



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 2 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, N₂-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 N₂-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.

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1. Introduction

In recent years the determination of carbon (C) and nutrient fluxes in agro-ecosystems has received increasing attention by agricultural scientists world-

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wide 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 assess 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., 1998a,b; Van den Bosch et al., 1998a,b).

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, N₂-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., 2004a,b). 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; 950–1020 m a.s.l.; 0–240 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 0.4–1.3 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., 2005). 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.,

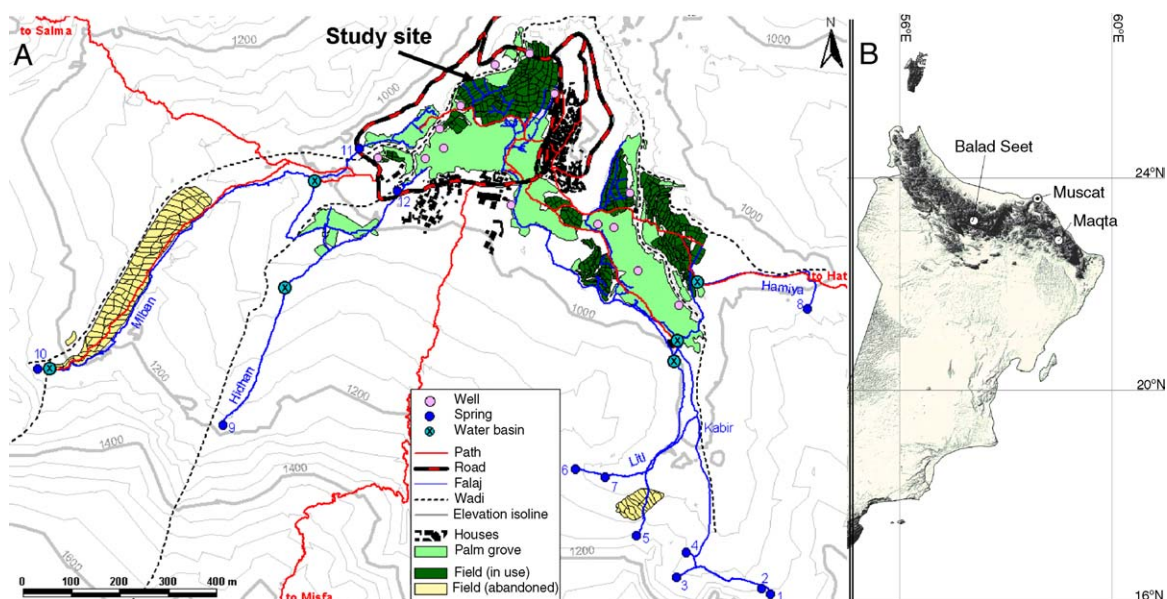


Fig. 1. GIS-based map with the main features of the ‘core oasis’ of Balad Seet, Oman (left) and position of the two mountain oases under study (right). The arrow indicates the field where the ^{15}N experiment was conducted to quantify N_2 -fixation of alfalfa.

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 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 second millennium BC. This likely reflects the ideal ecological conditions provided by an abundant and relatively stable water supply from 12 springs originating at the foot of a 1000 m high calcareous cliff (Luedeling et al., 2005). Depending on rainfall conditions, the total flow of the springs varied between 20 and 30 $\text{m}^3 \text{h}^{-1}$ 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; 1050 m a.s.l.) of 73 houses and 12 widely dispersed temporary settlements in a vast rocky grazing area (Fig. 3; Siebert et al.,

2005). 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 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 $\text{m}^3 \text{h}^{-1}$ during the 12-month measurement period of this study (February 2001–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; Trimble Pathfinder, Sunnyvale, CA, USA) at decimeter precision were used to record important features

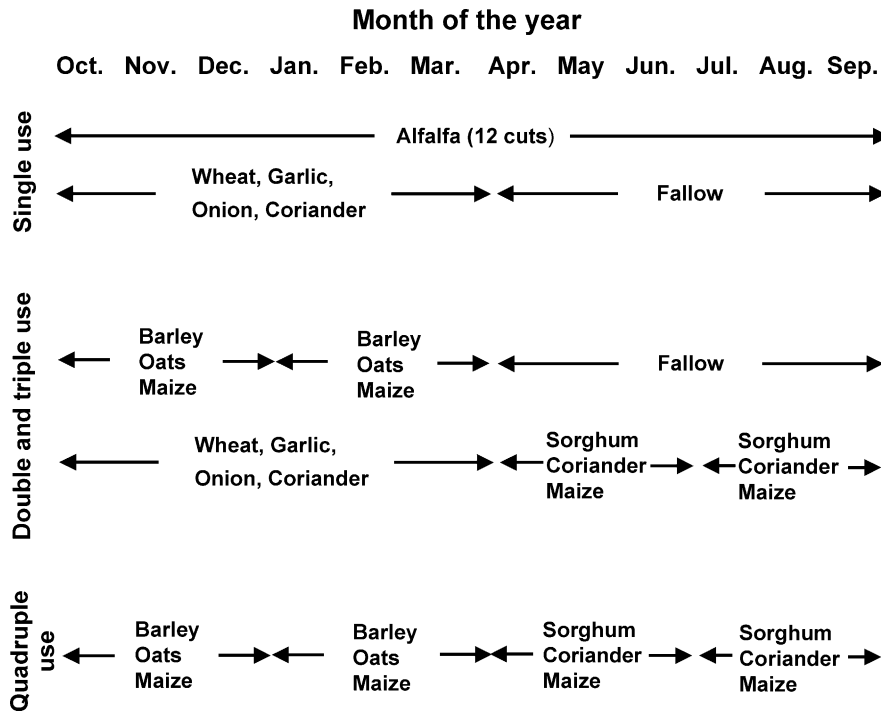


Fig. 2. Cropping sequences on terraced fields at Balad Seet, Oman.

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 N₂-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).

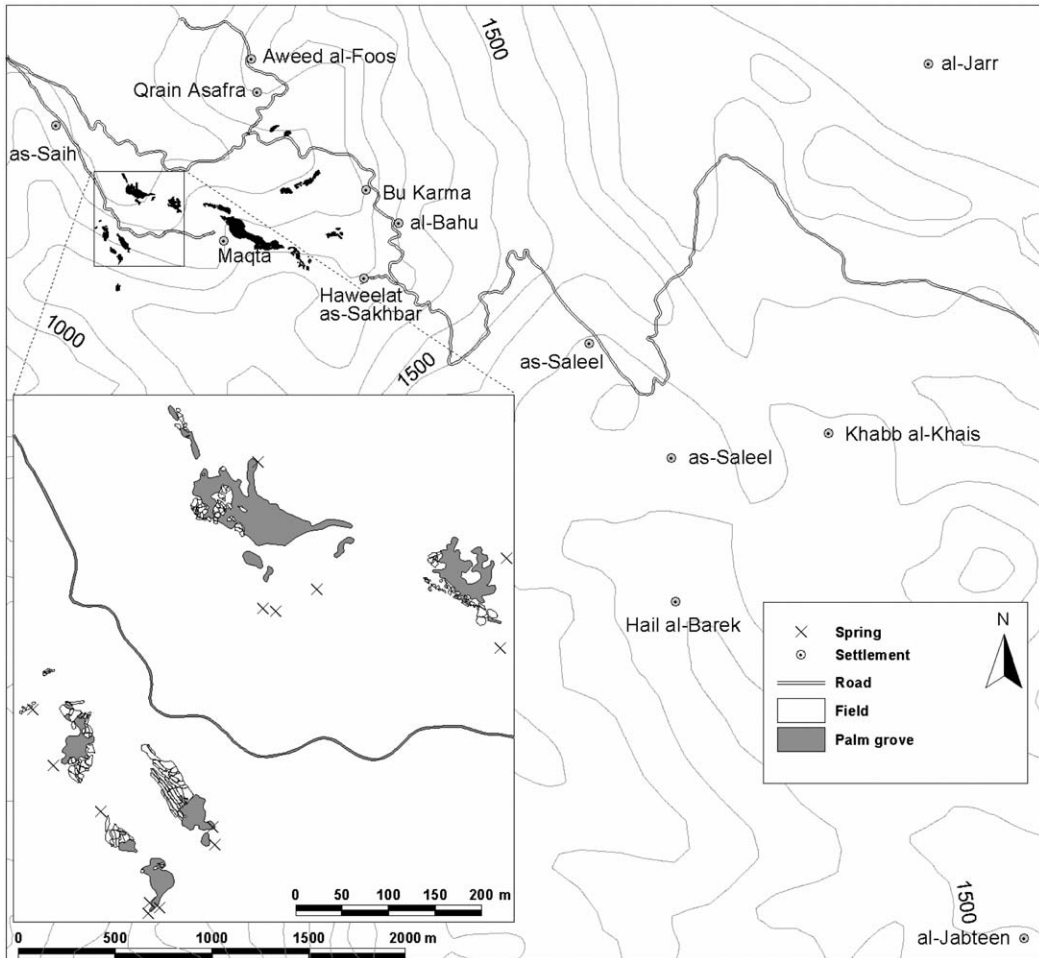


Fig. 3. GIS-based map of the Maqta territory in Oman with the terrace systems, the central housing area, the dispersed settlements, the natural grazing basin, major archaeological sites and altitude lines (Siebert et al., 2005).

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 annual N losses were estimated at about 215 g N

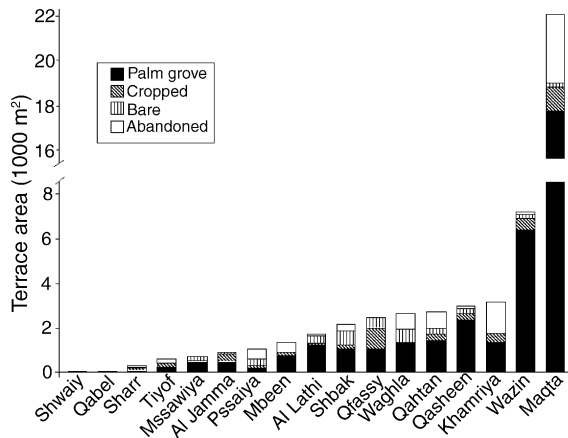


Fig. 4. Size and land use of the 17 terrace systems at the 'scattered' oasis of Maqta, Oman.

per fruit bearing tree with 35 kg of dates and at 54 g per young tree. At Maqta annual 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.

At Balad Seet biological N₂-fixation in alfalfa was estimated from a 18-month long factorial ¹⁵N study

(¹⁵N was applied twice at 15.1 g (NH₄)₂SO₄ enriched with 10% ¹⁵N) with wheat as a test crop. First data indicated N₂-fixation rates (dNfa) of 69–85% at an alfalfa shoot N concentration of 29 g kg⁻¹ (Nagieb, 2004). Based on these results an average N₂-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 one-third of the above ground N. From this it was assumed that total N₂-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 N₂-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 N₂-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 N₂-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 m². 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 partial oasis balances were set up to show aggregated inputs and outputs, 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.

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

Crop	Straw				Grain			
	Low	Medium	High	Very high	Low	Medium	High	Very high
2000/2001								
Wheat	11070	11250	11880	11970	2610	2700	3060	3150
Barley	5490	6300	6570	7020	^a	^a	^a	^a
Sorghum	11440	12760	13200	14960	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	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	10800	11970	2020	2880	3600	3780
Barley	3600	4050	4500	5850	^a	^a	^a	^a
Sorghum	11700	12600	13500	15300	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	1720	2150	2580	3440	4680 ^c	5460 ^c	7020 ^c	10140 ^c
Coriander	2250	2520	2880	3420	^a	^a	^a	^a

^a Only vegetative parts were harvested and except for animals used 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

Class	Wheat straw				Wheat grain			
	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

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 $22,520 \text{ kg ha}^{-1}$. 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).

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 $100\text{--}500 \text{ kg N ha}^{-1}$, 25% received $500\text{--}1400 \text{ kg N ha}^{-1}$, 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 $90\text{--}210 \text{ kg P ha}^{-1}$, and the same percentage received no P. Similarly to P no K was applied on 27% of the fields, whereas 32% received $1\text{--}300 \text{ kg K ha}^{-1}$, and the remaining fields received up to $1400 \text{ kg K ha}^{-1}$ (Fig. 5). The distribution of all three nutrients tended

to be slightly skewed at the upper end meaning that 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 $61\text{ to }277 \text{ kg N ha}^{-1}$ in palm groves and from $112\text{ to }225 \text{ kg N ha}^{-1}$ in wheat fields, to P inputs from $9\text{ to }40 \text{ kg P ha}^{-1}$ in palms and $14\text{ to }29 \text{ kg P ha}^{-1}$ in wheat, and to K inputs from $98\text{ to }421 \text{ kg K ha}^{-1}$ in palms and $113\text{ to }227 \text{ kg K ha}^{-1}$ 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

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

Class	Straw												Grain											
	Low			Medium			High			Very high			Low			Medium			High			Very high		
	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	17.6	1.8	26	12.1	1.2	36	17.6	2.4	22	10.7	2.6	20	18.0 ^b	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

All data are in g kg^{-1} dry matter.

^a Only vegetative parts were harvested and except for coriander used as animal fodder.

^b Dry bulbs.

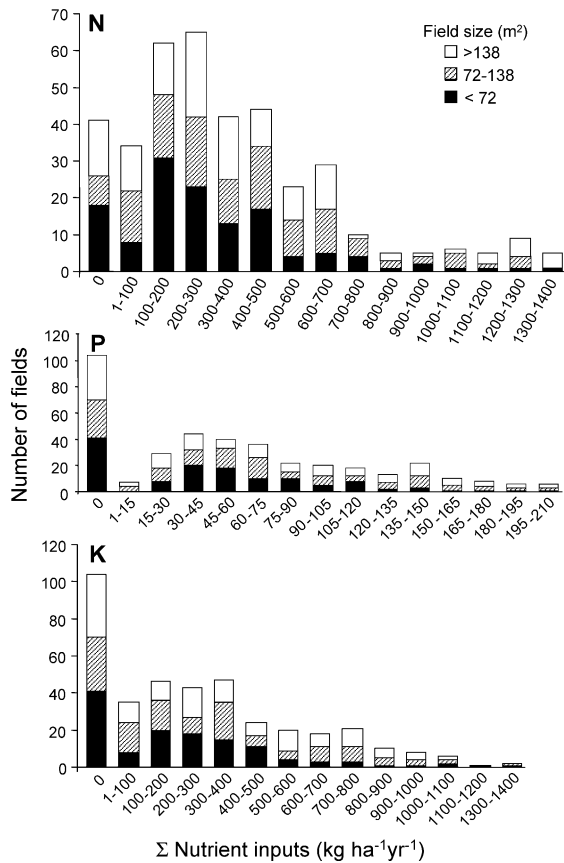


Fig. 5. Annual amounts of nitrogen (N), phosphorus (P) and potassium (K) applied as animal manure or synthetic fertilizers to the three different field size classes at the ‘core oasis’ of Balad Seet, Oman, from 2001 to 2002. Columns show absolute frequencies in their respective input classes and comprise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

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. The reverse was true on the largest systems, particularly for N and P.

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 to 85 kg K ha⁻¹ in wheat

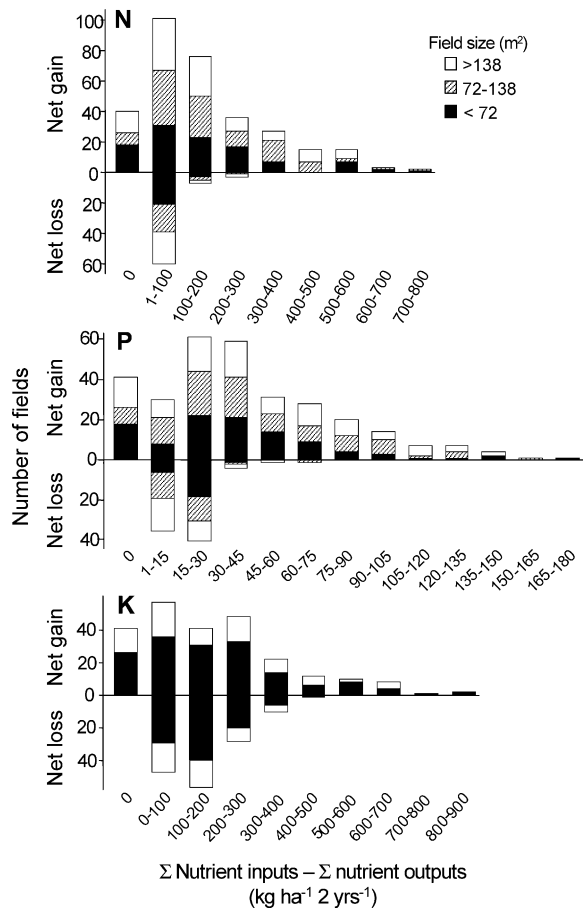


Fig. 6. Bi-annual partial balances (inputs minus outputs) of nitrogen (N), phosphorus (P) and potassium (K) on the three different field size classes at the ‘core oasis’ of Balad Seet, Oman, from 2001 to 2002. Columns show absolute frequencies in their respective input classes and comprise all 385 fields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

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

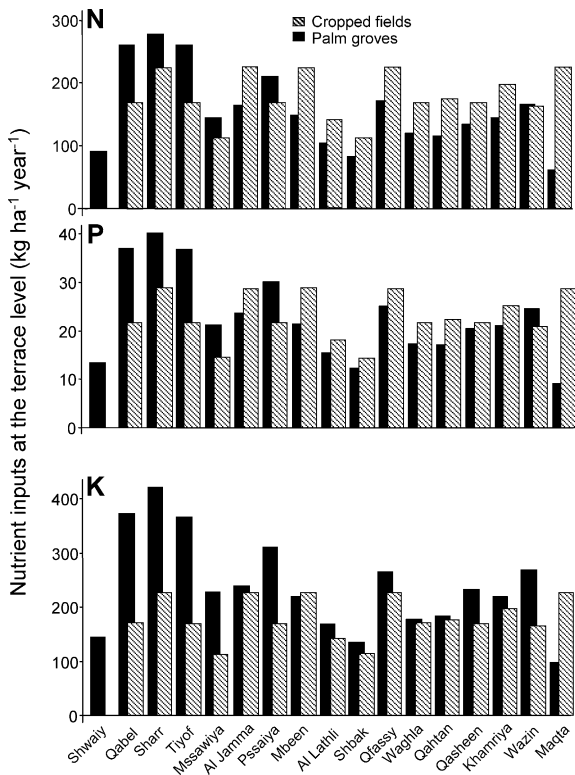


Fig. 7. Annual amounts of nitrogen (N), phosphorus (P) and potassium (K) applied as animal manure to cropped fields and palm groves of the 17 terrace systems belonging to the ‘scattered oasis’ of Maqta, Oman, in 2001/2002. Note that the terrace systems on the x-axis are arranged in order from smallest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

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.

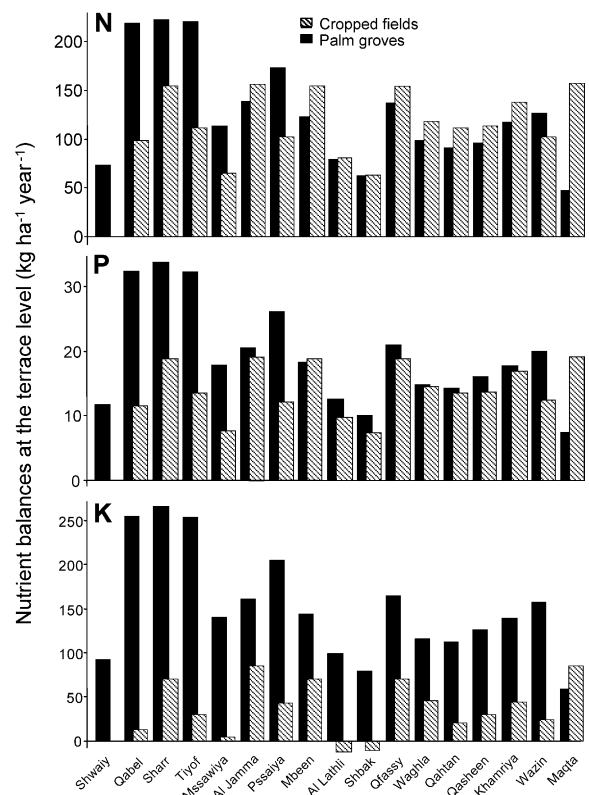


Fig. 8. Partial balances (inputs minus outputs) of nitrogen (N), phosphorus (P) and potassium (K) on cropped fields and palm groves of the 17 terrace systems belonging to the ‘scattered oasis’ of Maqta, Oman, in 2001/2002. Note that the terrace systems on the x-axis are arranged in order from smallest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

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 (Tables 4 and 5). In contrast to Balad Seet, irrigation and human faeces contributed only very small amounts of N, P, and K. Average annual area-based nutrient surpluses in cropland were similar at both oases, but were much higher for palm groves at Balad Seet than at Maqta (Tables 4 and 5).

4. Discussion

Yield levels were low for all of the irrigated crops except for sorghum, garlic, and alfalfa. This was likely

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

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 understorey 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

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.

^a Positive values indicate gains and negative ones losses.

^b Total annual spring flow of 228,587 m³ 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.

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 two to three times higher 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. Even if the preliminary Ndfa values used may be rather high, the results of the ¹⁵N experiment suggested a total annual N₂-fixation in the above-ground TDM of as much as 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 prior to application (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 Brouwer and Powell (1998) for sheep-cattle manure, P and K, at 5 and 29 g kg⁻¹, respectively, were much higher than respective values of 2 and 8 g kg⁻¹ from the West African Sahel.

Table 5

Annual inputs, outputs and partial balances of nitrogen (N), phosphorus (P) and potassium (K) in cropland and palms groves at Maqta, Oman

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. ^b	n.a.	n.a.	n.a.	n.a.	n.a.
	Animal manure	198	25.3	199	79	10.1	80
	Irrigation water ^c	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 understorey 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

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.

^a Positive values indicate gains and negative ones losses.

^b Not applicable.

^c Total annual spring flow of 51,666 m³ 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 4 months during the remainder of the year cropland was left fallow and therefore not irrigated.

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., 2005) 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 10–12 in the upper 0.2 m layer of terrace soils at Balad Seet and Maqta (Wichern et al., 2004a,c) 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 volatilization 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

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 (kg ha ⁻¹)		Share of manure (%)	Intensity (kg ha ⁻¹)		Share of manure (%)	Intensity (kg ha ⁻¹)		Share of manure (%)
	Range			Range			Range		
	Mean		Mean		Mean		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 (kg ha ⁻¹)		Share of manure (%)	Intensity (kg ha ⁻¹)		Share of manure (%)	Intensity (kg ha ⁻¹)		Share of manure (%)
	Range			Range			Range		
	Mean		Mean		Mean		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 N₂-fixation.

soil in Pakistan with 16 and 32 t annually applied farmyard manure (Mahmood et al., 1997). On the Omani oasis terraces such gaseous losses 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.

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 (kg ha ⁻¹)			Barley ^a (kg ha ⁻¹)			Sorghum (kg ha ⁻¹)		
	Inputs	Outputs	Partial balances	Inputs	Outputs	Partial balances	Inputs	Outputs	Partial balances
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 (kg ha ⁻¹)			Garlic (kg ha ⁻¹)			Coriander (kg ha ⁻¹)		
	Inputs	Outputs	Partial balances	Inputs	Outputs	Partial balances	Inputs	Outputs	Partial balances
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 N₂-fixation.

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 2 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 -emissions 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., 2005) 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., 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., 2005).

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 oases 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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