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Drainage, salt leaching and physico-chemical properties of irrigated man-made terrace soils in a mountain oasis of northern Oman

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Abstract

Little is known about the sustainability of irrigated oasis agriculture in northern Oman. The objective of this study therefore was to examine which factors allowed agricultural productivity to be apparently maintained during the two millenia of a mountain oasis' existence. Soil moisture and physico-chemical properties were measured in a typical flood-irrigated field sown to alfalfa (*Medicago sativa* L.). Particle size, organic (C_{org}) and inorganic carbon content, pH and electrical conductivity (EC) of the soil profile were analyzed at 0.15, 0.45 and 1.00 m. Saturated hydraulic conductivity and the soil's apparent bulk density and water potential were determined from undisturbed samples at 0.05, 0.25 and 0.60 m. During irrigation cycles of 6–9 days, volumetric water contents ranged from 30% to 13%. A tracer experiment with potassium bromide revealed that 52–56% of the irrigation water was stored in the upper 0.4 m of the soil. The rest of the water moved further down the profile, thus providing the necessary drainage to avoid the build-up of toxic salt concentrations. Due to differences in pore size, plant-available water in the topsoil amounted to 18.7% compared to 13% and 13.5% at 0.25- and 0.60-m depth, respectively. The aggregate structure in the upper 1.0 m of the profile is likely preserved by concentrations of calcium carbonate ($CaCO_3$) from 379 to 434 mg kg^{-1} and C_{org} from 157 to 368 mg kg^{-1} soil. The data indicate that the sustainability of this irrigated landuse system is due to high water quality with low sodium but high $CaCO_3$ concentration, the elaborate terrace structure and water management which allows adequate drainage.

Keywords: Aflaj; Anthropogenic soil; Leaching; Hydraulic conductivity; Salinization

1. Introduction

In arid regions, agriculture is mainly limited by the availability of suitable irrigation water. However, even with sufficient water, its use is often not

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sustainable, leading to soil salinization as a consequence of inappropriate irrigation and drainage techniques. Nevertheless, despite extremely xeric moisture regimes, some systems of intensive agriculture have been productive for millennia with only a moderate build-up of toxic salt levels (Nagieb et al., in press; Buerkert et al., 2005; Wichern et al., 2004b). The mechanisms that govern the sustainability of these systems, however, have not yet been sufficiently investigated.

A suitable location to study the effects of irrigation and the sustainability of dryland agriculture is the Sultanate of Oman on the Arabic peninsula. The country's climate is very arid and hot, with an average temperature of 27 °C, peak temperatures of 45 °C in summer and a mean annual rainfall of 105 mm, all measured in the capital Muscat (Dorvlo and Ampratwum, 1998, 1999). Over the years, precipitation shows a very erratic pattern in which relatively moist years of more than 300 mm alternate with dry years of less than 50 mm of annual rainfall (Norman et al., 1998; Victor and Al-Farsi, 2001). Droughts lasting as long as 5 years are also common. This climate makes only 0.3% of Oman's surface eligible for crop production (FAO, 1997), practically all of which is covered by two different types of intensive irrigation agriculture. About 74% of the total agricultural land is irrigated by sprinkler systems and large portions of it are facing serious problems of salinity and groundwater depletion after only a few decades of use. Most of these systems are located in the Batina region near the northeastern coast of the country (Victor and Al-Farsi, 2001).

In the mountainous regions of Northern Oman, a completely different form of agriculture has persisted for millennia (Nagieb et al., in press). Date palms and annual crops are cultivated in oases that are watered either by springs or by tunnel systems, called *aflaj* (sing. *Falaj*; Norman et al., 1998; Wilkinson, 1977) in Arabic, which were dug into the ground or carved into the rock to tap underground aquifers. Both systems require the oases to be located at the foot of cliffs, below plateaus, which accumulate the scarce rainfall of a large area. The accumulated water that resurfaces at the bottom of the cliffs becomes an important resource for irrigation. This geomorphological setting provides a reliable water supply necessary for intensive year-round date and crop cultivation on ancient, artificial terrace soils that are disconnected from the groundwater table and thus do not suffer from salinization due to capillary rise such as observed for non-terraced soils (Jorenush and Sepaskhah, 2003). Outside the terraces, a very rough landscape characterised by barren rock or unstructured dry sediments prevail.

In view of the above, the objective of this study was to examine how water quality and management, and profile structure of the man-made terraces allowed agricultural productivity and soil quality to be maintained during the more than two millennia of an oasis' existence.

2. Materials and methods

2.1. Site description

The study was conducted in the mountain oasis of Balad Seet (23.19°N, 57.39°E, 995 m asl) in the Jabal Akhdar mountains of Oman (Fig. 1). The agriculture of the oasis consists of extensive date palm (*Phoenix dactylifera* L.) gardens and terraced fields, where annual and perennial crops such as landraces of wheat (*Triticum* spp. L.; Al-Maskri et al., 2003), barley (*Hordeum vulgare* L.), garlic (*Allium sativum* L.), onion (*Allium cepa* L.), coriander (*Coriandrum sativum* L.) and alfalfa (*Medicago sativa* L.) are cultivated. The irrigation water for the oasis' agriculture is distributed through an elaborate *aini-aflaj* canal system fed from 12 springs originating at the foot of a calcareous rock wall of 1000-m height in the southwest of the settlement. The oasis is home to about 650 people, among whom 48 households cultivate the 13.1 ha of available agricultural land (Nagieb et al., in press).

Flood-irrigation of the terraces, which are divided into square plots (*jalba* in Arabic) of about 2 m^2, occurs at intervals between 5 to 18 days, depending on the season. The soils of the terraces are classified as Irragric Anthrosols (FAO, 2001). There is considerable variation of profile depth which is 1.3 m in the examined part of the Mazra terrace system (Fig. 2). The lower 0.3 m of the soil

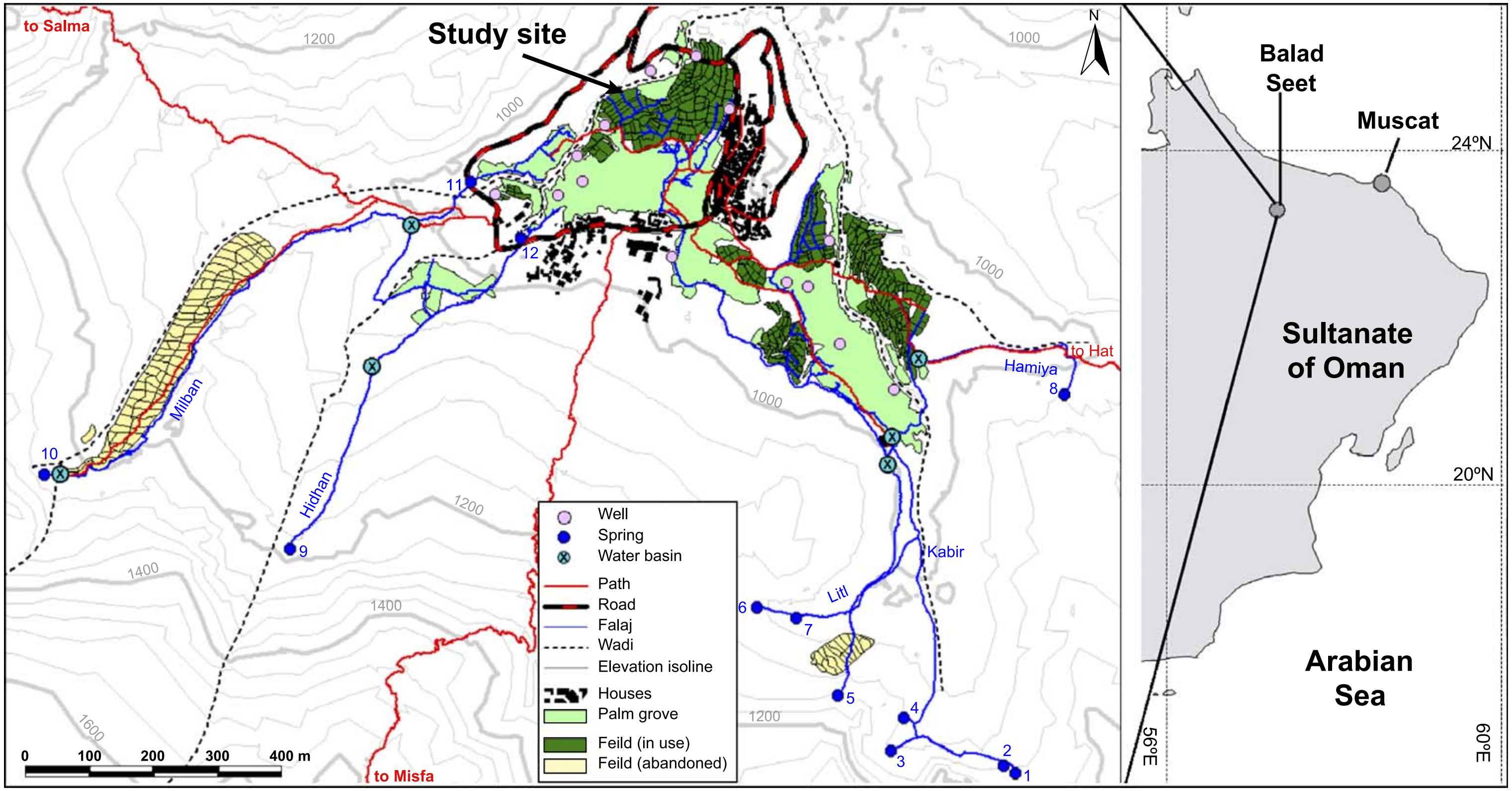

Fig. 1. Map of the Sultanate of Oman with the mountain oasis of Balad Seet inserted. The black arrow indicates the terraced field of alfalfa (*M. sativa* L.) where the study was conducted.

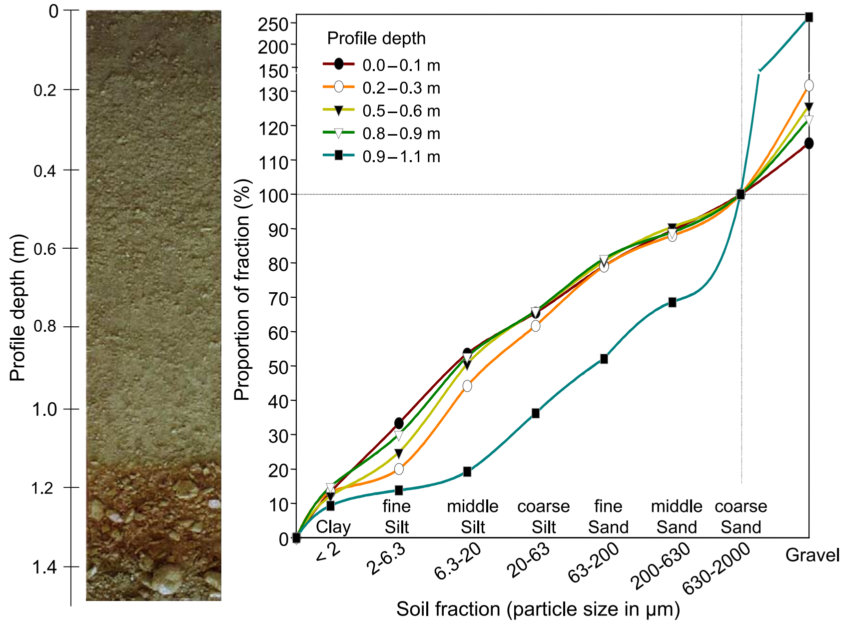

Fig. 2. Soil profile of the lower part of the *Mazra* terrace system at the mountain oasis Balad Seet (Oman) planted with annual crops and alfalfa. Note the difference between the gray, silt-rich upper layers of this man-made profile with their high water-holding capacity and the lower portion with its reddish, stony and rapidly draining structure (left) and the large difference in the particle size distribution curve below 0.9 m (right). The value of 100% refers to the mass of the mineral soil, the gravel fraction is not included in the mineral soil and thus leads to numbers exceeding 100%.

profile of Mazra consists of two layers of gravel with different colours and stone sizes, on top of which 1.0 m of silt-rich material, was placed at the time of terrace construction. That time has been dated to 1092±43 years using the ^{14}C method.

2.2. Basic soil characteristics

Organic (C_{org}) and inorganic (C_{inorg}) carbon concentrations ($C_{inorg}=C_{total}-C_{org}$) were determined in samples from three different depth intervals (0–0.15, 0.15–0.45, 0.45–1.00 m) of an irrigated plot cultivated with alfalfa (*M. sativa* L.) using a LECO-RC 412 C-Analyser (LECO, St. Joseph, MI, USA). The electrical conductivity of the samples (EC_e) was analyzed in a saturated soil paste (United States Salinity Laboratory Staff, 1954) by extracting the water from the paste using a suction filter and measuring the EC with a LF 90 conductivity meter (WTW, Weilheim, Germany). Analysis in a saturated paste was preferred over a fixed soil/water ratio, as it relates more closely to plant growth (United States Salinity Laboratory Staff, 1954). The pH of the soil was determined in a 1:2 soil suspension with deionised water.

2.3. Particle size distribution

To determine the particle size of the soil, 25 ml of sodiumpolyphosphate was added to 10 g of soil. The samples were shaken and treated with ultrasound for 5 min for complete dispersion. Calcium carbonate ($CaCO_3$) and organic matter were not destroyed as the $CaCO_3$ fraction amounted to more than 35% of this soil (Wichern et al., 2004a). A particle size analysis with a large proportion of compound particles being destroyed would not allow any conclusion about its hydraulic properties (Lado et al., 2004). The sand and coarse silt fractions were determined by sieving and the finer fractions by the pipette method (Gee and Bauder, 1986).

2.4. Soil moisture

The volumetric water content (θ, [m^3 m^{-3}]) of the topsoil (0–0.2 m) was determined by continuously measuring the electrical conductivity (EC, [S m^{-1}]) of the soil using four 20-cm-long ECH$_2$O dielectric capacitance probes (Decagon Devices, Pullman, Washington, USA). The voltage readings (in mV) on the probes are based on the difference between the dielectric number (ε) of the soil water (ε=80 at 20 °C), the soil matrix (ε<10) and the soil air (ε=1) (Fares and Alva, 2000). A close correlation between EC and soil water content has been described by several authors (Wu, 1998; Fares and Alva, 2000). An influence of irrigation water quality on probe readings was unlikely given its low salt concentration.

The readings of the ECH$_2$O probes were collected in 30-min intervals and stored with a Campbell CR10 (Campbell Scientific, Logan, UT, USA) datalogger. To calibrate the measurements (Mead et al., 1995; Khosla and Persaud, 1997; Chanzy et al., 1998; Lane and Mackenzie, 2001), the volumetric water content of the soil was determined thermogravimetrically on nine occasions. Subsequently, a linear regression was estimated (r^2=0.96) using the data obtained from the ECH$_2$O probes and these volumetric measurements. As the readings for the individual probes varied considerably, each probe had to be calibrated separately. After initial experiments under controlled conditions, no temperature correction (Campbell, 2002) was applied to the readings obtained as such corrections rather aggravated than alleviated the slight irregularities in the measurements (Fig. 3). The exact cause for these irregularities is unknown, but they are likely to be caused by the temperature extremes on the site, which lead to enhanced water vapour production in the soil. This vapour may have interacted with the salts in the profile. This phenomenon, however, was of minor importance compared to the overall moisture fluctuations during an irrigation cycle and will not be further discussed.

2.5. Saturated hydraulic conductivity

The saturated hydraulic conductivity (k_f) of the soil was determined using a hood permeameter as described by Hartge (1966). Five undisturbed soil samples were vertically excavated with 250-cm^3 cylinders at each of three depths (0.00–0.06, 0.20–0.25 and 0.55–0.60 m). This sampling occurred at a <5-m distance of the plot where the tracer experiment was conducted. The cylinders were sealed with a lid and tape and transported to Germany, where the soil was carefully saturated with water. This was achieved by placing the cylinders on a layer of rough wire netting in a tub and then slowly raising the water level above the top of the cylinders. The

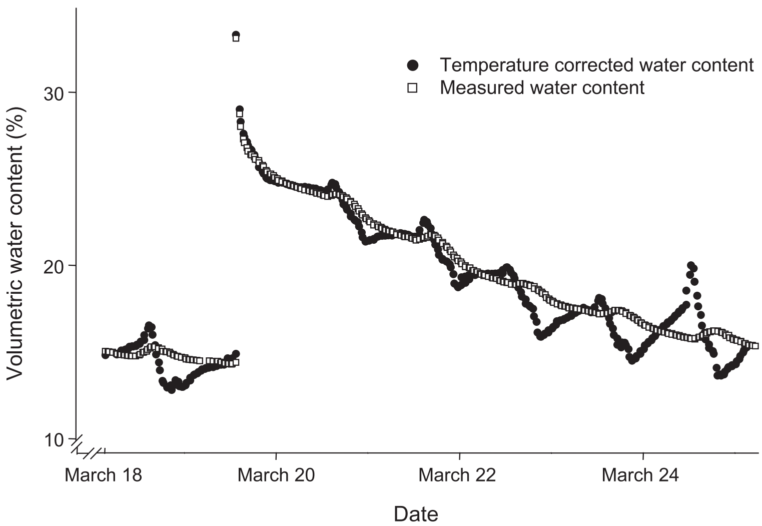

Fig. 3. Soil water dynamics during 7 days in an alfalfa-planted field at the mountain oasis Balad Seet (Oman) in March 2002 with and without the temperature correction for the volumetric water content (θ) as provided by the probe manufacturer.

permeameter was then connected to the top of the cylinders and water was added to the top of the permeameter to create excess pressure on the soil surface. The amount of water percolating through the profile was measured and the k_f determined by the Darcy equation.

2.6. Soil water potential

To determine a typical water characteristic function for the terrace soil, five undisturbed samples were taken in 100-cm^3 volumetric cylinders from the same depths of the same plot as the k_f samples. Sampling occurred vertically (instead of horizontally) to better represent the pore system relevant for drainage. The samples were analyzed using 5 and 15 bar pressure plate extractors (Soil Moisture Equipment, Santa Barbara, CA, USA). The soil in the cylinders was first slowly saturated with water from the bottom and placed on a porous, water-saturated ceramic plate in a pressure chamber. Then different levels of excess pressure corresponding to different soil water potentials were applied to the extractor and the water quantity draining from the samples at the specific pressures was determined. From these data, the overall pore volume was computed and the bulk density determined after drying of the samples.

2.7. Vertical water movement

To obtain information about the vertical movement of water in the soil profile, 10 g of potassium bromide (KBr), corresponding to 6.7 g of bromide ions, was dissolved in 40 L, respectively, 60 L, of irrigation water and applied to two nearby 1×1 m fallow plots (thereafter denoted as variant Br_{40}, and Br_{60}, respectively). These volumes and the flooding of the plot were similar to typical irrigation practices on this soil. The plots were then covered with plastic sheets to prevent evaporation. Thirteen days after tracer application, soil samples were taken in triplicate from each of the plots at four different depth intervals (0–0.20, 0.20–0.40, 0.40–0.60 and 0.60–0.80 m). Bromide was analyzed according to Flury (1993), where 40 ml of deionised water was added as an extraction agent to 20 g of soil. After shaking for 30 min, the mixture was centrifuged and microfiltrated. Subsequently, the Br^- concentration in the extract was measured with a DIONEX ICS-90 ion chromatograph (Dionex, Sunnyvale, CA, USA). From the average of the diluted and undiluted extracts, blind values from samples of an adjacent plot where no Br^- had been applied were subtracted to account for the natural background of Br^- in the soil. From the bulk density at the different soil depths, the soil mass of the layers and the total amount of Br^- contained therein were calculated. For this the bulk densities were corrected for the gravel content of the samples, as gravel cannot store water. Correlating these data with the Br^- concentration in the irrigation water allowed the amount of water stored in the soil at different depths to be estimated as well as the amount of water leached beyond 0.80 m. This correlation is expected to be realistic as bromide is known to behave conservatively in most soils (Brooks et al., 1998) with anion exclusion and other transport retardation or acceleration factors playing only minor roles (Porro et al., 1993). Given the physical structure of the profile, this latter portion of water was considered to be draining to the aquifer.

2.8. Quality of irrigation water

Spring water samples were taken from the main *aflaj* of the oasis. As all springs originate from only one aquifer, unfiltered samples were pooled, placed in a PE bottle, transported frozen to Germany and analyzed according to standard German DIN methods at SEWA (Essen) as follows: an ICP-AES was used for Mg, Ca, Na and K; Cl was analyzed by titration and SO_4, HCO_3 and CO_3 by ion chromatography. Electrical conductivity was measured conductometrically and pH potentiometrically.

The sodium adsorption ration (SAR) which indicates the effect of relative cation concentration on sodium accumulation in the soil was calculated as follows whereby ions are expressed as milliequivalents per liter (meq L^{-1}).

$$SAR = \frac{Na}{\sqrt{\frac{Ca+Mg}{2}}}$$

Residual sodium carbonate was calculated as [$RSC=(CO_3+HCO_3)-(Ca+Mg)$].

2.9. Calculation of leaching fractions and leaching requirements

The leaching fraction establishes a relation between drainage and salinity. It may be estimated from a steady-state salt-balance equation (Hoffman and Durnford, 1999) as:

$$Lf = \frac{D_d}{D_a} = \frac{EC_w}{EC_d},$$

where D_d [mm] is the amount of drainage water from the root zone, D_a [mm] is the amount of irrigated water, EC_w [dS/m] is the electrical conductivity of the irrigation water and EC_d [dS/m] is the electrical conductivity of the water draining from the root zone. It is difficult to measure EC_d in situ. Therefore we estimated EC_d as recommended by Ayers and Westcot (1994) as 2 EC_e, where EC_e [dS/m] is the average soil salinity measured in a saturation extract.

The leaching requirement (Lr) is the amount of additional irrigation water required to avoid a harmful built-up of salts in the root zone of plants. This amount depends on numerous factors, including the salinity of the soil, soil type, water quality, rainfall, drainage, and crop tolerance. Probably the single most important factor is the quality of the water. The water quality sets the lower limit for the minimum salinity that can accommodate the growth of a specific crop (such as alfalfa). The leaching requirement for a specific crop can be estimated with different methods, one of which is given by Ayers and Westcot (1994) as:

$$Lr = \frac{EC_w}{[5EC_{e,C} - EC_w]},$$

where $EC_{e,C}$ [dS/m] is the average soil salinity measured in a saturation extract tolerated by a specific crop C. For alfalfa, no yield reduction is expected for $EC_e < 2.0$ (Ayers and Westcot, 1994).

2.10. Statistics

One-way analyses of variance of all data were carried out using Statview 5.0 (SAS Inst., Cary, NC, USA) and Fisher's protected least significant difference (LSD) test was used to separate means.

3. Results

3.1. Basic soil characteristics

The C_{inorg} concentration exceeded 4% at all depths. These high values reflect the lime content of up to 43% throughout the profile (Table 1). Alkaline soil conditions are reflected in pH values ranging between 8.3 and 8.4. However, this alkalinity is not the result of increased salinization (see below). Organic carbon was 3.7% in the topsoil, but declined substantially with depth. The soil's electrical conductivity (EC) was moderately high in the upper 0.45 m of the soil but four to five times higher below 0.45 m (Table 1).

3.2. Particle size

The soil profile can be stratified into two layers. The upper grayish coloured part (0–0.9 m) has a homogeneous particle size distribution with about 14% clay, 51% silt, 35% sand, and an additional 24% gravel, relative to the fine mineral soil. The lower layer (0.90–1.10 m), in contrast, showed a much higher proportion of coarse material with only 9% clay and 27% silt, but 64% sand and a very high gravel content that amounted to 163% of the mass of mineral soil. Comparisons of the profile's colours with material from the surrounding mountains indicate that the upper layers likely are sediment deposits collected from the floor of the valley (wadi) after heavy rainfall events, while the lower layers, particularly the reddish subsoil material (>1.10 m; Fig. 2) come from broken bedrock material.

Table 1
pH and concentration of inorganic carbon (C_{inorg}), $CaCO_3$, organic carbon (C_{org}), electrical conductivity of the soil (EC_e) and leaching fraction (Lf) at three different depths of a terrace soil from Balad Seet (Oman)

Depth (m)	pH	C_{inorg} (%)	$CaCO_3$ (%)	C_{org} (%)	EC_e (dS m^{-1})	Lf[a]
0.00–0.15	8.3	4.6	37.9	3.7	1.40	0.18
0.15–0.45	8.4	4.7	38.9	3.0	0.88	0.28
0.45–1.00	8.4	5.2	43.4	1.6	4.83	0.05

[a] Estimated according to Ayers and Westcot (1994) as EC_w/(2 EC_e).

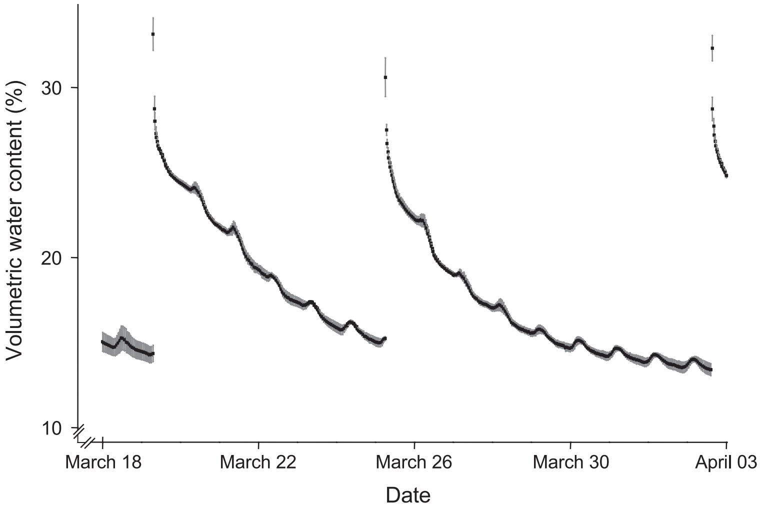

Fig. 4. Soil water dynamics during two irrigation cycles in an alfalfa-planted field at the mountain oasis Balad Seet (Oman) in March and April 2002. The data are means of four probes with the grey bars indicating ±one standard error.

3.3. Soil moisture

In each of two selected irrigation cycles between March 18th and April 3rd 2002, an initial rise of the volumetric water content to between 30.6% and 33.1% was recorded in the topsoil, with a subsequent decline in soil moisture to between 13.4% and 15.0% (Fig. 4). Cycle durations lasted 5 days, 21 h and 8 days, 14½ h, respectively. For the rest of the year 2002, the irrigation cycles varied between 5 and 18 days, with cycle duration decreasing during the hot summer months when the plant water demand was higher. The probes indicated a slight rise in soil water content around noon of each day (Fig. 4).

Table 2
Saturated hydraulic conductivity, total pore volume, bulk density and available field capacity (±one standard error of the mean) of undisturbed soil samples from a terrace plot at Balad Seet

Depth (m)	Saturated hydraulic conductivity (k_f) (m day^{-1})	Total pore volume (%)	Bulk density (kg m^{-3})	Available field capacity [a] (m^3 m^{-3})
0.00–0.06	2.76±0.4a	61.6±0.3a	1020±10a	0.187±0.02a
0.20–0.25	8.40±0.7b	56.9±0.5b	1140±10b	0.130±0.01b
0.55–0.60	6.81±0.8b	56.7±0.6b	1150±20b	0.135±0.01b

[a] Amount of water a soil is able to retain against gravity (field capacity, FK) minus the amount of water which is retained by soil water tension (>pF 4.2; still water) and therefore not usable for agricultural crops. Values within one variable with the same letter do not differ at $p<0.05$. Data are means of four replicates.

3.4. Saturated hydraulic conductivity (k_f)

Of the five samples for each depth, typically one had a conductivity that was several-fold higher than that of the other samples from that layer. After conducting an outlier test (Dixon, 1950), these samples, which might not have been properly filled on site and therefore been disturbed during their transport on the bumpy mountain access road, were

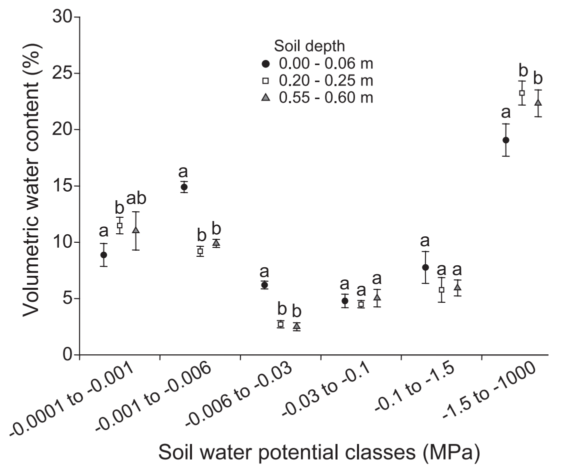

Fig. 5. Pore volume at different depths and soil water potential classes of a terrace soil at the mountain oasis of Balad Seet, Oman. Vertical bars indicate±one standard error. Values at the same soil water potential with the same letter are not significantly different at $p<0.05$.

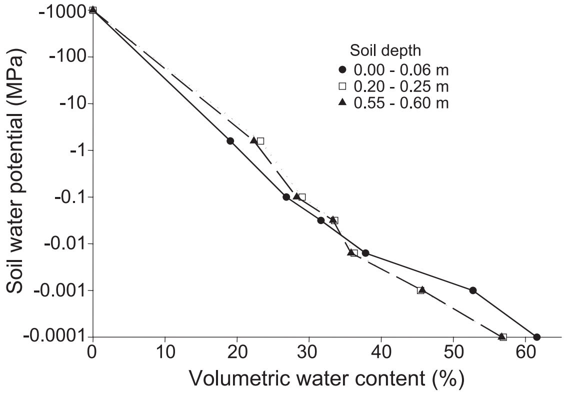

Fig. 6. Soil water characteristic function showing water contents at different soil water potentials for three depths of a terrace soil at the mountain oasis of Balad Seet, Oman. Vertical bars indicate ±one standard error.

discarded. The four replicates used for comparison consistently showed a high saturated hydraulic conductivity. Nevertheless, the hydraulic conductivity (k_f) in the subsoil was with 840±69 and 681±83 cm day^{-1} much higher than in the topsoil (276±41 cm day^{-1}) (Table 2). The greater total pore volume in the topsoil reflected its lower bulk density (Fig. 5).

3.5. Soil water potential

The fractions of soil macropores (defined by a soil water potential of −0.0001 to −0.001 MPa) and of water not available for plants (defined by a soil water potential of −1.5 to −1000 MPa) were higher at lower depths. The water characteristic function of the topsoil, however, showed a significantly higher fraction at a potential from −0.001 to −0.03 MPa. This is the pressure range from which water can be extracted easily by plants. The equivalent pore volume at potentials between −0.03 and −1.5 MPa was relatively low and did not differ between the individual soil depths (p<0.05). The soil water characteristic curve clearly shows the higher proportion of intermediate-size pores in the topsoil and the predominance of smaller pores at 0.20–0.25 and 0.55–0.60 m (Fig. 6).

3.6. Vertical water movement

The tracer experiment reveals that most of the applied water does not leave the topsoil of the profile, but remains in the upper 0.2 m of the soil (Table 3), where in both variants, the centre of mass of the Br^- concentration versus depth distribution is found. With increasing depth, the Br^- concentration rapidly declines. In the topsoil, the Br^- peak tends to be higher with the lower amount of applied water in variant Br_{40} than in Br_{60}, whereas the reverse occurs at deeper layers. However, these differences are significant only at 0.20–0.40 m.

The amount of water stored in the different layers also is affected by the amount of applied water (Table 3). Irrespective of depth, significantly more water is

Table 3

Bromide (Br^-) concentrations and mass balance (% of applied Br^- recovered) in the soil after irrigation with 40 and 60 L m^{-2} (Br_{40} and Br_{60}, respectively, containing 0.17 and 0.11 g Br L^{-1}) of water in a tracer experiment conducted at Balad Seet (Oman) and estimated amounts of stored water at different soil depths

Irrigation	Soil depth (m)	Gravel corrected bulk density (kg m^{-3})	Soil mass (kg)	Br^- concentration (mg kg^{-1} soil)	Total Br^- in soil (g)	Stored water (L)
Br_{40}	0.00–0.20	940	188	17.2±0.2	3.2±0.1	19.2±0.4
	0.20–0.40	880	175	1.5±0.3	0.3±0.0	1.6±0.1
	0.40–0.60	1010	202	1.0±0.2	0.2±0.0	1.2±0.2
	0.60–0.80	940	189	0.9±0.2	0.2±0.1	1.0±0.3
	Sum				3.9±0.2	23.0±1.1
	% of applied				57	
Br_{60}	0.00–0.20	940	216	16.1±0.7	3.0±0.2	27.0±1.8
	0.20–0.40	880	228	4.5±0.6	0.8±0.2	7.0±1.8
	0.40–0.60	1010	230	1.9±0.2	0.4±0.1	3.4±0.5
	0.60–0.80	940	230	1.5±0.1	0.3±0.0	2.5±0.1
	Sum				4.5±0.5	39.9±4.2
	% of applied				67	

Data are means of four replicates and wherever applicable followed by ±one standard error of the mean.

Table 4
Quality of spring irrigation water at Balad Seet, Oman comprising pH, electrical conductivity (EC), concentration of chloride (Cl), sulfate (SO_4), hydrogencarbonate (HCO_3), carbonate (CO_3), calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), total anions and total cations, total alkalinity, residual sodium carbonate (RSC) and sodium adsorption ratio (SAR)

pH	EC (dS m^{-1})	Cl^- ($mmol_c\ l^{-1}$)	SO_4^{2-} ($mmol_c\ l^{-1}$)	HCO_3^- ($mmol_c\ l^{-1}$)	CO_3^{2-} ($mmol_c\ l^{-1}$)	Ca^{2+} ($mmol_c\ l^{-1}$)	Mg^{2+} ($mmol_c\ l^{-1}$)	K^+ ($mmol_c\ l^{-1}$)	Na^+ ($mmol_c\ l^{-1}$)	Total anions ($mmol_c\ l^{-1}$)	Total cations ($mmol_c\ l^{-1}$)	Alkalinity ($mmol_c\ l^{-1}$)	RSC	SAR
8.24	0.51	0.56	0.48	4.26	0.02	2.85	2.30	0.01	0.56	5.64	5.73	4.56	−0.85	0.35

stored with Br_{60} than with Br_{40}. However, as calculated from the amount of Br^- applied but not accounted for in the analysis, there were only minor treatment effects on the amounts of drainage to deeper layers (Br_{40}=17.0±1.1 L; Br_{60}=20.1±4.2 L). Based on the mass balance calculations for Br^-, the total amount of leaching beyond 0.8 m was estimated at 43% for 40-mm irrigation (Br_{40}) and at 33% for 60 mm (Br_{60}, Table 3). Consequently, 57% or 67% of the applied water was stored in the well rooted upper soil layers.

3.7. Quality of irrigation water and leaching requirement

The analysis of the irrigation water revealed that the water was moderately hard with a sum of alkaline earth ions (total hardness) of 2.57 mmol L^{-1}. Most of this hardness is caused by carbonate ions. The chloride (Cl^-) concentration was low, the SAR much below critical levels for Na hazards and RSC negative (Table 4). Given the high quality of the irrigation water the leaching fraction for alfalfa with EC_w=0.5 and $EC_{e,C}$=2.0 for a 100% crop yield is 0.05 (Table 1).

4. Discussion

The maintenance of the soil's salt concentration at a level which is not hampering the growth of even salt sensitive plants such as alfalfa by little, but regular, drainage is the main parameter which under the prevailing arid conditions determines the oasis' sustained productivity over time. Neither the measured pH levels of 8.3 to 8.4 nor the EC values of 0.88 to 1.40 dS m^{-1} show the effects of salt accumulation in the upper soil layers where most of the roots are observed. A major reason for the avoidance of salinization in the upper soil layers certainly is the quality of the spring irrigation water, with its high concentrations of hardly soluble carbonates and high HCO_3 versus low Na and Cl. According to the classification proposed by Rhoades et al. (1992), the irrigation water at Balad Seet has drinking water quality. It appears that most of its alkalinity is buffered by Ca and Mg leading to large precipitations of those minerals. This would explain the high $CaCO_3$-concentrations throughout the profile (Table 1) and also leads to a low risk of alkalinisation or sodification.

The availability of high quality irrigation water and sufficient leaching within the traditional management system of this mountain oasis is also reflected in the low EC of the soil saturation extract. Even sensitive crops such as maize and alfalfa experience major yield declines only at between 1.7 and 5.9 dS m^{-1} and between 2.0 and 8.9 dS m^{-1} (Maas and Hoffmann, 1977; Rhoades, 1982).

This irrigation water quality also leads to small leaching requirements, such as 0.05 for alfalfa. Therefore, even with limited water resources, the main strategy to avoid salinization in the soils of the oasis seems to have been to establish leaching fractions in the root zone that are considerably higher than the leaching requirement (Table 1). In the main rooting zone (0–0.45-m depth), the salinity is well below the value (EC_e=2.0) that would reduce the alfalfa yield. Only from the bottom of the root zone (0.45 m) downward a small build-up of salinity was observed (Table 1). The reason for this likely is the intensive extraction of water by the roots in the topsoil increasing the salinity of the residual water that leaches further downwards.

The mass of Br lost from the profile in 0–0.8 m (see Table 3) represents the leaching fractions for two typical irrigation cycles. It was 0.43 for Br_{40} and 0.33 for Br_{60}. A smaller amount of irrigation at this site seems to be less effective (more Br lost) and leads to higher leaching fractions. Generally, the variation of the leaching fraction between individual irrigation cycles is high. Still the value of 0.33 is fairly close to the long-term leaching fraction of 0.16 that can be calculated by integrating the depth dependent leaching fractions (Table 1) over the depth of the tracer balance (0–0.8 m).

The available field capacity is particularly high in the topsoil (19%), which likely reflects the effects of regular soil tillage and of abundant root growth. It also indicates that the topsoil has a significantly higher ability to store plant-available water than the deeper layers (Table 2). In the untilled subsoil, in contrast, the available field capacity is only moderately high (13%). The necessary drainage of the soil is provided by the large proportion of macro-pores (at a soil water potential of >−0.006 MPa) in the unploughed lower soil layers of 20.7% and 20.9% at 0.20- and 0.55-m depth, respectively, and among these especially by the large proportion of quickly draining pores (soil water potential of >−0.001 MPa) of 11.5% and 11.0%. During irrigation events, the significantly lower saturated water conductivity in the topsoil prevents a rapid leaching of water to deeper soil layers, thereby increasing the time available for infiltration into the smaller soil pores. After flooding, the macro-pores are rapidly drained, avoiding harmful effects of waterlogging on crop growth. The small amount of leached water (estimated in this study to be about 17 to 20 L m^{-2}) is sufficient to transport salts to greater depths. However, the subsoil peak in the EC of 4.8 dS m^{-1} suggests that some solutes do not reach the gravely drainage layer at the bottom, but remain in the profile.

The very high C_{org} concentrations in the oasis soil investigated are a third important prerequisite for the oasis' sustainability, as they contribute to aggregate stability, reduce the effects of salinization on plant growth by providing active cation and anion exchange sites, and supply plant nutrients by a high turnover rate (Wichern et al., 2004a). The high C_{org} levels reflect the regular application of manure at rates of up to 20 tons ha^{-1} $year^{-1}$. A decrease in manure application and partial replenishment of extracted nutrients by mineral fertilizers, as observed in recent years in some plots of the oasis' terrace systems, may lead to a long-term decline of soil C_{org}. In the long-term, increasing levels of salts in the soil profile may be the consequence of a deteriorating soil structure and hampered drainage.

The moisture dynamics of the soil profile describe the efficacy of the elaborate distribution system for the springs' outflow. The scarcity of water may motivate farmers to optimize its availability with crop evapotranspiration throughout the year. Lacking symptoms of water stress indicates that within an irrigation cycle the minimum topsoil moisture content of 13.4% is sufficient for maintaining crop metabolisms, even though according to the soil water curve, all water at that level should be non-available to plants. It must be assumed that during the latter part of the irrigation cycle, plants extract less water from the topsoil, in which the probes were installed, than from the rooted soil below, which extends to approximately 0.5 m depth. This layer is not exposed to solar radiation and consequently does not dry out rapidly.

The daily rise in the moisture level at noon (Fig. 3) is an unexpected result and may reflect an experimental artefact. One explanation for this phenomenon could be the penetration of warm midday air into the soil and subsequent condensation around the impermeable plastic probes, thereby leading to erroneous increases in their soil moisture readings. However, this could not be verified experimentally.

5. Conclusions

High quality irrigation water, the elaborately built soil structure of the terraces, a system of water distribution designed to match crop needs during their different growth stages and adequate drainage are the main factors explaining the lack of salinization in ancient mountain oases of Oman. It remains to be seen, however, whether these *aflaj*-based systems can withstand the challenges posed by overpopulation, rapidly rising labour costs and the heavy use of mineral fertilizers instead of manure-based recycling to maintain their productivity. Given the aridity of the climate and high ambient temperatures, maintaining soil C_{org} levels and appropriate leaching will certainly remain a key prerequisite to avoid the build-up of salts over time.

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