land planted to date palms. In cropland nutrient inputs from manure were 1.3–5.9-fold higher than those from synthetic fertilizers, in palm groves this ratio varied from 2.3–73-fold. Nutrient gains per unit area in palm groves were higher than on cropland, by 131% for N, by 1% for P, and by 106% for K (Table 4). The relatively lower rates of manure and synthetic fertilizers applied to palm groves compared to cropland were for N and P compensated by the application of human faeces. Compared to palm groves nutrient removal by harvested products from cropland was 344% higher for N, 231% higher for P, and 131% higher for K (Table 4). Overall nutrient surpluses on the cultivated oasis land were particularly high for N and K. The application of human faeces amounted to 46% of the excess N, 65% of excess P, and 24% of excess K (Table 4).

Maqta. An average of 16.0 and 9.3 t manure ha^{-1} were applied to cropland and date palms, respectively. Compared to cropland at Balad Seet, wheat fields at Maqta received on average only 61% of the total N, 39% of the P, and 64% of the K inputs. Similar differences in input intensities were noted for palm groves (Table 4 and 5). In contrast to Balad Seet, irrigation and human faeces contributed only very small amounts of N, P, and K. Average

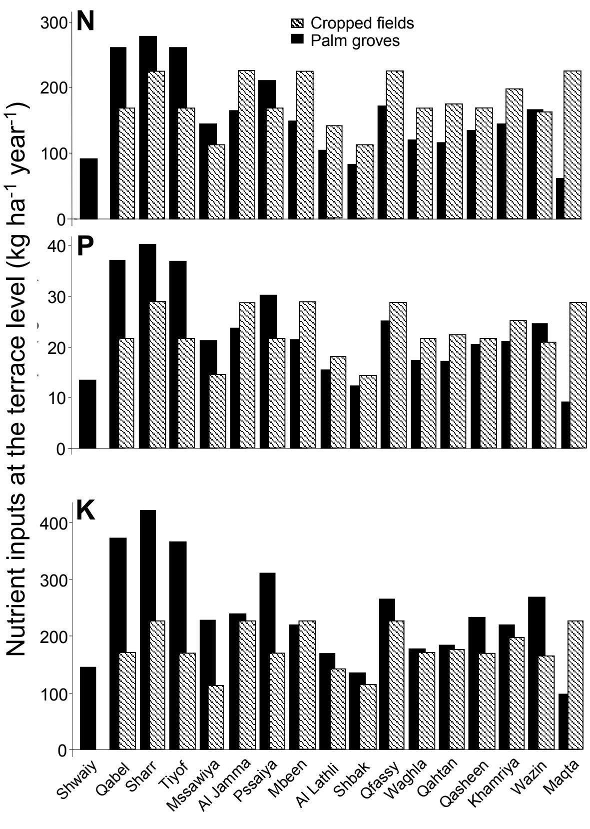

Fig. 7. Annual amounts of nitrogen (N), phosphorus (P) and potassium (K) applied as animal manure to cropped fields and palm groves of the 17 terrace systems belonging to the 'scattered oasis' of Maqta, Oman, in 2001/2002. Note that the terrace systems on the x-axis are arranged in order from smallest (left) to largest (right).

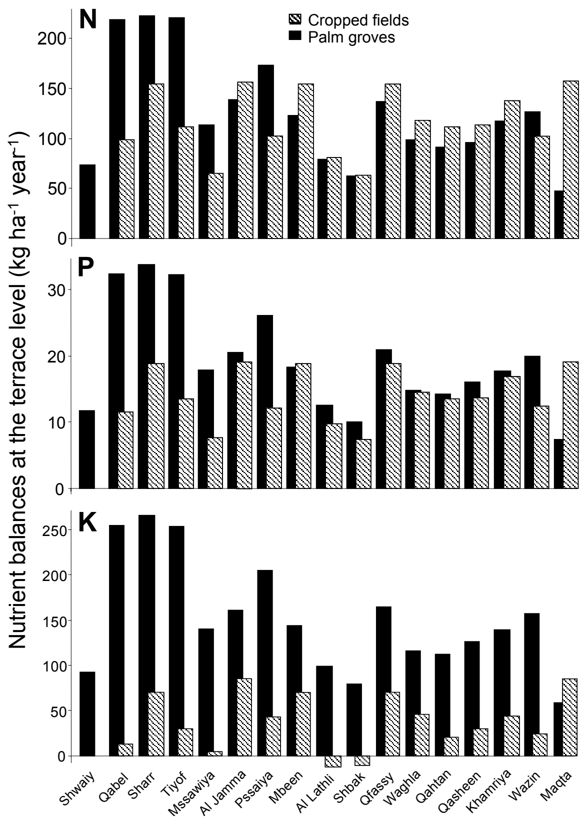

Fig. 8. Partial balances (inputs minus outputs) of nitrogen (N), phosphorus (P) and potassium (K) on cropped fields and palm groves of the 17 terrace systems belonging to the 'scattered oasis' of Maqta, Oman, in 2001/2002. Note that the terrace systems on the x-axis are arranged in order from smallest (left) to largest (right).

Table 4. Annual inputs, outputs and partial balances of nitrogen (N), phosphorus (P) and potassium (K) in cropland and palms groves at Balad Seet (Oman). All data are given as amounts per unit area and as totals (partial balance) for each land use system and represent annual averages of a 24-month measurement period from October 2000 to October 2002.

Land use system	Source / Process	Input and output (kg ha^{-1} yr^{-1})[a]			Partial balance (kg yr^{-1})[a]		
		N	P	K	N	P	K
Cropland (4.6 ha)	Synthetic fertilizer	143	23.9	45	658	119.9	207
	Animal manure	180	40.2	267	828	184.9	1228
	Irrigation water[b]	10	5.2	17	46	23.9	78
	Symbiotic N_2-fixation	63	n.a.[c]	n.a.	290	n.a.	n.a.
	Crop harvest	-265	-32.8	-245	-1219	-150.9	-1127
	Partial balance	**131**	**36.5**	**84**	**603**	**177.8**	**386**
Palm groves (8.8 ha)	Synthetic fertilizer	59	1.8	4	519	15.8	35
	Animal manure + ashes	141	8.0	289	1241	70.4	2543
	Irrigation water	10	5.2	17	88	45.8	150
	Human faeces	170	37.0	50	1496	325.6	440
	Date palm harvest (dates + stems + leaves)	-63	-12.7	-176	-554	-111.8	-1549
	Harvested understory fodder	-14	-1.5	-11	-123	-15.8	-97
	Partial balance	**303**	**37.8**	**173**	**2632**	**324.1**	**1469**
Oasis (13.4 ha)	**Total partial balance**	**244**	**37.4**	**142**	**3235**	**501.9**	**1855**

[a]: Positive values indicate gains and negative ones losses
[b]: Total annual spring flow of 228 587 m^3 was multiplied by nutrient concentrations of 0.57 mg N l^{-1}, 0.30 mg P l^{-1} and 1.0 mg K l^{-1} and adjusted to the respective irrigated surface area. Average irrigation intensity was assumed to be similar on both types of land use.
[c]: not applicable

annual area-based nutrient surpluses in cropland were similar in both oases, but were much higher for palm groves at Balad Seet than at Maqta (Table 4 and 5).

4 DISCUSSION

Yield levels were low for all of the irrigated crops except for sorghum, garlic, and alfalfa. This was likely due to the traditional germplasm with its low harvest index and to the low planting densities used. Total dry matter yields of alfalfa at Balad Seet were 2-3 times higher

Table 5. Annual inputs, outputs and partial balances of nitrogen (N), phosphorus (P) and potassium (K) in cropland and palms groves at Maqta (Oman). All data are given as amounts per unit area and as totals (partial balance) for each land use system and represent annual averages of a 12-month measurement period from February 2001 to March 2002.

Land use system	Source / Process	Input and output ($kg\ ha^{-1}\ yr^{-1}$)[a]			Partial balance ($kg\ yr^{-1}$)[a]		
		N	P	K	N	P	K
Cropland (0.4 ha)	Synthetic fertilizer	n.a.[c]	n.a.	n.a.	n.a.	n.a.	n.a.
	Animal manure	198	25.3	199	79	10.1	80
	Irrigation water[b]	2	0.05	12	0.9	0.02	5
	Symbiotic N_2-fixation	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	Crop harvest	-64	-9.0	-145	-26	-3.6	-58
	Partial balance	**136**	**16.4**	**66**	**54**	**6.5**	**27**
Palm groves (3.6 ha)	Synthetic fertilizer	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	Animal manure + ashes	104	15.4	166	374	55.4	598
	Irrigation water	7	0.1	35	24	0.5	125
	Human faeces	17	3.8	5	64	13.8	19
	Date palm harvest (dates + stems + leaves)	-24	-2.7	-66	-86	-9.7	-238
	Harvested understory fodder	-19	-2.2	-49	-68	-7.9	-176
	Partial balance	**85**	**14.0**	**91**	**308**	**52.1**	**328**
Oasis (4 ha)	**Total partial balance**	**90**	**14.2**	**89**	**283**	**47.5**	**298**

[a]: Positive values indicate gains and negative ones losses
[b]: Total annual spring flow of 51 666 m^3 was multiplied by nutrient concentrations of 0.49 mg N l^{-1}, 0.01 mg P l^{-1} and 2.5 mg K l^{-1} and adjusted to the respective irrigated surface area. Irrigation intensity was assumed to be similar on both types of land use for only four months, during the remainder of the year cropland was left fallow and therefore not irrigated.
[c]: not applicable

than those reported from other high intensity cultivation sites in the USA (Haby et al., 1999; Hoy et al., 2002) or in Brazil (Monteiro et al., 1998) even if yields per cutting reached similar levels (Ottman et al., 1996). They likely reflected the effects of monthly cuttings throughout the year and of rapid regrowth as reflected in the surprisingly high soil respiration rates detected in alfalfa plots (Wichern et al., 2004a). For all crops and both sites concentrations of N, P, and K in straw and grain (Table 2) were well above the critical levels reported by Bergmann (1988), thereby reflecting the high input intensity of manure and mineral fertilizers. The results of the ^{15}N experiment suggested a total annual N_2-fixation in the above-ground TDM of about 480 kg ha^{-1}.

Partial balances of both oases were excessively high for all nutrients studied, thereby supporting our initial hypothesis that the two sites were large sinks for nutrients. Similar balance studies on rice in Thailand indicated partial balances of only +12 kg N, +8 kg P and +7 kg K ha^{-1} (Wijnhoud et al., 2003), whereas in Kenya total balances of -71 kg N, +3 kg P and -9 kg K ha^{-1} were calculated for mixed crop-livestock farms (van den Bosch et al., 1998b). At Balad Seet the large apparent nutrient excesses on cropland resulted mainly from annually applied animal manure and mineral fertilizers. In palm groves the application of human faeces played a major role in our calculated surpluses even if in reality some of the nutrients, particularly N may have been lost by volatilization or leaching (Table 4). Both types of organic inputs give evidence of the connection of today's oasis agriculture with the outside economy, which contributed large nutrient inputs through purchased food and fish meal as animal feed supplement. This was also reflected by the nutrient concentrations in manure. While N at 18 g kg^{-1} was similar to the 15-23 g kg^{-1} reported by Esse et al. (2001) and Brower and Powell (1998) for sheep-cattle manure, P and K, at 5 g kg^{-1} and 29 g kg^{-1}, respectively, were much higher than respective values of 2 g kg^{-1} and 8 g kg^{-1} from the West African Sahel. There was a clear differentiation of synthetic fertilizers and manure application for the different crops. Sorghum, alfalfa, and garlic received their nutrient inputs almost exclusively from animal manure, whereas wheat, barley, and coriander obtained large inputs from synthetic fertilizers (Table 6). The largest contribution to the positive partial oasis balances on cropland at Balad Seet came from sorghum and alfalfa, followed by garlic and coriander. In wheat and barley, however, inputs by far exceeded outputs for N, whereas the reverse was true for K (Table 7).

The small size of the terraces in Maqta and their relatively large proportion of bare and abandoned fields is a typical feature of scattered oases in Oman (Siebert et al., 2004) which are subject to rapid decay under the current economic conditions. The positive partial nutrient balances based on large inputs of manure give, nevertheless, strong evidence of the continuing agro-pastoral linkage. The 47-72% smaller nutrient surpluses in palm groves compared to Balad Seet reflected the much lower population density in the Maqta territory, where the majority of its population is living in the small settlements surrounding the oasis in a 10 km radius. The much lower nutrient concentrations (except for K) in the irrigation water at Maqta reflect the absence of clothes washing places in the upper parts of the upper irrigation canal system, typical for Balad Seet.

The low C/N ratios of 10 to 12 in the upper 0.2 m layer of terrace soils at Balad Seet and Maqta (Wichern et al., 2004ac) make it unlikely that substantial additional amounts of N surpluses can be stored for prolonged time periods in the soil bacterial biomass or in soil organic matter. Large gaseous and leaching losses of N are therefore likely to occur, particularly if manure and urea are not incorporated immediately after application or during likely leaching phases in winter months.

Soil pH values of 7.6-8.4 and day-time maximum temperatures between 30 and 45°C suggest that gaseous losses (particularly as a result of ammonia volatilisation and to a likely minor proportion after denitrification) on the heavily manured soils undergoing repeated wetting and drying cycles may exceed the 11 and 14 kg N ha^{-1} measured in irrigated maize-wheat systems on a sandy clay-loam soil in Pakistan with 16 and 32 t annually applied farmyard manure (Mahmood et al., 1997). On the Omani oasis terraces these are, however, tedious to measure representatively given the large variety of crops grown over time and distance. Experiments under controlled conditions, such as in field-based closed chambers and wind tunnels may be needed to derive and calibrate models for the agro-environmental conditions prevailing in both oases.

In irrigated maize under the cooler conditions of the North China Plain, NH_3 losses of 44-48% of the applied N plus additional N_2O emissions of about 2 kg N ha^{-1} during the two months following urea application at 75 and 200 kg ha^{-1} were determined (Cai et al., 2002). In Indian rice-wheat systems on irrigation-supplemented alluvial soils recorded NH_3-emissons were about 60 kg ha^{-1} at 60 kg urea N plus 60 kg ha^{-1} manure N for rice and 120 kg ha^{-1} urea N for wheat (Banerjee et al., 2002).

Leaching losses of N, but also of organic P might also be relatively large but limited to specific periods. Tracer experiments at Balad Seet monitoring the water movement (Luedeling et al., 2004) indicate that deep drainage may only occur during the winter months when abundance of water, lower evaporation, and occasional strong rainfall events cause a temporary and thorough wetting of the terrace soils.

Nutrient losses by erosion, in contrast, seem unlikely given the terrace structure that effectively prevents lateral soil movement. Similarly low should be atmospheric nutrient inputs given the large distance of the oases from sites of industrial emission or volcanic activity.

For our partial N balances nutrient concentrations in manure were based on measurements of field-applied manure compost. However, during storage of this material with its C/N ratio varying from 24 to 16 for fresh and mature manure, respectively (Wichern et al.,

Table 6. Summary statistics of sources (mineral versus organic) and intensity of nutrients (per harvest) applied to fields planted with wheat, barley, sorghum, alfalfa, garlic and coriander at the oasis of Balad Seet (Oman) in 2001/2002.

	Wheat			Barley			Sorghum		
	Type of fertilization (field no.)			Type of fertilization (field no.)			Type of fertilization (field no.)		
	Mineral (30)	Organic (15)	Both (11)	Mineral (53)	Organic (2)	Both (2)	Mineral (6)	Organic (26)	Both (15)
	Intensity	Share of manure (%)		Intensity	Share of manure (%)		Intensity	Share of manure (%)	
	(kg ha^{-1})	Range	Mean	(kg ha^{-1})	Range	Mean	(kg ha^{-1})	Range	Mean
N input	50-375	0-100	37	34-352	0-100	8	0-423	0-100	85
P input	0-102	0-100	73	0- 50	0-100	24	0- 94	0-100	98
K input	0-462	0-100	89	0-274	0-100	47	0-458	0-100	99

	Alfalfa			Garlic			Coriander		
	Type of fertilization (field no.)			Type of fertilization (field no.)			Type of fertilization (field no.)		
	Mineral (0)	Organic (25)	Both (3)	Mineral (0)	Organic (52)	Both (12)	Mineral (5)	Organic (15)	Both (10)
	Intensity	Share of manure (%)		Intensity	Share of manure (%)		Intensity	Share of manure (%)	
	(kg ha^{-1})	Range	Mean	(kg ha^{-1})	Range	Mean	(kg ha^{-1})	Range	Mean
N input	285-551[a]	39- 58	52	177-514	39-100	96	31-503	0-100	69
P input	34-100	70-100	96	45-117	66-100	98	14- 95	0-100	84
K input	190-467	87-100	99	250-558	85-100	99	25-527	0-100	94

[a]: About 45% of the total N-input originated from symbiotic N_2-fixation

Table 7. Average crop-specific inputs, outputs and partial balances of nitrogen (N), phosphorus (P) and potassium (K) for wheat, barley, sorghum, alfalfa, garlic and coriander in cropping systems of Balad Seet (Oman) in 2001/2002.

	Wheat			Barley[a]			Sorghum		
	Inputs	Outputs	Partial balances	Inputs	Outputs	Partial balances	Inputs	Outputs	Partial balances
	kg ha^{-1}			kg ha^{-1}			kg ha^{-1}		
N	85	45	40	155	142	13	208	106	102
P	16	5	11	13	15	-2	52	37	15
K	72	82	-10	37	111	-74	276	125	151

	Alfalfa			Garlic			Coriander		
	Inputs	Outputs	Partial balances	Inputs	Outputs	Partial balances	Inputs	Outputs	Partial balances
	kg ha^{-1}			kg ha^{-1}			kg ha^{-1}		
N	322[b]	198	124	121	75	46	179	111	68
P	35	13	22	34	8	26	44	12	32
K	184	104	80	185	54	131	203	110	93

[a]: Harvested as green animal fodder and fertilized mainly with urea

[b]: About 45% of the total N-input originated from symbiotic N_2-fixation

2004b), considerable NH_3-losses are likely which may far exceed the 5-24% of total N measured by Petersen et al. (1998) for cattle and pig manure under temperate conditions.

5 CONCLUSIONS

The data provide solid evidence of the oases being large temporary sinks for nutrients until they are released to the surrounding atmosphere or watershed. Nutrient losses through leaching are probably restricted to the winter months when potential evaporation is much lower than in summer and when sufficient water is available to allow its regular application at 90 mm per irrigation event. It is this leaching, occasionally aggravated by a torrential rainfall which likely helps to avoid the built-up of toxic salt levels (Luedeling et al., 2004).

Ammonia volatilization, denitrification, and NO_3-, P- and K-leaching losses in the highly spatially and temporarily diverse cropping patterns at Balad Seet will need further quantification to better explain the fate of the applied nutrients.

The apparent oversupply of N may be an already old, largely unavoidable phenomenon in these oasis systems given volatilization losses due to high ambient temperatures and pH and leaching losses as a consequence of salt removal by drainage. The oversupply of P seems, in contrast, seems a relatively recent phenomenon reflecting the oases' overpopulation and the transformation of oasis agriculture from a need to survive to a mainly culturally based leisure.

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6

Settlement history of a mountain oasis in northern Oman – evidence from land-use and archaeological studies

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ABSTRACT

Little is known about the development history of the rapidly decaying ancient mountain oases in Northern Oman. In the Wadi Bani Awf with its head oasis Balad Seet biophysical measurements were combined with archaeological surveys to derive a series of comprehensive settlement hypotheses. The main driving force for the dynamic development of this exemplary selected watershed at the northern foot of the Hajar mountain range was the availability of an abundant and stable outflow of springs. The likely construction of an aini-aflaj irrigation system in the first millenium BC and of elaborate terraces allowed an increasingly efficient water use for the production of dates, wheat and alfalfa. The changing scarcity of land and water might have been the major driving force for the development and apparent relative stable wealth of this mountain oasis over its three millennia of existence.

1 INTRODUCTION

Situated at the eastern edge of the Arabian Peninsula (Fig. 1), the Sultanate of Oman has experienced a very rapid modernization process since the early 1970s. Following the political opening and the rapid infrastructural changes triggered by the oil-derived economic boom, desert oasis agriculture – once with fisheries and trade the backbone of the country's economy – has undergone major changes. Due to the aridity of its climate (from 30 to 300 mm annual precipitation compared to a potential evapotranspiration >2000 mm) agriculture in Oman heavily depends on artificial irrigation. At present about 2% of Oman's total land surface, equivalent to 150 377 ha is cultivated (Anonymous, 1995). Of this area about 74% is irrigated by modern sprinkler systems drawing subsurface water from pump wells (mostly situated in the flat northern coastal area, the Batina region and intensively cropped with modern technologies), 14% by ancient falaj systems, 0.4% by springs, and the remainder by a combination of the former (Ibrahim, 1999). The basic irrigation infrastructure of the complicated, partly underground falaj (pl. aflaj) systems, referring to a canal which conveys groundwater from the foot of a mountain or another impermeable layer to a distant oasis, has been investigated by several authors (Costa, 1983; Dutton, 1986; Norman et al., 1998; Omezzine and Lokman, 1998; Wilkinson, 1974), but little is known about how these systems have developed over time.

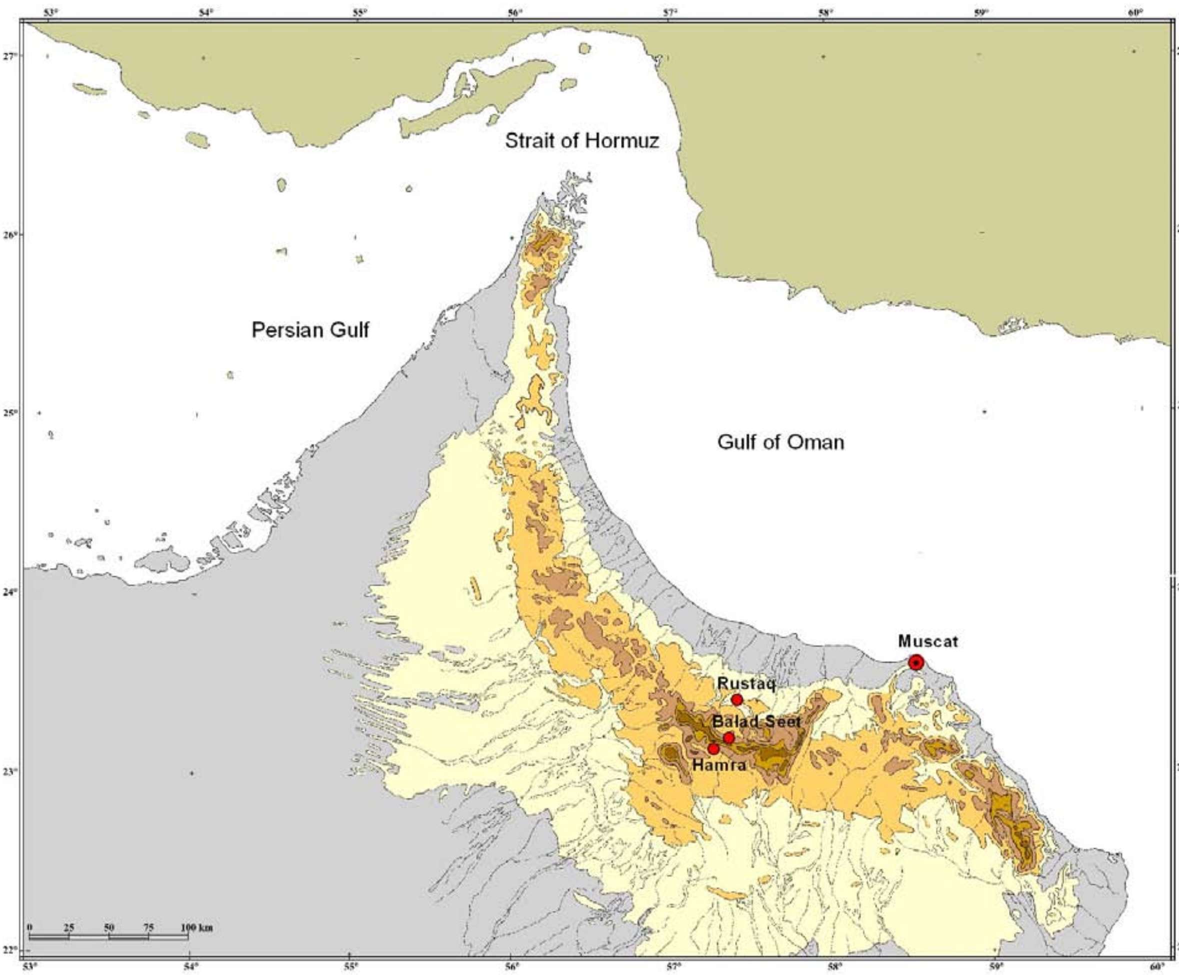

Fig. 1. Relief map of northern Oman showing the major mountain ranges, important towns and villages and the research site of Balad Seet (modified after Gebel, 1988).

Furthermore, little has been done to unravel the settlement history of northern Oman and it is obvious that the development of the oasis settlements has to be seen in the broader context of cultural development in Oman. The earliest oasis settlement in this region is thought to be Hili 8 in the modern oasis of Al Ain in the United Arab Emirates, which was dated to the early 3rd millennium BC (Cleuziou, 1998). Costantini (1980) concluded from charred date stones and imprints of barley, wheat, and sorghum in dried mud found at this place, that it had already at this early time a well organized oasis agriculture. The excavations at Al Ain also uncovered a canal that surrounds a large building, however, the underlying mode of irrigation has not yet been understood.

Since the Umm an-Nar period (2700 BC, Table 1) many other oasis settlements at the eastern and western coast of the Oman Peninsula, as well as at the south-western and southern foreland of the Hajar mountains were established. During the Wadi Suq period around 2000 BC for still unknown reasons most of the inland oases were given up. During the following

Table 1. Sequence of settlement phases at Balad Seet in the context of archaeological and historic time periods in Oman. The settlement phases partly overlap with the duration of the time periods.

Time period	Duration	Settlement phase
Hafit	3100–2700 BC[a]	(1)
Umm an-Nar	2700–2000 BC	(1)
Wadi Suq	2000–1300 BC	(1)
Iron Age I	1300–1100 BC	(1)
Iron Age II	1100–600 BC	(2) (3)
Iron Age III	600–300 BC	(3)
Late Iron Age (Samad)	300 BC–630 AD[b]	(3)
Early Islamic	630–1055 AD	(4)
Middle Islamic	1055–1500 AD	(5)
Late Islamic	1500–1930 AD	(6)
Sub-recent	1930–1970 AD	(7)
Recent	1970–today	(8)

[a]: Before the birth of Christ
[b]: After the birth of Christ

900 years some of the older settlements at the coast were still in use, but in most areas one can only find faint traces of settlements. The large cemeteries, which were discovered at many places provide, however, convincing evidence, that these areas were not completely abandoned (Carter, 1997).

For the Iron Age II period between 1100 and 600 BC (Table 1) a dramatic rise of settlements as well as a shift of settlements from the mountain foreland towards the mountainous regions has been documented (Magee, 1999). Since many of the new established villages were situated very close to traditional falaj systems, it seems reasonable to explain the rise of oases with the introduction of this intrinsic method of irrigation. There is a long lasting discussion about the introduction of the falaj system on the Oman Peninsula (Boucharlat, 2001), but the excavations of the last ten years show that the old theory of an introduction from Iran by the Achaemenians as late as in the 6th century BC is no longer convincing. Still it remains open to further discussion, whether the falaj system was introduced from outside or whether it was developed in Oman.

To fill the remaining gap of knowledge in the settlement history of oases in northern Oman, an interdisciplinary study including archaeologists and agriculturalists was initiated. Its aim was to elucidate the biophysical and historical bases for the transformation processes of such ancient systems based on detailed biophysical measurements and archaeological findings. The first results of this study, which are presented below allow to derive hypotheses for the millennia-old development of oasis agriculture for a specific section of northern Oman.

2 MATERIALS AND METHODS

2.1 Experimental area

The study area comprised the Wadi Bani Awf, a watershed on the northern side of the Hajar range of the Jabal Akhdar mountains with the small oases of Fara, Qismatayn, Wasit, Tikha, Zamma, Salma, and Hat. It extended until the towns of Misfa and Hamra on the southern flank of these mountains (Fig. 2). For centuries Hamra with its sheikh was the traditional political center of the region and a market place for goods from and into the Wadi Bani Awf (Ribbeck et al., 1999). The strong contacts across the mountains are also reflected by families living at Hamra but also owning fields at Balad Seet (Mershen, 1999; Nagieb et al., unpublished).

Within this area the central observation unit for the agronomic research was the mountain oasis of Balad Seet (23.19° N, 57.39° E; 996 m a.s.l. about 90 mm of total average annual precipitation) situated at the upper end of the watershed in a small natural valley at the foot of a 1000 m high cliff and surrounded by mountains (Photo 1). In the middle of this valley is a major rocky outcrop which contains most of the village buildings. The surrounding rock formation consists of highly permeable carbonates (dolomites and lime stones of the Mahi formation) resting over impermeable, red-greyish-green silt- and clay-stones of the Muaydin formation. The silt-stones have very little fracture porosity and act therefore as an aquifuge, whereas the carbonates above are highly fractured and karstic which allows the groundwater to be stored and to migrate over long distances (Weier, personal communication; Fig. 3). Next to Balad Seet and at the foot of the same cliff is the slightly smaller oasis of Hat with three springs that drain into the same watershed. The lower part of the wadi contains the oases of Zamma, Tikha, and Fara which are much smaller than Balad Seet. They derive their water partly from the drainage flow of the two head-oases filtrating through the rocky valley and partly from smaller local springs.

2.2 Recording of topography, agro-infrastructural features, available water and soil properties

At Balad Seet the period of on-going measurements started in April 2000 and comprised the establishment of a three-dimensional digital base map of the oasis within a Geographical Information System (GIS). First, the topography of the rugged surrounding mountains was digitized from Russian military maps (1:100 000, Joint Stock Company SK-IMPEX, Moscow,

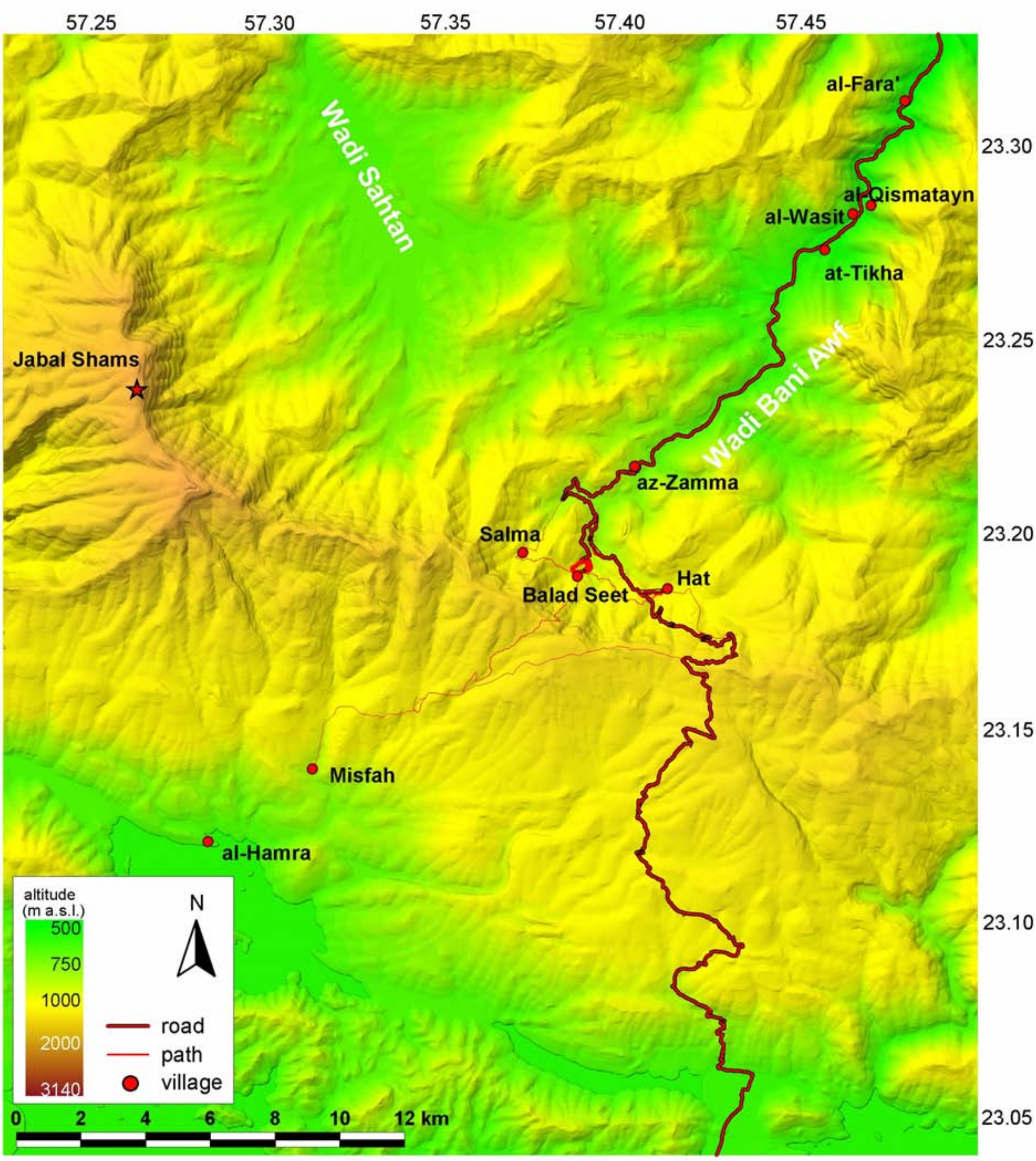

Fig. 2. Relief map of the study area with the Wadi Bani Awf, the Hajar mountain range and the al-Hamra area comprising the modern roads and ancient trading paths. Data from Russian military maps (1 : 100 000), own GPS-measurements and aerial photographs.

Photo 1. The mountain oasis of Balad Seet situated at the upper end of wadi Bani Awf on the northern side of the Hajar range of the Jabal Akhdar mountains, Oman.

Russia) with 40-m altitude lines. Subsequently, all major features governing the oasis agriculture were mapped using a differential Global Positioning System (GPS; Trimble Pathfinder, Sunnyvale, CA, USA) with decimeter precision. Those features comprised the position of the 12 springs, the 14 shallow wells that have been dug into the wadi sediments to allow seeping ground- and leaching-water to be reused for irrigation, the canals conveying thespring outflow to the fields (aini-aflaj or shortly called aflaj below), the terraces as well as the position of the date palms, foot paths and roads. The borders of the plots in the six terrace systems of the oasis and the houses were digitized from aerial photographs taken with a remotely controlled camera from a helium-filled balloon (Buerkert et al., 1996). Additional 3-D measurements of the terraces were taken with an electronic tachymeter at ± 0.01 m (Leica-Geosystems TPS300, Leica GmbH, Switzerland).

Between November 2000 and April 2003 monthly outflow measurements of all springs at Balad Seet, which convey their water into four major aflaj systems, were taken with a hand-operated barrel system to determine the total influx of irrigation water and the relative contribution of each spring to this total over time. Additionally daily precipitation data were collected to observe the response of spring outflow to rainfall. In November 2002 and January

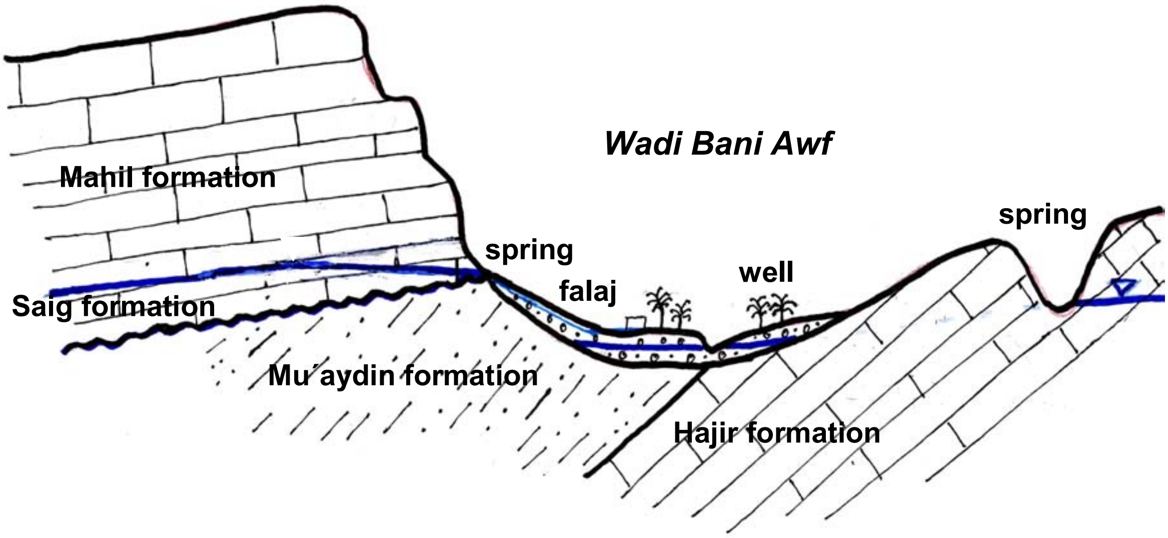

Fig. 3. Schematic cross-section of the geological setting at Balad seet in the upper Wadi Bani Awf, Oman (approximatively in NW-SE direction).

2003 selected springs in Balad Seet and Hat were also sampled to determine the age of the water storage through the tritium/^{3}helium ratio and concentration of the anthropogenic trace gases sulphurhexafluoride (SF_6) and chlorfluorcarbohydrates (CFC) according to methods described in detail by Aeschbach-Hertig et al. (1998) and Beyerle et al. (1999). The purpose of these water measurements in the context of this paper was to show the relative importance of the different aflaj as water sources and the 'elasticity' of their water flow during the extended period of drought experienced during the measurement period. Given the constancy of the geological properties of the springs' parent rocks insights into the 'elasticity' of the water supply would be an important basis for subsequent hypotheses about any pre-historic settlement of the oasis system under study.

In October 2002 two soil pits were dug in the palm grove area and the cropped portion of the Mazra terrace system. A lacquer peel technique (modified after Hähnel, 1961) was used to conserve and study the structure of the anthropogenic profiles (Photo 2). In the second pit soil samples were taken at four depth intervals (0 to 0.2 m, 0.2 to 0.4 m, 0.4 to 0.6 m and 0.6 to 0.9 m) to determine the size distribution and hydraulic properties of the different layers. About 0.2 m below the plough layer at 0.45 m depth, this profile also contained a small piece of charcoal which could be used for ^{14}C-dating using accelerated mass spectrometry (AMS) at the Institute of Physics at the University of Erlangen-Nürnberg, Germany. In the same pit also a single green glazed sherd was found that allowed a typological age determination.

2.3 Agricultural production and carrying capacity

To estimate the agricultural production and the carrying capacity for small ruminants and the size of the farming community at Balad Seet over time from the biophysical and archaeological data collected, the following eight assumptions were made (Table 2):

(1) The water outflow of the springs in the valley of Balad Seet remained unchanged over long periods of time and thus present day flow rates could be used as a proxy.

(2) Potential evapotranspiration in the valley could be calculated according to Priestley and Taylor (1972) modified by Shuttleworth (1993). The necessary input data (global radiation and air temperature) came from an automatic weather station established at Balad Seet from Dezember 2002 to April 2003. Crop coefficients were taken from Allen et al. (1998).

(3) Date yields and energy levels from unfertilized local palms genotypes remained largely unchanged over time. Present day yield levels (10-20 kg DM tree^{-1} year^{-1}, Nagieb et al., unpublished) were in close agreement with data reported from Oman prior to modernization (FAO, 2003).

(4) The germplasm for wheat (ancient landraces, Al-Maskri et al., 2003), sorghum, and alfalfa has remained unchanged over time. Therefore yield levels prior to 1960 (FAO, 2003) and energy contents of crops were representative for all previous periods. Human energy consumption for a farm-working adult also remained constant over time.

(5) The largely genetically determined ratio between crop residues and grain yield, also known as harvest index, remained constant over time and could thus be taken from present day measurements in the oasis.

(6) The construction of the access road in 1980 led to a large increase in the cropland grown to alfalfa as the basis for feeding the oasis's herd of small ruminants.

(7) The fraction of dates used as an energy supplement for the nutrition of goats and sheep grazing the desert mountains, the DM intake of these animals and the meat yield per slaughtered animal remained constant over time and was taken from the literature (George, 1987).

(8) The useable fraction of the total spring outflow can be calculated as a function of the irrigation system available during a specific time period. This refers particularly to the constructed aflaj. With the exception of the likely oldest wadi well, major additional amounts of supplementary well water became only available after the arrival of motor pumps after 1980.

Table 2. Listing of input variables used to model the carrying capacity of the mountain oasis of Balad Seet (Oman) through time. The approximate duration of the settlement phases does not always correspond to the time span of the archaeological and historic time periods.

Settlement phase	1	2	3	4	5	6	7	8
Approximate duration	3100-1100BC	1100-900BC	900BC–630AD	630-1055AD	1055-1650AD	1650-1930AD	1930-1970AD	> 1970
Input data								
Energy content of mutton and goat meat (kJ kg^{-1})	8360	→	→	→	→	→	→	→
Energy content of dates (kJ kg^{-1})	6530	→	→	→	→	→	→	→
Energy content of cereals (kJ kg^{-1})	12 130	→	→	→	→	→	→	→
Human energy demand (kJ (head x $day)^{-1}$)	7530	→	→	→	→	→	→	→
Fraction of cropping area cropped with alfalfa (-)	0.3	→	→	→	→	→	→	0.84[b]
Fraction of dates used as food (-)	0.8	→	→	→	→	→	→	→
Ratio crop residues DM[a] / grain yield (-)	3	→	→	→	→	→		→
Date yield (kg $tree^{-1}$)	18.8	→	→	→	→	→	20	32.5[b]
Wheat yield (kg ha^{-1})	1400	→	→	→	→	→	→	6000[b]
Sorghum yield (kg ha^{-1})	3000	→	→	→	→	→	→	18 000[b]
Alfalfa yield (kg ha^{-1})	15 000	→	→	→	→	→	→	33 600[b]
Livestock DM demand (kg DM (day x $head)^{-1}$)	2	→	→	→	→	→	→	2[b]
Meat yield per slaughtered animal (kg $head^{-1}$)	15	→	→	→	→	→	→	15
Usable fraction of spring flow (-)	0.01	0.1	1.0	→	→	→	→	→
Water pumped from wells (m^3 day^{-1})	0	→	→	→	→	→	→	63[b]

[a]: Dry matter, data assumed to remain unchanged for prior periods
[b]: Actual measurement

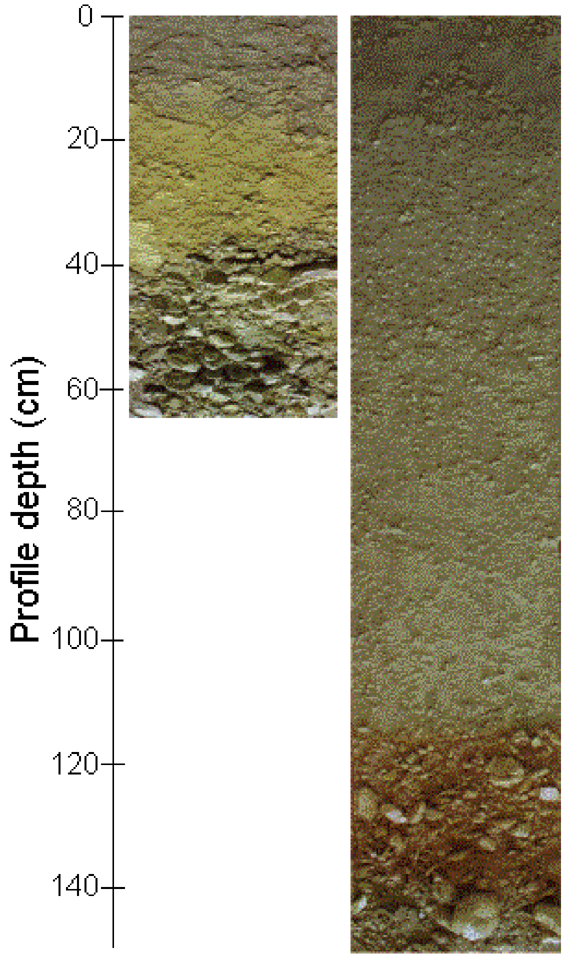

Photo 2. Soil profile of the shallow upper part of the Mazra terrace system in Balad Seet (Oman) planted with palm trees (left) and the lower part planted with annual crops and alfalfa (right). In the latter note the difference between the gray, silt-rich upper layers of this man-made profile with their high water-holding capacity and the lower portion with its reddish, stony and rapidly draining structure.

2.4 Collection of archaeological data

An archaeological survey totaling 14 weeks was undertaken during three campaigns in 1999 and 2000. Given that the study aimed at a regional appraisal of settlement patterns, only surface material was collected and no excavations were undertaken. During the survey Balad Seet received the registration number 63 and its 18 sites were sub-numbered from 1-18. In the following description only these sub-numbers were used.

The surface material consisted - with few exceptions - of pottery sherds which after comparison with a previously established pottery typology allowed a provisional dating of the archaeological sites. However, the chronological scheme for Oman's history is still vague and therefore the dating spans of the different periods are broad (Table 1). This certainly has major effects on the precision with which the settlement development can be interpreted.

Additionally, the pottery may allow insights into the functional context of the sites, as in many cases it was possible to distinguish between the remains of domestic items and grave wares. Furthermore, pottery sherds can indicate trade connections between different sites and areas.

Since typological studies of the pottery in Oman are rare, especially for the Islamic periods, it was decided to collect all pottery sherds and not only a subsample as it was previously done in other surveys of the Near East. However, this was only possible because the amount of finds was relatively small at all archaeological sites. Upon completion of the field collection all pottery was processed typologically and with an archaeological seriation technique (The Bonn Seriation and Archaeological Statistics Package, Version 4.0).

In addition to the pottery, all built ancient structures such as houses, towers, shelters, protection walls and tombs were mapped and described. This mapping was made with the help of a GPS and aerial photographs at the scale of 1:20 000 (National Survey Authority, Sultanate of Oman, 1985). From selected oases aerial photographs were taken from a helium-filled balloon as described above to obtain a better overview of the architectural remains of the sites.

3 RESULTS

3.1 Settlement and agriculture in Balad Seet

In early 2001, the oasis system of Balad Seet comprised 650 inhabitants distributed in 80 households who rented land in and out. About 2800 date palms comprising 14 varieties covered 8.8 ha of terraced land. The 418 fields of the oasis were divided into six terrace systems totaling 4.6 ha. These comprised Mazra with 145 plots and a total area of 2.03 ha, Zahir with 137 plots and 1.27 ha, Khaw with 53 plots and 0.54 ha, Libsi with 58 plots and 0.47 ha, Rud with 19 plots and 0.25 ha, and Khtawi, a small private terrace system with 6 plots and 0.06 ha. Average plot size is 110 m^2 with a variation between 7.5 and 593 m^2 (Fig. 4). The terraces contained traditional wheat landraces (*Triticum aestivum* L. and *Triticum durum*; Al-Maskri et al., 2003), sorghum (*Sorghum bicolor* Moench s. l.), barley (*Hordeum vulgare* L. s. l.), oats (*Avena sativa* L.), alfalfa (*Medicago sativa* L.), garlic (*Allium sativum* L.), onion (*Allium cepa* L.), lime (*Citrus aurantiifolia* [Christm. et Panz.] Swingle), and banana (*Musa* spp.) in rotation or interplanted cropping systems. The analysis of the land use pattern across the year (winter compared to summer months) also showed a characteristic fluctuation of used and unused plots. In the cooler winter months the fallow rate was only 15-

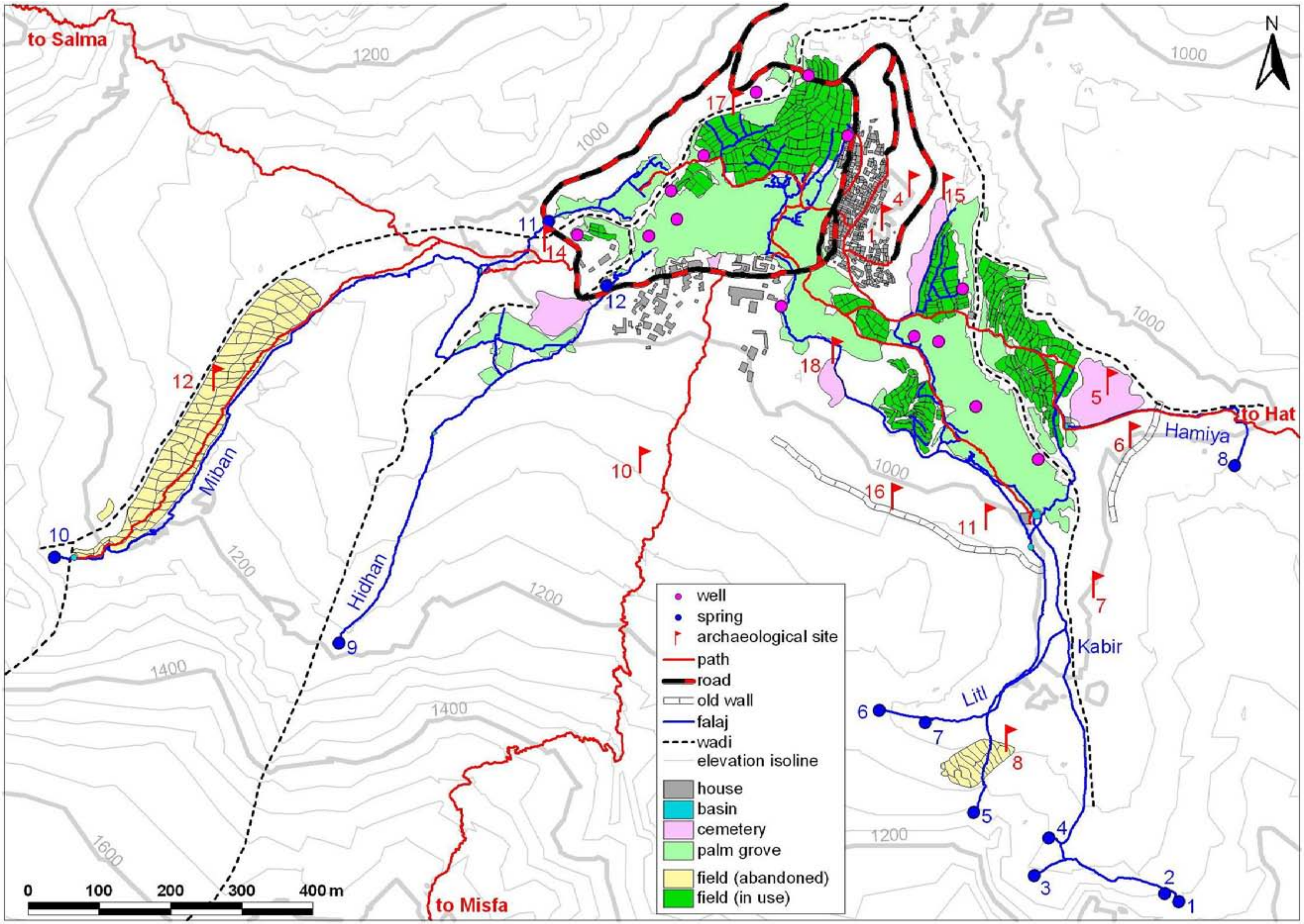

Fig. 4. GIS-based map with the agricultural features and archaeological sites of the mountain oasis of Balad Seet, Oman.

20% and had a larger variation of crops than the summer months with a total fallow portion of 50-70% and mainly drought-tolerant crops such as sorghum.

A major proportion of the farm income is derived from the up to 200 small ruminants (sheep and goats) which are fed mainly by alfalfa, immature barley and crop residues at home plus a minor amount of forage browsed during two 3-hr herded grazing periods per day in the oasis neighborhood. On separate grazing grounds in the surrounding mountains and at altitudes above 1300 m small ruminants are also herded by semi-nomadic families commonly referred to by the term of shawawi.

Until the early 1980s when an unpaved road was built across the Wadi Bani Awf to connect it with Rustaq, the major administrative town northwest of the area near the foothills of the Hajar range, most trade occurred with Hamra to which Balad Seet was connected by two ancient trade routes. The major 27 km long donkey trade path connected the two places via Hat but there also was a 19 km long foot path which allowed to climb the cliff of Balad Seet partly by rock stairs.

3.2 Rainfall, runoff and hydrological features

With only one major rainfall event in July 2001, the total aflaj outflow declined from 30.0 m^3 h^{-1} in November 2001 to 22.3 m^3 h^{-1} in March 2003 but it recovered within 4 days after two long expected rainfall events on 15 and 17 April 2003 with 20 and 44 mm precipitation to 31.3 m^3 h^{-1} (Fig. 5). During the prolonged drought period the total outflow of all springs decreased at a monthly rate of about 3 % but there were clear differences for the different aflaj. The springs in the eastern part of the oasis which joint their water into the aflaj Kabir (with a flow rate of 24.7 m^3 h^{-1} on 20 April 2003), Litl (1.7 m^3 h^{-1}) and Hamiya (0.2 m^3 h^{-1}) showed a much slower decline in their outflow over the prolonged drought period than the springs in the south (Hidan with 2.0 m^3 h^{-1}) and west (Miban with 2.9 m^3 h^{-1}) indicating a more buffered hydrological reservoir with a larger water storage capacity (Fig. 5). In winter months the oasis farmers of today's Balad Seet draw in addition to the springs' outflow up to 63 m^3 of groundwater per day by motor pumps from the 14 wells, which have been dug into the wadi sediments. In summer months, however, seepage is too low to allow the extraction of substantial amounts of water from these wells.

The first results of the isotopic analyses of the water's age indicated a range of 2 to 10 years for the percolation from the mountain tops to the springs feeding Balad Seet. Given the karstic nature of the parent rock it is most likely that the age of the apparently younger waters reflect a contact between water and air at some point of the flow path through the rocks.

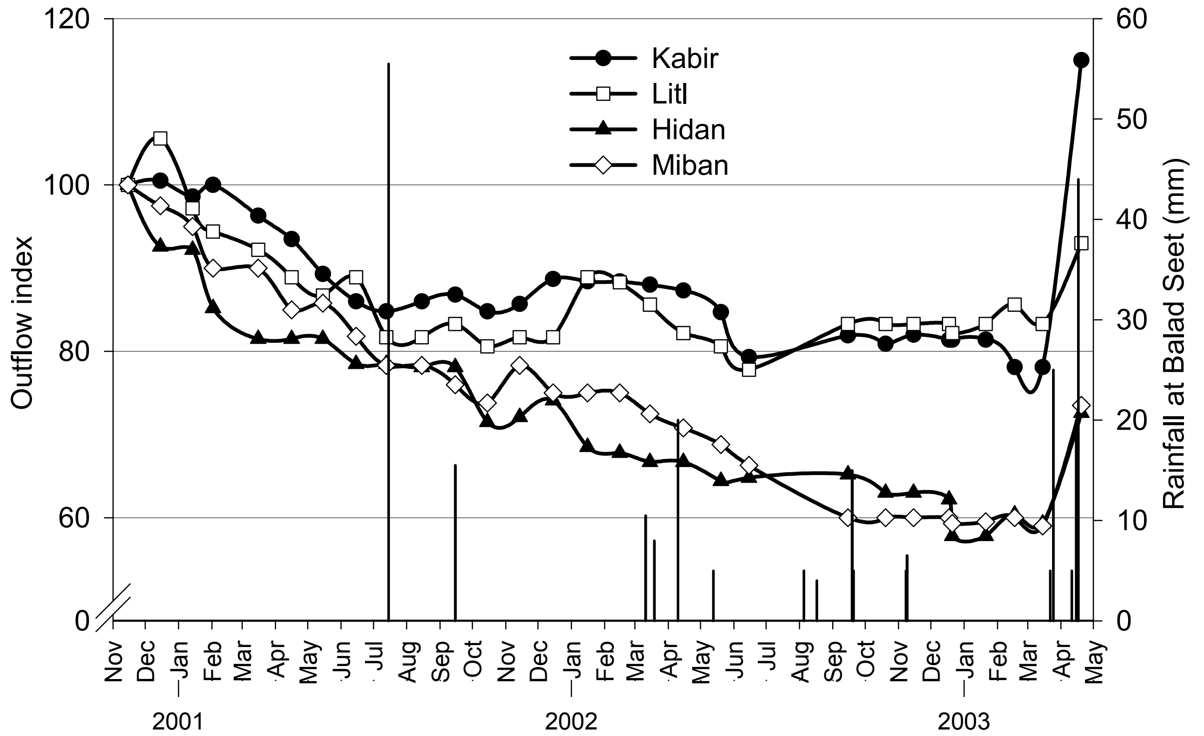

Fig. 5. Relative outflow of the four major aflaj and rainfall at Balad Seet. Flow rates were set to 100 at the onset of the measurement period on 15 November 2000, no rainfall measurements were taken before January 2001.

Therefore the average water age is probably at the upper end of the determined range with substantial scope for variation between individual springs.

3.3 Soil analyses

The analyses of the soil profiles indicated that the cropped, man-made terrace soils of Mazra were made up of three successive top layers in total 0.9 m thick and with pH 8.4, 12-15% clay, 48-54% silt, 34-38% sand, and an organic carbon (C_{org}) concentration of 23 g kg^{-1} (Luedeling et al., 2003). The very high C_{org} levels reflect the regular application of manure at rates up to 10 t ha^{-1} year^{-1} and is the basis for the high fertility and productivity of these oases soils despite high C turnover rates (Wichern et al., 2003).

The ^{14}C-dating of the charcoal in the Mazra terrace system revealed an age of 911 ± 43 years or an origin between 1027-1212 AD at a 95% probability. This corresponds well to the age determination of the sherd which dates back to the early Islamic period probably between 800-1000 AD.

During the period of terrace construction the large amounts of silt needed have probably been collected from wadi sediments after heavy rainfalls as there is barely any other soil material available in the rocky surroundings of the oasis. Below the upper layers there is a clearly differentiated fourth stratum with 9% clay, 27% silt and 64% sand, and an increasing amount of big stones. This clear stratification of horizons allows the storage of water and nutrients in the upper 0.9 m of the terrace soils and a rapid drainage below, thereby avoiding the typical built-up of toxic salt concentrations with irrigation in many arid environments. The upper, shallow soils planted to date palms have a similar structure but reach the coarsely weathered bedrock at 0.4 m.

3.4 Archaeological findings

The most important archaeological place of Balad Seet is situated at the steep eastern slope of the outcrop, where the modern settlement is located (site 4 on Fig. 4, Photo 3). A total of 785 pottery sherds of different periods but no architectural structures or tombs were discovered there. The sherds covered the entire period from the Iron Age II period (Table 1) to modern times. The fact that only ceramic sherds were found at the bottom of the eastern slope indicated that over time this part of the outcrop was the rubbish dump of the settlement above. It may thus be hypothesized that the site was continuously inhabited since the Iron Age. As there are no architectural remains older than of the late Islamic period in the village itself, the archaeological finds did not allow to estimate the extension of the settlement nor the size of population for these early periods. The fact that all Iron Age II sherds (579 pieces) were from domestic wares and no grave pottery was found precludes the possibility that they are utensils from tombs situated at the top of the outcrop.

21 out of a total of 38 sherds of the same archaeological period were collected on site 5 (Figs. 3 and 4), situated at the eastern edge of the fields. This area is covered with an Islamic cemetery. The graves were constructed inside the remains of stone-built house foundations (Photo 4). Three rooms or houses were distinguishable but the area was very disturbed which made it impossible to determine whether there once was a small settlement or only a few individual houses. Since the stones of the foundations were laid out carefully, it may be assumed that they were not from stables but from homes. The determination of the age of these house foundations is as difficult as that of the remaining sherds on site (5): 21 sherds were of the early Iron Age, 10 of the early Islamic period and 7 of the middle or late Islamic period (Table 1). Since the Islamic graves were built inside the house foundations, the former must be older than the latter. If the graves are late Islamic, the houses could be of the early Islamic or late Iron Age period.

A local story in Balad Seet refers to an ancient settlement (site 8) called madina qadima (old city) in Arabic. Its inspection revealed a number of very dilapidated terrace fields

Photo 3. Balad Seet from the east. The white arrow marks the rubbish dump with pottery of different periods.

with remains of a falaj system. These were situated at a slope south–east of Balad Seet close to spring 5 (Fig. 4). Here 45 of the 47 discovered pottery sherds were of the Iron Age II. It is unclear whether they really allow to date the terraces because they could have also been carried with manure from other places to this site. However, the physical state of these terraces and the fact that the residents of the village did not anymore remember their function and interpreted them as remains of an ancient settlement indicated that they were abandoned a long time ago.

Besides the former madima qadima terraces there was a second area of abandoned terrace fields in the situated south-western part of the village (site 12, Fig. 4). However, it was much better preserved. The old men of the village remembered that these fields were abandoned about 70 years ago due to a successive shortage of water. According to oral records after the abandonment of these terraces, a smaller system was built together with an access falaj to allow the outflow of spring 10 (Fig. 4) to reach these structures that were planted with date palms. In the immediate surroundings of these fields the remains of a few scattered enclosures were identified on site 14 (Fig. 4). They appeared to be former camp sites of the shawawi and their livestock. The four pottery sherds found inside these enclosures are of Iron Age and very late Islamic date. Some further remains of stone built houses are scattered south and south-east of Balad Seet. Given their architectural layout also these houses are probably of the late Islamic period.

South and east of the oasis two long and massive walls were erected. The southern near site 16 (Fig. 4) stretches parallel to the slope over 440 m. It was built of undressed stones, about 1.5 m high and its width varies between 0.6 and 1.0 m. The eastern wall near site 6 (Fig. 4) was also built of undressed stones but is more massive than the first one. It also extends parallel to the slope and ends near the eastern wadi. No finds were discovered near these walls and today's inhabitants of Balad Seet have no records who might have built them. They explained their purpose as part of a fortification system but their position on the rocky steep slope makes this very unlikely. Walls of a similar type have been found elsewhere in Oman and are often interpreted as boundaries with, however, unclear functions.

Near site 4 (Fig. 4) two Islamic cemeteries were found: one at the eastern foot of the outcrop with the modern village (site 15, Fig. 4), the other one south of the village (site 18, Fig. 4). The latter one is still in use, whereas the former is overgrown with bushes and

Photo 4. Islamic cemetery with graves inside the remains of stone-built house foundations. The graves may be of the late Islamic period (1500–1930 AD) and the houses of the early Islamic (630–1055 AD) or Iron Age II period (1000-600 BC, Table 1).

littered with rubbish. In contrary to the cemetery of site 5 (Fig. 4), no finds were discovered on the latter cemeteries. Presumably, they belong to the late Islamic and recent settlement phases.

In contrast to other parts of Wadi Bani Awf, Wadi Hat and Hamra where tombs of the Hafit period were discovered, no such structures were found at Balad Seet, nor were there any settlements from this period. Presumably during these early times the population lived from herding goats and sheep and their dwellings have completely vanished. Wherever identified elsewhere such early tombs were located in clearly visible positions marking long axes which gave raise to the hypothesis that they not only served as burial sites but also as landmarks pointing to important features in the landscape. As Balad Seet is topographically a dead end and the mountain crests nearby could only be crossed on a steep footpath unsuitable for animals there may have been no cause for the construction of early tombs as landmarks. The settlement history during the following periods (the Umm an-Nar period, the Wadi Suq period and the Iron Age I period, Table 1) is even more difficult to determine for the area as only a few graves were found in Wadi Bani Awf and Hamra and none at Balad Seet.

At Hamra two settlements of the Iron Age II period were identified, similar to Balad Seet, and there are also several cemeteries of this period. Two additional small Iron Age cemeteries were discovered in the Wadi Bani Awf between Zamma and Tikha. Since there are no remains of Iron Age tombs at Balad Seet, it remains open to further debate, where the deceased of Balad Seet may have been buried.

The following periods of the early Iron Age and the late Iron Age are only represented by some tombs and faint traces of a wall at Hamra, but not in the Wadi Bani Awf. The latter also preserved only very few remains of the early Islamic period.

In the 11^{th} / 12^{th} century AD a slight increase of settlement activities in the Wadi Bani Awf as well as at Hamra was observed. At Hamra these sites are sometimes close to the former Iron Age settlements. Pottery of this period was also found at Hat and in Wadi Bani Awf at the junction to Bi´r. The last mentioned oasis was probably abandoned already in the middle Islamic period or in the early phase of the late Islamic period.

A dramatic change in the settlement history of the wadi was observed for the late Islamic period. All now existing oases were established by then. This was conclusively shown by the appearance of the so-called Bahla ware, which is the typical glazed pottery for this period, found at all settlements. Two additional sites, now abandoned, were established during this period. At Hamra a new falaj was built, which provided the basis for erecting a much larger settlement.

4 DISCUSSION

4.1 Settlement hypotheses

There is no archaeological evidence for any settlement at Balad Seet during the first phase of occupation in the lower Wadi Bani Awf, that is the period from 3100-1100 BC. However, in view of the unusually large and reliable water resources at the upper end of the valley it is most likely that it was used intensively by shepherds and their flocks which were watered in the small natural basins of the wadi below what later became the falaj Kabir's main reservoir (Fig. 6-1). The settlement history of Balad Seet probably started in the Iron Age II period (1100-600 BC) when, as indicated by the findings of the rubbish dump on the south eastern side of the rocky outcrop, a small village was established on its top. It would have been the first village of that period ever found north of the Hajar mountains but during the same period two villages were built, like many others on the southern and southeastern flanks of the Hajar range, at Hamra. There is evidence that the sudden appearance of settlements in this area may be explained by the introduction of the falaj system (Boucharlat, 2001; Häser, 2003). In this context it is particularly noteworthy that the Iron Age II sites at Hamra were attached to two different falaj systems, however there is no direct proof that these aflaj already existed in the Iron Age. At Balad Seet the villagers of this second settlement phase would have lived from hundreds of date palms planted on the first, relatively archaic terraces of 2.5 ha size located between today's Zahir and Khaw terrace systems. Before the construction of the aflaj Kabir and Litl in the following third phase (the second part of the Iron Age II period), the outflow from the most abundant springs of Balad Seet (springs 1 to 4) would likely have surfaced in the south-eastern wadi and provided year-round a relatively constant water supply. Irrigation of the data palms could thus have easily occurred from the large ancient and partly natural well tapping the wadi sediments there (Fig. 6-2). Given the strong infrastructural and cultural connections between Hamra and the upper Wadi Bani Awf, for which there also is evidence in the surprising similarity of the pottery sherds found for the Iron Age II period at both sites, it is likely that the first villagers of Balad Seet came from Hamra. As early as in the first half of the first millennium BC they might have brought with them the innovative falaj system. This allowed to more efficiently exploit the reliable waters from springs 1 to 4 and to irrigate the 0.4 ha of terraces in the so called madina qadima area (8). In this context, the major old basin should have been built to collect and redistribute the water of the aflaj Kabir and Litl (Fig. 6-3). The absence of tombs from the early and late Iron Age periods Balad Seet could be explained if one assumed that the bodies of its dead settlers from the small village on the

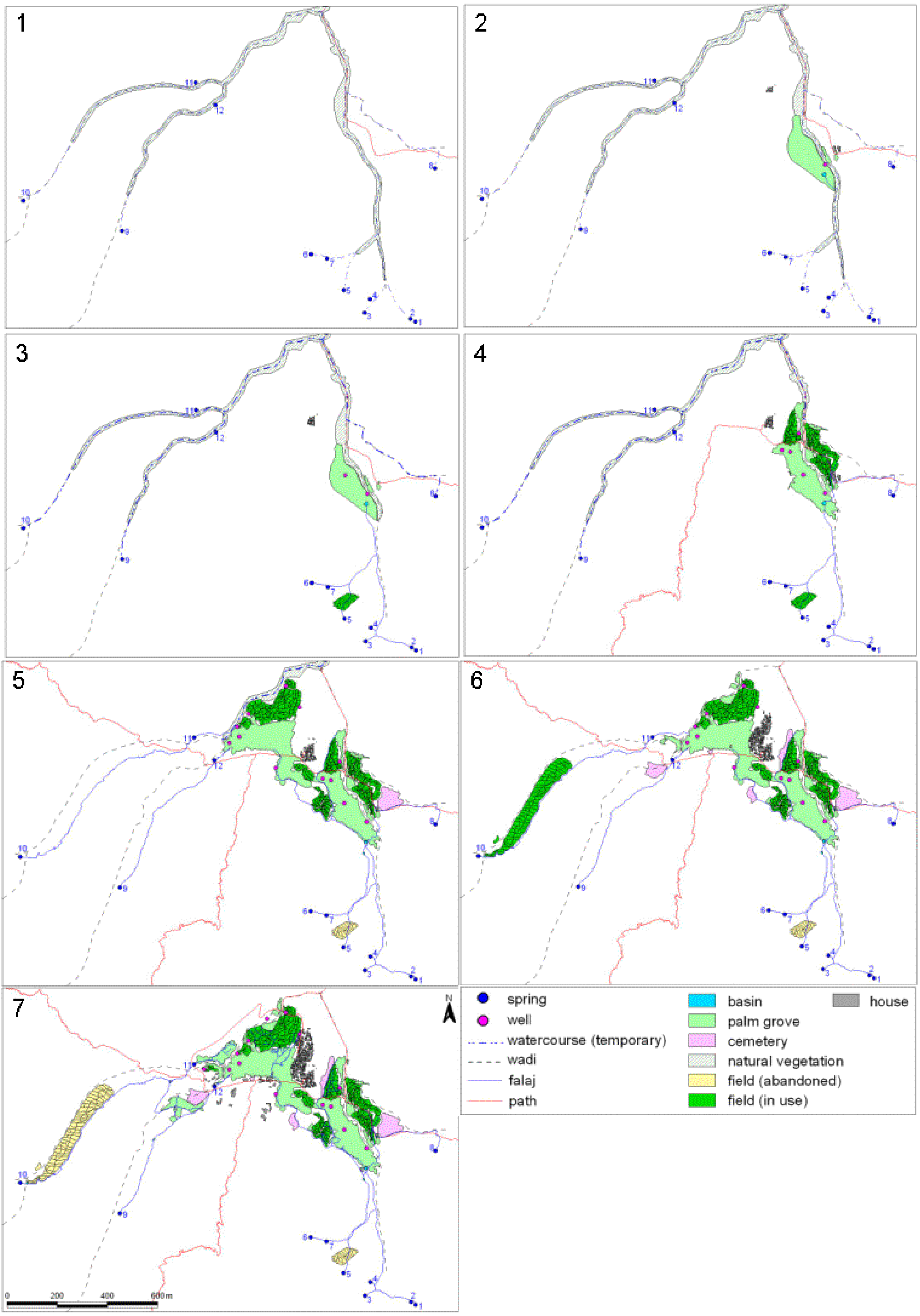

Fig. 6. Settlement phases of the mountain oasis of Balad Seet (Oman). Timings relate to settlement phases rather than to archaeological and historic periods and may show some overlap. **(1)** Hafit period (3100–2700 BC), Umm an-Nar period (2700–2000 BC), Wadi Suq period (2000–1300 BC), and Iron Age I period (1300–1100 BC), **(2)** 1st part of Iron Age II period (1100–900 BC), **(3)** 2nd part of Iron Age II and Iron Age III period (900–300 BC) and Late Iron Age (Samad) period (300 BC–630 AD), **(4)** early Islamic period (630 AD–1055 AD), **(5)** middle Islamic period and 1st part late Islamic period (1055 AD–1650 AD), **(6)** 2nd part late Islamic period (1650 AD–1930) and **(7)** Sub-recent period (1930–1970).

outcrop were either buried at Hamra or that their graves vanished during the following periods of intensive settlement activities in the mountain valley.

The fourth settlement phase of Balad Seet has taken place sometime in the early Islamic period (630-1055 AD) and was apparently characterized by a large expansion of the cropping and housing area. The abundance of water from the two aflaj should have allowed the establishment of the terrace systems of Zahir and Khaw planted with wheat landraces (Fig. 6-4; Al-Maski et al., 2003) and lime. Their construction certainly required substantial amounts of labor to collect the necessary stones and silt material from the wadi sediments. During this period the rocky outcrop remained inhabited and a few additional buildings were established on site 5 (Fig. 4), east of the Zahir terraces. Their foundations are still visible and carry sherds of simple turquoise glazed vessels probably imported from Iran or Mesopotamia. This likely reflects an at least modest wealth of the local settlers growing dates, wheat and lime at a time when the long distance trade with the large harbor at Sohar on the Oman's Batina coast and the other Gulf countries flourished.

The fifth settlement phase fell into the middle Islamic and the first part the late Islamic period (1055-1500 AD and 1500-1650 AD). The surprisingly consistent age of the ^{14}C-dated charcoal piece and the turquoise sherd found in the lower part of the Mazra soil profile (site 17) indicate a large expansion of the agricultural area during this period. The cultivation of large palm groves and cropping terraces at Mazra certainly required a major modification of the aflaj system to take advantage of the abundant water from the falaj Kabir system. It is therefore likely that this period saw the construction of a new basin to redistribute this water from a higher topographic position thereby also allowing the irrigation of the newly built Khaw, Rud, and Libsi terraces (Fig. 6-5). However, continuous cultivation of Mazra required so much water that also the aflaj Hidan and Miban needed to be constructed. This major work increased the village's total amount of crop land by 137% and of date palm groves by 105% thereby providing the broad hydro-infrastructural condition for its subsequent continued flourishing. With respect to the settlement structure the remains showed that the small building area east of Zahir was given up, whereas the houses on the outcrop remained. Pottery sherds of underglazed sgrafiatto wares from the 12th/13th century AD found in the rubbish dump indicated persisting trade relationships with Iran. This provided additional evidence of continued wealth in the farming community, despite the unstable political situation of Oman at that time. During this period the existing settlements of Balad Seet, and the later abandoned oasis at the junction to Bi´r, Hat, and Hamra were probably closely connected by the two trans-mountain trade routes described earlier.

No sherds of imported pottery were found for the time after the 13th century AD and it was also difficult to recognize marked typological features in the local pottery which would allow their dating.

The sixth settlement phase comprises the second part of the late Islamic period (1650-1930 AD, Table 1). The small fortress and also the layout of the modern village were presumably built during this period. On the other side of the Hajar mountains a new major falaj was laid out which formed the economic basis of the mud brick town of Hamra. This falaj was financed by the Ya'ariba dynasty to support the tribe of the Abriyin and subsequently Hamra became the local center of this tribe. For this period a strong rise of settlement and agricultural activities was noted along the entire Wadi Bani Awf which must have required massive investments. Though there is no firm evidence, it is likely that also these activities were economically supported by the Ya'ariba dynasty. It is likely that during this time the 2.5 ha sized terrace system at the western slope of the valley of Balad Seet was built (Fig. 6-6). It was irrigated by the falaj Miban until it was, according to oral history, abandoned in the 1930.

Typical for this period are glazed vessels of the so-called Bahla ware. Bahla is a large town about 20 km south of Hamra where high quality clay was found so that major pottery workshops were established there. All of the glazed pottery from Hamra and the other sites in the Wadi Bani Awf came from these workshops and is thus an indicator for local trade. In the entire study area only a few sherds of celadon or porcelain were found which might have been imported from south-east Asia. Even the local center of Hamra produced only a few finds of this kind. This points to a more local role of Hamra which, however, extended north of the Hajar mountains to at least Awabi for which ample evidence was found in the recently discovered archives of the sheikh of Hamra (Gaube et al., unpublished data).

A last still puzzling finding were the two large walls along the southern and eastern slopes of the Balad Seet valley of which the function and age were difficult to determine. Some old stone houses at the slope south of the village had the typical, simple layout of houses of the late Islamic period and were of a type also found elsewhere in the Wadi Bani Awf and at Hamra. Latest in this phase cemeteries were laid out east and south of the outcrop and east of the Zahir terrace system (5). The two last mentioned cemeteries are still in use today.

The sub-recent settlement phase (Table 1) saw the construction of the 1.2 ha sized Hillhila palm grove to which the waters of the aflaj Miban and Hidan were conveyed after the western terraces had been abandoned (Fig. 6-7). The final recent phase is characterized by the renovation of the aflaj and of many houses with cement and by the establishment of a southern housing area with a large school building (Fig. 4).

4.2 Agricultural production and carrying capacity over time

The previously described sequence of aflaj and terrace construction and the amounts of food and fodder likely to be produced from these terraces allowed to draw a sketchy but surprisingly convincing picture of the agricultural activities at Balad Seet (Table 3). It appears as if the cropping area steadily increased between the 3rd and 6th settlement phase and only declined again after the western terraces of size 2.5 ha had been abandoned in the 1930s. Thereafter the 2.9 m^3 water outflow h^{-1} of the Miban falaj was used for date production in the 1.2 ha of the Hillhila palm groves. Wheat production reflected the expansion and shrinkage of the cropping area except for the present period when the arrival of mineral nitrogen and phosphorus fertilizers allowed to double grain yield per unit area. The presented settlement hypotheses allow to postulate an interesting infrastructure-driven swing between periods of water limitation and those of land limitation. This can be exemplified by the assumed production of sorghum, a heat-tolerant typical summer cereal. It expanded several-fold during the 4th settlement phase when water should have abounded year round after the construction of the Kabir falaj system and before the large expansion of land following the subsequent construction of the Mazra terrace system. A steadily increasing production of dates over the centuries seems very likely reflecting both, an expansion of the palm grove area and, during the modern period, the intensification of the palm production by manure application to the trees. The latter was a consequence of the larger herd sizes maintained at Balad Seet (Table 3). The road construction in the 1980s with the subsequent large influx of food commodities from external markets should have led to a reduced area dedicated to wheat and a major conversion of the former ‘food land’ into ‘fodder land’. This would have allowed to increase the herd size of sheep and goats to the present levels of up to 200 heads and herewith much above the drought-limited carrying capacity of the grazing grounds in the surrounding ecosystem. In an increasingly market-oriented economy the animals are sold at premium prices on regional markets or are eaten by the farmers’ extended families when returning to their village of origin on occasion of religious feasts such as Ramadan and Id.

The number of settlers at Balad Seet may have always substantially exceeded the agriculture-based carrying capacity of the upper Wadi Bani Awf. Revenues from trade may have allowed the import of grain from a town like Hamra with larger land resources. The large difference between today’s calculated carrying capacity of 156 adults and the four-fold

Table 3. Listing of input variables used to model the carrying capacity of the mountain oasis of Balad Seet (Oman) through time. The approximate duration of the settlement phases does not always correspond to the time span of the archaeological and historic time periods.

Settlement phase	1	2	3	4	5	6	7	8
Approximate duration	3100-1100BC	1100-900BC	900BC–630AD	630-1055AD	1055-1650AD	1650-1930AD	1930-1970AD	> 1970
Output estimation								
Cropping area (ha)	0	0	0.4	2.2	4.6	7.0	4.6	4.6
Total wheat production (kg $year^{-1}$)	0	0	390	2170	4490	6900	4540	11 110
Total sorghum production (kg $year^{-1}$)	0	0	840	4641	0	0	0	0
Number of adult date palms	0	400	400	690	1535	1600	1700	1700
Palm grove area (ha)	0	2.5	2.5	3.1	7.0	7.6	8.8	8.8
Total date production (kg $year^{-1}$)	0	7500	7500	12 940	28 780	30 000	34 000	55 250
Total fodder production (kg DM[a] $year^{-1}$)	0	0	1800	9950	20 610	31 680	20 840	90 370
Water available (minimum) (m^3 day^{-1})	4	44	438	442	538	538	538	601
Minimum evapotranspiration (m^3 day^{-1})	0	138	138	171	383	419	487	487
Medium evapotranspiration (m^3 day^{-1})	0	138	149	234	513	618	619	622
Maximum evapotranspiration (m^3 day^{-1})	0	138	163	308	667.3	855.8	774.7	774.7
Number od adult sheep and goats	**0**	**2**	**11**	**29**	**56**	**84**	**59**	**186**
Energy from dates (MJ $year^{-1}$)	0	39 130	39 130	67 490	150 140	156 500	177 370	288 220
Energy from crops (MJ $year^{-1}$)	0	0	14 930	26 250	54 410	83 640	55 000	134 700
Energy from meat (MJ $year^{-1}$)	0	60	350	900	1750	2620	1850	5840
Number of adults living from agriculture	**0**	**14**	**20**	**34**	**75**	**88**	**85**	**156**

[a]: Dry matter

higher actual village population, however, is the result of the revenues from the flourishing secondary (trading) and tertiary sector (education and administration) of the modern economy which is based on the oil-economy. These revenues allow large amounts of calories and plant nutrients in the form of mineral fertilizers to be imported into the oasis and may finally lead to the conversion of the agriculturally exploited resource base into an increasingly vacation-oriented setting. Such transformation processes have been taken place in many oases of Oman and can presently be observed in its ultimate stages at Hamra, Balad Seet's presumed mother town.

5 CONCLUSIONS

Despite the scanty find situation in the study area, the combination of biophysical and archaeological data allowed the establishment of conclusive settlement hypotheses for the Wadi Bani Awf with a focus on its head oasis Balad Seet, a likely early offspring of Hamra. The main driving force for the settlement dynamics at Balad Seet was the availability of an abundant and stable outflow of springs at the northern foot of the Hajar mountain range. This triggered the early construction of an interrelated infrastructure of aflaj and terraces for the sustainable and increasingly efficient production of dates, lime, annual crops and meat. The closely connected scarcity of land and water and their eventual optimization by the immigrated settlers of Balad Seet might have been the major driving force for the development and apparent relative stable wealth of this oasis over the millennia.

The absence of settlements of the 3rd millennium BC in the area of this study leads to the hypothesis, that the earliest oases of Oman may not have been established in the mountainous regions of the Hajar range but were concentrated in its foreland and at the coast. The reasons for the choice of settlement areas are still poorly understood. The emergence of the first mountain occupations between 1100 and 600 BC confirm the existing theory on the one hand, but provide new hints to the strong correlation between the increase of settlements at this period and the introduction of the falaj system. The origin of the falaj irrigation system remains still open to further debate. The discovery of an Iron Age settlement at Balad Seet, an oasis on the northern side of the Hajar mountains which was tidely connected with Hamra on its southern side is of major surprise. It contradicts the conclusion of Magee (1999) who argued that the Hajar range formed a cultural barrier. The finds of this study rather indicate that a political and presumably also economical frontier went right through the Wadi Bani Awf. For the first time, this study shows the existence of the early and middle Islamic settlements that were not based on trade such as in Sohar, or on metal resources such as in

Arja and Wadi Safafir, but on agriculture alone. The apparently uninterrupted occupation of Balad Seet during periods of major crisis and revival at other sites in Oman reflects the role of oasis agriculture for the settlement history in this xeric country. As such, oasis agriculture certainly merits further process-oriented research.

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