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Effects of changing water availability on land use in irrigated mountain oases of Al Jabal Al Akhdar, northern Oman

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Abstract

In Oman, during the last three decades, agricultural water use and groundwater extraction has dramatically increased to meet the needs of a rapidly growing population and major changes in lifestyle. This has triggered agricultural land-use changes which have been poorly investigated. In view of this our study aimed at analysing patterns of short-term land-use changes (2007-2009) in the five irrigated mountain oases of Ash Sharayjah, Al'Ayn, Al'Aqr, Qasha' and Masayrat ar Ruwajah situated in the northern Oman Hajar mountains of Al Jabal Al Akhdar where competitive uses of irrigation water are particularly apparent. Comprehensive GIS-based field surveys were conducted over three years to record changes in terrace use in these five oases where farmers have traditionally adapted to rain-derived variations of irrigation water supply, e.g. by leaving agricultural terraces of annual crops uncultivated in drought years. Results show that the area occupied with field crops decreased in the dry years of 2008 and 2009 for all oases. In Ash Sharayjah, terrace areas grown with field crops declined from 4.7 ha (32.4 % of total terrace area) in 2007 to 3.1 ha (21.6 %) in 2008 and 3.0 ha (20.5 %) in 2009. Similarly, the area proportion of field crops shrunk in Al'Ayn, Qasha' and Masayrat from 35.2, 36.3 and 49.6 % in 2007 to 19.8, 8.5 and 41.3 % in 2009, respectively. In Al'Aqr, the area of field crops slightly increased from 0.3 ha (17.0 %) in 2007 to 0.7 (39.1 %) in 2008, and decreased to 0.5 ha (28.8 %) in 2009. During the same period annual dry matter yields of the cash crop garlic in Ash Sharayjah increased from 16.3 t ha^{-1} in 2007 to 19.8 t ha^{-1} in 2008 and 18.3 t ha^{-1} in 2009, while the same crop yielded only 0.4, 1.6 and 1.1 t ha^{-1} in Masayrat. In 2009, the total estimated agricultural area of the new town of Sayh Qatanah above the five oases was around 13.5 ha. Our results suggest that scarcity of irrigation water as a result of low precipitation and increased irrigation and home water consumption in the new urban settlements above the five oases have led to major shifts in the land-use pattern and increasingly threaten the centuries-long tradition and drought-resilience of agriculture in the oases of the studied watershed.

Zusammenfassung

Im Sultanat Oman hat im Laufe der vergangenen drei Jahrzehnte die Nutzung von Bewässerungswasser und die damit zusammenhängende Grundwasserbeanspruchung stark zugenommen, um damit die Ansprüche einer stark wachsenden Bevölkerung sowie Änderungen im Lebensstil befriedigen zu können. Dies führte zu Landnutzungsänderungen, die bisher nur unzureichend dokumentiert und verstanden sind. Um dazu beizutragen, diese Wissenslücke zu füllen, untersuchten wir kurzfristige adaptative Änderungen im Landnutzungsmuster (2007-2009) in den fünf traditionell oberflächenbewässerten Oasen Ash Sharayjah, Al'Ayn, Al'Aqr, Qasha' und Masayrat

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ar Ruwajah im nordomanischen Hajar Gebirgszug des Al Jabal Al Akhdar Massivs, in denen Wassernutzungskonflikte besonders deutlich sind. In detaillierten, dreijährigen GIS-gestützten Felduntersuchungen quantifizierten wir Nutzungsänderungen in der Terrassenbelegung mit Feldfrüchten, mit der sich Bauern seit Jahrhunderten an niederschlagsbedingte Änderungen der Verfügbarkeit von Bewässerungswasser anpassen. Insbesondere in Trockenperioden bleiben traditionell größere Flächenstücke brach. Unsere Ergebnisse zeigen, dass in allen fünf Oasen die mit Feldfrüchten bestellte Terrassenfläche in den besonders trockenen Jahren 2008 und 2009 abnahm. In der Oase Ash Sharayjah verringerten sich die Feldfruchtflächen von insgesamt 4,7 ha (32,4 % der Gesamtfläche) im Jahr 2007 auf 3,1 ha (21,6 %) im Jahr 2008 und 3,0 ha (20,5 %) im Jahr 2009. In ähnlicher Weise verringerte sich die Feldfruchtfläche in Al'Ayn, Qasha' und Masayrat von 35,2, 36,3 und 49,6 % (2007) auf 19,8, 8,5 und 41,3 % im Jahr 2009. In der Oase Al'Aqr erhöhte sich die gesamte Feldfruchtfläche von 0,3 ha (17,0 %) im Jahr 2007 auf 0,7 (39,1 %) 2008 und fiel 2009 auf 0,5 ha (28,8 %). In diesem Zeitraum stieg die Trockenmasse der Verkaufskultur Knoblauch in Ash Sharayjah von 16,3 t ha^{-1} im Jahr 2007 auf 19,8 t ha^{-1} (2008) und 18,3 t ha^{-1} (2009), während diese Pflanzenart in Masayrat nur Erträge von 0,4, 1,6 und 1,1 t ha^{-1} hatte. Im Jahr 2009 betrug die gesamte Grünfläche der über den Oasen liegenden neuen und stark wachsenden Stadt Sayh Qatanah 13,5 ha. Unsere Ergebnisse zeigen, dass die Knappheit von Bewässerungswasser in Folge schwankender Niederschläge und seines verstärkten Einsatzes für städtische Grünflächen sowie die Haushaltsnutzung zu größeren Nutzungsveränderungen im Landnutzungsmuster der fünf untersuchten Oasen führte und damit zunehmend die landwirtschaftliche Struktur und Adaptationsfähigkeit dieser uralten Landnutzungssysteme an natürliche Niederschlagsschwankungen bedroht.

Keywords Aflaj, drought mitigation, irrigation water, rainfall, Al Jabal Al Akhdar, Oman

1. Introduction

In recent years, the apparent sustainability (*Wichern* et al. 2004, *Luedeling* et al. 2005, *Luedeling* and *Buerkert*, 2008, *Golombek* et al. 2007, *Siebert* et al. 2007) and plant-biodiversity (*Al-Maskri* et al. 2003, *Filatenko* et al. 2010, *Zhang* et al. 2006, *Al Khanjari* et al. 2007ab, *Buerkert* et al. 2009, *Gebauer* et al 2007, *Hammer* et al. 2009) of the often millennia-old oasis systems of the northern Omani Hajar mountains have raised considerable scientific interest. Farmers in these oases irrigate their terraced agricultural area using the ancient aflaj irrigation system which is directly fed by natural springs. The judicious management of the aflaj system (Arabic: 'aflaj' is plural of 'falaj'; *Norman* et al. 1998, *Siebert* et al. 2007, *Nash* and *Agius* 2011) and the interaction between plant production and animal husbandry systems (*Buerkert* et al. 2005, *Schlecht* et al. 2009, *Dickhoefer* et al. 2010, *Brinkmann* et al. 2011) are considered key factors in the sustainability of agricultural production in Oman as in many other arid areas throughout the Middle East. In recent decades, these mountain oases have undergone major social and economic transformations leading to more pressure on water resources. The rapid growth of the population, changes in people's lifestyle and irrigation of non-agricultural areas for landscaping have (at least outside of the Muscat Metropolitan Area where waste water and desalinised water are increasingly used to sustain plant growth) led to a widespread increase in water demand (*Rajmohan* et al. 2007). In the oases this may lead to major modifications in land use the severity of which largely depends on changes in water flow from the springs. Understanding such farmer managed adaptations in land use and cropping patterns over time is an interesting research topic as it strongly determines the resilience of oasis agriculture (*Alemayehu* et al. 2009).

Given hyperarid conditions and an annual rainfall of between < 100 mm and 318 mm (*Fisher* 1994), agriculture in Oman depends mainly on mountain spring and groundwater irrigation, consuming about 80-90 % of the country's renewable fresh water resources on < 2 % of its land surface (*Norman* et al. 1998, *Victor* and *Al-Farsi* 2001, *Nagieb* et al. 2004). After an analysis of a 27-year rainfall record (1977-2003) from Oman *Kwarteng* et al. (2009) reported a negative trend in the total amount of annual precipitation. This aggravates the findings of a study conducted in the costal Al Batinah plain suggesting that the current level of water consumption exceeds the long-term recharge (*Omezzine* and *Zaibet* 1998). Despite the remarkable hydraulic buffer capacity of the Hajar Mountain range with its large overlays of lime- and claystones (*Nagieb* et al. 2004, *Siebert* et al. 2007), variation of total annual precipitation rather than occurrence of major rainstorm events is a major factor limiting the sustainability of Oman's irrigated oasis agriculture (*Luedeling* et al. 2005, *Abdalla* and *Al-Abri* 2011).

Photo 1 Wadi Mu'aydin watershed on Al Jabal Al Akhdar, northern Oman, with the ancient irrigated terrace systems of Ash Sharayjah, Al'Ayn, Al'Aqr and Qasha' (from left to right) carrying temperate crops, fruit trees and rose bushes

For the oases of the Wadi Mu'aydin watershed on Al Jabal Al Akhdar (*Matter* et al. 2005, *Photo 1*), a previous study by *Luedeling* and *Buerkert* (2008), using data from 1978 to 2005, indicated a water-consuming expansion of land planted with perennial trees and shrubs, of which – depending on altitude – the most frequent were pomegranate (*Punica granatum* L.), rose (*Rosa x damascena*), date palm (*Phoenix dactylifera* L.), lime (*Citrus aurantiifolia* L. Swingle), peach (*Prunus persica* L.) and in smaller numbers banana (*Musa x paradisiaca* L.), apricot (*Prunus armeniaca* L.), grape (*Vitis vinifera* L.), walnut (*Juglans regia* L.), pear (*Pyrus communis* L.), plum (*Prunus domestica* L.), apple (*Malus domestica* Borkh.), papaya (*Carica papaya* L.), guava (*Psidium guajava* L.) and fig (*Ficus carica* L.). Our study aimed at verifying the effects of increasing water scarcity and a growing share of perennials by analysing patterns of land-use change during the period of 2007 to 2009 in five oases of the Northern Hajar Mountains of Oman (*Photos 2* and *3*). We hypothesised that changes in annual precipitation as well as the increasing use of irrigation water for residential gardens at the top of the watershed embracing these oases affect the availability of irrigation water and subsequent land use and drought adaptation strategies.

2. Materials and methods

2.1 Site description

The study focused on land-use changes in the five major oases of the heavily eroded Wadi Mu'aydin watershed stretching below the rapidly growing town of Sayh Qatanah on the Sayq Plateau: Ash Sharayjah (57°39'30" E, 23°04'10" N, 1900 m asl), Al'Ayn (57°39'44" E, 23°04'22" N, 1900 m asl) and Al'Aqr (57°39'58" E, 23°04'22" N, 1950 m asl) are near the edge of the plateau (*Fig. 1*). Below these three oases lies the oasis of Qasha' (57°39'50" E, 23°04'00"N, 1640 m asl) and the lowest settlement of the watershed is Masayrat ar Ruwajah (57°40'13" E, 23°02'37" N, 1030 m asl). The total terraced agricultural area in Ash Sharayjah is about 14.4 ha, while the agricultural area of Al'Ayn and Al'Aqr is about 2.5 and 1.7 ha, respectively. Farmers in the high-altitude oases irrigate their terraces from two springs that emerge from the oasis of Al'Ayn, while in the lower oasis of Masayrat (3.3 ha) water is supplied

Photo 2 Two aspects of the oasis of Al'Ayn in Wadi Mu'aydin on Al Jabal Al Akhdar, northern Oman, with ancient irrigated terraces carrying temperate crops, fruit trees and rose bushes

Photo 3 Aerial image of the oasis of Masayrat ar Ruwajah in Wadi Mu'aydin on Al Jabal Al Akhdar, northern Oman

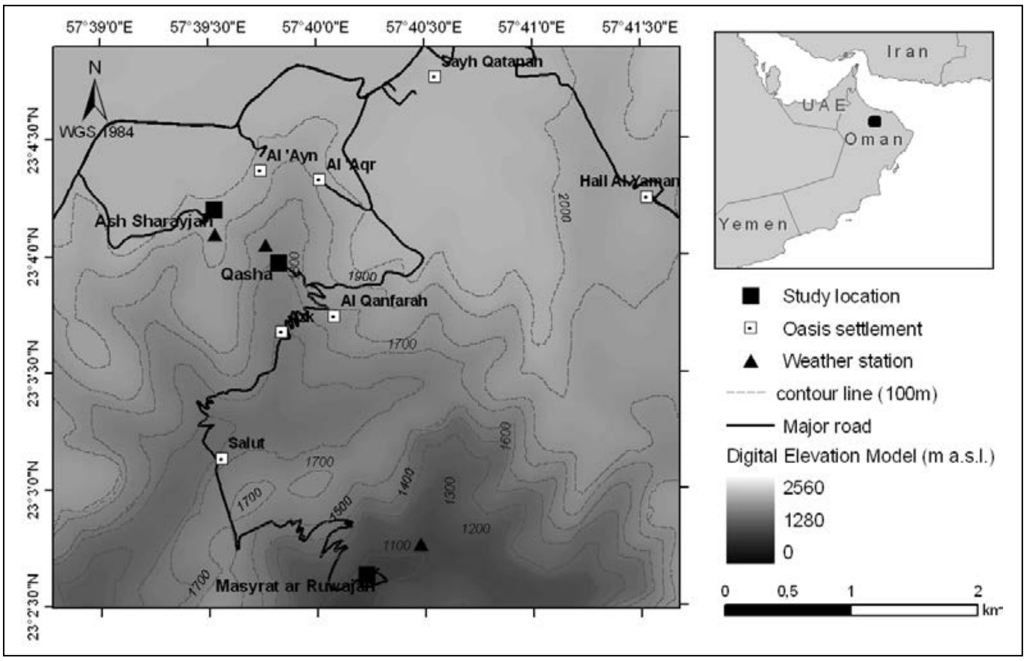

Fig. 1 Relief map based on a 100 m digital elevation model of Wadi Mu'aydin on Al Jabal Al Akhdar, northern Oman

by an irrigation dam. Qasha' contains about 2.6 ha of terraced fields and also obtains its water from one of the springs of Al'Ayn, from where the water flows through a steep channel down to the oasis.

Agricultural terraces in the four high-altitude oases are typically planted with perennials (*Luedeling* et al. 2008) and fodder crops such as alfalfa (*Medicago sativa* L.), maize (*Zea mays* L.), barley (*Hordeum vulgare* L.), oat (*Avena sativa* L.), and the cash crop garlic (*Allium sativum* L.).

The low altitude oasis of Masyrat ar Ruwajah is dominated by the typical three-storey arrangement of date palm, lime, sweet lime (*Citrus limettioides* Tan.), bitter orange (*Citrus aurantium* L.), citron (*Citrus medica* Burm.), orange (*Citrus sinensis* Osbeck), lemon (*Citrus lemon* (L.) Burm. f.), banana, papaya (*Carica papaya* L.), guava (*Psidium guajava* L.), mango (*Mangifera indica* L.) and annual crops that are similar to those in the high altitude oases (*Table 1*).

Table 1 Annual and perennial crops calendar at the oases of Ash Sharayjah, Al'Ayn, Al'Aqr, Qasha' and Masayrat ar Ruwajah on Al Jabal Al Akhdar, northern Oman

Crops	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Maize*			◆	—	—	—	—	—	—	—	→	
Garlic	—	—	—	→						◆	—	→
Oats*	—	—	—	→						◆	—	→
Barley*	—	—	—	→						◆	—	→
Alfalfa*	◀	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -	▶
Rose**				◆	→							
Peach**							◆	—	→			
Apricot**					◆	→						
Walnut**									◆	—	→	
Pomegranate**									◆	—	→	
Date palm***							◆	—	—	—	→	

* Harvested as green animal fodder
** Grown only in the high altitude oases
*** Grown only in lowland oases

Photo 4 Pomegranate gardens in the town of Sayh Qatanah on the Sayq Plateau of Al Jabal Al Akhdar

2.2 Irrigation water supply and climatic conditions

Water flow rates of all relevant springs in the watershed were measured using the methodology described by *Nagieb* et al. (2004). Because of the strong flow rate and difficult topography, the flow of the irrigation water to Ash Sharayjah and Masayrat was estimated by measuring 10 times the speed of a floating device on the main irrigation channel of a known diameter. For the spring-fed terraces of Al'Ayn, Al'Aqr, and Qasha', records were based on a volumetric (barrel) method. To monitor soil moisture as affected by irrigation cycles in one of the six garlic plots at Ash Sharayjah, a soil moisture tension probe was installed at 20 cm depth and connected to a WatchDog® 200 data logger (Spectrum Technologies, Inc., Plainfield, IL, USA) which recorded moisture readings at 30 min intervals. These data allowed to determine the beginning of each irrigation cycle on the field and to compute the total number of irrigation cycles and their seasonal variations. Watchdog® weather stations (Spectrum Technologies Inc., Plainfield, IL, USA) were placed at representative locations in the Ash Sharayjah and Masayrat oases to record climatic data throughout the study period. In Qasha', air temperature was recorded at 30 min intervals throughout the research period using Hobo-Pro® climate loggers (Onset Corp., Bourne, MA, USA). In addition, climatic data of previous years were collected from the Ministry of Transport and Communications, Directorate General of Civil Aviation and Meteorology, Muscat, Sultanate of Oman and data of water extraction from the central well in Sayh Qatanah from local authorities.

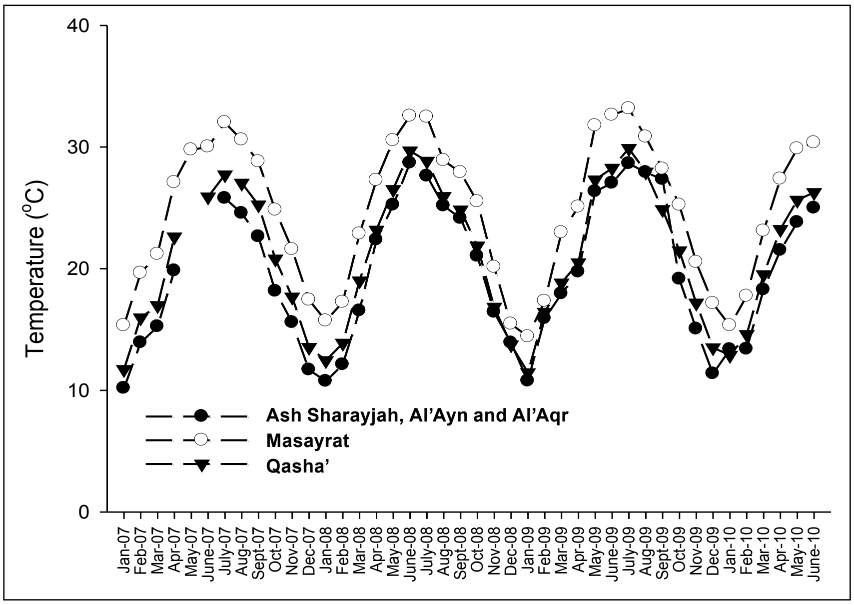

Fig. 2 Mean monthly air temperatures recorded at the oases of Ash Sharayjah, Qasha' and Masayrat ar Ruwajah in northern Oman during the research period

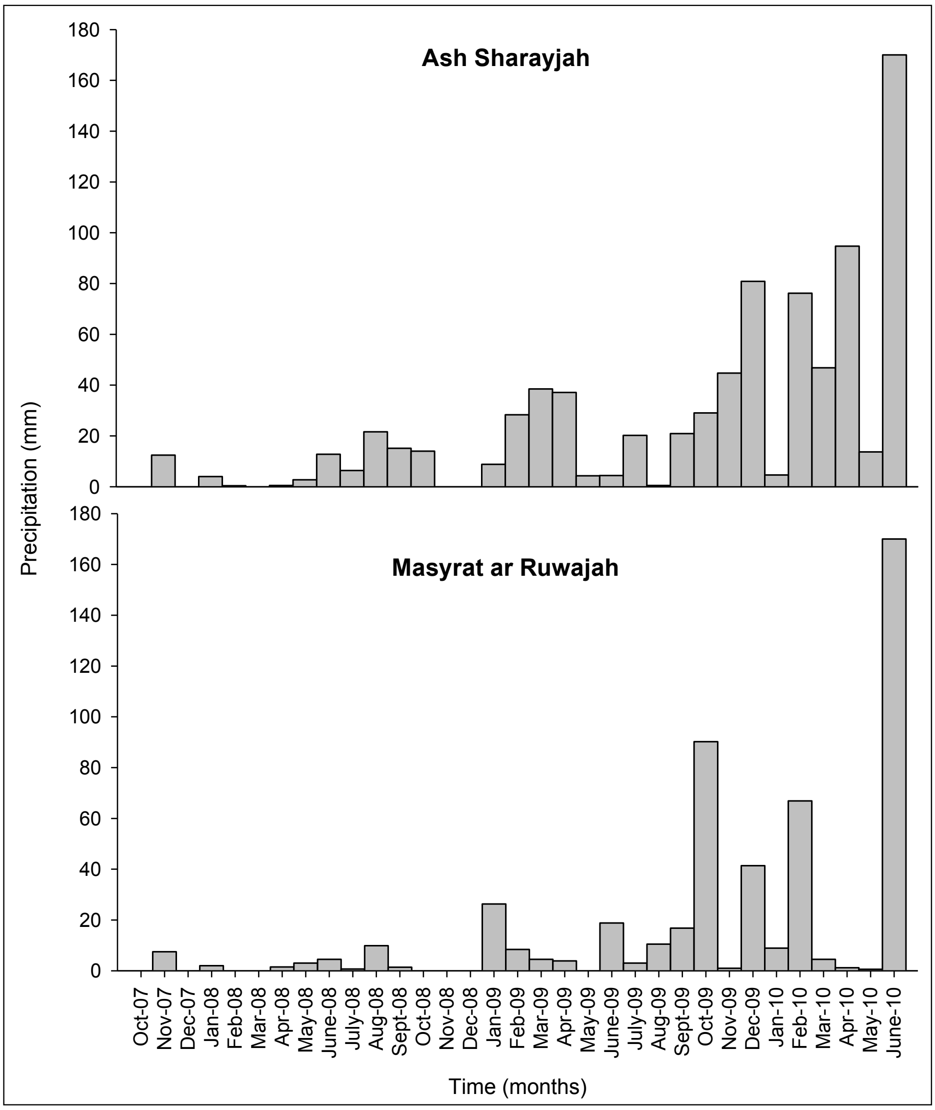

Fig. 3 Average monthly rainfall (mm) recorded at the oases of Ash Sharayjah and Masayrat ar Ruwajah from October 2007 to June 2010

2.3. Land-use changes

All mapping was based on geo-referenced aerial images with a spatial resolution of 2-5 cm taken by a remotely controlled plane (*Schaeper* 2006) and major ground truthing that led to cadastral maps of the oasis areas (*Luedeling* et al. 2008). The distribution of land-use type per oasis was assessed based on the absolute area (ha) and its percentage of the total oasis area. Agricultural land uses were categorised into five types: (1) abandoned, (2) fallow, (3) trees and crops, (4) only crops, and (5) only trees. Changes in field crop area were assessed separately for major crops. In order to calculate changes in annual yields of indicator crops, six garlic fields were selected in Ash Sharayjah and Masayrat as a winter crop and monitored for two growing seasons (2008/09-2009/10). Similarly, six fodder maize (*Zea mays* L.) fields were selected in the same oases during the summer season of 2009. In order to calculate total fresh yield per area, yields of three subplots of 1 m^2 size were determined for each field. For fodder maize and garlic agronomic water use efficiency (WUE) was calculated as the amount of dry matter (DM) produced divided by the amount of irrigation water used plus the amount of rainfall received during the respective growing period using six plots per oasis for each of the two crops.

2.4 Estimation of the urban development and the new agricultural areas at Sayh Qatanah

To estimate Sayh Qatanah's urban area over time, we used a Corona scene of 01/05/1972 (KH-4B), an aerial photograph of 16/10/1993 (NSA/HLB, Al Dakhlyiah Oman Nr. 47 at the scale 1:50,000) obtained from the National Survey Authority of Oman and Google Earth satellite images of 19/03/2009 and 14/01/2014. The 2009 image was also used

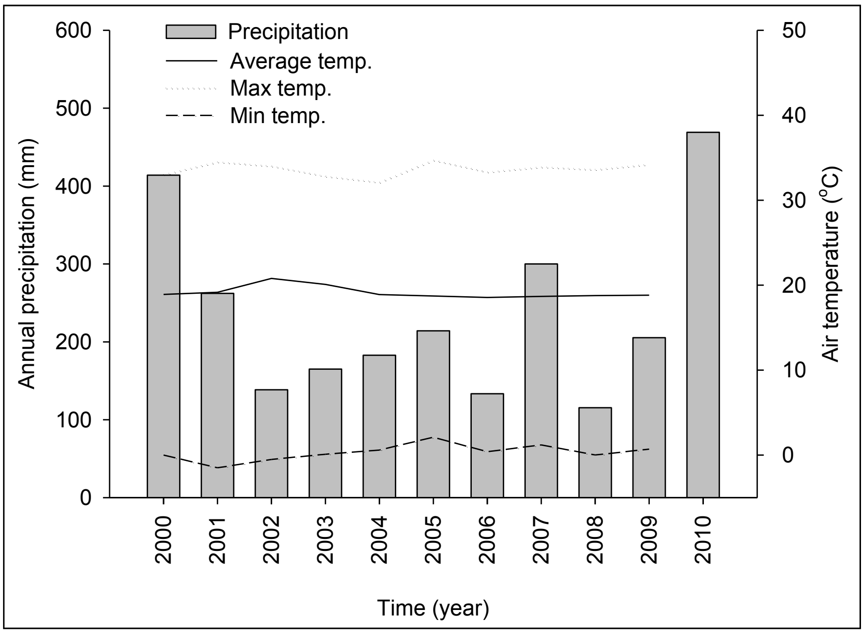

Fig. 4 *Annual precipitation, average, maximum and minimum air temperature from 2001 to 2010 at Sayh Qatanah, Al Jabal Al Akhdar*

to calculate the town's total irrigated agricultural areas in 2009 (*Fig. 8*) which were classified into five categories: (i) larger areas comprising military and other governmental buildings, mosques, and hotels, (ii) houses with intensive, (iii) medium-, (iv) small-scale backyard agriculture, and (v) Sha'biah housing blocks where green areas are smaller than around other houses. The size of larger areas was measured using the area calculator of Free Map Tools (http://www.freemaptools.com/area-calculator.htm), while houses were counted into the previously mentioned categories and multiplied by the average agricultural area for each category.

2.5 Statistical analysis

Data were statistically analysed with SPSS version 17.0 (SPSS Inc., Chicago, USA), while graphs were made with Sigma Plot 10.0. Differences between the two growing seasons were tested with paired t-tests at $P < 0.05$.

3. Results

3.1. Climatic conditions and irrigation water supply

Average ambient air temperature was 19.6 °C at Ash Sharayjah, 21.0 °C at Qasha', and 24.7 °C at Masayrat (*Fig. 2*).

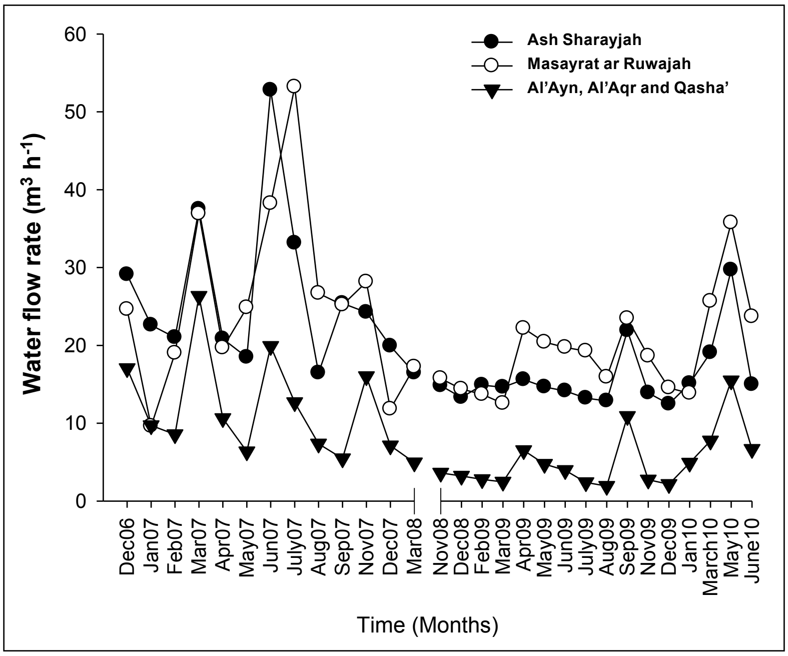

Fig. 5 *Water flow rate from springs supplying the oases of Ash Sharayjah, Al'Ayn, Al'Aqr, Qasha' and Masayrat ar Ruwajah in Wadi Mu'aydin*

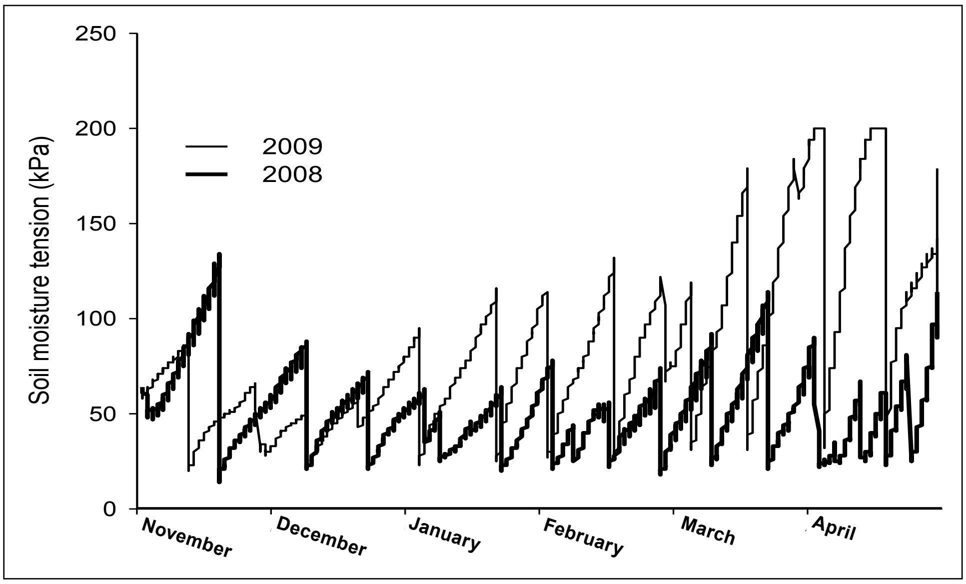

Fig. 6 Soil moisture tension curve under garlic fields grown in two seasons (2008/2009) in the oasis of Ash Sharayjah, Wadi Mu'aydin

In 2008 and 2009, annual rainfall was below the 312 mm long-term average (*Brinkmann* et al. 2011). During the three study years annual rainfall varied widely. In 2008 and 2009, precipitation totaled 90 and 205 mm at Ash Sharayjah and 31 and 224 at Masayrat, while in 2010 more rainfall events occurred and annual precipitation totaled 639 and 379 mm at Ash Sharayjah and Masayrat, respectively (*Fig. 3*), which is well in the range of long-term precipitation variation (*Fig. 4*).

Overall flow rates of irrigation water were substantially higher in 2007 than in 2008 and 2009 (*Fig. 5*) even if in each year high flow rates were measured shortly after rainfall events. The particularly high water flow rates in 2007 and 2010 reflected heavy precipitation events which occurred as a result of summer cyclones and storms. In all cases, spring discharge quickly deceased only a few months after such heavy summer rainfalls.

From March to November 2009 water flow rates were substantially higher at Masayrat than at Ash Sharayjah. Throughout 2009 the average amount of irrigation water supplied to the cultivated area (annual and perennial) of Ash Sharayjah was 17,453 m^3 ha^{-1} $year^{-1}$, whereas the oases of Al'Ayn, Al'Aqr and Qasha' received an average of 23,959 m^3 ha^{-1} $year^{-1}$, and irrigated cropland in Masayrat 57,231 m^3 ha^{-1} $year^{-1}$. Soil moisture measurements conducted in the garlic field in Ash Sharayjah showed 15 irrigation events with intervals of 5-17 days in 2008 (surface soil moisture varied from 14 to 134 kPa), while 13 events were recorded in 2009 with soil moisture tension varying from 20 to 200 kPa (*Fig. 6*).

3.2 Land-use changes

Mixed fields (trees and crops) occupied 4.5, 0.9, 0.4, 0.8 and 1.3 ha (31.5, 37.2, 24.4, 29.1 and 38.1 %) in 2007 and 2.8, 0.4, 0.6, 0.2 and 1.3 ha (19.7, 14.5, 33.6, 8.8 and 40.8 %) in 2009 of the total areas of Ash Sharayjah, Al'Ayn, Al'Aqr, Qasha' and Masayrat, respectively. Meanwhile, in Ash Sharayjah the area of terraces with only trees increased from 1.8 ha (12.7 %) of the total area in 2007 to 4.8 ha (33.9 %) in 2008 and fell to 4.1 ha (28.3 %) in 2009. Similarly, in Masayrat, fields with only trees occupied less than 0.01 ha (0.27 %) in 2007, 1.2 ha (36.3 %) in 2008, and 1.2 ha (36.2%) in 2009.

In contrast, in Ash Sharayjah, the area of terrace-grown field crops (barley, garlic, maize, oat, alfalfa, other fodder crops and small amounts of vegetables) decreased gradually from 4.7 ha in 2007 to 3.1 ha in 2008 and 2.9 ha in 2009 (*Table 2*). In Ash Sharayjah and Al'Ayn competition for water is particularly severe and potential evaporation largest because of their exposed position at the top of Wadi Mu'aydin. There the area decrease between 2007 and 2009 was particularly strong for fodder crops. Here farmers used barley as feed supplement that could be easily purchased from the outside. Area adaptation to the multi-annual alfalfa was slower but finally very strong (*Table 2*).

In Ash Sharayjah, the garlic fields totaled around one hectare throughout the research period resulting in a total annual dry matter yield of 16.3 t in 2007, compared to 19.8 t in 2008, and 18.3 t in 2009. Mean-

Table 2 Land-use changes of annual crops grown at the five oases in the Northern Oman Mountains investigated from 2007 to 2009

Oasis	**Crops**	**2007**		**2008**		**2009**	
		Area (m^2)	%	Area (m^2)	%	Area (m^2)	%
Ash Sharayjah	Alfalfa	135	0.3	180	0.6	0	0.0
	Barley	17985	38.7	4980	16.0	3113	10.6
	Garlic	8694	18.7	10571	34.1	9769	33.2
	Maize	13860	29.8	3449	11.1	12987	44.1
	Oats	4243	9.1	11607	37.4	3324	11.2
	Other fodders	1147	2.5	195	0.6	70	0.2
	Vegetables	415	0.9	64	0.2	202	0.7
	Total area	**46479**	**100.0**	**31046**	**100.0**	**29465**	**100.0**
	14.36 ha	**32.4 %**		**21.6 %**		**20.5 %**	
Al'Ayn	Alfalfa	887	10.0	458	7.1	297	5.96
	Barley	3096	34.9	327	5.1	843	16.89
	Garlic	1591	17.9	978	15.2	1161	23.28
	Maize	238	2.7	2405	37.2	1809	36.27
	Oats	2655	29.9	2097	32.6	878	17.60
	Other fodders	307	3.5	113	1.8	0	0.00
	Vegetables	99	1.1	62	1.0	0	0.00
	Total area	**8873**	**100.0**	**6440**	**100.0**	**4988**	**100.0**
	2.52 ha	**35.2%**		**25.6%**		**19.8%**	
Al'Aqr	Alfalfa	62	2.1	42	0.6	0	0.0
	Barley	455	16.0	738	11.3	2091	43.3
	Garlic	585	20.5	2499	38.0	645	13.4
	Maize	66	2.3	1850	28.1	615	12.7
	Oats	1684	59.1	1447	22.0	1470	30.4
	Other fodders	0	0.0	0	0.0	0	0.0
	Vegetables	0	0.0	0	0.0	11	0.2
	Total area	**2852**	**100.0**	**6576**	**100.0**	**4832**	**100.0**
	1.68 ha	**17.0%**		**39.1%**		**28.8%**	
Qasha'	Alfalfa	0	0.0	0	0.0	0	0.0
	Barley	1533	16.5	23	1.5	62	2.9
	Garlic	1369	14.7	886	58.3	0	0.0
	Maize	3953	42.6	187	12.3	1629	75.3
	Oats	1210	13.0	12	0.8	0	0.0
	Other fodders	623	6.7	200	13.1	345	15.9
	Vegetables	598	6.5	214	14.1	128	5.9
	Total area	**9286**	**100.0**	**1522**	**100.0**	**2164**	**100.0**
	2.56 ha	**36.3%**		**5.9%**		**8.5%**	
Masayrat	Alfalfa	911	5.6	601	5.2	51	0.4
	Barley	976	6.0	223	2.0	0	0.0
	Garlic	232	1.4	889	7.8	598	4.4
	Maize	5333	32.8	3607	31.6	5710	42.1
	Oats	2271	14.0	1287	11.2	274	2.0
	Other fodders	6245	38.4	4402	38.5	6851	50.6
	Vegetables	304	1.8	417	3.7	67	0.5
	Total area	**16272**	**100.0**	**11426**	**100.0**	**13551**	**100.0**
	3.28 ha	**49.6%**		**34.8%**		**41.3%**	

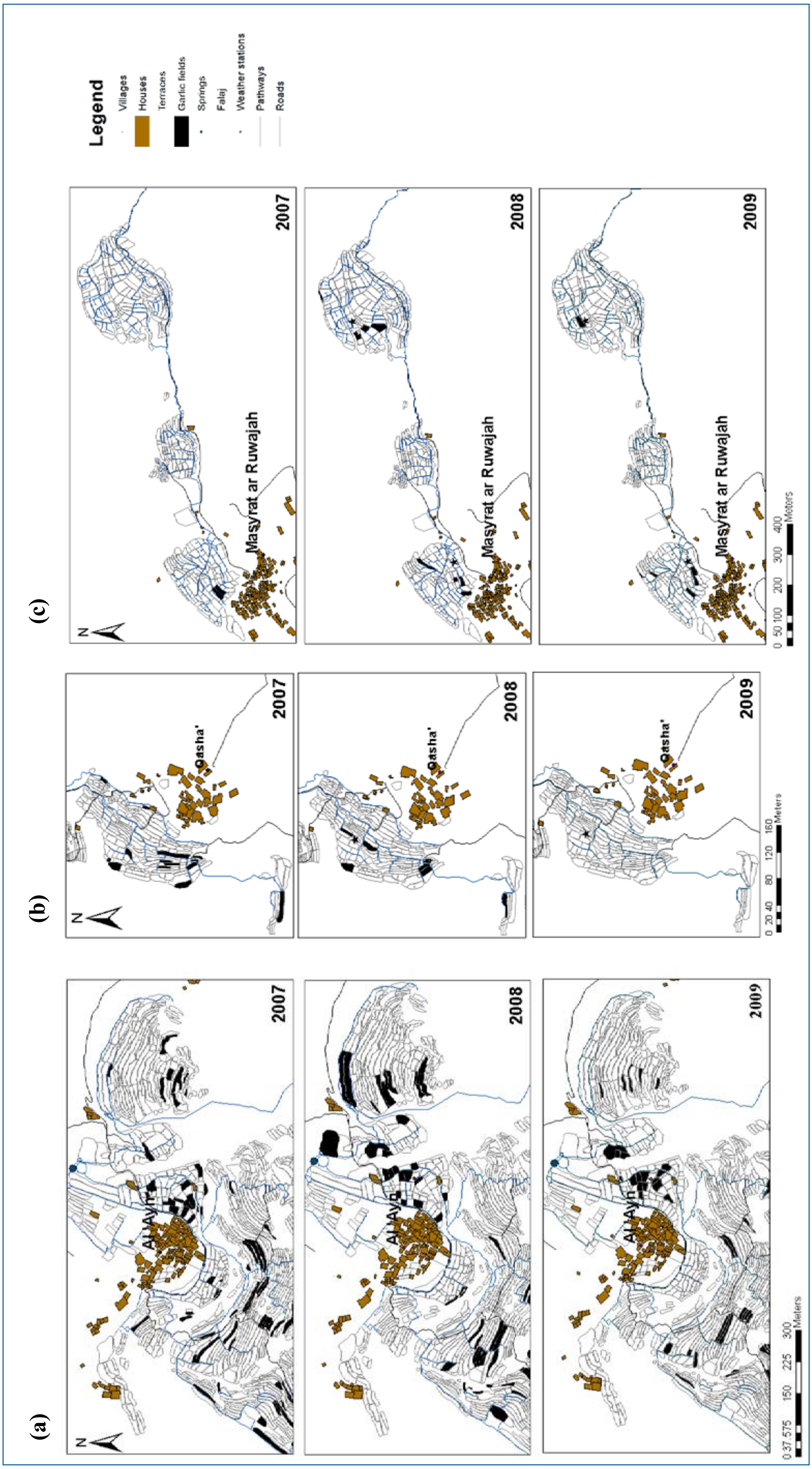

Fig. 7 Changes in the garlic growing areas in the oases of (a) Al'Ayn, Ash Sharayjah and Al'Aqr, (b) Qasha', and (c) Masayrat ar Ruwajah, 2007-2009

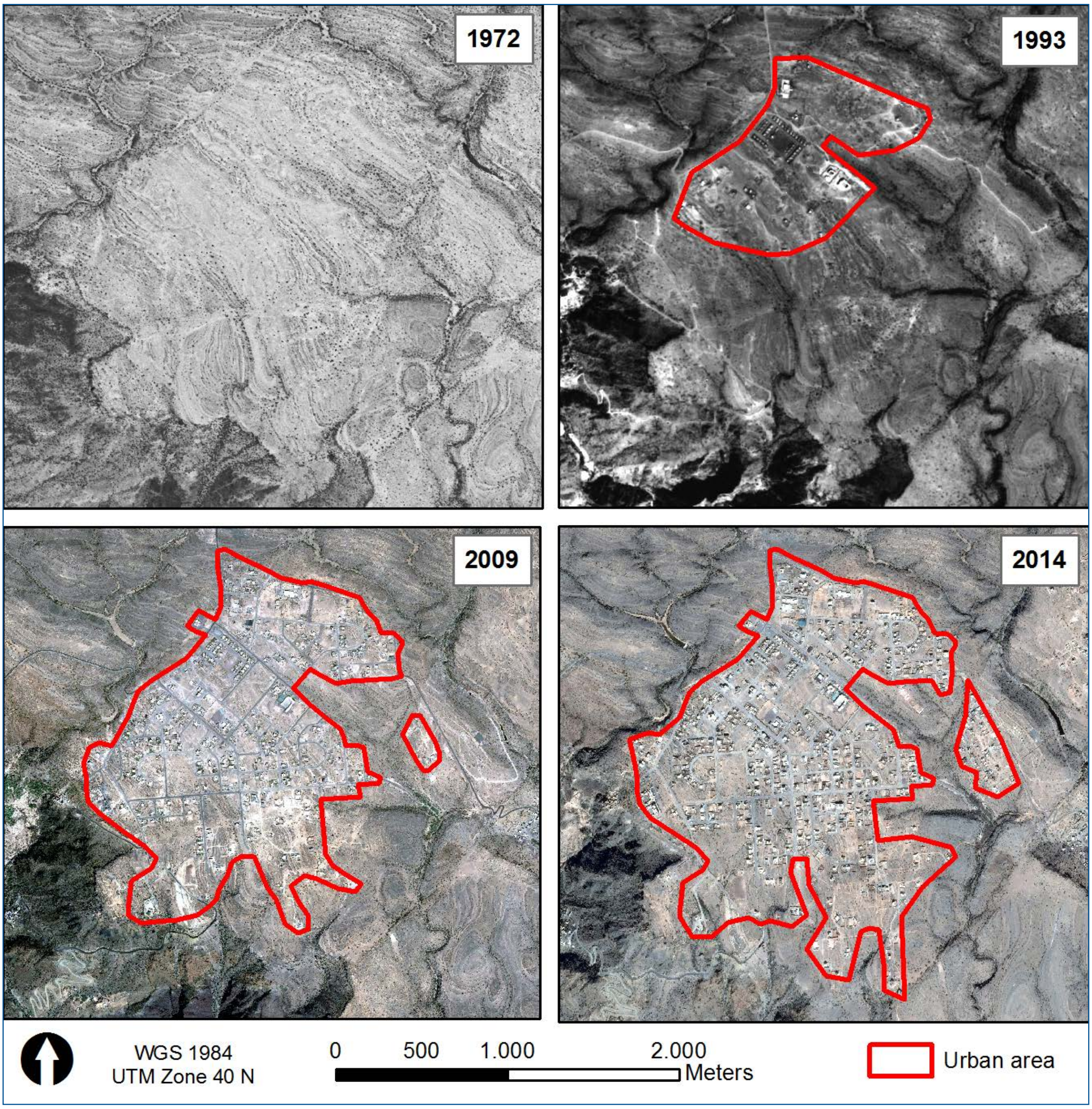

Fig. 8 Urban area of Sayh Qatanah on the Sayq Plateau, as shown by a Corona image of 1972 (top left), a historical aerial photograph of 1993 (top right), a Google Earth image of 2009 (lower left) and a Google Earth image of 2014 (lower right)

while, garlic fields in Masayrat occupied only 230, 890 and 600 m^2 and produced total annual dry matter yields of 0.4, 1.6, and 1.1 t during the years 2007, 2008 and 2009 respectively (*Fig. 7*). In summer, maize was grown as a fodder crop and harvested within 40-50 days. This allowed 4-5 cropping cycles in the high-altitude oases and 5-6 cropping cycles in Masayrat and total annual maize dry matter yields in Ash Sharayjah of 86.0, 21.5 and 80.5 t $year^{-1}$, whereas they were 30.0, 20.4 and 32.4 t $year^{-1}$ in Masayrat for 2007, 2008 and 2009, respectively.

For garlic WUE averaged across years was 0.80 kg DM m^{-2} m^{-3} in Masayrat and 1.2 kg DM m^{-2} m^{-3} in Sharayjah while maize WUE amounted to 0.95 kg DM m^{-2} m^{-3} and 2.05 kg DM m^{-2} m^{-3}, respectively.

3.3 Urban development and the new agricultural area of Sayh Qatanah

The 1972 Corona image did not show any settlement at the top of Wadi Muaydin, but the aerial image of 1993

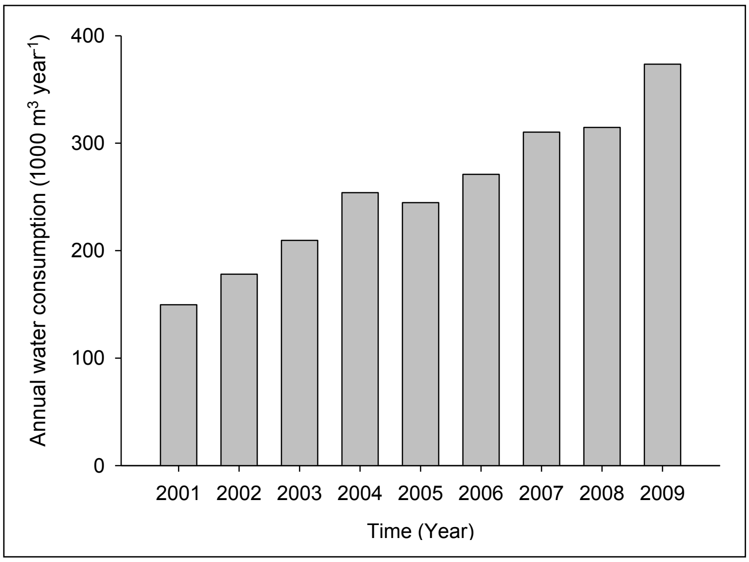

Fig. 9 *Total water consumption in the town area of Sayh Qatanah, 2001-2009*

revealed a total urban area of 88 ha which, based on the subsequent satellite images, grew to 230 ha in 2009 and to 276 ha in 2014 (*Fig. 8*). In 2009, the total estimated irrigated agricultural area in Sayh Qatanah amounted to 13.5 ha. Around 8.4 ha (61 %) of this area consisted of backyard house gardens, while 2.8 ha (21 %) were newly established gardens of the military camp and 2.3 ha (17 %) belonged to governmental buildings.

4. Discussion

Our data suggest that Omani farmers adapt to changes in rainfall and subsequent spring flow by adjusting their area planted to field crops, whereby timing and quantity of precipitation play a major role. Winter precipitation has a direct impact on garlic cultivation as this important cash crop requires to maintain water supply until the harvest. Consequently, farmers diverted the water available in winter to growing garlic to reap higher revenues per unit of water applied compared with growing fodder maize despite lower agronomic WUE of garlic. Thus water scarcity mainly affected areas planted to fodder barley and oats which could be relatively easily replaced by imported alfalfa hay. Water scarcity effects were particularly severe in Qasha' resulting in a major reduction of the area planted to annual crops: from 36.3 % of the total oasis area in 2007 to 8.5 % in 2009. In 2009, farmers were not able to grow garlic at all (*Fig. 7*).

Because of its short cropping cycle and the long growing season starting in April and ending in November, farmers try to compensate eventual shortages in winter fodder crops by growing large areas with fodder maize often grown as an understorey crop immediately after torrential summer precipitation. In March, April and May, farmers of the high-altitude oases allocate substantial amounts of irrigation water to fields cultivated with roses (*Rosa damascena* Mill.) for rose water production. From May to November, irrigation water is typically diverted to pomegranate, the most important cash crop in the high-altitude oases with their temperate climate. Our data revealed that the area of mixed cropping fields (annual crops grown under trees) decreased from 4.5, 0.9, 0.4, 0.8 and 1.3 ha in 2007 to 2.8, 0.4, 0.6, 0.2 and 1.3 ha in 2009 of the total area of Ash Sharayjah, Al'Ayn, Al'Aqr, Qasha' and Masayrat, respectively.

Due to population increase and changes in lifestyle, the modern settlement of the town of Sayh Qatanah on the Sayq plateau at the top of Wadi Mu'aydin has been growing profusely. Two wells located on top of the plateau supply water to houses in Sayh Qatanah and other villages leading to a 2,5-fold increase in water extraction in less than a decade (from 149,600 m^3 in 2001 to 373,470 m^3 in 2009, *Fig. 9*). This water is largely used for irrigation of homestead gardens devoted to growing crops and trees in the backyards of Sayh Qatanah as well as for household purposes, even if people have also started to establish underground cisterns to harvest rainwater as an alternative source of irrigation water. The estimated 13.5 ha of agricultural area determined for 2009 within this new urban settlement entered thus in major competition for irrigation water with the ancient terrace agriculture.

From their analysis of a time series of aerial photographs taken from 1975-2005 *Luedeling* and *Buerkert*

(2008) had concluded that long-term land use of the Al Jabal Al Akhdar oases had shifted towards perennial trees which caused a higher vulnerability of the systems to inter-annual changes in water availability. Our study suggests that farmers are still able to use traditional agronomic coping strategies through adjustments in annual crops towards cash crops and increased fodder imports during drought years. However, the effectiveness of such mitigation strategies is increasingly limited by new water uses for the beautification of housing environments in the sprawling new city on the top of the Wadi Mu'aydin watershed. This may need urgent legal attention.

5. Conclusions

The high altitude aquifer of Wadi Mu'aydin is under increasing pressure from water extraction to satisfy the drinking and irrigation water needs of the rapidly growing town of Sayh Qatanah. This likely affects flow rates of springs below the plateau where water consumption depends on regular recharge from unpredictable rainfall events. Oasis farmers are still able to adapt to shortage of irrigation water by reducing areas planted to annual crops and by choosing cash crop species such as garlic with higher returns per unit water, whereby the variation in land-use changes differs among the oases of Wadi Mu'aydin. In Qasha', where farmers shared irrigation water from the same spring with Al'Ayn and Al'Aqr, changes were most pronounced. Further studies should clarify the competitive effects and relative water use efficiencies of the recently introduced homestead gardens in Sayh Qatanah compared to the water consumption of the traditional terraces, foster strategies of rainwater harvesting in cisterns, and encourage a more effective re-use of recycled waste water for trees such as widely practiced in the modern city environments of Oman's lowlands.

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