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The importance of semi-arid natural mountain pastures for feed intake and recycling of nutrients by traditionally managed goats on the Arabian Peninsula

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ABSTRACT

Goat husbandry in Oman's Hajar Mountains supplies income and manure to farmers. An earlier analysis concluded that it uses purchased feeds inefficiently, but did not value the contribution of mountain pastures to goat nutrition and cropland fertilization. Therefore intake of pasture vegetation, cultivated forages and purchased feeds was determined in goats from three villages in spring and autumn 2005. Faecal excretion was quantified using TiO_2 and diet digestibility was calculated from faecal nitrogen (N).

Organic matter (OM) intake varied from 71 to 107 g $kg^{-0.75}$ d^{-1}. Pasture vegetation supplied 45–71% of OM intake, and at least 28%, 33% and 42% of phosphorus (P), metabolizable energy (ME) and N intake. While ME intake just covered maintenance and locomotion requirements, N and P intake exceeded the animals' requirements. Therefore faecal concentrations (g kg^{-1} OM) of 26–36 g N and 4–8 g P were high, making goat dung a key element of sustainability for the local cropping systems.

Since mountain pastures supply nutrients to goats and cropland, their long-term productivity is crucial. Feeding cultivated forages seemingly reduces intake on pasture, but a comprehensive evaluation of nutritional and economic implications of this strategy and possible alternatives is needed.

1. Introduction

On Al Jabal al Akhdar, the highest elevation in Oman's Hajar Mountains, the interaction of a strongly variable rainfall of 150–300 mm a^{-1} (Wilkinson, 1977) with a particular geology, topography and land use history resulted in a typical open shrubland vegetation (Brinkmann et al., 2009; Mandaville, 1977) giving the rugged range its name "The Green Mountain". Through skillful soil fertility management and irrigation of century-old terraces, farmers in scattered oases settlements maintain a productive system of cereal and vegetable cropping combined with fruit production (Gebauer et al., 2007). Goat husbandry is a major component of this small-scale mixed farming system (Zaibet et al., 2004), supplying food and income to the rural population (Dickhoefer, 2009) and dung to the crops in the irrigated gardens (Buerkert et al., 2005). The typically 1–55 goats per household (Dickhoefer, 2009) are kept in a barn overnight, where they are fed with dates, dried sardines and cultivated green forages. During the day goats graze the mountain pastures, which, due to their year-round use, show clear signs of overgrazing (Brinkmann et al., 2009; Ghazanfar, 2003; Schlecht et al., 2009). From their economic analysis of this system Zaibet et al. (2004) concluded that goat husbandry is substantially fueled by off-farm income and purchased feedstuffs are used inefficiently. Yet, these authors' conclusion that a shift from the traditional grazing system plus homestead feeding to a zero-grazing system would increase resource use efficiency fails to evaluate the contribution of the vegetation of the mountain pastures to goat nutrition and nutrient recycling to cropland. Such evaluation therefore was the aim of the present study.

2. Materials and methods

2.1. Site and farming system

The study was carried out in the oases settlements of Masayrat ar Ruwajah (Masayrat; 57 °40′13″E, 23 °02′37″N, 1030 m a.s.l.), Qasha' (57 °39′50″E, 23 °04′00″N, 1640 m) and Ash Sharayjah

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(Sharayjah 57 °39′30″E, 23 °04′10″N, 1900 m). The villages are situated within a distance of 10 km from Sayh Qatanah (57 °40′35″E, 23 °04′44″N, 1975 m), the major settlement and administrative center of Al Jabal al Akhdar. The region receives a precipitation of 100–340 mm a^{-1} that may occur throughout the year, but rainfall probability is highest in February–March and July–August (Luedeling and Buerkert, 2008). Just before the start of the present study (December 2004–March 2005) 150 mm of rain had fallen. Thereafter, no more rain was registered until November 2005. Annual average air temperature is 18.1 °C, with a monthly minimum of 3.6 °C in January and a maximum of 36.3 °C in June in Sharayjah.

Each of the three villages consists of a central settlement and surrounding terrace systems for crop cultivation. Water is supplied by springs fed by rainwater that percolates through highly fractured calcareous rocks (Luedeling et al., 2005). An elaborated canal system conveys irrigation water to small plots cultivated with garlic (*Allium sativum* L.), onion (*Allium cepa* L.) and coriander (*Coriandrum sativum* L.). Perennials cultivated above 1500 m are roses (*Rosa damascena* Miller) for rosewater distillation, pomegranates (*Punica granatum* L.), peaches (*Prunus persica* L.), apricots (*Prunus armeniaca* L.), and walnuts (*Juglans regia* L.); at lower altitudes the dominant date palm (*Phoenix dactylifera* L.) is interplanted with some lime (*Citrus aurantiifolia* [Christm. et Panz.] Swingle) and banana (*Musa* spp.) plants. A major part of each village terrace area is sole- or intercropped with fodder crops such as alfalfa (*Medicago sativa* L.), barley (*Hordeum vulgare* L.), oat (*Avena sativa* L.), sorghum (*Sorghum bicolor* L. Moench), and maize (*Zea mays* L.). In addition sown or spontaneously growing understorey grasses and weeds in fruit orchards, such as *Anagallis arvensis* L., *A. sativa* L., *Convolvulus arvensis* L., *Digitaria nodosa* Parl., *Eragrostis papposa* (Roem. & Schult.) Steud., *Euphorbia peplus* L., *Fumaria abyssinica* Hamm., *Lolium temulentum* L., *Stellaria media* (L.) Vill., and *Torilis stocksiana* (Boiss.) Drude (Patzelt, 2009), are regularly harvested and fed to livestock.

2.2. Characteristics of the goat husbandry system

During daytime, the Jebel Akhdar breed goats (Maghoub et al., 2005) of different families are grouped into several herds to graze the mountain pastures surrounding the settlements. Among these, one herd per village was selected for the present study. In all villages, goats started grazing between 6:30 and 7:30 a.m. The herd in Masayrat was conducted to pasture and left there to graze on its own (herd-release mode), while the herd in Sharayjah was accompanied by a herder who determined the grazing itinerary. In Qasha' two families alternately took care of the goats: one family herded them to pastures northeast of the village, while the other family turned to an area southwest of the village and released the goats there. Herded goats returned to the homestead around 5.30 p.m., whereas herd-release animals already returned around 3 p.m. At the homesteads, goats were subsequently fed with cultivated green forages and weeds, dried dates, dried sardines and cereal-based supplements. In some households, groups of pregnant and lactating goats or fattening males were fed separately, but mostly all animals were fed together. The type and amount of feed given was determined by each farmer individually and could vary from day to day, according to the availability of particular feedstuffs.

2.3. Determination of feed intake at the homestead

In spring (March/April) and in autumn (October/November) 2005, the feed intake of 5–8 male goats per village (Table 1) was determined during a 7 day experimental period. Since we studied the habitual goat feeding practices of farmers and did not introduce new feedstuffs, the adaptation of goats to experimental conditions was limited to 5 days. Selected goats were loosely tied to poles in the farmyard and fed from individual troughs. Feeding in Qasha' and Sharayjah took place at 6 a.m. and 6 p.m., while in Masayrat goats were only fed at 6 p.m. Shoots of barley, maize, and oats from the gardens were offered in the milk or dough stage of the grain. On some days, collected garden weeds or leaves from wild olive (*Olea europaea* ssp. *cuspitata* [Wall. ex G. Don] Ciferri) and Ziziphus trees (*Ziziphus spina-christi* L. Desf.) were also fed. In addition purchased supplement feeds such as dried fish, dry dates, wheat meal, bread, barley grain, and meal leftovers, such as boiled rice, were used. The type and amount of feed offered depended on the farmers' decision and could slightly vary from one day to the next. Before being offered, all feeds were weighed individually on a portable scale (range 0–5 kg, accuracy 2 g). Per type of cultivated green forage, one sample was kept daily; the different concentrate feeds were sampled every second day. At the end of each meal, leftovers were weighed and a sample of each type of leftover feed was kept. Leftovers of supplement mixtures were separated into individual components (such as dates and fish) and these were weighed separately. Samples of forages and supplement feeds were air-dried in cotton bags; for rice, the dry grain was sampled and was analysed after boiling in the laboratory.

2.4. Observation of fodder selection on pasture

In parallel to the two intake studies, the forage selection behavior of goats on pasture was observed during four consecutive days per village. Every 3 min an observer recorded the total number of goats in sight and the number of animals feeding on the shrub and tree strata or on the herbaceous vegetation, respectively. If identifiable, the grazed plant species were noted individually, whereby the vascular plant nomenclature followed Ghazanfar (1992, 2003) and Jongbloed et al. (2003). The observed number of goats per species or strata, respectively, was multiplied with the length of the observation interval. The daily sum of all animal-intervals per species or strata was divided by the total number of goats observed times the total daily observation time, to obtain the proportion of feeding time

Table 1
Number of goat keeping households, participating households and live weight of experimental (exp.) goats in three study villages on Al Jabal al Akhdar, Northern Oman, in spring (S) and autumn (A) 2005.

Parameter	Village	Masayrat	Qasha'	Sharayjah
Altitude (m a.s.l.)		1060	1640	1930
Households, total (n)		13	10	20
Goat keeping households (n)		11	7	15
Goats per village (n)		245	112	152
Participating households (n)	S/A	4/3	2/2	3/3
Total experimental goats (n)	S/A	8/8	7/8	8/5
Live weight of exp. goats (kg ± S.D.)	S/A	34.9 ± 11.01/25.9 ± 2.38	31.7 ± 6.57/33.8 ± 14.58	27.2 ± 5.55/36.4 ± 12.23
Goat management at pasture		herd-release	herded and herd-release	herded

spent on the species or stratum. This value was taken as an indicator for the preference of plant species by the goats (Appendix I) and was cross-checked against farmers' perception of the palatability of these pasture plants to goats.

Of the grazed plant species, the observer collected two to four samples of approximately 30 g air-dry matter (ADM). Care was taken to collect the same plant parts that were consumed by the observed goats. Individual samples were weighed fresh, air-dried, and weighed again, and pooled into one sample per species, which was subjected to proximate analysis (Section 2.6).

2.5. Determination of faecal excretion

Total organic matter (OM) intake was calculated from total faecal OM excretion using the external faecal marker titanium dioxide (TiO_2). To establish a constant marker concentration in the faeces, TiO_2 application started four days prior to the experimental period and continued until its end. Each experimental animal was orally dosed with one gelatine capsule containing 3 g TiO_2 (±0.03) every evening prior to homestead feeding. In case of incomplete swallowing or regurgitation of part of the marker, one additional capsule containing 1 g TiO_2 (±0.03) was administered. The amount of marker applied was recorded and eventual losses were estimated as precisely as possible. Faecal collection bags were fitted to the animals overnight; bags were taken off and emptied in the morning before the goats went out for grazing. After weighing and homogenization of the collected faeces, a representative sample of 500 g (±2) fresh matter (FM) was kept from each animal every day and deep-frozen. After the 7 day sampling period, 100 g FM of the faecal samples collected on days 1 and 2, days 3–5, and days 6 and 7, respectively, were pooled into three composite samples per animal and stored frozen. One additional pool sample (70 g ADM) from faeces collected on days 1–7 was stored air-dried.

2.6. Analysis of feed and faecal samples

All samples of cultivated and collected green forages, purchased supplement feeds and pasture plants were analyzed in duplicate for their proximate composition following standard procedures (Naumann et al., 2004). Except for dates, air-dried samples were ground to pass a 1 mm mesh screen and were subsequently dried at 105 °C during 4 h to determine residual dry matter (DM). The pulp of dates was freeze-dried and pulverized manually in liquid nitrogen. Of the freeze-dried material, 2 g (±0.5) were used to determine DM concentration. Following standard procedures (Naumann et al., 2004), samples were analysed for the concentration of organic matter (OM), total phosphorus (P) and total nitrogen (N), and ash-free neutral detergent fiber (NDF without amylase pre-treatment; Van Soest et al., 1991). The concentration of crude protein (CP) was calculated by multiplying the N concentration by 6.25 (Close and Menke, 1986).

In Germany, concentrations of digestible organic matter (DOM; Eq. (1)) and metabolizable energy (ME; Eq. (2)) of all feedstuffs were determined by triplicate *in vitro* incubation of air-dry sample material (0.200 g ± 0.02) with rumen fluid for 24 h (Menke et al., 1979) on two subsequent days. Rumen liquor was obtained from two ruminally fistulated Holstein Frisian cows maintained on a 60% good quality grass hay and 40% concentrate diet according to their requirements.

$$DOM = 14.88 + 0.889*Gp + 0.0045*CP + 0.065*CA \quad [1]$$

where:

DOM = digestible organic matter concentration in %.

Gp = gas production in ml after incubation of 200 mg sample DM for 24 h.

CP = crude protein concentration of the sample in g kg^{-1} DM.

CA = crude ash concentration of the sample in g kg^{-1} DM

$$ME = 1.242 + 0.146*Gp + 0.007*CP + 0.0224*CL \quad [2]$$

where:

ME = concentration of metabolizable energy in MJ kg^{-1} DM.

Gp = gas production in ml after incubation of 200 mg sample DM for 24 h

CP = sample crude protein concentration in g kg^{-1} DM.

CL = sample crude lipid concentration in g kg^{-1} DM (taken from feed composition tables by Close and Menke, 1986 for forages and supplement feeds, and assumed to be 20 g kg^{-1} DM in pasture plants).

Fifteen pasture plants with an *in vitro* gas release of <30 ml per 200 mg DM were screened for tannins using the polyethylene glycol (PEG) method (Makkar et al., 1995). Of each plant, three samples (0.350 g ± 0.02) were incubated with rumen fluid adding PEG (0.750 g ± 0.02) and three samples were incubated without PEG addition. The incubation was repeated on a second day with the same number of replicates per sample. For samples of fish, DOM and ME concentrations were taken from feed composition tables provided by Close and Menke (1986).

Air-dry faecal samples were ground to pass a 1 mm mesh screen and were analysed for DM, OM, and P concentrations as described for the feed samples. The N concentration was determined in 0.03 g (±0.005) manually pulverized frozen samples. Concomitantly, a sub-sample of each frozen sample was dried at 105 °C for DM determination (Naumann et al., 2004). For the analysis of TiO_2 in each of the three pooled faecal samples per animal, the slightly modified method of Brandt and Allam (1987) was used.

2.7. Calculations and statistical analysis

The total amount of faeces excreted daily (F_T, kg OM d^{-1}) was calculated [Eq. (3)] according to Lippke (2002) from the average marker dose administered (M_D, g d^{-1}), the average marker concentration in faecal samples (M_{conc}, g kg^{-1} OM) and an unvarying total recovery (R) of 0.93 of TiO_2 in ruminant faeces (Titgemeyer et al., 2001).

$$F_T = M_D*(M_{conc})^{-1}*R \quad [3]$$

Total diet OM digestibility (DOM_T; percentage) was derived [Eq. (4)] from the faecal CP concentration (Lukas et al., 2005). After converting percentage DOM_T to the respective fraction (dom_T), total OM intake (IOM_T, kg OM d^{-1}) was calculated [Eq. (5)] according to Gordon (1995).

$$DOM_T = 79.76 - 107.7*e^{(-0.01515*CP)} \quad [4]$$

$$IOM_T = F_T*(1 - dom_T)^{-1} \quad [5]$$

Feed intake at the homestead was obtained by subtracting the amount of leftovers from the initially offered amount. Feed intake on pasture resulted from subtracting feed intake at the homestead from IOM_T. Intake and faecal excretion of nutrients and energy (intake only) were calculated from OM intake and excretion and the respective concentrations in feeds (N, P, ME) and faeces (N, P).

Multivariate analysis of variance and the *post hoc* Mann-Whitney-U test for not normally distributed data (Zöfel, 1988) were conducted in SPSS 12.0 for Windows XP (SPSS Inc., Chicago, USA) to determine the effect of season (S_i; spring, autumn) and village (V_j; Sharayjah, Qasha', Masayrat) on feed quality, feed and nutrient intake from pasture, cultivated forages and concentrate feeds as well as faecal OM, N, and P excretion [Eq. (6)]:

$$Y_{hijk} = \mu + S_i + V_j + (SV)_{ij} + e_{ijk} \quad [6]$$

whereby μ is the overall mean and e is the experimental error including the animal effect. As far as the independent variable 'village' is concerned, it comprised herd management (Section 2.2), size of pasture area, stocking density, vegetation productivity and composition (Dickhoefer et al., 2010). The latter four variables could not be addressed separately since pasture areas of villages overlapped to various degrees (Dickhoefer et al., 2010). Significant differences were reported at $P < 0.05$. The correlation between OM intake at the homestead and on pasture was tested by simple and stepwise multiple linear regression analysis.

3. Results

3.1. Quality of pasture vegetation and homestead feed

On spring pasture, goats of Masayrat devoted 71% (S.D. ± 15.0) of their daily feeding time to the ligneous stratum, while the respective values were 26% (±12.1) in Qasha' and 43% (±5.2) in Sharayjah ($P < 0.01$); in the remaining time the herbaceous stratum was grazed. In autumn, the time spent browsing ligneous plants decreased to 61% (±8.9) in Masayrat, but increased to 47% (±13.6) and 74% (±5.3) in Qasha' and Sharayjah ($P < 0.01$; further details are provided by Schlecht et al., 2009).

Since the pasture areas of three villages overlapped, no significant differences in the quality of selected fodder plants between the three villages could be demonstrated. While the concentration of OM was higher ($P < 0.05$) in ligneous than in herbaceous plants (Table 2), concentrations of P (1.7 mg P kg^{-1} OM; $P < 0.05$), DOM (613 g DOM kg^{-1} OM $P < 0.001$), and ME (7.0 MJ ME kg^{-1} OM $P < 0.001$) determined in spring where higher in the herbaceous than in the ligneous species (Table 2). Concentrations of CP did not significantly differ between seasons and plant strata, with the majority of highly and moderately preferred plants containing more than 80 g CP kg^{-1} OM throughout the study period (Table 2). Similarly, concentrations of NDF were mostly in the range of 400–600 g kg^{-1} OM.

In both seasons and across the two plant strata, DOM and ME concentrations of moderately and highly preferred plants were higher ($P < 0.01$) compared to plants that were only occasionally nibbled. For all other quality parameters, differences between the three preference classes were not statistically significant (Table 2). For the four herbaceous out of the fifteen pasture plant samples that showed a low 24-h *in vitro* gas release (Section 2.6), the incubation with PEG (Fig. 1) resulted in an increase in gas release of 9% (*Cymbopogon commutatus* (Steud). Stapf) and 29% (*Trigonella stellata* Forssk.), and a slight reduction of −2% (*Solanum incanum* L.) and −5% (*Aizoon canariense* L.), respectively ($P > 0.05$). For ten ligneous plant samples, PEG addition increased *in vitro* gas release by 8–204% as compared to the incubation without PEG ($P < 0.001$), while no changes were obtained for *Ochradenus arabicus* Chaudhary, Hillcoat & A.G. Miller. Differences in 24-h gas release between ligneous ($n = 11$) and herbaceous samples ($n = 4$) were only significant when incubated without PEG ($P < 0.001$).

The quality of individual feedstuffs offered at the homestead was similar among villages, so that they could be grouped by type of feed (Table 3). Quality differences were insignificant between seasons, except for the DM concentration of cultivated green forages that was higher in autumn ($n = 10$) than in spring ($n = 11$; $P < 0.05$). Differences between the group of energy feeds (wheat meal, dates, barley grain, rice, bread, maize grain), the group of cultivated forages (alfalfa, barley, maize, oats, garden weeds), Rhodes grass hay (*Chloris gayana* Kunth.) and the protein feed (dried sardines) were significant for the concentrations of OM and DOM ($P < 0.001$), ME, CP, NDF and DM ($P < 0.05$ in all cases) but not significant for P ($P > 0.05$).

For the overall diet, which consisted of varying proportions of feed ingested on pasture and at the homestead, respectively, the concentration of DOM_T (g kg^{-1} OM) was derived from the faecal CP concentration (Lukas et al., 2005; Section 2.7). While in spring DOM_T averaged 761 (±13.9), 746 (±8.5), and 743 (±10.4) in Masayrat, Qasha and Sharayjah, the values decreased to 719 (±20.5), 713 (±13.3), and 707 (±16.5) in autumn ($P < 0.001$ for each

Table 2
Proximate composition of differently appreciated herbaceous and ligneous plants[a] sampled on pastures of Al Jabal al Akhdar, Northern Oman, in spring and autumn 2005.

Season	Stratum	Goats' preference[b]	n	OM (g kg^{-1} DM)	DOM (g kg^{-1} OM)	ME (MJ kg^{-1} OM)	CP (g kg^{-1} OM)	P (mg kg^{-1} OM)	NDF (g kg^{-1} OM)
Spring	Herbaceous	H	10	854.3	623.1	7.1	101.4	1.3	645.1
		M	11	884.1	620.1	7.1	148.4	1.9	n.d.
		N	1	876.0	556.0	5.6	239.0	3.1	405.2
	Ligneous	H	5	900.6	531.6	5.9	129.6	1.3	367.8
		M	6	930.7	515.3	6.1	106.0	1.8	414.9
		N	6	920.2	398.0	4.2	63.0	0.8	589.0
Autumn	Herbaceous	H	2	924.2	445.1	5.3	84.4	0.5	685.9
	Ligneous	H	7	918.3	475.8	5.7	100.8	1.0	513.1
		M	5	882.3	502.1	5.4	103.3	1.3	405.4
		N	1	942.8	382.3	4.6	85.7	0.7	359.1
			SEM	7.53	15.74	0.21	7.00	0.11	20.75
Variable			df	$P \leq F$					
Season			1	0.493	0.035	0.027	0.228	0.011	0.782
Stratum			1	0.009	0.001	0.001	0.050	0.132	0.120
Preference			2	0.224	0.006	0.003	0.068	0.112	0.441
Season*Stratum			3	0.015	0.001	0.001	0.155	0.032	0.439
Season*Preference			3	0.181	0003	0.002	0.187	0.042	0.387
Stratum*Preference			5	0.116	0.001	0.001	0.008	0.076	0.232
Season*Preference*Season			9	0.056	0.003	0.005	0.038	0.047	0.217

DM dry matter; OM organic matter; DOM digestible organic matter; ME metabolizable energy; CP crude protein (nitrogen × 6.25); P phosphorus; NDF neutral detergent fiber; SEM standard error of the mean; n.d. not determined. DOM and ME were derived from *in vitro* incubation.
[a] For names of plants refer to the Appendix.
[b] Preference: H high; M moderate; N nibbled.

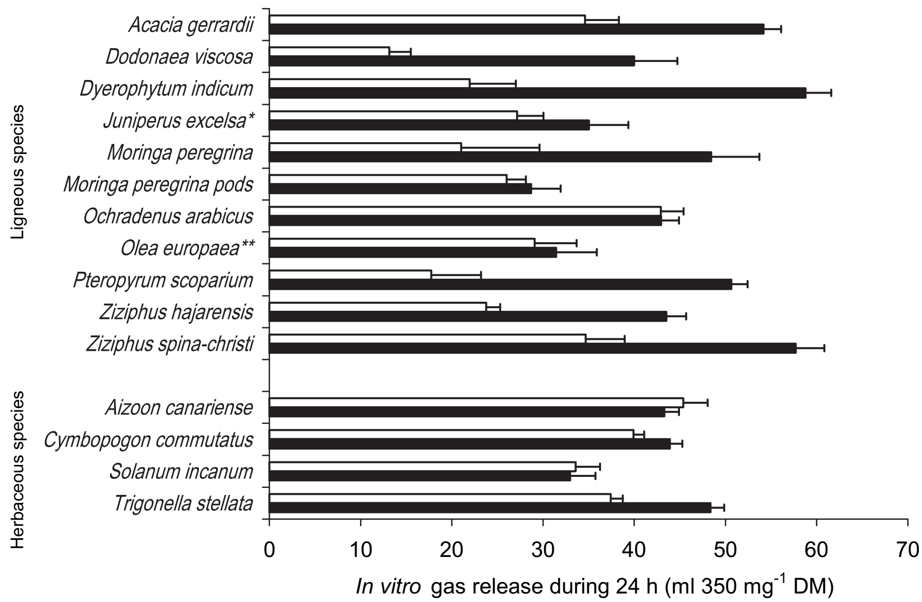


Fig. 1. Cumulative 24-h *in vitro* gas release from fifteen forage plants (tree leaves and whole herbaceous plants unless stated otherwise) selected by goats on rangelands of Al Jabal al Akhdar, Northern Oman, and incubated without (white) and with (black) polyethylene glycol. Bars represent means (and S.D.) of six replications. * *Juniperus excelsa* subsp. *policarpos;* ** *Olea europaea* subsp. *cuspidata*. DM dry matter.

village), with insignificant differences between villages but significant interactions ($P < 0.001$) between seasons and villages.

3.2. Feed and nutrient intake at the homestead and on pasture

The type and quantity of feedstuffs offered at the homestead varied between farmers, and sometimes even between days within a farm. The OM intake from cultivated forages and supplement feeds was not significantly different between the two seasons, but ingested amounts of cultivated forages differed between villages (Table 4). At 106 and 107 g kg$^{-0.75}$ d^{-1}, total OM intake (IOM_T) was higher in Qasha' than in Masayrat ($P < 0.001$) and Sharayjah ($P < 0.05$), both in spring and autumn (Fig. 2). Organic matter intake from pasture accounted for 72% (spring) and 71% (autumn) of IOM_T in Qasha' compared to 45% and 56% in Masayrat, and 52% and 46% in Sharayjah ($P < 0.001$). An increased OM intake at the homestead significantly reduced OM intake on pasture ($R^2 = 0.28$, $P = 0.001$, $n = 44$; Fig. 3), whereby the ingestion of cultivated forages reduced intake on pasture more efficiently (stepwise multiple linear regression, partial $R^2 = 0.36$, $P = 0.001$) than the intake of supplement feeds (partial $R^2 = 0.035$, $P = 0.128$).

The location-specific differences in IOM_T resulted in a higher ($P < 0.05$) total ME intake (kJ kg$^{-0.75}$ d^{-1}) of goats in Qasha (spring 876 ± 73.6; autumn 893 ± 148.4) compared to Masayrat (spring 727 ± 85.6; autumn 779 ± 112.5) and Sharayjah (spring 742 ± 163.8; autumn 837 ± 144.5). This was mainly due to differences ($P < 0.001$) between villages in the ME intake of cultivated forages that ranged from about 1.5% (Qasha, spring and autumn) to 30% (Masayrat, spring), and of pasture, which provided 33% (Masayrat, spring) to 64% (Qasha', spring) of total ME intake (Table 4). In contrast there to, ME intake from supplement feeds varied between seasons ($P < 0.01$) but not between villages. Intake of N and P from the pasture vegetation varied from 21% (Sharayjah, autumn) to 67% (Qasha', spring) and from 42% (Masayrat, spring) to 76% (Qasha', spring) respectively, mirroring differences in feeding strategies between villages and seasonal changes in nutrient

Table 3
Quality of purchased supplement feeds and cultivated green forages offered to goats at the homesteads. Values are averages across the three study villages on Al Jabal al Akhdar, Northern Oman, and the spring and autumn 2005 study periods.

Type	Feed	Samples (n)	DM (g kg^{-1} FM)	OM (g kg^{-1} DM)	DOM (g kg^{-1} OM)	ME (MJ kg^{-1} OM)	CP (g kg^{-1} OM)	P (mg kg^{-1} OM)	NDF (g kg^{-1} OM)
Energy feeds	Barley grain	4	866.6	976.0	820.8	12.4	103.9	2.9	242.5
	Bread	5	935.1	977.2	891.7	13.1	120.1	1.7	0.0
	Dates	13	885.2	973.5	734.9	10.5	25.9	0.7	0.0
	Rice	2	937.5	994.4	832.2	12.5	81.2	0.8	n.d.
	Wheat meal	3	920.9	942.8	719.8	9.9	161.9	10.8	274.7
Cultivated and collected forages	Alfalfa	5	230.4	871.5	672.7	11.6	174.5	2.8	469.6
	Barley, green	3	141.2	852.7	760.0	8.3	236.5	7.0	590.0
	Hay	1	963.8	904.8	559.7	6.7	97.2	1.3	856.9
	Maize, green	7	262.0	889.5	686.3	10.2	93.3	4.4	654.3
	Oats, green	6	193.6	861.2	674.1	14.0	89.1	4.1	688.0
	Olive leaves	2	576.8	937.8	491.7	6.3	74.4	1.0	346.4
	Weeds	3	241.9	854.0	628.6	6.3	135.7	2.8	516.2
Protein feed	Fish[a]	11	922.2	760.5	870.0	13.4	781.5	17.9	0.0

FM, fresh matter; DM, dry matter; OM, organic matter; DOM, digestible organic matter; ME, metabolizable energy; CP, crude protein (nitrogen × 6.25); P, phosphorus; NDF, neutral detergent fiber.
n.d. not determined.
[a] DOM and ME were derived from *in vitro* incubation for all feeds except for fish, where they were taken from feed composition tables by Close and Menke (1986).

Table 4
Intake of organic matter (OM), metabolizable energy (ME), nitrogen (N) and phosphorus (P) from pasture vegetation (Past), cultivated forages (Green) and purchased supplement feeds (Suppl) by Jebel Akhdar goats in the villages of Masayrat (M), Qasha' (Q) and Sharayjah (S) in Northern Oman in spring and autumn 2005.

Season	Village	OM (g $kg^{-0.75}$ d^{-1})				ME (kJ $kg^{-0.75}$ d^{-1})			N (g $kg^{-0.75}$ d^{-1})			P (mg $kg^{-0.75}$ d^{-1})		
		Past	Green	Suppl	Total	Past	Green	Suppl	Past	Green	Suppl	Past	Green	Suppl
Spring	M	32	16	23	71	243	218	266	0.68	0.34	0.62	56	53	88
	Q	76	2	28	105	564	15	298	1.58	0.05	0.45	130	12	52
	S	43	15	26	83	319	131	291	0.89	0.31	0.74	73	64	94
Autumn	M	49	9	29	88	342	82	355	0.59	0.22	0.36	38	29	46
	Q	76	2	29	107	527	13	352	0.93	0.03	0.48	46	2	84
	S	44	16	35	95	307	128	403	0.61	0.27	0.25	22	36	46
	SEM	3.6	1.1	1.2	3.2	25.9	11.8	13.5	0.067	0.022	0.051	6.1	4.1	7.9
Variable	df	$P \leq F$												
Season	1	0.307	0.230	0.053	0.162	0.534	0.063	0.003	0.022	0.151	0.004	0.001	0.015	0.023
Village	2	0.001	0.001	0.411	0.001	0.001	0.001	0.775	0.001	0.001	0.643	0.031	0.001	0.500
Village*Season	5	0.001	0.001	0.180	0.004	0.001	0.001	0.061	0.001	0.001	0.061	0.001	0.001	0.150

concentrations of the selected pasture plants (Section 3.1). While P intake from cultivated forages also varied significantly between seasons ($P < 0.05$) and villages ($P < 0.001$), significant seasonal variations in N intake from cultivated forages were not observed. Despite insignificant seasonal variations in OM intake from supplement feeds, seasonal differences became apparent in their quantitative supply of N ($P < 0.01$) and P ($P < 0.05$).

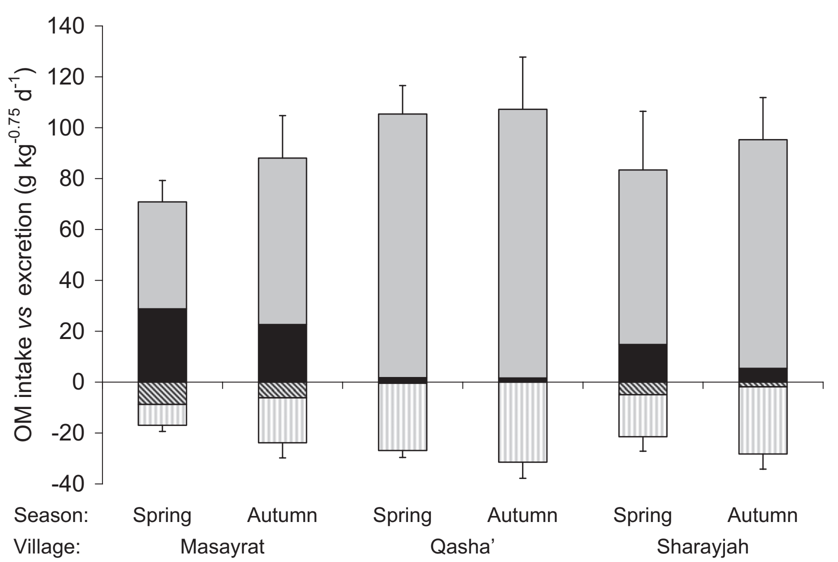
3.3. Organic matter and nutrient excretion

In the agro-pastoral system under study, cultivated forages, understorey grasses and weeds from the terrace gardens represent farm internal sources of nutrients, while the pasture vegetation and the purchased supplement feeds are nutrient sources external to the farm. Varying from 21 to 31 g OM $kg^{-0.75}$ and from 113 to 217 mg P $kg^{-0.75}$, daily faecal excretion of OM (Fig. 2) and P (Fig. 4) was higher in autumn than in spring, and was always significantly higher in Qasha' than in the other two villages. Faecal N excretion (Fig. 4), which varied from 0.61 to 0.86 g N $kg^{-0.75}$ d^{-1}, was also significantly higher in Qasha' than in the other two villages. The contribution of farm internal and farm external feed sources to faecal N excretion was not assessed given the unknown partitioning of feed N into urine and faeces and the proportion of microbial and endogenous N in faeces. In both seasons farm external feed resources contributed 98% of total OM excretion in Qasha' (Fig. 2), while values in Sharayjah (77% in spring, 93% in autumn) and Masayrat (49% in spring, 74% in autumn) were lower. Contribution of farm internal and external feed resources to the excretion of P (Fig. 4) was similar to the excretion of OM, and significant season × village interactions ($P < 0.001$) were obtained for both.

4. Discussion

4.1. Quality of diet and diet components

The main constraint to primary production in the Al Jabal al Akhdar region, as in the whole of Oman, is low and irregular rainfall. Ligneous and herbaceous plants on the mountain pastures



P-values:	df	Total OM intake	Total OM excretion
Season	1	0.162	0.003
Village	2	0.001	0.002
Village*Season	5	0.004	0.001

Fig. 2. Intake (positive values) and excretion (negative values) of organic matter (OM) from farm internal sources (black patterns) and sources external to the farm (gray patterns) by Jebel Akhdar goats in three mountain oases of Northern Oman in spring and autumn 2005.

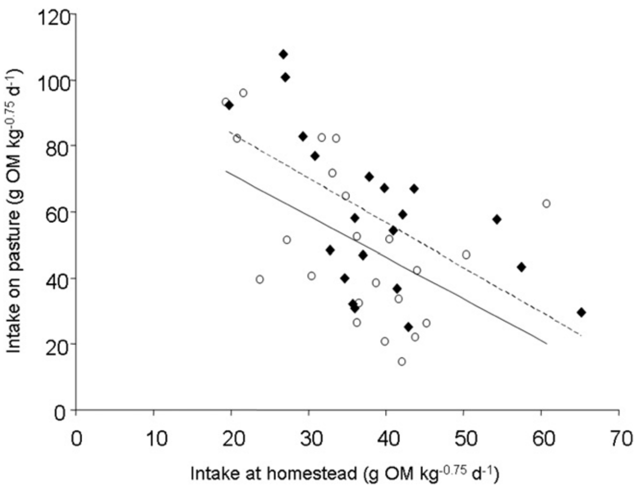


Fig. 3. Correlation between organic matter (OM) intake at the homestead (supplements, cultivated and collected forages) and intake of pasture vegetation by Jebel Akhdar goats in spring (○ dashed line; $R^2 = 0.26$, $n = 23$) and autumn 2005 (◆, solid line; $R^2 = 0.36$ $n = 21$).

are therefore well-adapted to long periods of drought, one mechanism being their immediate reaction to moisture by quick germination, tillering, leaf flushing, flowering, and seeding. A few rainfall events totaling about 150 mm during December 2004–March 2005 resulted in the development of a relatively lush and qualitatively good pasture vegetation in spring 2005 compared to the situation in autumn 2005 (Schlecht et al., 2009). The decrease in concentrations of DOM, ME, CP, and P in pasture plants and the increase in NDF from spring to autumn 2005 reflect the seasonal changes in plant physiology from young to maturing plants (herbaceous) or plant parts (ligneous). Nevertheless, in both seasons, concentrations of all nutrients in the majority of pasture plants were above the minimum values stipulated for goat feeds (NRC, 1981). Taking the NRC (1981) recommendations as a standard, the supplement feeds and cultivated green forages offered at the homestead were also of acceptable or even high nutritional quality for extensively managed goats. Although only offered in moderate quantities averaging between 1.1 g OM kg$^{-0.75}$ d^{-1} (Sharayjah, autumn) and 8.0 g OM kg$^{-0.75}$ d^{-1} (Masayrat, autumn), dried sardines are an important source of high quality protein, P and ME in the goat husbandry systems of Oman (Maghoub et al., 2005). Complemented by considerable quantities of dates (minimum 14.7 g OM kg$^{-0.75}$ d^{-1} in Masayrat in spring; maximum 32.9 g OM kg$^{-0.75}$ d^{-1} in Sharayjah in autumn), the supply of highly digestible protein was ideally matched by readily available carbohydrates (Elhag and Elkhanjari, 1992).

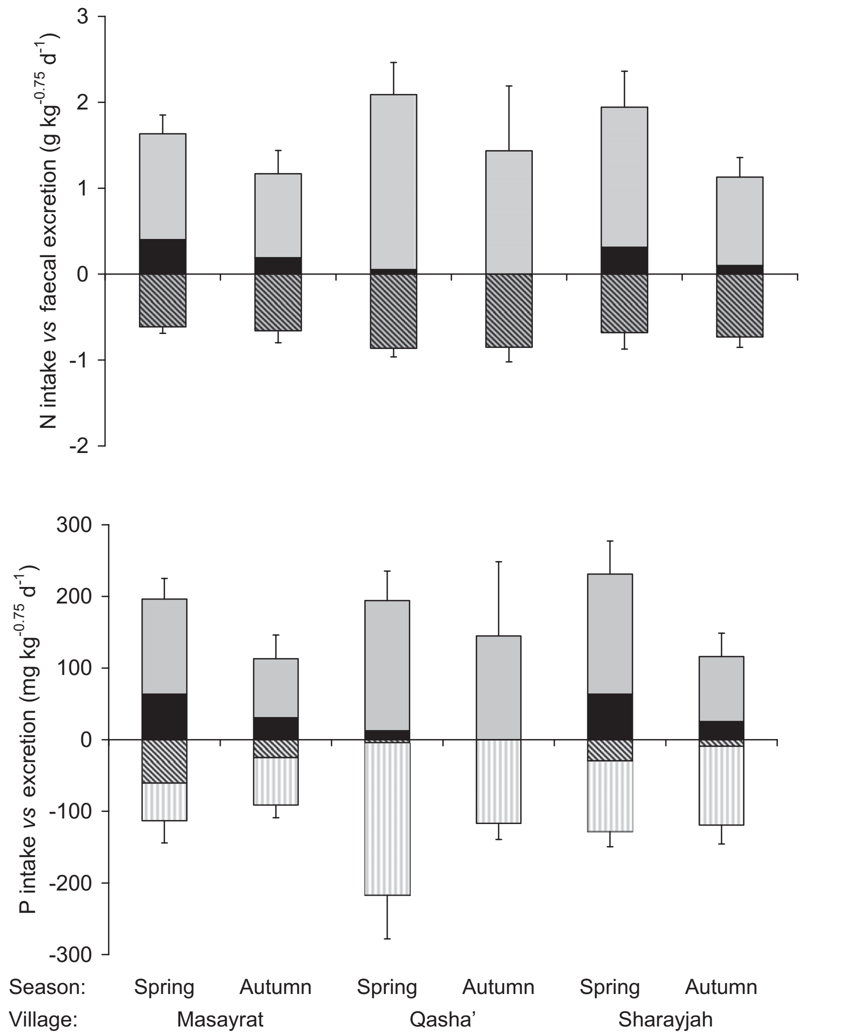
Although the concentrations of secondary plant compounds were not determined in the collected pasture plants, the results obtained for 12 out of the 15 plant samples tested by the PEG bioassay point to biologically active tannins as the responsible compounds for reduced *in vitro* gas release (Bueno et al., 2008; Makkar et al., 1995; Selje et al., 2007). Whether and to which degree tannins also had a negative impact on nutrient digestibility *in vivo* is difficult to evaluate because well-adapted goats are to a considerable extent able to decrease the anti-nutritional effects of tannins through different detoxifying mechanisms (Silanikove et al., 1996). Additionally, the *in vitro* test was performed on singular plant species, while the proportion of tannin-containing plants in the total diet was certainly below 72%, which was the maximum contribution of pasture biomass to total OM intake (Section 3.2). Therefore, dilution effects of tannin-free diet components certainly reduced negative effects of the ingested tannins (Hess et al., 2008).

4.2. Feed intake on pasture and at the homestead

The presence of tannins in the diet (Section 4.1) enhances the excretion of tannin-protein complexes in faeces (Powell et al., 2009) and would lead to an overestimation of diet digestibility with our approach that calculated DOM_T from the faecal crude protein concentration (Section 2.7). Since feed intake at the homestead was directly quantified, any miscalculation would have exclusively overestimated OM intake at pasture. For Sahelian cattle consuming a diet with at least 30% tannin-containing browse plants (Diarra et al., 1995), the coefficient of determination between measured DOM_T and the values predicted by the equation of Lukas et al. (2005) was 0.83 (Schlecht and Susenbeth, 2006). To cross-check our feed intake estimations, we multiplied the amounts of feedstuffs offered at the homestead with their respective *in vitro* digestibility. The resulting faecal OM was then subtracted from the marker-derived total faecal OM, resulting in the amount of faeces attributable to OM intake from pasture. Intake from pasture was then back-calculated from the weighted average *in vitro* digestibility of herbaceous and ligneous plants (omitting plants for which PEG effects on gas release were >50%). In autumn, the sum of the thus estimated intake from pasture plus the intake measured at the homestead was only 5.2 g OM kg$^{-0.75}$ d^{-1} (equivalent to 6.7%) less than total OM intake estimated from DOM_T based on faecal CP concentration. In spring, however, the difference between the two estimates averaged 27.8 g kg$^{-0.75}$ d^{-1}, equivalent to 19.4%, with the higher estimates derived from DOM_T. One reason for this divergence between the two estimates might be that even for pasture plants without a major PEG effect, the *in vitro* incubation with rumen fluid from cows fed hay plus concentrate underestimated their *in vivo* digestibility in the studied mountain goats. Furthermore, a simple weighting that assumes proportional and additive effects of the digestibility of individual feedstuffs towards overall diet digestibility is certainly underestimating the latter in rations containing energy-rich feeds (Van Soest, 1994), as was the case here. The close agreement between the two intake estimates in autumn suggests that our data reliably depicts the quantitative feed intake of goats on pasture, although the performed cross-check via weighted *in vitro* digestibilities is of course no true validation of our intake estimates. The comparison of the present values to the intake of goats measured under similar agro-ecological conditions in the highlands of northern Mexico (Cerrillo et al., 2006) also supports the plausibility of our intake estimates. It must, however, be kept in mind that, due to the strong variation of feeding practices of individual farmers, our intake values cover the range typical for the grazing and feeding strategies encountered in mountain goat husbandry of the Northern Hajar, but are not representative values *sensus stricto*.

Comparing the daily intake of energy and nutrients to the requirements of male goats of 20–40 kg live weight that are growing at 100 g d^{-1} (NRC, 1981), CP and P intake largely exceeded the recommended daily values of 50 g CP and 3.5 g P per animal. However, the average ME intake of 727–892 kJ ME kg^{-075} d^{-1} might not in all cases have allowed for a weight gain of 100 g d^{-1} due to energy expenses of 3.3 and 18.5 kJ ME per kilogram of live weight and meter of horizontal and vertical movement (Lachica et al., 1997), which average 11 km d^{-1} (horizontal) and 2.5 km d^{-1} (vertical) at the study sites (Schlecht et al., 2009) and add to maintenance requirements of 422 kJ ME kg$^{-0.75}$ (Lachica and Aguilera, 2005).

The vegetation of the mountain pastures supplied 45–72% of the total daily OM intake of goats whereby marked differences between villages existed in the contribution of pasture vegetation, cultivated forages and supplements. In particular, the high intake of pasture vegetation in Qasha' compared to Sharayjah and Masayrat might in



P-values:	*df*	*Total N intake*	*Faecal N excretion*	*Total P intake*	*Total P excretion*
Season	*1*	*0.162*	*0.549*	*0.001*	*0.002*
Village	*2*	*0.001*	*0.001*	*0.515*	*0.002*
*Village*Season*	*5*	*0.004*	*0.013*	*0.001*	*0.001*

Fig. 4. Intake (positive values) and faecal excretion (negative values) of nitrogen (N, above) and phosphorus (P, below) from farm internal sources (black patterns) and farm external sources (grey patterns) by Jebel Akhdar goats in three mountain oases of Northern Oman in spring and autumn 2005.

part be explained by the larger grazing area and lower stocking rate at Qasha' (Dickhoefer et al., 2010). More pasture vegetation might thus have been available to goats from this village, reducing the need for additional supply of cultivated green forages, while farmers in the other two villages might have aimed at complementing roughage intake of their goats by supplying substantial quantities of cultivated feeds. Secondly, differences in feed intake on pasture might also be due to herd management. With the herd-release mode practiced in Masayrat, many goats returned to the homestead after approximately 6 h, which probably reduced their feed intake on pasture (Kennedy et al., 2009) as compared to that of the (partly) herded goats in Sharayjah and Qasha'. Thirdly, since only moderate amounts of dates, fish and wheat bran were offered at the homestead, the rapid ruminal release of glucose instead of short chain fatty acids after the morning feeding did apparently not suppress subsequent roughage intake on pasture of goats from Qasha'. This is in line with the results of Boudon et al. (2009). In contrast there to, an increased supply of cultivated green forages reduced OM intake on pasture, which may have advantages as well as disadvantages for the studied agro-ecological system.

Since in Oman pasture vegetation is a communally managed resource, its intensive exploitation through grazing increases the use efficiency of cultivated and purchased feeds in the goat production system if only the latter are valued by their market prices (Dickhoefer, 2009). On the other hand, recent comparisons of grazed and ungrazed areas in the study region clearly demonstrate the negative impact of year-round grazing on biomass production and plant species composition of the mountain pastures, pointing to the need of a more cautious use of this vital but fragile natural resource (Brinkmann et al., 2009; Dickhoefer et al., 2010; Schlecht et al., 2009). In this regard, the partial substitution of intake from pasture vegetation by cultivated forages might seem advisable. However, the water needs for producing these feeds in the terrace gardens and the opportunity costs for water, land, and labor should be determined before such recommendations can be made. Recurrent water shortages in the recent past (Luedeling and Buerkert, 2008) suggest that additional green feeds should better be produced outside the Al Jabal al Akhdar mountain oases.

4.3. Manure-based nutrient recycling

The vegetables, forages and fruit trees grown on the terraces of the agro-pastoral mountain oases are heavily fertilized with goat dung (Buerkert et al., 2005, 2010), which compensates for high mineralization rates, thereby maintaining soil organic matter and preventing soil salinization despite century-long irrigation (Luedeling et al., 2005; Wichern et al., 2004). This intensive recycling of carbon and nutrients together with high solar radiation and intensive irrigation allows for up to twelve alfalfa harvests per year on the small but intensively managed terrace surfaces (Buerkert et al., 2005). Under these circumstances regular applications of goat manure cannot simply be replaced by additions of mineral fertilizers, but are essential for the long-term sustainability of the cropping system. As our results show (Section 3.3.) goat manure production in the studied villages largely relies on feed resources external to the farm, particularly on the pasture vegetation and only to a lesser extent on purchased supplement feeds. At faecal concentrations of 26–36 g N kg^{-1} OM and 4–8 g P kg^{-1} OM, the present dung quality was higher than that reported for the Omani oases of Balad Seet (Wadi Bani Awf) and Maqta (Jabal Bani Jabir) where values of 18 g N kg^{-1} OM and 5 g P kg^{-1} OM were determined (Buerkert et al., 2005). As far as the N concentration is concerned, this difference may partly be ascribed to dietary tannins (Section 4.1), but also reflects the year-round feeding of non-negligible amounts of dried sardines in the studied villages, that are a major source of N as well as of P, particularly in dry or drought periods (Dickhoefer, 2009).

Since faecal excretion is almost equally distributed across the 24-h day (Schlecht et al., 2007) and goats stay on the mountain pastures during daytime, only about half of the daily amount of excreta is accumulating at the homestead. Of this, further losses occur during collection and transportation for application on the fields. Furthermore, the quality of the manure brought to the fields cannot be directly deduced from the quality of faeces determined here, but also depends on the proportion of feed residues and other organic wastes added and the eventual recovery of urine through bedding material. However, the latter was not used for goats in the studied farming system. Furthermore, the mode and duration of manure storage (Predotova et al., 2010; Rufino et al., 2007) strongly affect its N concentration. If despite these reservations an attempt is made to estimate the availability of goat manure to an average farm household in Masayrat keeping 20 adult goats of 30 kg live weight each and cropping 0.43 ha of land (Luedeling and Buerkert, 2008), 955 kg faecal OM yr^{-1}, equivalent to 2220 kg OM ha^{-1} yr^{-1} of manure would be available for this area, supplying 70 kg N ha^{-1} yr^{-1} and 12 kg P ha^{-1} yr^{-1}, and as such contributing substantially to the total nutrient removal of crops, which for the mountain oasis of Balad Seet was estimated to average 265 N ha^{-1} yr^{-1} and 33 P ha^{-1} yr^{-1} (Buerkert et al., 2005).

5. Conclusions

At the studied locations, the high contribution of the natural mountain vegetation to the organic matter intake of goats supplies at least 30%, 48% and 80% of goats' daily maintenance requirements of P, ME (including for locomotion), and CP. However, the availability of the latter may be reduced by the presence of tannins in a number of pasture plants. Indirectly, mountain pastures also supply important amounts of OM and nutrients to crop fields via dung recycling. As long as grazing of the communal mountain pastures is not implying noticeable costs, farmers will unlikely renounce these advantages and shift to a zero-grazing system. However, since recently reported clear signs of overgrazing of high altitude pastures in Oman call for a cautious use of this resource, an increased homestead feeding of cultivated green forages to reduce feed intake of goats on pasture seems to be a management strategy that merits further evaluation of nutritional aspects, labour and water needs as well as farm economics.

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Appendix I

Botanical names, family, Raunkiaer life form, live span and chorotype of collected pasture plants, and their preference by grazing goats as determined from animal observation on Al Jabal al Akhdar, Northern Oman.

Botanical name, ligneous plants		Preference[a]	Family	Raunkiaer life form	Live span	Chorotype[b]
Acacia gerrardii Benth.	leaves	H	Fabaceae	phanerophyte	perennial	Sudanian-African
Acacia gerrardii Benth.	pods	H				
Acacia gerrardii Benth.	seeds	H				
Dodonaea viscosa (L.) Jacq.		N	Sapindaceae	phanerophyte	perennial	Australian
Dyerophytum indicum (Gibs. ex Wight) Kuntze		M	Plumbaginaceae	phanerophyte	perennial	Southern Arabian West Indian
Euphorbia larica Boiss.		N	Euphorbiaceae	chamaephyte	perennial	Saharo-Sindian
Euryops arabicus Steud ex Jaub. & Spach		M	Composite	phanerophyte	perennial	Arabian
Ficus cordata Thunb. subsp. *salicifolia* (Vahl) C.C. Berg		M	Moraceae	phanerophyte	perennial	tropical

(*continued*)

Botanical name, ligneous plants		Preference[a]	Family	Raunkiaer life form	Live span	Chorotype[b]
Juniperus excelsa M. Bieb. subsp. *Polycarpos (K. Koch)*		N	Cupressaceae	phanerophyte	perennial	Mediterranean Euro-Siberian
Moringa peregrina (Forssk.) Fiori	leaves	N	Moringaceae	phanerophyte	perennial	Sudanian
Moringa peregrina (Forssk.) Fiori	pods	N				
Nerium mascatense DC		N	Apocynaceae	phanerophyte	perennial	Mediterranean
Ochradenus arabicus Chaudhary, Hillcoat & A.G. Miller		M	Resedaceae	phanerophyte	perennial	Southern Arabian
Olea europaea L. subsp. *Cuspidata (Wall. ex G.Don) Ciferri*		M	Oleaceae	phanerophyte	perennial	Mediterranean
Phoenix dactylifera L.		M	Arecaceae	phanerophyte	perennial	Saharo-Arabian
Pteropyrum scoparium Jaub. & Spach		H	Polygonaceae	phanerophyte	perennial	South-eastern Arabian
Sideroxylon mascatense (A. DC.) Penn.		H	Sapotaceae	phanerophyte	perennial	Irano-Turanian Saharo-Arabian
Taverniera glabra Boiss.		M	Fabaceae	phanerophyte	perennial	Saharo-Sindian
Ziziphus hajarensis Duling, Ghaz. & Prendergast		H	Rhamnaceae	phanerophyte	perennial	Arabian
Ziziphus spina-christi (L.) Willd.		H	Rhamnaceae	phanerophyte	perennial	Sudanian
Aizoon canariense L.		H	Aizoaceae	therophyte	annual	Mediterranean Saharo-Sindian
Aristida adscensionis L. *Aristida adscensionis* L.		H	Poaceae	hemicryptophyte	annual	Mediterranean-Irano-Turanian Saharo-Arabian
Boerhavia diffusa L.		M	Nyctaginaceae	therophyte	annual	Saharo-Arabian tropical
Capparis cartilaginea Decne.		H	Capparaceae	chamaephyte	perennial (semi-shrub)	Sudanian
Capparis spinosa L.		H	Capparaceae	chamaephyte	perennial (semi-shrub)	Mediterranean
Cymbopogon commutatus (Steud.) Stapf		H	Poaceae	hemicryptophyte	perennial	pluri-regional
Cynodon dactylon (L.) Pers.		H	Poaceae	geophyte	perennial	pluri-regional borreal-tropical
Dichanthium annulatum (Forssk.) Stapf		M	Poaceae	hemicryptophyte	perennial	subtropical-tropical
Eragrostis sp.		H	Poaceae	therophyte	annual	Mediterranean-Sudanian
Fagonia bruguieri DC		M	Zygophyllaceae	chamaephyte	perennial (semi-shrub)	Saharo-Arabian
Helianthemum lippii (L.) Dum.Cours.		H	Cistaceae	chamaephyte	perennial (semi-shrub)	Saharo-Arabian
Helichrysum macranicum (Rech.f. & Esfand.) Rech.f.		H	Composite	hemicryptophyte	perennial (semi-shrub)	Sudanian
Herniaria sp.		M	Carophyllaceae	chamaephyte/therophyte	annual	Irano-Turanian Saharo-Sindian
Notoceras bicorne (Aiton) Amo		M	Brassicaceae	therophyte	perennial	Saharo-Arabian
Paracaryum intermedium (Fresen.) Lipsky		M	Boraginaceae	hemicryptophyte	annual	regional
Plantago afra L.		M	Plantaginaceae	therophyte	annual	Mediterranean-Irano-Turanian
Saccharum ravennae (L.) Murr.		H	Poaceae	hemicryptophyte	perennial	Mediterranean-Irano-Turanian
Solanum incanum L.		N	Solanaceae	chamaephyte	perennial	Sudanian
Spergula fallax (Lowe) E.H.L. Krause		M	Caryophyllaceae	therophyte	annual	Saharo-Arabian
Tetrapogon villosus Desf.		H	Poaceae	hemicryptophyte	perennial	Saharo-Arabian-Sudanian
Trigonella stellata Forssk.		H	Fabaceae	therophyte	annual	Saharo-Arabian

[a] Preference: H = high; M = moderate; N = nibbled.
[b] References for Chorotypes were taken from Mosallam (2007) and Flora of Israel Online.

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