Journal of Arid Environments 74 (2010) 962–972

Contents lists available at ScienceDirect

Journal of Arid Environments

journal homepage: www.elsevier.com/locate/jaridenv

The role of pasture management for sustainable livestock production in semi-arid subtropical mountain regions

U. Dickhoefer[a,*,1], A. Buerkert[b], K. Brinkmann[b], E. Schlecht[a]

[a] Animal Husbandry in the Tropics and Subtropics, University of Kassel and Georg-August Universität Göttingen, Steinstr. 19, 37213 Witzenhausen, Germany
[b] Organic Plant Production and Agroecosystems Research in the Tropics and Subtropics, University of Kassel, Steinstr. 19, 37213 Witzenhausen, Germany

A R T I C L E I N F O

Article history:
Received 20 December 2008
Received in revised form
12 December 2009
Accepted 24 December 2009
Available online 1 February 2010

Keywords:
Biomass yield
Browse foliage
Equilibrium concept
Highlands
Oman
Rangeland vegetation

A B S T R A C T

Grazing livestock is an important asset to the livelihoods of people in most semi-arid environments, where natural resources cannot be used directly for human consumption. However, overgrazing commonly reduces pasture productivity and therefore threaten people's long-term food security. Ligneous and herbaceous vegetation on grazed and ungrazed sites in the Hajar Mountains, Oman, was studied to evaluate the possibilities of improving pasture management to maintain fodder production. Foliar biomass was 3–6 t dry matter ha^{-1} on the grazed and ungrazed plateau areas and 41 t dry matter ha^{-1} in the shallow valleys. Herbaceous yields changed over seasons and contributed ≤13% to accessible biomass, stressing the importance of ligneous foliage for livestock nutrition in particular during dry periods. While botanical composition and biomass of the vegetation differed between grazed and ungrazed sites, canopy cover and biomass yields were similar in a 15-year old enclosure and on a naturally ungrazed mountain plateau. Despite the climatic conditions, pastures encompass characteristics of equilibrium systems, where vegetation is strongly influenced by grazing livestock but recovers in its absence. The sustainable use of the natural fodder resources through improved pasture management is therefore a valuable alternative to intense supplement feeding or the introduction of zero-grazing management.

1. Introduction

In the past decades, much research has been directed towards interactions between grazing herbivores and pasture vegetation. The overall aim of most studies was to develop management options that avoid negative short-term effects of livestock grazing on vegetation and soil as well as long-term changes in plant species composition and biomass production on the one hand without compromising its use for animal production on the other hand (Hiernaux et al., 1999). Arid and semi-arid rangelands were in this context originally understood as equilibrium systems with a strong interdependency between livestock and natural vegetation. According to the equilibrium concept, changes in vegetation are reversible and continuous towards a climax vegetation depending on the grazing intensity, while lack of rainfall is perceived as an increase in grazing pressure (Briske et al., 2003; Illius and O'Connor, 1999; Vetter, 2005). In contrast thereto, the non-equilibrium concept assumes that climatic factors rather than livestock grazing are the decisive driving forces in many rangeland ecosystems and that changes in the vegetation are discontinuous and may be irreversible over management time-scale (Briske et al., 2003; Illius and O'Connor, 1999; Vetter, 2005). In non-equilibrium systems, herbivore grazing has no effect on vegetation and overgrazing does not occur, because livestock mortality during drought years maintains herbivore numbers below the normal carrying capacity. Therefore, management recommendations shifted from conservative to opportunistic strategies (Briske et al., 2003; Illius and O'Connor, 1999; Vetter, 2005). Most underlying research, however, has focused on ecosystems dominated by herbaceous vegetation, such as those in Africa, Australia and the United States, while only little work has so far been done to address the applicability of these concepts to shrubland ecosystems of the highlands in the Middle East and Northern Africa, such as the Atlas mountains in Morocco, the Asir and Hijaz mountains in Saudi Arabia, the southern Zagros mountains in Iran as well as the highlands of Ethiopia, Oman and Yemen. Agricultural production in these countries is largely constrained by scarce and variable rainfall, and due to rapid population growth and increasing meat consumption, they increasingly rely on

* Corresponding author.
E-mail address: tropanimals@uni-kassel.de (U. Dickhoefer).
[1] Present address: Institute of Animal Nutrition and Physiology, Christian-Albrechts-University of Kiel, Hermann-Rodewald-Str. 9, 24118 Kiel, Germany.

0140-1963/$ – see front matter
doi:10.1016/j.jaridenv.2009.12.006

the import of staple foods, meat and meat products as well as animal feed (Amid, 2007; Sarris, 2000). In the context of raising import prices for all these commodities, the improvement of livestock production in traditional systems, which is commonly criticized for its low productivity (Hamadeh et al., 2001; Thomas et al., 2002; Zaibet et al., 2004) and strongly relies on the natural shrublands as fodder resources, has consequently become an important task. The objective of this study was therefore to evaluate the importance of pasture management for an improved and sustainable livestock production in the highlands of Middle East and Northern Africa and to study the contribution of current rangeland concepts to the understanding of pasture ecology in these regions.

2. Materials and methods

Our study focused on the traditional agro-pastoral system in the central Al Jabal al Akhdar region of the Al Hajar range in Northern Oman, where the deeply dissected limestone mountains reach elevations of about 3000 m a.s.l. (Ghanzafar, 1991). While in most of the country's lowlands, the annual mean temperature is 28 °C and rainfall is less than 100 mm per year, precipitation on Al Jabal al Akhdar is substantially higher (318 mm; mean annual temperature of 18 °C measured at Sayq; Fisher, 1994). Most of this rainfall occurs in spring (February–March) and in autumn (July–October), whereby the coefficient of variation in rainfall of 48% reflects the high inter-annual variability (Fisher, 1994). The natural vegetation is characterized by open shrublands dominated by *Sideroxylon mascatense*, *Olea europaea* ssp. *cuspidata* and *Dodonaea viscosa* and, above 2000 m a.s.l., by *Juniperus excelsa* ssp. *polycarpos* (Brinkmann et al., 2009; Ghanzafar, 1991; Mandaville, 1977), giving this region its name "The Green mountain". The oasis agriculture on Al Jabal al Akhdar combines goat husbandry with the cultivation of food and fodder crops. The goats graze the natural vegetation surrounding the settlements, thereby covering distances of 12–20 km each day (Schlecht et al., 2009).

For this study, vegetation analyses were carried out at five different locations near Sayh Qatanah (57°40′35″E; 23°40′51″N, 2050 m a.s.l.), the main settlement of Al Jabal al Akhdar: i) the grazed plateau areas (P_{Gr}) surrounding Sayh Qatanah; ii) the grazed wadi Al 'Ayn (W_{Gr}), a shallow valley crossing the plateau; iii) the ungrazed plateau areas (P_{Ref}) including an enclosure (P_{Ref1}) and the Al Jabul plateau (P_{Ref2}), a mountain plateau, where goat grazing is very limited due to difficult access; iv) the grazed mountain slopes (S_{Gr}) and v) the grazed valley (V_{Gr}) near Al Qasha' (57°39′50″E, 23°04′00″N, 1700 m a.s.l.; Fig. 1, Table 1). The grazed plateau and wadi Al 'Ayn belong to the main grazing area of the village of Ash Sharayjah (57°39′30″E, 23°04′10″N, 1950 m a.s.l.); however, also goats and sheep of Sayh Qatanah, Al 'Ayn (57°39′44″E, 23°04′22″N, 1950 m a.s.l.) and Al 'Aqr (57°39′58″E, 23°04′22″N, 1900 m a.s.l.) are grazing in this region as well as an unknown number of feral donkeys.

The enclosure (P_{Ref1}) was established by the Ministry of Agriculture and Fisheries in 1992/93 and comprises an area of 10 ha. While one half is used for the cultivation of various agricultural crops, the other remains unused. The Al Jabul plateau (P_{Ref2}; about 80 ha at 2000 m a.s.l.) is almost at the same elevation as the grazed plateau (2050 m a.s.l.) and both are situated on the same limestone rocks. In the past, the Al Jabul vegetation has been used for occasional animal grazing, but most importantly to collect fodder for livestock. Nowadays, this plateau is nearly undisturbed, since the forage is not harvested anymore and no donkeys or sheep and hardly any goats are grazing there. Thus, the enclosure and the Al Jabul plateau were used as reference sites in the analysis of the pasture vegetation. The grazed slopes (S_{Gr}) and valleys (V_{Gr}) are the main grazing area of goats from Al Qasha', but at higher altitude also animals of Hail al Yaman (57°41′31″E 23°4015″N, 1950 m a.s.l.), Al 'Aqr and Sayh Qatanah graze there. The vegetation of the slopes and valleys benefits from the runoff water of the surrounding plateau and the consequently higher water availability. Thus, in contrast to the shallow wadis, permanent water flow and small water pools characterize the deep mountain valleys. In addition to vegetation measurements, map-based interviews were carried out with two key informants per village in Hail Al Yaman, Sayq (57°38′17″E, 23°40′12″N, 1900 m a.s.l.), Ash Sharayjah, Al Qasha' and Masayrat Ar Ruwajah (57°40′13″E, 23°02′37″N, 1050 m a.s.l.) on Al Jabal al Akhdar to identify village pasture areas as well as the seasonal grazing intensity.

2.1. Sampling of tree and shrub vegetation

The point-centered quarter (PCQ) method (Cottam and Curtis, 1956) was applied from September 2007 to January 2008 to record

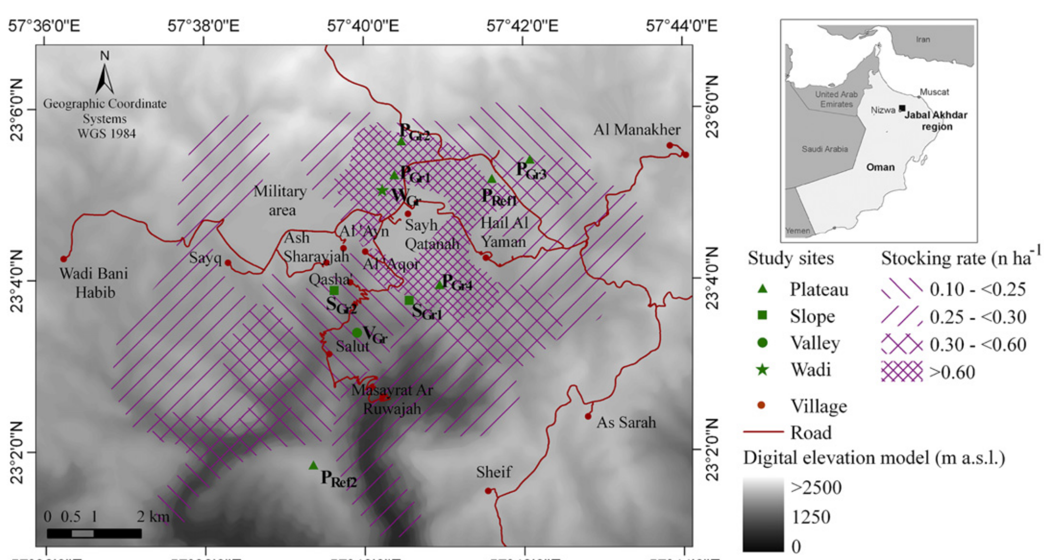

Fig. 1. Study sites for the analyses of the ligneous and herbaceous vegetation conducted during August 2006–April 2008 and stocking rates on grazing areas of nine villages on Al Jabal al Akhdar, Oman.

Table 1
Altitude, exposition, inclination (%) and stone cover (%) of study sites on Al Jabal al Akhdar, Oman.

Location	Site	Altitude (m a.s.l.)	Main exposition	Inclination (Mean ± SD)	Stone cover (Mean ± SD)
Ungrazed plateau	P_{Ref1}	2050	S–E	3 ± 3.4	28 ± 19.4
	P_{Ref2}	2000	S–SW	14 ± 15.1	52 ± 32.8
Grazed plateau	P_{Gr1}	2050	S–SW	7 ± 10.1	60 ± 27.9
	P_{Gr2}	2100	S–SE	7 ± 9.0	53 ± 28.4
	P_{Gr3}	2070	SE–NE	4 ± 4.4	61 ± 31.6
	P_{Gr4}	2050	E–SE	4 ± 2.7	38 ± 35.5
Grazed wadi	W_{Gr}	2040	S–SW	2 ± 1.0	27 ± 22.8
Grazed slope	S_{Gr1}	1850	S–SW	15 ± 13.0	32 ± 22.8
	S_{Gr2}	1750	E–NE	33 ± 18.9	12 ± 12.3
Grazed valley	V_{Gr}	1550	S–SW	1 ± 0.5	24 ± 18.4

the composition of the tree and shrub strata as well as the distribution and density of single shrub and tree species. Data were collected along four transects at P_{Gr} and one transect each at P_{Ref1} and P_{Ref2}. At W_{Gr}, tree and shrub density is much higher than on the plateau areas and smaller shrubs grow under the cover of trees. Since according to the PCQ method, only the shrub or tree nearest to the sampling point is recorded, data for shrubs with a height <2.5 m and for trees ≥2.5 m high were collected separately at W_{Gr}, to avoid an underestimation of the tree density. Additional sites were chosen at S_{Gr} (n = 2) and V_{Gr} (n = 1) to cover other landscape types of Al Jabal al Akhdar. The transects' lengths were 700 m at P_{Ref} and 1400 m at the grazed sites. While at the grazed sites data were collected at 30 randomly arranged sampling points per transect with a minimum distance of 30 m between each point, only 20 sampling points per transect were chosen at P_{Ref} due to the limited extension of these sites. At each sampling point, the nearest shrub or tree > 30 cm height was recorded in each quarter, including the species name, distance to the sampling point (m), the minimum and maximum height (m) and crown diameter (m) measured at two axes at 90 degrees to each other. Browsing intensity was estimated by five classes from ungrazed or very little grazed (1) to very highly grazed (5) according to the percentage of browsed branches. Dead trees or shrubs were also included in the measurements and in 30 trees of the most abundant browse species the maximum browsing height (m) was recorded. Additionally, for each sampling point, the three most abundant herbaceous species were listed, their individual ground cover (%) estimated visually and the grazing intensity recorded according to five classes from none or very little (1) to very high (5). To describe growing conditions at each sampling plot, exposition, inclination (%) and stone cover (%) were recorded. Tree and shrub density (n ha^{-1}) was calculated for each transect using the mean distance (m) of trees or shrubs to the sampling point (Cottam and Curtis, 1956). The average crown cover was calculated as a circle (m^2) and the volume as a cylinder (m^3) for each species and multiplied by the respective density to obtain the total crown cover (m^2 ha^{-1}) and crown volume (m^3 ha^{-1}). Importance values (IV) for different ligneous and herbaceous species were calculated as the sum of the relative density, frequency and canopy cover (IV = rel. density (%) + rel. frequency (%) + rel. canopy cover (%); Cottam and Curtis, 1956). Since for the herbaceous layer only frequency and canopy cover were determined, the importance value was adapted and the sum of the two parameters taken to compare species composition at different locations (IV = rel. frequency (%) + rel. canopy cover (%)).

To identify relationships between the crown cover (m^2) or crown volume (m^3) and the available leaf and twig biomass per species (kg dry matter, DM), 30 individuals of each of the four most abundant species on the grazed plateau, namely *Olea europaea* L. ssp. *cuspidata* (Wall. ex G. Don) Ciferri, *Sideroxylon mascatense* (A. DC.) Penn., *D. viscosa* (L.) Jacq. and *Euryops arabicus* Steud. ex Jaub. & Spach were sampled from December 2006 to February 2007. Bottom and top height (m) of the crown and the crown diameter (m) at two axes at 90 degrees to each other were measured and all leaves and twigs (diameter ≤ 3 mm) harvested and weighed. In September 2007, the relationship between allometric variables and the available leaf and twig biomass was additionally determined for *Sageretia thea* (Osb.) M.C. Johnst, a summer-green shrub. For larger individuals, representative parts were stripped and the weight of the collected leaves and twigs (kg) multiplied by the number of branches to estimate the leaf and twig biomass (kg) of the whole plant. Four composite samples were taken for each species to determine the DM, organic matter (OM), nitrogen (N) and phosphorus (P) concentrations following standard procedures (Naumann et al., 2004). To calculate total plant DM of the most abundant species on the mountain pastures, the leaf and twig biomass was calculated for individual plants recorded along the transects based on the established allometric regression equations. Additionally, the regression equation determined by Sanon et al. (2007) between the crown diameter and the foliar biomass of *Acacia senegal* trees was used to calculate foliar biomass of *Acacia gerrardii* Benth., an abundant species on the mountain slopes and in the valleys at lower altitudes. The average biomass (kg DM) determined for each species was multiplied by the number of individuals of the respective species per hectare (=species density) and summed up to the total foliar biomass of the tree and shrub stratum.

2.2. Sampling of ground vegetation

Ground vegetation was analyzed at P_{Gr1}, P_{Gr2}, W_{Gr}, P_{Ref1} and P_{Ref2} in September 2006, January, May and September 2007 to capture the seasonal differences in the standing herbaceous biomass (Fig. 2). Since farmers claimed that after a long period without any significant rainfall no forage was available on the mountain pastures, further data were collected at P_{Gr1}, P_{Gr2}, W_{Gr} and P_{Ref2} in April 2008. To better account for differences in the herbaceous

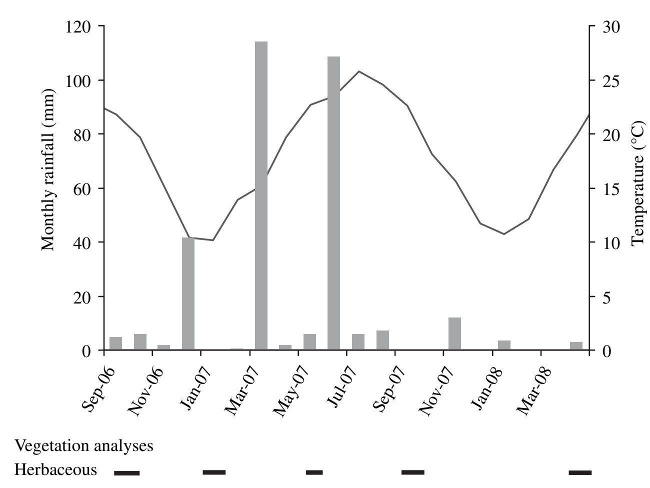

Fig. 2. Monthly rainfall (mm, bars) and mean daily temperature (°C, line) on Al Jabal al Akhdar, Oman, from 15 September 2006 to 15 April 2008 according to a Hobo Pro climate logger (Onset Computer Corp., Pocasset, MA, USA) and own rainfall measurements with standard gauge at Sayh Qatanah (23.20°N, 57.40°E; 2040 m a.s.l.); and time periods of measurements of the herbaceous and ligneous vegetation (horizontal bars below diagram).

biomass at different locations, above-ground biomass was additionally quantified at S_{Gr1} in April 2008.

Herbaceous biomass has previously been quantified on Al Jabal al Akhdar by harvesting representative sample plots along transects and in minimum sampling areas (Schlecht et al., 2009). Following this approach, 10×10 m^2 sampling plots (n = 5–10) were laid out at every 150 m and at every 70 m along transects of a minimum length of 1000 m on the grazed and of 500 m at the ungrazed sites, respectively. In these sampling plots, which were equivalent to the minimum suitable area for vegetation analyses determined by Brinkmann et al. (2009), the proportion (%) of highly, moderately and sparsely vegetated areas as well as of bare ground was estimated. Subsequently, the above-ground biomass of herbaceous plants was harvested in four quadrates (1 m^2) representative for the biomass cover classes sparsely (n = 1), moderately (n = 2) and highly (n = 1) vegetated. In case the class highly vegetated was not represented, two samples were collected each for the classes sparsely and moderately. The samples were weighed, air-dried and weighed again. Subsequently, all samples per location were pooled and analyzed for DM, OM, N and P content. For each location and season, average biomass (kg DM ha^{-1}) for the three cover classes was calculated and multiplied by the average proportion of the respective cover class to determine the weighted standing biomass (kg DM ha^{-1}) of the herbaceous vegetation.

2.3. Statistical analysis

Means and standard deviations of the measured variables were calculated for locations and transects at P_{Gr} (n = 4), W_{Gr} (n = 1), S_{Gr} (n = 2), P_{Ref} (n = 2) and V_{Gr} (n = 1). Statistical analyses were carried out using the SPSS software 12.0 for Windows XP (SPSS Inc., Chicago, USA). Data were analyzed for significant differences between seasons and locations, applying the independent *t*-test for normally distributed and the Mann–Whitney *U*-Test for not normally distributed sample sets (Zöfel, 1988). Linear, exponential, logarithmic and power regression between the canopy cover (m^2, x) or volume (m^3, x) and the total leaf and twig biomass (kg DM, y) were tested to define allometric regression equations.

3. Results

3.1. Species composition of the ligneous vegetation

At $P_{Ref1,}$ and P_{Ref2}, the number of trees and shrubs was with 279 and 300 individuals per hectare much smaller than at P_{Gr} (439–636 shrubs and trees per hectare). A very low density of ligneous species was determined at P_{Gr4} (220 trees ha^{-1}), where goats of four different villages as well as those of Sayh Qatanah were grazing (Table 2). At W_{Gr}, the shrub and tree density of 2751 individuals per hectare was more than six times higher than at P_{Gr}. At 3.7–4.8%, the canopy cover at P_{Ref} was similar or higher than at P_{Gr} (4.3%, SD 2.23), despite the low tree and shrub density. While it reached 12.5% (SD 6.34) at S_{Gr}, canopy cover was highest at W_{Gr} (30%).

Between 4 and 9 different ligneous species per transect were recorded at P_{Gr} and at P_{Ref}; however, species composition differed between locations (Fig. 3). *O. europaea* ssp. *cuspidata* and *S. mascatense* were the main trees found at P_{Ref}, P_{Gr} and at W_{Gr}. While *S. mascatense* showed a higher frequency and density at the grazed than at the ungrazed sites, relative density of *O. europaea* ssp. *cuspidata* was lowest at P_{Gr} with 6%, equivalent to 27 trees ha^{-1}. At S_{Gr} and V_{Gr}, where 9–17 ligneous species per transect were recorded, the dominant species were *A. gerrardii* (20–94 trees ha^{-1}), *Ziziphus spina-christi* (L.) Desf. (7–24 trees ha^{-1}) and *Salix acmophylla* Boiss. (1 tree ha^{-1}). Further tree species at W_{Gr} were *Phoenix dactylifera* L. (90 trees ha^{-1}), *Ziziphus hajarensis* Duling, Ghaz. & Prendergast (1 tree ha^{-1}) and *Juniperus excelsa* M. Bieb. ssp. *polycarpos* K. Koch (1 tree ha^{-1}).

Table 2
Relative density (%) of selected tree and shrub species on grazed and ungrazed study locations of Al Jabal al Akhdar, Oman (means ± one standard deviation).

	P_{Ref}	P_{Gr}	W_{Gr}	S_{Gr}
Density (n ha^{-1})	289 ± 15	390 ± 187	2751	759 ± 526
Trees (%)				
Acacia gerrardii	1 ± 0.7	0.2 ± 0.4	0	13 ± 6.4
Olea europaea ssp. *cuspidata*	21 ± 7.1	10 ± 5.1	11	2 ± 2.1
Sideroxylon mascatense	10 ± 2.1	17 ± 2.4	22	13 ± 9.2
Shrubs (%)				
Dodonaea viscosa	36 ± 25.5	67 ± 9.5	43	46 ± 37.5
Euryops arabicus	0	1 ± 1.3	16	2 ± 2.1
Grewia erythraea	4 ± 5.0	4 ± 4.4	0	18 ± 22.6
Sageretia thea	1 ± 0.7	0.4 ± 0.5	3	1 ± 0.0

For abbreviations of locations see Table 1 and for plant authorities see text.

D. viscosa and *E. arabicus* were the main shrub species at the grazed sites. Although *D. viscosa* was also abundant at P_{Ref} (53–150 shrubs ha^{-1}), its density was lower than at P_{Gr} (135–433 shrubs ha^{-1}) and W_{Gr} (1707 shrubs ha^{-1}). At the latter two locations, this species together with *E. arabicus* (866 shrubs ha^{-1}) characterized the shrub stratum. Both species were less abundant at S_{Gr} and V_{Gr} and were partly replaced by *Capparis spinosa* L. ($\leq$59 shrubs ha^{-1}) and *Ochradenus arabicus* Chaudhary ($\leq$24 shrubs ha^{-1}) at S_{Gr} as well as by *Nerium oleander* L. (29 shrubs ha^{-1}) and *Chrozophora oblongifolia* (Delile) Juss. ex Spreng. (26 shrubs ha^{-1}) at V_{Gr}, where water availability is higher. *Grewia erythraea* (Schweinf.) and *S. thea* were two species recorded at grazed and ungrazed sites across different elevations. While *S. thea* was most abundant at W_{Gr} (27 shrubs ha^{-1}), *G. erythraea* is a common shrub at S_{Gr} (24–130 shrubs ha^{-1}) and at P_{Ref2} (22 shrubs ha^{-1}), where together with *Ebenus stellata* Boiss. and *Farsetia aegyptiaca* Turra it dominated the shrub strata. Although the latter two species each represented 23% of the total shrubs and trees per hectare at this site, they were not recorded at P_{Gr} and *E. stellata* was only recorded once at S_{Gr}.

3.2. Species composition of the herbaceous vegetation

Overall ground cover of the herbaceous vegetation ranged between 8% (SD 5.0) at P_{Gr} and 15% (SD 7.4) at W_{Gr} and was significantly ($P < 0.05$) lower than at P_{Ref} (25%, SD 14.0; Table 3). With the exception of S_{Gr} (n = 18), 9–12 different species per site were recorded. Abundant species at the grazed sites were grasses such as *Chrysopogon plumulosus* Hochst., *Cymbopogon schoenanthus* (L.) Spreng., *Cenchrus ciliaris* L., *Cynodon dactylon* (L.) Pers., *Eragrostis* sp. and *Tetrapogon villosus* Desf. as well as dicots such as *Salvia aeqyptiaca* L., *Teucrium* sp. (*T. mascatense* Boiss. and *T. stocksianum* Boiss. ssp. *stenophyllum* R.A. King) and *Helianthemum lippii* (L.) Dum.-Cours.

Fingerhutia africana Lehm. and *Heteropogon contortus* (L.) Roem. & Schultes were dominant grass species at P_{Ref} with a mean ground cover of 10% (SD 10.4) and 9% (SD 7.3) respectively, while both species were not recorded at the grazed sites. In contrast thereto, *Teucrium* sp. was a common dicot at P_{Gr}, recorded at 21–59% of the sampling points, but not at P_{Ref}. *C. plumulosus* and *C. schoenanthus* were found in grazed and ungrazed areas. Ground cover of *C. schoenanthus* was higher at P_{Ref} (5%, SD 3.2) than at P_{Gr} (2%, SD 1.9; $P < 0.01$). However, the species was only recorded at 65% and even 8% of the sampling points at P_{Ref1} and P_{Ref2} respectively, whereas the frequency of *C. schoenanthus* reached up to 76% (SD 20.0) at P_{Gr} and 80% at W_{Gr}. Therefore, its importance values (IV) of 45 (SD 10.9; P_{Gr}) and 58 (W_{Gr}) were higher at P_{Gr} than at P_{Ref} (IV = 23, SD15.8).

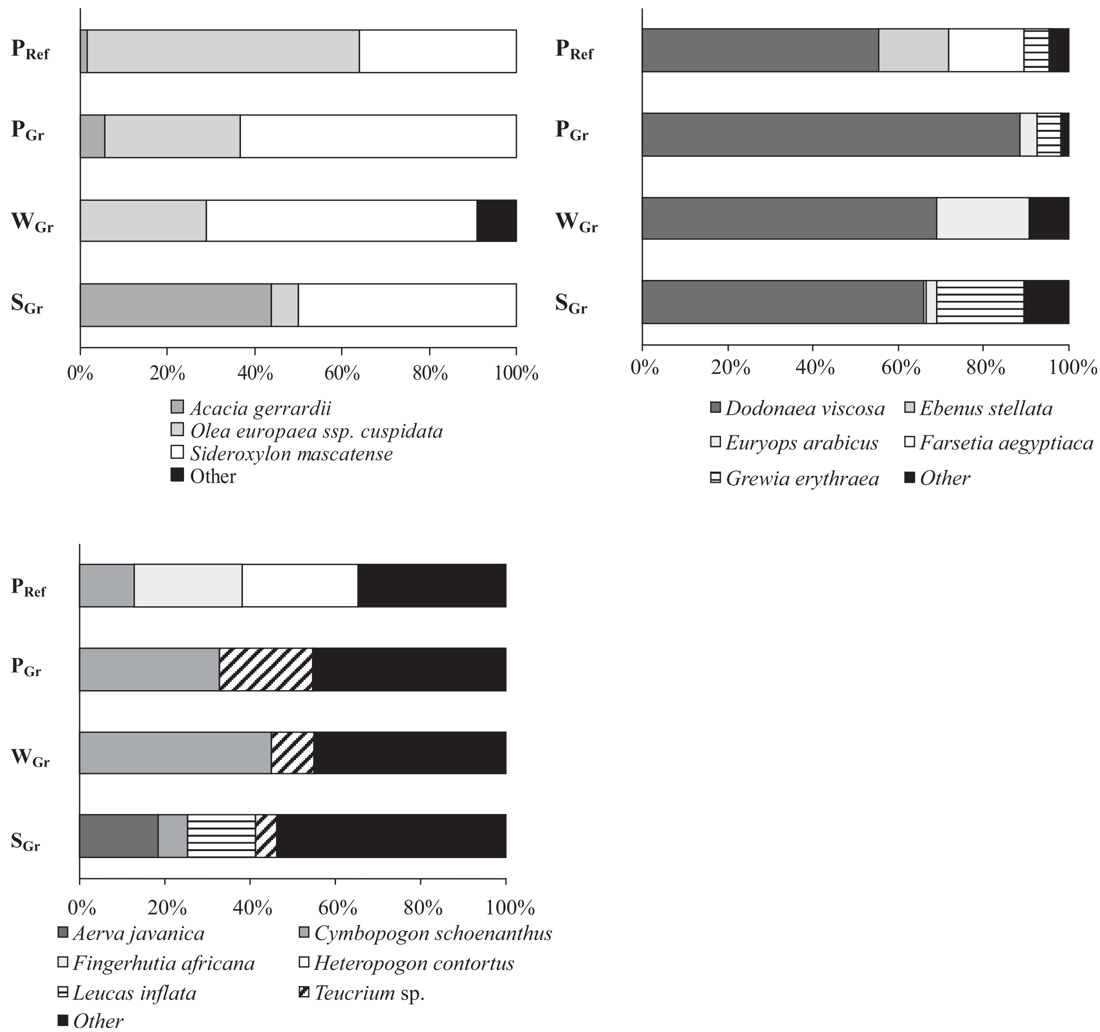

Fig. 3. Relative importance values (%) of selected tree (top), shrub (middle) and herbaceous species (bottom) on grazed and ungrazed study locations of Al Jabal al Akhdar, Oman. For abbreviations of locations see Table 1 and for plant authorities see text.

Although its ground cover was not significantly lower at P_{Ref} ($P > 0.05$), importance values of *C. plumulosus* were almost two to three times higher at the grazed than at the ungrazed sites (IV = 22, SD 1.0).

Leucas inflata Benth and *Aerva javanica* (Burm.F.) Juss. ex J.A. Schultes were characteristic species at S_{Gr} (IV = 25–29), the latter also being recorded at V_{Gr} (IV = 8), where overall ground cover of the herbaceous vegetation was only 6% (SD 5.6). The main species were here *Juncus rigidus* Desf. (IV = 76), *C. ciliaris* (IV = 21) and *C. dactylon* (IV = 16).

Table 3
Ground cover (%) of selected herbaceous species at grazed and ungrazed study locations on Al Jabal al Akhdar, Oman (means ± one standard deviation).

	P_{Ref}	P_{Gr}	W_{Gr}	S_{Gr}	P
Species (n)	11	12	9	18	
Total	25 ± 14.0	8^a ± 5.0	15^b ± 7.4	10^a ± 7.0	<0.01
Chrysopogon plumulosus	3^a ± 1.9	4^a ± 3.8	7^b ± 6.2	4^a ± 4.7	<0.05
Cymbopogon schoenanthus	5^a ± 3.2	2^b ± 1.9	8^a ± 6.7	3^b ± 3.4	<0.01
Eragrostis sp.	0.5^a ± 0.2	0.3^a ± 0.2	1^a ± 0.2	0.3^a ± 0.5	>0.05
Helianthemum lippii	3^a ± 1.0	0.7^b ± 0.5	0	1^{ab} ± 1.0	<0.05
Teucrium sp.	0	2^a ± 1.6	1^a ± 0.5	1^a ± 0.4	<0.001
Tetrapogon villosus	4^a ± 2.6	0.9^b ± 0.4	2.3^{ab} ± 1.5	1.1^b ± 0.5	<0.05

Within rows (a, b) values with different letters differ at the indicated probability level.
For abbreviations of locations see Table 1 and for plant authorities see text.

3.3. Grazing intensity, grazing areas and fodder quality

The grazing intensity as evaluated on a scale of 0–5 was high in *O. europaea* ssp. *cuspidata* (Mdn = 5, n = 78), *S. mascatense* (Mdn = 4, n = 95) and *G. erythraea* (Mdn = 5, n = 65), followed by *S. thea* (Mdn = 3, n = 12) and *Z. spina-christi* (Mdn = 3, n = 58). In contrast thereto, no or little signs of browsing were observed in *E. arabicus* (Mdn = 1; n = 48), *N. oleander* (Mdn = 1, n = 22) and *D. viscosa* (Mdn = 1, n = 524) at the different study sites. The maximum height at which signs of browsing were determined was 188 cm (SD 11.7). Heavily grazed herbaceous species were *C. plumulosus* (Mdn = 5, n = 128), *S. aegyptiaca* (Mdn = 4.5, n = 6) and *C. dactylon* (Mdn = 5, n = 17), whereas no or few signs of grazing were visible in *C. schoenanthus* (Mdn = 1, n = 125), *Teucrium* sp. (Mdn = 1, n = 58) and *Aristida* sp. (Mdn = 1, n = 25). Organic matter and nutrient concentrations in the leaves and twigs of the sampled tree and shrub species ranged between 912–949 g OM kg^{-1} DM, 10.2–13.7 g N and 0.5–1.3 g P kg^{-1} DM (Table 4). Nutrient concentrations were highest in *E. arabicus*, which is poisonous to goats (Jongbloed et al., 2003), followed by *O. europaea* ssp. *cuspidata*, whereas N and

Table 4
Dry matter (DM; g kg^{-1} FM[a]) and organic matter (OM), nitrogen (N) and phosphorus (P) concentrations (all in g kg^{-1} DM) of selected tree and shrub species on pastures on Al Jabal al Akhdar, Oman. Values are means ± one standard deviation for pooled leaf and twig samples collected during January–March 2007 and September 2007; n = 4 for all species.

Species	DM	OM	N	P
Dodonaea viscosa	488 ± 6.2	949 ± 4.9	10.5 ± 0.51	0.7 ± 0.08
Euryops arabicus	361 ± 12.5	912 ± 3.8	13.7 ± 3.58	1.3 ± 0.33
Olea europaea ssp. *cuspidata*	638 ± 21.4	940 ± 5.1	12.4 ± 0.44	0.7 ± 0.03
Sageretia thea	687 ± 20.6	937 ± 8.1	10.2 ± 1.88	0.5 ± 0.12
Sideroxylon mascatense	666 ± 63.7	947 ± 2.0	11.7 ± 1.82	0.7 ± 0.06

For plant authorities see text.
[a] FM = Fresh matter.

P concentrations of *S. thea* samples collected in September 2007 were relatively low. Organic matter, N and P concentrations of the herbaceous vegetation varied between locations. Organic matter ranged between 866–901 g kg^{-1} DM at P_{Gr} and W_{Gr} and 909–939 g kg^{-1} DM at P_{Ref}. In contrast thereto, N and P concentrations of the vegetation at the grazed sites (7.1–15.9 g N kg^{-1} DM; 0.6–1.4 g P kg^{-1} DM) were higher than for the herbaceous biomass collected at P_{Ref} (5.8–8.8 g N kg^{-1} DM; 0.3–0.5 g P kg^{-1} DM). While nutrient concentrations at P_{Ref} did not differ between seasons, P concentration was highest in September 2006 and N concentration of the vegetation at the grazed sites was highest in September 2006 and 2007.

The average grazing area as determined by key informants for eight villages and the new settlement Sayh Qatanah ranged between 4–17 km^2 (Table 5). While grazing areas of Ash Sharayjah, Al 'Ayn, Al 'Aqr, Sayq and Sayh Qatanah were located on the plateau, pastures of villages at lower altitudes mainly comprised mountain slopes and deep valleys. Average stocking rate ranged between 0.03–0.28 small ruminants per hectare for the village pastures and 0.57 animals per hectare on pastures of Sayh Qatanah. However, since pastures of different villages overlapped (Fig. 1), actual stocking rate was partly more than twice as high.

3.4. Leaf and twig biomass

Although power functions between the crown cover and the leaf and twig biomass gave best results ($r^2 = 0.72$–0.89, Table 6), regression equations based on the crown volume were chosen, because the proportion of the leaf and twig biomass accessible to goats (<188 cm crown height) was calculated subsequently by multiplying the total leaf and twig biomass per tree by the percentage of the crown volume <188 cm. The leaf and twig biomass edible by goats was defined as the accessible leaf and twig biomass per hectare minus the biomass of *D. viscosa* and *E. arabicus*, which showed little or no signs of browsing. Since between 3% and 5% of the trees and shrubs per hectare at P_{Ref2} and at most grazed sites and up to 13% at P_{Gr4} were dead, dead trees were not considered in the calculation of the leaf and twig biomass. The dead shrubs and trees recorded at all sites (n = 33) belonged to the most abundant species, 69% being *D. viscosa*.

At P_{Gr}, total leaf and twig biomass of the six species ranged between 2.8–6.0 t DM ha^{-1} near Sayh Qatanah (P_{Gr1}, P_{Gr2}, P_{Gr4}) and reached 10.7 t DM ha^{-1} at P_{Gr3}, where the tree and shrub cover was higher (7.4% versus 2.1–4.3%). Similarly, foliar biomass was high at S_{Gr} (17.7 t DM ha^{-1}, SD 11.91) as well as at W_{Gr}, where it reached 40.8 t DM ha^{-1} as a result of the very high shrub and tree density. Due to either a large crown volume or a high canopy cover, *S. mascatense*, *O. europaea* ssp. *cuspidata* and *D. viscosa* contributed most to the total leaf and twig biomass at W_{Gr} as well as at P_{Gr} and P_{Ref} (Fig. 4). While 84% of the foliar biomass was provided by *S. mascatense* at P_{Ref2}, leaf and twigs of this species and of *O. europaea* ssp. *cuspidata* accounted for 52% and 40% of the foliar biomass at P_{Ref1}. Total leaf and twig biomass at P_{Ref1} (5.1 t DM ha^{-1}) and P_{Ref2} (5.7 t DM ha^{-1}) did not differ from P_{Gr} ($P > 0.05$).

At P_{Gr}, 2.1–7.8 t DM ha^{-1} were accessible and 2.0–7.5 t DM ha^{-1} edible for goats, equivalent to 81% and 71% of the total foliar biomass. At W_{Gr} and S_{Gr}, trees > 188 cm crown height accounted for 9% and 21% and unpalatable species for 60% and 47% of the total trees and shrubs per hectare. Therefore only 37% and 84% of the total leaf and twig biomass were accessible and 27% and 55% edible for goats at the two locations, respectively. While most of the species were ever-green, *S. thea* and *G. erythraea* were leafless from November to February, the dry winter months.

While at P_{Gr}, P_{Ref}, W_{Gr} and S_{Gr}, the six selected ligneous species accounted for 94–100% of the total canopy cover, they only summed up to 30% at V_{Gr}, and other species such as *N. oleander* and *Z. spina-christi* were more abundant. Thus, the calculated leaf and twig biomass of 334 kg DM ha^{-1} only represents part of the total foliar biomass there. However, since 29% of the trees recorded were higher than the maximum browsing height of goats and 24% of the trees per hectare were unpalatable species, accessible and edible foliar biomass was much lower at this site than at the other ones.

3.5. Herbaceous biomass

The proportion of bare ground was significantly higher at P_{Gr} and W_{Gr} than at P_{Ref}, with the exception of May 2007, when values determined for P_{Ref1} at 29% (SD 13.9) were similar to those obtained at W_{Gr} (30%, SD 11.4; $P < 0.05$; Table 7). While the proportion of bare ground was <20% at P_{Ref2} and P_{Ref1} for all other sampling dates ($P > 0.05$), 29% (SD 12.6) and 47% (SD 10.2) of the ground were not vegetated at W_{Gr} and at P_{Gr}, respectively. In April 2008, after five month without significant rainfall, the proportion of bare ground even reached 56% (SD 11.2) at P_{Gr}, being significantly higher than during the other seasons ($P < 0.05$).

Table 5
Size and composition of pastures, herd sizes and calculated stocking rates of nine villages on Al Jabal al Akhdar, Oman, as determined in winter 2007/08.

Village	Grazing area (km^2)	Plateau (% of grazing area)	Wadi	Slopes	Valley	Goats/Sheep[a], n	Stocking rate, n ha^{-1}
Al 'Aqr	3.6	24	28	47	0	12	0.03
Al 'Ayn	5.0	56	27	16	0	138	0.28
Al Qasha'	11.4	8	0	69	23	123	0.11
Ash Sharayjah	7.1	45	41	15	0	189	0.27
Hail Al Yaman	14.8	25	12	52	11	377	0.26
Masayrat Ar Ruwajah	10.5	0	0	73	27	295	0.28
Salut	11.7	5	0	78	17	140	0.12
Sayh Qatanah	6.7	73	20	6	0	433	0.63
Sayq	17.0	29	14	36	21	473	0.28

[a] Ministry of Agriculture and Fisheries, 2001.

Table 6
Relation between canopy cover (m^2, x) or volume (m^3, x) and leaf and twig biomass (kg DM, y) of five species on pastures of Al Jabal al Akhdar, Oman – parameters of power regression equations ($y = bx^a$).

Species	a	b	r^2	SE
Canopy cover				
Dodonaea viscosa	1.71	1.25	0.89	0.52
Euryops arabicus	1.30	0.79	0.82	0.53
Sideroxylon mascatense	1.93	10.20	0.72	0.63
Olea europaea ssp. *cuspidata*	1.68	4.16	0.81	0.60
Sageretia thea	1.52	1.54	0.77	0.66
Canopy volume				
Dodonaea viscosa	1.17	1.17	0.88	0.54
Euryops arabicus	1.05	1.12	0.85	0.46
Sideroxylon mascatense	1.33	9.61	0.63	0.71
Olea europaea ssp. *cuspidata*	1.19	3.57	0.78	0.65
Sageretia thea	1.00	1.70	0.73	0.72

All correlations were significant at a 0.1% level.
For plant authorities see text.

While correspondingly the proportion of sparsely vegetated ground was higher at P_{Gr} and W_{Gr}, moderately and highly vegetated areas increased at P_{Ref}. Between 0.2%–2.6% at P_{Gr} and 3.5–5.6% at W_{Gr} were highly vegetated, whereas 7–26% of the ground were highly vegetated at P_{Ref}. The average biomass yield (kg DM ha^{-1}) for the three biomass classes ranged between 8–30 kg DM and 106–282 kg DM for sparsely and highly vegetated areas at P_{Gr}, respectively, and was significantly lower than at W_{Gr} (36–51 kg DM for sparsely and 384–539 kg DM ha^{-1} for highly vegetated areas, $P < 0.001$). At P_{Ref}, biomass yields of 111–322 kg DM ha^{-1} in sparsely vegetated patches and 990–2150 kg DM ha^{-1} in highly vegetated areas were significantly higher than at P_{Gr} and W_{Gr} for the different sampling dates ($P < 0.001$).

As a result of the variations in the ground cover and yield per biomass class, the total herbaceous biomass of the ground vegetation (kg DM ha^{-1}) differed between locations (Table 8). While at W_{Gr} standing herbaceous biomass ranged between 62–85 kg DM ha^{-1} and did not vary between seasons ($P > 0.05$), herbaceous biomass at P_{Gr} was significantly lower, reaching 14–20 kg DM ha^{-1} in the spring and summer months and only 8 kg DM ha^{-1} in December 2006 and in April 2008 after a long drought spell. Thus, values were significantly lower than those calculated for P_{Ref1} and P_{Ref2}, where 209–637 kg DM ha^{-1} and 318–840 kg DM ha^{-1} were obtained. With the exception of May 2007, differences in the herbaceous biomass between the two P_{Ref} sampling sites were not significant ($P > 0.05$). The biomass of 37 kg DM ha^{-1} determined at S_{Gr1} in April 2008 was lower than the value recorded at W_{Gr} in the same month, but almost five times as high the herbaceous biomass at P_{Gr}.

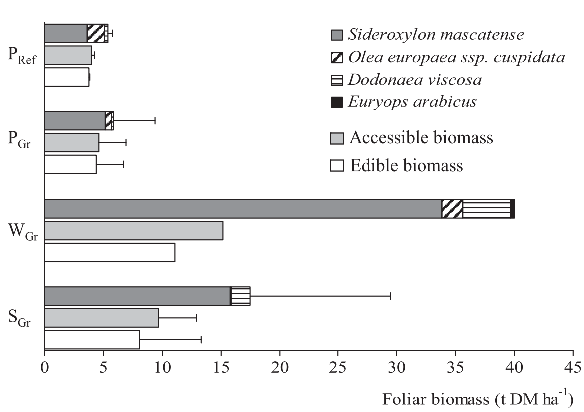

Fig. 4. Total, accessible and edible foliar biomass at grazed and ungrazed study locations on Al Jabal al Akhdar, Oman (bars indicate one standard deviation).

Table 7
Proportion of bare ground (%) at grazed and ungrazed study sites on Al Jabal al Akhdar, Oman, during different seasons (means ± one standard deviation).

	P_{Ref1}		P_{Ref2}		P_{Gr}		W_{Gr}		P
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
Aug-06	$13^{a;\alpha\beta}$	9.7	$7^{a;\alpha}$	3.9	$42^{b;\alpha}$	7.6	$28^{c;\alpha}$	10.4	<0.05
Jan-07	$9^{a;\alpha}$	8.3	$9^{a;\alpha}$	4.9	$44^{b;\alpha}$	10.8	$25^{c;\alpha}$	13.3	<0.05
May-07	$29^{ab;\beta}$	13.9	$13^{b;\alpha\beta}$	10.1	$47^{c;\alpha}$	6.7	$30^{a;\alpha}$	11.4	<0.05
Sep-07	$16^{a;\alpha\beta}$	14.2	$19^{a;\beta}$	10.5	$45^{b;\alpha}$	10.1	$36^{c;\alpha}$	13.6	<0.01
Apr-08			$18^{a;\alpha\beta}$	15.8	$56^{b;\beta}$	10.4	$26^{c;\alpha}$	13.1	<0.001
P	< 0.05		< 0.05		< 0.05		> 0.05		

Within rows (a, b, c) and columns (α, β) respectively, values with different letters differ at the indicated probability level. For abbreviations of sites see Table 1.

4. Discussion

4.1. Species composition and grazing intensity

The natural vegetation of Al Jabal al Akhdar is characterized by open shrublands of broad-leafed tree and shrub species. The ligneous and herbaceous species identified at the different locations are typical for the Al Jabal al Akhdar region (Brinkmann et al., 2009; Ghanzafar, 1991; Schlecht et al., 2009). As little quantitative data on the natural vegetation in the highlands of the Middle East and Northern Africa is available, comparisons with rangelands of West and Central Africa were partly necessary. The tree and shrub densities in our study area were higher than those of rangelands in the West African Sahel at <500 m a.s.l. (Sanon et al., 2007), but similar to the highlands of Ethiopia at 1500–2500 m a.s.l. (Mekuria et al., 2007). Tree and shrub density, ground cover and species composition of the ligneous and herbaceous vegetation clearly differed between the grazed and ungrazed sites. As a result of goat grazing, tree and shrub density was higher at P_{Gr} than at P_{Ref}, which is seen as an indicator for overgrazing (Todd and Hoffmann, 1999). Furthermore, *D. viscosa*, an unpalatable shrub species, and *S. mascatense*, which is more resistant to browsing due to its thorny physiognomy, characterized the vegetation at the grazed sites at 2000 m a.s.l.. In contrast thereto, *O. europaea* ssp. *cuspidata* and *G. erythraea*, which were preferably grazed by livestock, were dominant at the ungrazed sites. Unpalatable plants and species resistant to herbivore grazing can even proliferate under high grazing pressure and replace valuable fodder species (Todd and Hoffmann, 1999). Therefore, the dominance of *S. mascatense* and *D. viscosa* and the low density of *G. erythraea* and *O. europaea* ssp. *cuspidata* at P_{Gr} in comparison to P_{Ref} further reflected the effect of grazing on the ligneous vegetation.

Ground cover of the herbaceous vegetation was strongly reduced at P_{Gr} as compared to P_{Ref} and the proportion of bare ground was much higher than described for the Ethiopian Middle Awash valley at 809–1028 m a.s.l. (Abule et al., 2007a) and the

Table 8
Overall herbaceous biomass (kg dry matter ha^{-1})at grazed and ungrazed study sites on Al Jabal al Akhdar, Oman, during different seasons (means ± one standard deviation).

	P_{Ref1}		P_{Ref2}		P_{Gr}		W_{Gr}		P
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
Aug-06	$637^{a;\alpha}$	183	$840^{a;\alpha}$	100	$19^{b;\alpha}$	1.3	$85^{c;\alpha}$	21.7	<0.001
Jan-07	$494^{a;\alpha}$	130	$553^{a;\beta}$	71	$8^{b;\beta}$	3.2	$66^{c;\alpha}$	18.0	<0.001
May-07	$209^{a;\beta}$	89	$602^{b;\beta}$	68	$14^{c;\alpha}$	3.1	$77^{d;\alpha}$	27.3	<0.01
Sep-07	$505^{a;\alpha}$	182	$629^{a;\beta}$	171	$20^{b;\alpha}$	8.2	$64^{c;\alpha}$	21.0	<0.01
Apr-08			$318^{a;\gamma}$	143	$8^{b;\beta}$	2.8	$62^{c;\alpha}$	23.7	<0.01
P	<0.05		<0.05		<0.001		>0.05		

Within rows (a, b, c, d) and columns (α, β, γ) respectively, values with different letters differ at the indicated probability level. For abbreviations of sites see Table 1.

Tigray highlands at 1500–2500 m a.s.l. (Mekuria et al., 2007). The methodology we applied did not aim to generate a complete species lists for the different study locations. This was done by Brinkmann et al. (2009), who thoroughly described the species composition of the natural vegetation in the study region. Our results nevertheless showed that *C. schoenanthus* and *Teucrium* sp. were important species at P_{Gr} and their frequency and canopy cover were particularly high at the intensively grazed P_{Gr4}. Both species contain aromatic compounds and are not grazed by livestock (Jongbloed et al., 2003). In contrast thereto, *H. contortus* and *F. africana* were two perennial grasses exclusively found at P_{Ref}.

Tree and shrub density as well as canopy cover of the herbaceous layer increased at S_{Gr} and W_{Gr}. The unpalatable species found at P_{Gr}, namely *D. viscosa*, *E. arabicus*, *C. schoenanthus* and *Teucrium* sp. also characterized the ligneous and herbaceous vegetation at W_{Gr}, whereas *A. gerrardii*, *G. erythraea*, *L. inflata*, *A. javanica* and *C. oblongifolia* were dominant at S_{Gr}. While *A. gerrardii* and *G. erythraea* were preferred fodder shrubs, *A. javanica* and *C. oblongifolia* showed only light signs of goat grazing. Similar to *Teucrium* sp., also *L. inflata* belongs to the family of *Labiatae*, whose species commonly contain aromatic compounds, which likely render them less palatable for livestock.

4.2. Leaf and twig biomass

Allometric regression equations based on easily measurable phenotypic parameters are frequently used to predict biomass of single ligneous species or the total shrub and tree stratum, because they minimize the need for destructive sampling. Allometric regressions based on logarithmic transformations of the trunk diameter at breast height are commonly used (Salis et al., 2006; Sanon et al., 2007). However, the selected species included multi-stemmed tree as well as several shrub species; thus, using the trunk diameter was not suitable for the purpose of this study. Crown parameters were tested instead and power functions gave best results for the data collected here. Regressions between the foliar biomass and the crown volume were significant at a probability level of 0.1% and coefficients ($0.64 < r^2 < 0.89$) were only slightly lower or similar to results obtained by Sanon et al. (2007); $0.68 < r^2 < 0.98$.

The importance of foliage for livestock nutrition in semi-arid rangelands has been stressed (Le Houerou, 1980; Schlecht et al., 2009) and the results obtained during this study confirm these findings. Due to the higher tree and shrub density, total foliar biomass at P_{Gr} was higher than yields described for the highlands of Ethiopia (196–3311 kg DM ha^{-1}; Abule et al., 2007a), but similar or even lower than average biomass determined for shrublands in central Kenya (4737–11,991 kg DM ha^{-1}; Rosenschein et al., 1999). Dry matter yields obtained for P_{Gr} and P_{Ref} on Al Jabal al Akhdar were therefore within the range of the African values. However, total foliar biomass at S_{Gr} and W_{Gr} was higher than the maximum values determined for rangelands in Africa, stressing the importance of these areas of higher water availability for forage production and livestock grazing. Moreover, *A. gerrardii* is an abundant tree on the mountain slopes (20–94 trees ha^{-1} at S_{Gr}). *Acacia* species are valuable fodder trees, since nutrient and mineral concentrations in their leaves are high (Le Houerou, 1980) and their pods are readily eaten by livestock. Sanon et al. (2005) determined an average amount of fallen *Acacia raddiana* pods of 4.1 kg DM per tree. Assuming a similar pod production of *A. gerrardii* on Al Jabal al Akhdar, additional 406 kg DM ha^{-1} of high quality fodder would be available for livestock on the mountain slopes and in the valleys at lower altitude. These areas are therefore valuable grazing areas, in particular during September and October, when the pods are produced and farmers preferentially use these areas for livestock grazing.

Accessible foliar biomass calculated by multiplying the total foliar biomass by the percentage of the crown volume <188 cm assumes a regular cylindrical crown shape and does not consider that women are collecting the foliage of *O. europaea* ssp. *cuspidata*, *Z. spina-christi* and *S. mascatense* as livestock fodder from higher parts of the crown. Nevertheless, calculations still provide a more plausible estimation of the amount of fodder accessible to goats than the total leaf and twig biomass. At P_{Gr}, 71–81% of the total foliar biomass were accessible to goats. These values are much higher than the proportion described by Sanon et al. (2007) for browse species in West Africa, since the maximum grazing height of goats used by this author was 165 cm compared to 188 cm in our study. At W_{Gr} and S_{Gr}, where the density of trees >188 cm was higher, only 37–84% of the foliar biomass was accessible to livestock. The proportion of edible foliar biomass was particularly low at W_{Gr} (27% of the total foliar biomass), where *D. viscosa* and *E. arabicus* were abundant. The high abundance of unpalatable species on mountain pastures of Al Jabal al Akhdar as a result of intense livestock grazing therefore strongly decreased foliar biomass edible for goats (see Section 4.4).

4.3. Herbaceous biomass

Herbaceous biomass differed significantly between P_{Gr}, W_{Gr} and S_{Gr} as well as P_{Ref} and was similar to results obtained by Schlecht et al. (2009) at the grazed plateau and wadi and the ungrazed Al Jabul plateau in October 2005. The comparison of the herbaceous vegetation at P_{Gr} and at P_{Ref} not only showed the effects of livestock grazing, but also the high production potential of the natural vegetation. Thus, biomass at P_{Ref} was higher than in the highlands of Ethiopia (422–437 kg DM ha^{-1}; Abule et al., 2007b) and the mountain plains in central Yemen (290–420 kg DM ha^{-1}; Kessler, 1995). However, it only contributed little to accessible and edible biomass at P_{Gr}, W_{Gr} and S_{Gr}, where the ground cover of herbaceous vegetation was low and unpalatable species such as *Teucrium* sp. and *C. schoenanthus* were important. Even at P_{Ref2}, where average herbaceous biomass was high, it only accounted for 13% of accessible and 14% of edible biomass. At P_{Gr} and at P_{Ref2}, herbaceous biomass varied between seasons and was particularly low in January 2007 during the cold winter months with daily mean temperatures of 10 °C (SD 1.8; Dec. 2006–Jan. 2007) and in April 2008 after five months with <5 mm of rainfall. In contrast thereto, values were highest at the end of the rainy summer months in September 2006 and 2007, each time two weeks after rainfall events of >5 mm. These seasonal changes in fodder availability comply with results of studies in the highlands of Ethiopia, where highest leaf litter production was observed after summer rainfall (Descheemaeker et al., 2006). Similar to the ligneous stratum, herbaceous biomass was higher at W_{Gr} and S_{Gr} and did not vary across the seasons. Thus, the herbaceous vegetation in these areas appears to be more resistant to the lack of rainfall.

Although the fodder quality of the herbaceous biomass did not differ between seasons, N and in particular P concentrations of the herbaceous samples as well as of the samples of the five shrub and tree species were lower than recommended for maintenance and locomotion of goats grazing on arid mountain rangelands (NRC, 1981). Low nutrient concentrations of these abundant forage species grazed by goats (Schlecht et al., 2009), seasonal changes in the available herbaceous biomass and the leaf fall of deciduous fodder shrubs such as *G. erythraea* and *S. thea* point to the need of supplementing animals during dry periods and in particular during the main kidding period of local goats in November–February.

4.4. Pasture management options

Different concepts and underlying theories for the management of rangeland ecosystems have been developed in the past. The low and highly variable rainfall with a coefficient of variation > 33% suggests that the conditions on Al Jabal al Akhdar resemble typical non-equilibrium environments, where the natural vegetation is rather influenced by water availability than by livestock grazing (Ellis et al., 1993; Vetter, 2005). Our results also show that water availability has indeed an effect on the natural vegetation. Thus, foliar and herbaceous biomass were higher on the mountain slopes and wadis than on plateau areas and changed over the seasons depending on rainfall events. However, comparing the results from the grazed and the ungrazed plateau with similar elevation and identical geomorphology and climatic conditions reveals the strong influence of livestock grazing on the natural vegetation. Since according to key informants as well as the Omani Ministry of Agriculture and Fisheries, livestock numbers in villages of Al Jabal al Akhdar were similar or even higher in the past, grazing pressure on the natural vegetation appears to be high for a long time, which supports reports of Mandaville (1977). Nevertheless, tree and shrub density, ground cover of the herbaceous layer and the foliar and herbaceous biomass in the 15-year old enclosure (P_{Ref1}) did not differ from the ligneous and herbaceous vegetation on the traditionally ungrazed Al Jabul plateau (P_{Ref2}). And although *D. viscosa* and *C. schoenanthus* were more abundant in the enclosure and *F. africana* and *E. stellata* were in contrast more important on the Al Jabul plateau, overall species composition was similar at both sites. These similarities and in particular the increased relative density of the otherwise highly grazed *O. europaea* ssp. *cuspidata* trees in the enclosure (P_{Ref1}) indicate the ability of the vegetation to recover from livestock grazing. Our data therefore suggest that despite the highly variable rainfall, the open shrublands of Al Jabal al Akhdar exhibit the resilience typical for equilibrium systems. Other research showed that many grazing systems include characteristics of both, equilibrium and non-equilibrium systems. Thus, Illius and O'Connor (1999) argued that even in non-equilibrium environments, livestock numbers will be in equilibrium with key resources, which delay mortality during drought, so that the impact of livestock grazing on the vegetation might be even larger than in equilibrium systems. In contrast to the herbaceous biomass that fluctuates over the seasons, the high foliar biomass particularly on the mountain slopes and in wadis of Al Jabal al Akhdar is less dependent on rainfall and the main fodder trees *S. mascatense* and *O. europaea* ssp. *cuspidata* are ever-green. Moreover, small ruminants on Al Jabal al Akhdar are offered supplement feeds at the homestead and an extended veterinary service has been established. Hence, the presence of these key resources and key resource areas as well as human interventions in natural ecosystem processes reduce livestock mortality during dry seasons and drought years and thus maintain a high grazing pressure on the less productive plateau areas.

Rangeland management is fundamentally different depending on the concept it is based upon (Vetter, 2005). While the non-equilibrium model promotes opportunistic livestock numbers, the equilibrium concept suggests conservative stocking rates below the natural carrying capacity to avoid overgrazing. On Al Jabal al Akhdar, average edible foliar (3.8 t DM ha^{-1}, SD 0.13) and herbaceous biomass (532 kg DM ha^{-1}; SD 184) as determined on the ungrazed plateau (P_{Ref}) was high. Even assuming a potential loss of 30% of the herbaceous biomass due to trampling and decomposition as well as a resting period of four months per year to allow plant re-growth (Penning de Vries and Djitèye, 1991), edible forage biomass would cover the DM demand of five goats of a bodyweight of 40 kg for maintenance and locomotion in the mountainous landscape (1.41 kg DM d^{-1} at a metabolizable energy content of 8 MJ kg^{-1} DM; NRC, 1981). Considering that at least 26% of the village pastures are highly productive wadis and mountain slopes, the carrying capacity should even be higher. Current stocking rates per village of 0.25 goats and sheep per ha (SD 0.17) are similar to values determined earlier by Schlecht et al. (2009), but lower than described or experimentally tested for other arid and semi-arid rangelands (Osman et al., 2006). Although actual stocking rates might be at least five times higher than the calculated values, because grazing areas of different villages overlap and the number of donkeys grazing in the mountains is up to now unknown, stocking rates are still much lower than the calculated carrying capacity. Nevertheless, the pasture vegetation shows clear signs of livestock grazing; thus, a more differentiated evaluation of the current pasture management practices and the timing, duration and intensity of grazing is needed.

Traditional grazing practices of livestock keepers were the basis for management recommendations in many parts of the world: the *Hema* system in the highlands of Saudi Arabia, the *Mahjur* areas in the Dhamar Mountains of Yemen Arab Republic, the *Agdal* areas in Northern Africa or the *Hamiyah* areas in parts of Oman all aimed to preserve feed resources for dry periods and droughts, and the maintenance and re-establishment of these protected areas was recommended (Fisher et al., 1998; Kessler, 1995; Saleh, 1998). While livestock exclosures are criticized to accelerate overgrazing in neighboring rangelands (Descheemaeker et al., 2006), the use of the traditional grazing reserves temporarily eased grazing pressure and therefore allowed the natural vegetation to recover. Although, according to farmers, there were no such grazing reserves on Al Jabal al Akhdar in the past, grazing areas of villages on Al Jabal al Akhdar were clearly defined and the mountain slopes and wadis were important feed resources preferentially used during dry seasons. Nowadays however, roads, residential, governmental and military areas on the plateau surrounding Sayh Qatanah cover an area of about 500 ha and according to municipal plans, the town itself is projected to double its size in the near future, severely minimizing the area available for livestock grazing and limiting the access to highly productive pasture areas. Furthermore, pastures of different villages overlap and fewer animals are herded during grazing than in the past, leading to locally very high grazing pressure (Turner et al., 2005). Thus, systems of directed grazing or allowing certain pasture areas to remain ungrazed for short periods by a coordinated pasture use as in the past are nowadays not found anymore.

Contemporary research on pastoral livestock production in the Middle East and in Northern Africa has mainly focused on the possibility to increase pasture production by irrigation (Oatham et al., 1995) or the seeding and propagation of highly productive species (El-Kharbotly et al., 2003; Osman et al., 2006) and the potential of supplementation of livestock with concentrate feeds (Mahgoub et al., 2005). The introduction of such management schemes and the shift from traditional grazing systems towards stall-feeding has also been recommended for livestock husbandry on Al Jabal al Akhdar (Zaibet et al., 2004). However, both strategies neglect the high yield potential of the natural highland pastures and the potential of goat husbandry to use these resources by adapted grazing schemes. Supplementation of livestock will strongly raise feeding costs for farmers (Zaibet et al., 2004) and in particular the use of cereal grains for animal feeding has commonly been criticized to increase competition with human consumption (Bradford, 1999). The import of meat and livestock feed into Oman is nowadays three and five times higher than in 1980, and although exports of both commodities increased simultaneously, import of meat and feedstuffs largely exceeded exports in 2005 (FAO, 2008). Hence, the rapid increase in livestock numbers driven by rising per capita meat consumption as well as the supplementation of livestock will increase rather than reduce the dependence on food and feed imports.

5. Conclusions

In the highlands of the Middle East and Northern Africa, which are characterized by open shrublands, the foliage of trees and shrubs represents an important source of animal fodder, in particular in areas of higher water availability. Since ligneous plants are less affected by the distribution and the amount of rainfall than the herbaceous vegetation, these rangelands exhibit typical characteristics of equilibrium systems despite a high variability in rainfall. Livestock grazing strongly influenced species composition, ground cover and biomass yields on pastures of Al Jabal al Akhdar, whereas resting periods would allow the natural vegetation to recover. The dedication of sufficiently large areas to livestock grazing including access to highly productive areas, coordinated grazing to avoid simultaneous use by several herds as well as the herding of livestock would enable farmers to decide when pastures might be put at rest. It would allow for conservative grazing, in particular of those areas that serve as key resources during periods of fodder scarcity. A temporarily increased supplement feeding of goats at the homestead, shorter grazing times or grazing of only part of the herds could further reduce grazing pressure during germination and early growth stages of the ligneous and herbaceous vegetation. Together with the control of the increasing number of feral donkeys, management based on scientific and traditional knowledge could therefore allow for stocking rates that exceed conservative recommendations and the current number of animals grazing the mountain pastures (Section 4.4). Although at least temporary supplementation appears necessary, goats can effectively use the natural vegetation otherwise of little direct use for human consumption. Improved pasture management therefore appears to be a valuable alternative to sustain livestock production in semi-arid subtropical highlands, thereby limiting the need for food and feed imports and increasing the food security of their population.

Acknowledgements

We thank Sultan Qaboos University, Oman, and in particular Dr. Osman Mahgoub, Dr. Andrew Palfreman and Dr. Sulaiman Al Khanjari of the College of Agricultural and Marine Sciences for administrative and logistic assistance. We acknowledge the support of the Agricultural Extension Center of the Ministry of Agriculture and Fisheries on Al Jabal al Akhdar as well as funding by the German Research Foundation (BU1308). Special thanks to Dr. Maher Nagieb for coordination during initial field work, to families of villages on Al Jabal al Akhdar for continued support and hospitality and to Mrs. Gameela Al Zakwani for her help in data collection and mapping of grazing areas.

References

Abule, E., Snyman, H.A., Smit, G.N., 2007a. Rangeland evaluation in the middle Awash valley of Ethiopia: II Woody vegetation. Journal of Arid Environments 70, 272–292.

Abule, E., Snyman, H.A., Smit, G.N., 2007b. Rangeland evaluation in the middle Awash valley of Ethiopia: I Herbaceous vegetation cover. Journal of Arid Environments 70, 253–271.

Amid, J., 2007. The dilemma of cheap food and self-sufficiency: the case of wheat in Iran. Food Policy 32, 537–552.

Bradford, G.E., 1999. Contributions of animal agriculture to meeting global food demand. Livestock Production Science 59, 95–112.

Brinkmann, K., Dickhoefer, U., Schlecht, E., Buerkert, A., 2009. Effects of altitude and grazing intensity on species composition, vegetation structure and plant diversity of communal pastures in the Jabal al-Akhdar mountain range of northern Oman. Journal of Arid Environments 73, 1035–1045.

Briske, D.D., Fuhlendorf, D., Smeins, F.E., 2003. Vegetation dynamics on rangelands: a critique of current paradigms. Journal of Applied Ecology 40, 601–614.

Cottam, G., Curtis, J.T., 1956. The use of distance measures in phytosociological sampling. Ecology 37, 451–460.

Descheemaeker, K., Muys, B., Nyssen, J., Poesen, J., Raes, D., Haile, M., Deckers, J., 2006. Litter production and organic matter accumulation in exclosures of the Tigray highlands, Ethiopia. Forest Ecology and Management 233, 21–35.

El-Kharbotly, A., Mahgoub, O., Al-Subhi, A., Al-Halhali, A., 2003. Indigenous grass species with potential for maintaining rangeland and livestock feeding in Oman. Agriculture, Ecosystems and Environment 95, 623–627.

Ellis, J.E., Coughenour, M.B., Swift, D.M., 1993. Climate variability, ecosystem stability, and the implications for range and livestock development. In: Behnke, R.H., Scoones, I., Kerven, C. (Eds.), Range Ecology at Disequilibrium: New Models of Natural Variability and Pastoral Adaptation in African Savannas. Overseas Development Institute, London, UK, 248 pp.

FAO, 2008. FAOSTAT – Online Statistical Database. Food and Agriculture Organization (FAO) Statistics Division. Retrieved on 29.09.2008 from: http://faostat.fao.org.

Fisher, M., 1994. Another look at the variability of desert climates, using examples from Oman. Global Ecology and Biogeography Letters 4, 79–87.

Fisher, M., Ghazanfar, S.A., Chaudhary, S.A., Seddon, P.J., Robertson, E.F., Omar, S., Abbas, J.A., Boer, B., 1998. Diversity and conservation. In: Ghazanfar, S.A., Fisher, M. (Eds.), Vegetation of the Arabian Peninsula. Kluwer Academic Publishers, London, UK, pp. 265–302.

Ghanzafar, S.A., 1991. Vegetation structure and phytogeography of Jabal Shams, an arid mountain in Oman. Journal of Biogeography 18, 299–309.

Hamadeh, S.K., Bistanji, G.N., Darwish, M.R., Abi Said, M., Abi Ghanem, D., 2001. Economic sustainability of small ruminants production in semi-arid areas of Lebanon. Small Ruminant Research 40, 41–49.

Hiernaux, P., Bielders, C.L., Valentin, C., Bationo, A., Fernández-Rivera, S., 1999. Effects of livestock grazing on physical and chemical properties of sandy soils in Sahelian rangelands. Journal of Arid Environments 41, 231–245.

Illius, A.W., O'Connor, T.G., 1999. On the relevance of nonequilibrium concepts to arid and semiarid grazing systems. Ecological Applications 9, 798–813.

Jongbloed, M.V.D., Feulner, G.R., Boeer, B., Western, A.R., 2003. A Comprehensive Guide to the Wild Flowers of the United Arab Emirates. Environmental Research and Wildlife Development Agency, United Arab Emirates, 576 p.

Kessler, J.J., 1995. Mahjur areas: traditional rangeland reserves in the Dhamar Montane Plains (Yemen Arab Republic). Journal of Arid Environments 29, 395–401.

Le Houerou, H.N., 1980. Chemical composition and nutritive value of browse in West Africa. Papers Presented at the International Symposium, 8–12 April 1980. ILCA, Addis Ababa, Ethiopia, pp. 261–264.

Mahgoub, O., Kadim, I.T., Al-Saqry, N.M., Al-Busaidi, R.M., 2005. Potential of Omani Jebel Akhdar goat for meat production under feedlot conditions. Small Ruminant Research 56, 223–230.

Mandaville, J.P., 1977. Plants. In: Harrison, D.L. (Ed.), The Scientific Results of the Oman Flora and Fauna Survey 1975. Journal of Oman Studies Special Report 1, 229–267.

Mekuria, W., Veldkamp, E., Haile, M., Nyssen, J., Muys, B., Gebrehiwot, K., 2007. Effectiveness of exclosures to restore degraded soils as a result of overgrazing in Tigray, Ethiopia. Journal of Arid Environments 69, 270–284.

Naumann, K., Bassler, R., Seibold, R., Barth, K., 2004. Die chemische Untersuchung von Futtermitteln. VDLUFA-Verlag, Darmstadt, Germany. Methodenbuch Band III, Loseblattausgabe mit Ergänzungen 1983, 1988, 1993, 1997 and 2004.

NRC, 1981. Nutrient Requirements of Goats: Angora, Dairy and Meat Goats in Temperate and Tropical Countries. National Research Council, National Academy Press, Washington, DC.

Oatham, M.P., Nicholls, M.K., Swingland, I.R., 1995. The manipulation of vegetation communities on the Abu Dhabi rangelands. I. Effects of irrigation and release from long-term grazing. Biodiversity and Conservation 4, 696–709.

Osman, A.E., Bahhady, F., Hassan, N., Ghassali, F., Al Ibrahim, T., 2006. Livestock production and economic implications from augmenting degraded rangeland with *Atriplex halimus* and *Salsola vermiculata* in northwest Syria. Journal of Arid Environments 65, 474–490.

Penning de Vries, F.W.T., Djitèye, M.A. (Eds.), 1991. La productivité des paturages sahéliens. Une etude des sols, des végétations et de l'exploitation de cette resource naturelle. Agricultural Research Report No. 918. PUDOC, Wageningen, 525 pp.

Rosenschein, A., Tietema, T., Hall, D.O., 1999. Biomass measurement and monitoring of trees and shrubs in a semi-arid region of central Kenya. Journal of Arid Environments 42, 97–116.

Saleh, M.A.E., 1998. Alternative land management approaches in the highlands of south-western Saudi Arabia. Environmental Conservation 25, 295–304.

Salis, S.M., Assis, M.A., Mattos, P.P., Piao, A.C.S., 2006. Estimating the aboveground biomass and wood volume of savanna woodlands in Brazil's Pantanal wetlands based on allometric correlations. Forest Ecology and Management 228, 61–68.

Sanon, H.O., Nianogo, J.A., Nanglem, N.S., Sanou, S., 2005. Amount of fallen fodder components from *Acacia raddiana*, *Balanites aegyptiaca* and *Ziziphus mauritiana* available to ruminants in selected Sahelian pastures. Livestock Research for Rural Development 17 Article 147. Retrieved 17.09.2008. http://www.cipav.org.co/lrrd/lrrd17/12/sano17147.htm.

Sanon, H.O., Kaboré-Zoungrana, C., Ledin, I., 2007. Edible biomass production from some important browse species in the Sahelian zone of West Africa. Journal of Arid Environments 71, 376–392.

Sarris, A.H., 2000. World cereal price instability and a market based instrument for LDC food import risk management. Food Policy 25, 189–209.

Schlecht, E., Dickhoefer, U., Gumpertsberger, E., Buerkert, A., 2009. Grazing itineraries and forage selection of goats in the Jabal al Akhdar mountain range of northern Oman. Journal of Arid Environments 73, 355–363.
Thomas, D., Zerbini, E., Parthasarathy Rao, P., Vaidyanathan, A., 2002. Increasing animal productivity on small mixed farms in South Asia: a systems perspective. Agricultural Systems 71, 47–57.
Todd, S.W., Hoffmann, M.T., 1999. A fence-line contrast reveals effects of heavy grazing on plant diversity and community composition in Namaqualand, South Africa. Plant Ecology 142, 169–178.
Turner, M.D., Hiernaux, P., Schlecht, E., 2005. The distribution of grazing pressure in relation to vegetation resources in semi-arid West Africa: the role of herding. Ecosystems 8, 668–681.
Vetter, S., 2005. Rangelands at equilibrium and non-equilibrium: recent developments in the debate. Journal of Arid Environments 62, 321–341.
Zaibet, L., Dharmapala, P.S., Boughanmi, H., Mahgoub, O., Al-Marshudi, A., 2004. Social changes, economic performance and development: the case of goat production in Oman. Journal of Arid Environments 54, 131–140.
Zöfel, P., 1988. Statistik in der Praxis, vol. 2. Aufl., Stuttgart, 426 pp.