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Vegetation patterns and diversity along an altitudinal and a grazing gradient in the Jabal al Akhdar mountain range of northern Oman

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ABSTRACT

Little is known about the effects of grazing on vegetation composition on the Arabian Peninsula. The aim of this study therefore was to analyse the vegetation response to environmental conditions of open woodlands along an altitudinal and a grazing gradient in the Jabal al Akhdar mountain range of Oman. The species composition, vegetation structure, grazing damage and several environmental variables were investigated for 62 samples using a nested plot design. Classification analysis and a Canonical Variate Analysis (CVA) were used to define vegetation types and to identify underlying environmental gradients. The relationship between environmental variables and diversity was analysed using correlation coefficients and a main-effects ANOVA. The plant species richness followed a unimodal distribution along the altitudinal gradient with the highest number of species at the intermediate altitudinal belt. The cluster analysis led to five vegetation groups: The *Sideroxylon mascatense–Dodonaea viscosa* group on grazed and the *Olea europaea–Fingerhuthia africana* group on ungrazed plateau sites at 2000 m a.s.l., the *Ziziphus spina-christi–Nerium oleander* group at wadi sites and the *Moringa peregrina–Pteropyrum scoparium* group at 1200 m a.s.l, and the *Acacia gerrardii–Leucas inflata* group at 1700 m a.s.l. The CVA indicated a clear distinction of the groups obtained by the agglomerative cluster analysis. The landform, altitude and grazing intensity were found to be the most important variables distinguishing between clusters. Overgrazing of the studied rangeland is an increasing environmental problem, whereas the plant composition at ungrazed sites pointed to a relatively fast and high regeneration potential of the local vegetation.

1. Introduction

The Jabal al Akhdar massif in the Hajar mountains of northern Oman has been classified as a local centre of plant endemism (Miller and Nyberg, 1991; Ghazanfar, 2003). It belongs to the WWF's Global 200 ecoregion "Arabian Highland Woodlands and Shrublands" occurring on the Arabian Peninsula, Yemen, Oman, Saudi Arabia and the United Arab Emirates with a total area of 470,000 km^2 and has a ecologically "vulnerable" status (Olson and Dinerstein, 2002). Above 1500 m altitude, this area hosts about 33% of Oman's 1200 species of vascular plants, of which 14 taxa are endemic to Oman (Patzelt, 2008).

Prior to 1975 little was known about the flora and fauna of Oman as tribal conflicts rendered access to the rugged and inhospitable terrain very difficult for scientists. So far, only the first two volumes of the Flora of Oman (Ghazanfar, 2003, 2007) and two volumes of the Flora of Arabia have been completed (Miller and Cope, 1996; Cope, 2007). The first regional checklist of the flora of the Jabal al Akhdar range was published thirty years ago (Mandaville, 1977). This check list has recently been updated and completed (Patzelt, submitted for publication) and the first country-wide Red List of plants has been finalised (Patzelt, 2008). Several botanical studies have been conducted in different parts of the country (Radcliffe-Smith, 1980; Mandaville, 1985; Cope, 1988; Ghazanfar, 1992; Patzelt, 2004; Gebauer et al., 2007), but on the phytogeography and vegetation structure of the northern Oman Hajar mountain range only a few descriptive studies have been published (Mandaville, 1977; Sankary, 1980; Ghazanfar, 1991b; Kuerschner, 1998). Mandaville (1977) described the zoning

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of plant communities with respect to altitude for the central Jabal al Akhdar and the summit area of Jabal Aswad (eastern Hajar). Ghazanfar (1991b) analysed the altitudinal zoning, community composition and species diversity of the vegetation of Jabal Shams using multivariate analysis.

The rangelands of the Jabal al Akhdar (1580–2000 m) are characterised by semi-evergreen woodlands dominated by *Sideroxylon mascatense* (A. DC.) Penn. growing in scattered mixed stands with *Dodonaea viscosa* (L.) Jacq., *Euryops arabicus* Steud. ex Jaub. and Spach, *Olea europaea* L. subsp. *cuspidata* (Wall. ex G. Don) Ciferri and *Sageretia thea* (Osb.) M.C. Johnst. (Ghazanfar, 1991b). At these and higher altitudes, *Cymbopogon schoenanthus* (L.) Spreng. forms the dominant ground cover. From heights of 2000 m up to the summit, the vegetation is characterised by *Juniperus excelsa* M. Bieb subsp. *polycarpos* (K. Koch) Takhtajan, *Ephedra pachyclada* Boiss. subsp. *pachyclada* and *Teucrium mascatense* Boiss. (Ghazanfar, 1991b). It has been suggested that the occurrence of *Juniperus excelsa* and other plant species in the Hajar range may be due to plant migrations from southeastern Iran across the Arabian Gulf (Mandaville, 1977; Miller and Nyberg, 1991; Kuerschner, 1998).

Pastoral livestock husbandry is the prevalent form of land use in arid or semi-arid rangelands. During the last decades the grazing pressure on the desert rangelands has increased steadily across the entire Arabian Peninsula (Khan, 1982; Oatham et al., 1995) and overgrazing is now considered to be a serious environmental problem (CBD, 1997; Ghazanfar, 2003; Kharbotly et al., 2003; Patzelt, 2008). Goats are the most numerous livestock species in northern Oman, followed by sheep, cattle and camels. It is known that goat browsing results in changes of plant species composition whereby some species decline, whereas those avoided by goats increase (Riggs and Urness, 1989). The relationship between herbivory and plant species diversity can not be generalised. It varies across environmental gradients (Olff and Ritchie, 1998; Curtin, 2002) and often depends on the palatability of particular species (Pacala and Crawley, 1992).

A complex of various factors determines the botanical composition and the related species richness and functional trait variation among the species (=functional diversity; Petchey and Gaston, 2006) of the rangeland vegetation. One important factor is altitude, which has a strong influence on the structure of the vegetation of the Arabian Peninsula, with species richness reported to be greatest from 1000 to 1480 m (Deil and Al Gifri, 1998). Changes in species richness along altitudinal gradients have been the subject of numerous studies (Lomolino, 2001) and most of them found a "humped" distribution showing peak species richness near the middle of the gradient (Rahbek, 1995, 2005).

To better understand and manage rangeland ecosystems, it is important to study the relationships between environmental factors and vegetation. Despite some earlier work, data are lacking about the effects of (over-) grazing by domestic livestock, including feral donkeys, on plant composition and local diversity (CBD, 1997) on the Arabian Peninsula and particularly in the Sultanate of Oman. Equally lacking are quantitative data about the distribution and ecology of different plant species, and also the vegetation response to environmental conditions. The aim of this study therefore was to analyse the species composition, floristic diversity and stand structure of communal pastures within open woodlands of the Jabal al Akhdar along an environmental gradient. We hypothesise that the environmental factors "altitude" and "grazing intensity" discriminate best between the vegetation types identified by a cluster analysis and explain also a high proportion in the variability of plant species richness and stand structure.

2. Materials and methods

2.1. Study area

The Hajar-al-Gharbi mountain range is the highest in eastern Arabia, forming a spectacular rise from the surrounding deserts. The highest part of the Hajar is the limestone massif of Al Jabal al Akhdar ("The Green Mountain"), lying between the western and eastern parts of the range within which the Jabal al Akhdar (23.07 N, 57.66 E) reaches an elevation of almost 3000 m. The climatic conditions across the entire range are arid to semi-arid, with a potential evapotranspiration of more than 2000 mm per annum (Siebert et al., 2007).

The study was carried out at the three villages Masayrat ar Ruwajah (1030 m a.s.l.), Qasha' (1640 m a.s.l.) and Ash Sharayjah (1900 m a.s.l.), which are located within 10 km of Sayh Qatanah, the central settlement of the Jabal al Akhdar mountains (Fig. 1). The total annual precipitation at Sayh Qatanah ranges between 100 and 340 mm with a higher probability of rainfall in February–March and July–October (Luedeling and Buerkert, 2008). Fisher (1994) calculated a mean annual precipitation in this region of 312 mm.

The geology of the study area consists mainly of highly permeable carbonates (black limestones and brownish dolomites of the Saiq Formation) resting on rocks of the pre-Late Permian Sedimentary Basement, conformably overlain by the Mahil Formation (Béchennec et al., 1992). Masayrat ar Ruwajah and its surroundings are characterised by the Muaydin Formation with siltstone and shale with carbonate beds. The Mistal Formation with diamicite, greywacke, basalt and basaltic andesite occurs between the settlements Ash Sharayjah and Salut.

The rocks are largely exposed, steep, with almost no soil cover and sparsely covered with vegetation that is primarily limited to runnels or small depressions where some sediments have accumulated in pockets. Large boulders, small stones and gravel are found in the steep runnels. The wadi fans consist mainly of gravel and sandy soil. Occasional rainfalls in winter can lead to flash floods that rush through the barren wadis.

2.2. Data collection

The common pastures sampled were selected to comprise a wide range of sites with differing grazing intensities within a study area of 50 km^2. Site selection was based on a map highlighting the pasture area of the study area and the main grazing zone associated with the three selected villages Masayrat ar Ruwajah, Qasha' and Ash Sharayjah. The latter was determined by Schlecht et al. (2009) using a GIS-based analysis of GPS-tracked livestock grazing itineraries and animals' activity patterns classified as "resting", "grazing" and "walking" along the route. Further pasture areas of the surrounding settlements were defined by Dickhoefer et al. (submitted) based on farmer interviews. The resulting maps were subsequently classified into four grazing intensities (Fig. 1): ungrazed rangelands (exclosures or areas with poor accessibility, class 0), pastures with low grazing pressure outside the main grazing zone (class 1), pastures with a medium grazing pressure within the main grazing zone (class 2) and pastures with a high grazing pressure within the grazing area along the goat tracks (Pressure zone, class 3).

The sampling of the vegetation was based on a nested plot design, whereby the plots were randomly distributed within a relatively homogeneous area in terms of topography, landform and present vegetation. Each plot measured 20 × 30 m and contained nested subplots of two different sizes. All shrubs and trees (>50 cm) within the whole plot area were sampled. To ascertain

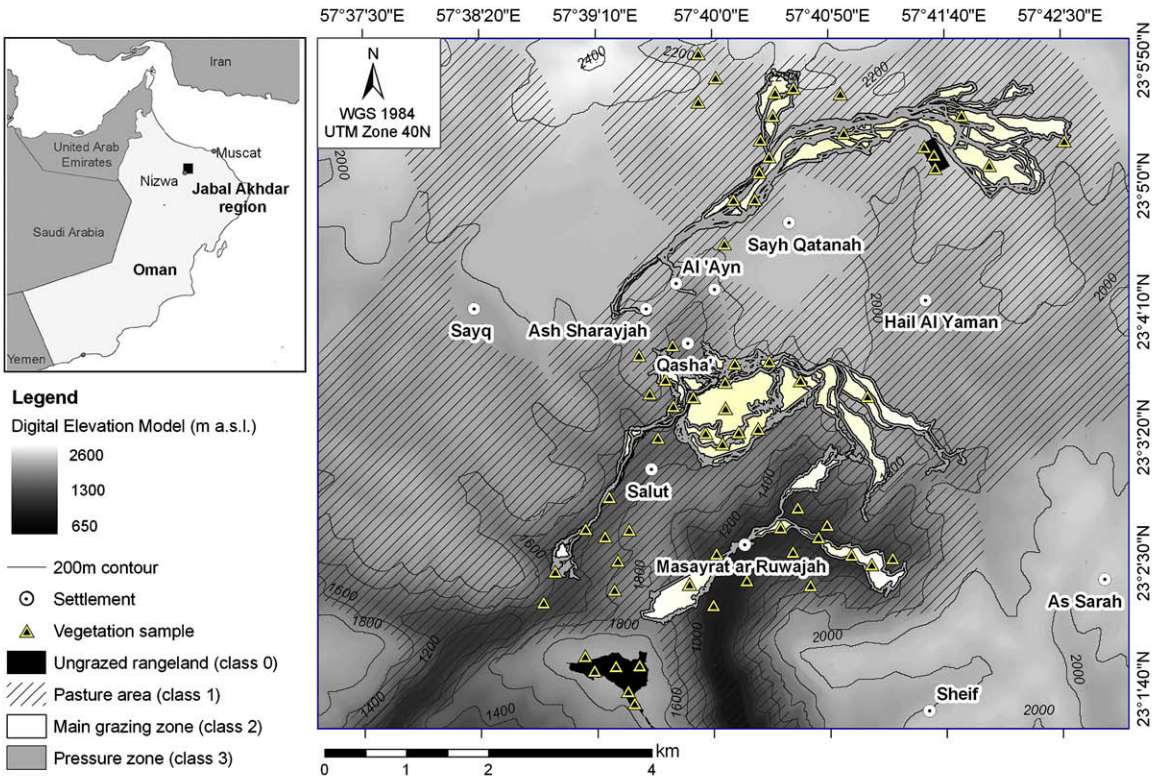

Fig. 1. Location of the Jabal al Akhdar mountains (top left) and overview of the study area with the identified grazing intensity classes and the vegetation samples along the three selected common pastures of the settlements Masayrat ar Ruwajah (1030 m a.s.l.), Qasha' (1640 m a.s.l.) and Ash Sharayjah (1900 m a.s.l.).

the optimal plot size for the survey of the ground vegetation, the minimum suitable area was calculated using species area curves (Dietvorst et al., 1982). The optimum quadrant size for the ground vegetation on plateau and wadi sites was found to be 100 m^2. Thus, two subplots of 100 m^2 were placed systematically within the larger plot to sample all of the vascular plants present.

The species cover was estimated using the following proportional ranks: 1%, 2%, 3%, 4%, 5%, 8%, 10%, 15%, 20%, 25%, 30%, 40%, 50%, 60%, 70%, 80%, 90%. Additionally, the sward structure (height and coverage of the tree, shrub and herb layer) was estimated and the GPS positions were measured for each sample plot. The environmental variables (altitude, aspect, slope) were determined using ArcGIS 9.2 (ESRI, Redlands, CA, USA) on the basis of a Digital Elevation Model (Luedeling et al., 2007). The distance to the settlement was calculated using the ArcGIS Extension Hawth's Analysis Tools (Beyer, 2004).

To obtain information about the animal grazing intensity and the palatability of the different plant species, the extent of the grazing damage to each plant species within a plot was classified according to the following scale: 1 = 0–20%, 2 = 20–40%, 3 = 40–60% and 4 = >60% of the plant grazed. The vascular plant nomenclature followed Cope (2007), Miller and Cope (1996), Ghazanfar (2003, 2007) and Patzelt (2008). All field work was conducted between October and November 2006, and between January and March 2007 within a period of typical climate conditions with average rainfall (approx. 180 mm for the year 2006).

2.3. Statistical analysis

The analyses were conducted using PC-Ord 5 (MjM Software, OR, USA) and CANOCO (version 4.5, Microcomputer Power, Ithaca, NY, USA). The analysed data set consisted of 62 samples containing 177 species. To reduce noise within the data set, species occurring in less than five plots were removed from the analysis, reducing the total number of species to 134.

The delimitation of plant communities on the common pastures was explored using a two-way cluster analysis. Two-way clustering uses one-way clustering on each of the two dimensions of the data matrix separately (Madeira and Oliveira, 2004). The cluster analysis was performed with the squared Euclidean distance and Ward's method as an amalgamation rule.

An indicator species analysis (ISA: Dufrêne and Legendre, 1997) was applied to determine the optimal number of final vegetation groups resulting from the cluster analysis. It produces percentage indicator values (IVs) for species and works on the assumption that, for a predetermined grouping of samples, an ideal indicator species can be found exclusively within one group and for all the samples in that group. The IVs are a simple combination of measures of relative abundance between groups and relative frequency within groups. If groups are too finely divided then indicator values will be low. On the other hand, if groups are too large then the internal heterogeneity will reduce the indicator values. The indicator values were tested for statistical significance using a randomisation (Monte Carlo) technique within PC-Ord (McCune et al., 2002). The ISA was run on the output from the hierarchical clustering cycles of the samples, yielding 2–20 groups with 4999 randomisations used in the Monte Carlo tests.

To test for multivariate differences between the pre-defined groups, a multi-response permutation procedure (MRPP) was used. The MRPP was run with the squared Euclidean distance on a matrix of ten environmental variables including altitude, exposition, grazing intensity, landform (wadi or plateau), geology and the species richness of a sample. The nominal variables, location and geology type, were included as dummies. Compared to the random expectation, the resulting statistic *A* is a descriptor of within-group homogeneity, also known as chance-corrected within-group agreement. When all of the observations within groups are identical, then the observed delta = 0 and $A = 1$ (McCune et al., 2002). The t-test statistic describes the separation between groups. The more negative the t-values, the stronger the separation.

To determine which linear combinations of explanatory variables discriminate best between the groups of the cluster analysis, a Canonical Variate Analysis (CVA) was performed with the software *CANOCO* with focus on inter-species distances and Hill's scaling. CVA is a variant of classical linear discriminant analysis (Jongman et al., 1987; Lepš and Šmilauer, 2003) and seeks to identify gradients of variation among groups of sample entities such that variation among groups is maximised and variation within groups is minimised along these gradients.

In CVA, the groups are used as dummy response variables instead of the species data. The environmental variables were logarithmically transformed before statistical analyses to normalise their distribution. An automatic forward selection and associated partial Monte Carlo permutation tests (999 permutations) were performed to test the discriminatory power of the explanatory variables [altitude (m a.s.l.), aspect (°), grazing intensity (from 0 = no grazing to 3 = high intensity), geology type (limestone, siltstone, greywacke and basalt), landform (wadi or plateau site) and the distance to the settlement (m)]. The nominal variables were recoded using a set of dummy variables; all other variables were log-transformed.

To examine the effects of grazing intensity and altitude on plant diversity, the functional diversity (FD) was calculated together with the Simpson diversity (D) according to Lepš et al. (2006) using the percentage cover of plant species. Functional diversity may be defined by the variety of responses to environmental change exhibited by the species in an ecosystem, or the number of ways in which an ecosystem can respond to change (Petchey and Gaston, 2006). The calculation of the functional diversity has to be based on a set of species traits. In the present study, the growth form (phanerophytes, chamaephytes, hemi-cryptophytes, geophytes, hydrophytes and therophytes) and the life span (annual and biennial; non-woody perennial; woody perennial) were chosen for this purpose. These traits were applicable to all of the 177 species found in the survey and could be validated by field observations. Detailed and specific information on additional functional traits of the species are not available for the flora of Oman.

The FD was calculated for the individual traits with the Rao coefficient (Botta-Dukát, 2005) as follows:

$$\mathrm{FD} = \sum_{i=1}^{s} \sum_{j=1}^{s} d_{ij} p_i p_j$$

where s is the number of species in the community and d_{ij} is the difference between the ith and jth species. The Rao coefficient is a generalisation of Simpson's index of diversity, and can be used with various measures of dissimilarity between species (Lepš et al., 2006). If $d_{ij} = 1$ for any pair of species, then FD is the Simpson index of diversity expressed as 1 minus Simpson index (see Botta-Dukát, 2005 and Lepš et al., 2006 for details). The average of the FDs calculated by single traits results in a compound index of functional diversity (Lepš et al., 2006).

The relationship between environmental variables (altitude and distance to the settlement), the rate of animal grazing damage to plants, the species diversity and the height of the ground layer (cm) was analysed on the basis of the 100 m^2 samples ($n = 124$).

Using Statistica 6.0 (StatSoft, Tulsa, USA), a main-effects ANOVA was employed to test the effects of altitude, aspect, grazing intensity (no grazing, low, medium and high grazing intensity) and landform (wadi and plateau sites) on the species and functional diversity, as well as on the height and cover of the ground vegetation and tree layer. The second-order interactions of this design were based on a low number of replicates. Therefore, only the main effects were included in the ANOVA model.

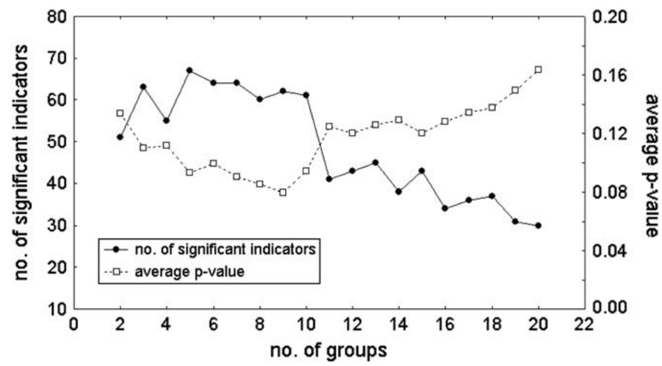

Fig. 2. Results of the indicator species analysis (ISA), with the number of significant indicators and the average p-value of all species at each step of the hierarchical cluster analysis for the main vegetation data set at Jabal al Akhdar as a criterion for pruning the dendrogram from the cluster analysis.

3. Results

Most of the species found in the study area were woody perennials (42%) and 21% herbaceous perennials. With 37%, the annual and biennial species made up another large group. These species flower irregularly from year to year, depending on the timing and amount of rainfall, but most blossoms appear from February to April (Ghazanfar, 1992).

Altogether 47 (27%) species were heavily grazed with a damage >40%. The plant species most preferred by grazing animals (mainly goats and feral donkeys) were grasses such as *Aristida adscensionis*,[1] *Eragrostis barrelieri*, *Tetrapogon villosus*, *Cynodon dactylon*, *Cymbopogon schoenanthus*, *Cenchrus ciliaris* and *Tripogon purpurascens*. The phanerophytes *Sideroxylon mascatense*, *Olea europaea* subsp. *cuspidata* and *Grewia erythraea*, as well as the chamaephytes *Leucas inflata* and *Polygala mascatense* were also heavily browsed.

A few species were unpalatable and consequently formed the dominant plant species in disturbed, overgrazed habitats, particularly *Dodonaea viscose* (Sapindaceae) and *Euryops arabicus* (Compositae). Members of the Euphorbiaceae, for example, *Euphorbia larica*, *Euphorbia granulata* and *Andrachne telephioides* were rarely grazed.

3.1. Main groups and vegetation types

The indicator values were calculated for each species at each level of grouping. In this study, the five group stage of the cluster analysis was found to be the most informative level in the dendrogram, because of the maximum number of significant indicators (67) and a relatively low average p-value (Fig. 2).

The multi-response permutation procedure (MRPP) indicated that there were significant differences between these groups in the environmental matrix ($A = 0.418$; $p < 0.001$). The average within-group distance showed that groups 3, 4 and 5 had relatively high dispersions, with an average distance of between 0.35 and 0.45, while groups 1 and 2 were relatively tight (average distance 0.12–016).

[1] The authorities of scientific plant names are listed in Table 3.

Table 1
Summary of the multi-response permutation procedure (MRPP) statistics of the vegetation groups on the Jabal al Akhdar. Results are given for multiple pairwise comparisons of the squared Euclidean distance. A = change-corrected within-group agreement; T = difference between the observed and expected deltas. Vegetation groups: 1 = Sideroxylon mascatense–Dodonaea viscosa group, 2 = Olea europaea–Fingerhuthia africana group, 3 = Ziziphus spina-christi–Nerium oleander group, 4 = Moringa peregrina–Pteropyrum scoparium group, 5 = Acacia gerrardii–Leucas inflata group.

Groups compared	T	A	p
1 vs. 2	−5.877	0.171	0.001
1 vs. 3	−14.922	0.387	0.000
1 vs. 4	−12.886	0.309	0.000
1 vs. 5	−18.583	0.444	0.000
2 vs. 3	−9.366	0.345	0.000
2 vs. 4	−6.544	0.205	0.000
2 vs. 5	−13.004	0.388	0.000
3 vs. 4	−3.298	0.119	0.015
3 vs. 5	−2.246	0.060	0.040
4 vs. 5	−1.542	0.040	0.079

The five groups occupied different regions of the species space, as shown by the strong chance- corrected within-group agreement (A) and test statistics (T). The pairwise comparisons indicated that groups 4 and 5 largely overlapped (Table 1). The comparisons of the other groups revealed significant differences between the groups.

Each group was named after both the tree species and the understorey species with the highest indicator value within the respective group (Table 2). A group of widespread species occurring in nearly every sample was observed with a high frequency along the altitudinal gradient from 1100 to 2000 m a.s.l. This group included *Tetrapogon villosus*, *Chrysopogon plumulosus*, *Cymbopogon schoenanthus*, *Aristida adscensionis*, *Solanum incanum* and *Salvia aegyptiaca*, as well as the endemic species *Teucrium mascatense.*

3.1.1. The Sideroxylon mascatense–Dodonaea viscosa group

This group characterised the vegetation of the rangeland situated on the limestone plateau at 2000 m a.s.l. This area was used as common pasture by the farmers of Al ’Ain, Ash Sharayjah and also by several inhabitants of Sayh Qatanah. Its floristic and structural composition reflected the high browsing intensity. The most frequent species of the tree and shrub layer were *Dodonaea viscosa*, *Sideroxylon mascatense* and *Euryops arabicus* mixed with *Olea europaea* subsp. *cuspidata* (frequency: 20%). *Sideroxylon mascatense* is a mesic tropical Asian relict species with a strong affinity to the mountains of eastern Afghanistan (Kuerschner, 1998). *Dodonaea viscosa* is a common species found in scrub and woodlands of the southern and western mountains of Arabia, throughout Baluchistan and on impoverished soils on the foothills of the Himalayas.

The coverage of the tree and shrub layer was relatively low on plateau areas and gravel slopes, ranging between 5% and 10%. Additionally, the ground vegetation was sparsely developed with a cover <8%. Frequent and potentially dominant species in the ground layer were *Cymbopogon schoenanthus* and *Polygala erioptera* and the annual *Telephium sphaerospermum* together with the widespread species *Tetrapogon villosus* and *Chrysopogon plumulosus*, which had the highest frequencies in the first group (Table 3). The chamaephytes *Teucrium mascatense*, *Salvia aegyptiaca* and *Helianthemum lippii* and the grass species *Tripogon purpurascen* also often occurred in this vegetation group.

3.1.1.1. Subgroup dominated by Euryops arabicus in wadi fans. The wadi fans are relatively short, narrow and without standing or permanently running water. In these temporarily wet locations and runnels, the shrub and tree layer was well developed with coverages of up to 65%, dominated by *Euryops arabicus*. Also *Ziziphus hajarensis* occurred in this subgroup, an endemic species at altitudes above 1000 m. *Acacia gerrardii*, *Daphne mucronata*, *Phoenix dactylifera*, *Cynodon dactylon* and *Pycnocyla prostata* were associated with the main species of the *Dodonaea viscosa–Sideroxylon mascatense* group. Dates are an important component of the livestock diet. Therefore the seeds of *Phoenix dactylifera*, which are able to germinate in wadi sediments, are mainly dispersed through the dung of grazing goats. On common pastures a few individuals of *Juniperus excelsa* subsp. *polycarpos* were found in the runnels and wadi fans.

Stands dominated by *Dodonaea viscosa* and *Euryops arabicus* have recently been described as a degraded form of a plant community new to science, the *Sideroxylon mascatense–Oleetum europaeum* (Patzelt, submitted for publication).

3.1.2. The Olea europaea–Fingerhuthia africana group

This vegetation type described the nearly ungrazed rangelands situated at an altitude of 2000 m a.s.l, on limestone and dolomite parent material. One ungrazed area was situated on the premises of the Agricultural Research Centre near Sayh Qatanah and was fenced off ten years ago. The other area, situated on a plateau at Ras al Kabul, is very difficult to access and therefore grazing by either domestic goats or feral donkeys rarely occurs, leaving the vegetation relatively undisturbed.

Although the site conditions were similar to the *Sideroxylon mascatense–Dodonaea viscosa* group, the floristic composition was clearly different. *Olea europaea* subsp. *cuspidata* was well developed and dominated the tree layer together with *Sideroxylon mascatense. Dodonaea viscosa* and *Euryops arabicus* occurred only in isolation, and with very low coverages. The shrub layer was characterised by *Grewia erythraea*, *Ochradenus arabicus*, *Ebenus stellata* and *Ephedra pachyclada*, as well as small shrubs such as *Lantana petitiana*, *Farsetia aegyptiaca*, *Endostemon tenuifolius* and *Fagonia bruguieri.*

The high diversity and good growth of the grass species was conspicuous. There were 11 grass species altogether, with a mean height of 35 cm. *Fingerhuthia africana* and *Heteropogon contortus*, in particular, were characterised by high frequencies and coverages, as indicated by the highest indicator values of 92 and 85% (Table 3). These species were seldom found within the *Sideroxylon mascatense–Dodonaea viscosa* group because of its exposure to high grazing intensity. The grass layer also comprised *Enneapogon persicus*, *Aristida mutabilis*, *Chrysopogon plumulosus*, *Cymbopogon schoenanthus* and *Cenchrus ciliaris*. Additional species observed within the ground layer were *Diplotaxis kohlaanensis*, *Helianthemum lippii*, *Caralluma arabica* and *C. flava.* This group was particularly well defined by the species indicator analysis with a number of high IV scores.

This community has syntaxonomically been classified as ungrazed form of the *Sideroxylon mascatense–Oleetum europaeum* (Patzelt, submitted for publication).

3.1.3. The Ziziphus spina-christi–Nerium oleander group

This group combined the wadi associations with Mediterranean and Irano-Turanian taxa on more mesic sites, at altitudes between 1100 and 1800 m a.s.l. The vegetation pattern in seasonal water beds or wadis was determined by the drainage system, the transport and texture of the sediments, the depth of the water table, the frequency of overflows and the variability of the rainfall. As a consequence, there was a higher degree of variability in the species composition within this group, as was also indicated by the standard deviation of the species richness given in Table 2.

The coverages of trees and shrubs were generally higher than on non-wadi sites (Table 2). The most frequent tree species with the highest indicator value was *Ziziphus spina-christi* (80%). This species occurred in association with *Acacia gerrardii*, which lined the sides of wadis and foothills, and *Ficus cordata* subsp. *salicifolia*. In more humid areas, *Salix acmophylla* was also found along the edges of permanent streams.

Table 2
Summary statistics (mean and standard deviation) of the environmental variables per vegetation group of the Jabal al Akhdar, Oman. For vegetation groups (1–5) see Table 1.

Vegetation group	1 ($n = 15$)		2 ($n = 9$)		3 ($n = 16$)		4 ($n = 12$)		5 ($n = 10$)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Altitude (m a.s.l.)	2041	47	1965	65	1405	195	1248	81	1723	131
Grazing intensity (%)	27	13	0	0	9	9	14	9	15	10
Species richness (on 100 m^2)	18.47	4.05	20.75	3.51	22.7	5.88	18.94	2.90	24.93	3.75
Functional diversity (FD)	0.25	0.04	0.29	0.03	0.23	0.04	0.26	0.02	0.26	0.02
Simpson diversity (D)	0.7	0.13	0.87	0.06	0.79	0.14	0.84	0.05	0.87	0.03
Height of the ground layer (cm)	12	2.83	30.33	4.82	16	5.62	14.66	3.43	14.88	3.29
Max. height of the ground layer (cm)	20.83	7.97	50	9.19	32.7	18.42	21.88	4.28	26.25	8.93
Ground layer cover (%)	7.83	7.77	10.64	3.01	8.87	4.88	7.5	2.24	10.8	2.72
Tree layer cover (%)	3.1	3.39	2.97	4.06	6.46	3.05	3.72	2.16	2.68	2.46
Height of the tree layer (m)	1.84	1.71	1.62	1.31	3.8	0.83	3.02	0.62	1.68	1.28

Nerium oleander and *Dyerophytum indicum* formed the shrub layer, together with *Pteropyrum scoparium* on the wadi fringe. Kuerschner (1998) and Deil and Al Gifri (1998) described the latter as typical of the narrow wadi outlets of the Jabal al Akhdar range. The tall tufted grass *Saccharum spontaneum*, *Cynodon dactylon* and *Cenchrus ciliaris* dominated the grass layer. On the flat gravelly ground, annuals such as *Oxalis corniculata*, *Spergula fallax*, *Reichardia tingitana*, *Plantago afra*, *Sisymbrium erysimoides* and *Notoceras bicorne* predominated.

Species requiring high humidity levels were found in the beds of the wadi water courses, where moisture was available for longer periods of time. These included *Blumea bovei*, *Mentha asiatica*, *Polypogon viridis*, *Juncus rigidus* and *Eleocharis geniculata*. *Potamogeton nodosus* was observed growing in ponds.

3.1.4. The Moringa peregrina–Pteropyrum scoparium group

This group dominated on the common pasture area near the Masayrat ar Ruwajah oasis settlement, situated mainly on siltstone and shale at an altitude of about 1200 m. The topography was characterised by steep slopes of up to 50°. In this upper altitudinal range, *Moringa peregrina*, *Pteropyrum scoparium* and *Acridocarpus orientalis* occurred in the tree and shrub layer, together with *Acacia gerrardi. Moringa peregrina* and *Acridocarpus orientalis* often grew in pockets of soil in the drainage channels.

Pteropyrum scoparium is endemic to Oman and the United Arab Emirates, whereby in the former distribution is restricted to the north of the country (Miller and Cope, 1996). A further endemic phanerophyte found in this group was *Rhus aucheri*, which occurred scattered across the common pasture of Masayrat ar Ruwajah.

Characteristic species of the ground layer with a high indicator value were *Teucrium mascatense*, *Filago desertorum*, *Caralluma arabica*, *Euphorbia arabica*, *Taverniera cuneifolia* and *Zataria multiflora*. *Euphorbia larica*, *Vernonia arabica*, *Leucas inflata*, *Echinops spinosissimus* and *Polygala mascatense* were frequent species of the understorey.

Euphorbia larica was the characteristic shrub of the rocky and stony slopes. It was typically about 1 m in height, with an open crown and succulent aphyllous stems (Ghazanfar, 1991b). The shade tolerant fern *Cheilanthes fragans* was frequently found between the rocks. *Schweinfurthia papilionacea* and the shrub *Lycium shawii* occurred sporadically in this group, but were not observed in any of the other vegetation groups.

3.1.5. The Acacia gerrardii–Leucas inflata group

This vegetation type shared many of the environmental characteristics of the *Moringa peregrina–Pteropyrum scoparium* group, but was generally found at higher altitudes (1700 m a.s.l.) and on different geological substrates. It described the common pasture of Qasha', ranging from the small settlements Quanfara and Azk to Salut (see Fig. 1). This group can be assigned to the *Euphorbia larica* zone described by Ghazanfar (1991a), and was characterised by gentle to steep, rocky slopes, alluvial soil, shallow pockets in the crevices of rocks and drainage channels.

The most frequent tree species was *Acacia gerrardii*, associated with *Sideroxylon mascatense*. The main characteristic species in the shrub layer were *Grewia erythraea* and *Euphorbia larica*, associated with chamaephytes such as *Leucas inflata*, *Aerva javanica*, *Blepharis ciliaris*, *Plectranthus rugosus*, *Abutilon fruticosum* and *Polygala mascatense*. *Aerva javanica* and *Abutilon fruticosum* occur throughout Oman (Ghazanfar, 2003). *Boerhavia diffusa*, *Portulaca quadrifida*, *Morettia parviflora*, *Phyllanthus maderaspatensis* and *Gypsophila bellidifolia* are frequent annual herbs that emerge after the occasional rainfalls. *Gypsophila bellidifolia* grows between stones, and is mainly found on siltstone scree.

Further species within this group were *Cyperus rubicundus*, the succulent *Caralluma arabica*, as well as scattered occurrences of *Lavandula subnuda* and the threatened *Epipactis veratrifolia*.

Compared to the other groups, the *Acacia gerrardii–Leucas inflata* group was less clearly defined by the cluster analysis and the species indicator analysis, as demonstrated by the low indicator scores (IVs, Table 3). This group represented a transition from the *Moringa peregrina–Pteropyrum scoparium* to the *Sideroxylon mascatense–Dodonaea viscosa* group.

The results of ordination by Canonical Variates Analysis (CVA) showed a very distinct phytogeographical pattern of differentiation between vegetation types identified by the cluster analysis (Fig. 3). The fist ($\lambda = 0.904$) and second canonical variates ($\lambda = 0.839$) represent 60% of the variation in the relationship between clusters (referred to as species in CVA) and the 10 explanatory variables. The first canonical variate represents the altitudinal gradient and distinguished the vegetation samples on wadi locations (the *Ziziphus spina-christi–Nerium oleander* group) from those on plateau locations. The greatest degree of an environmental overlap occurred between the *Moringa peregrina–Pteropyrum scoparium* group and the *Acacia gerrardii–Leucas inflata* group.

The arrows of the explanatory variables give an indication of the relative importance of each environmental factor in the cluster separation. Using the automatic forward selection of explanatory variables within CANOCO, the variables were added in the sequence: Grazing intensity, altitude, wadi, aspect, limestone, siltstone, plateau, slope, greywacke and distance to the settlement. The last two variables were not significant given the other eight variables. The relief situation on wadi sites ($F = 21.83$; $p = 0.001$), altitude ($F = 17.26$; $p = 0.001$) and the grazing intensity ($F = 14.88$; $p = 0.001$) were found to be the most important variables distinguishing between clusters.

Table 3
Frequencies, indicator values (IV = % of perfect indication) and *p*-values of the 11 most important indicator species per vegetation group on the Jabal al Akhdar, Oman. (*p*-value = Monte Carlo test of significance of the observed maximum indicator value for each species, based on 999 randomisations).

Species within each vegetation group	Frequency (%)	IV (%)	*p*-Value
Sideroxylon mascatense–Dodonaea viscosa group (11 significant indicator species)			
Dodonaea viscosa (L.) Jacq.	100	60.6	0.000
Sideroxylon mascatense (A. DC.) Penn.	82	39.8	0.007
Polygala erioptera DC.	80	57.7	0.000
Telephium sphaerospermum Boiss.	40	39.0	0.002
Cymbopogon schoenanthus (L.) Spreng.	90	37.4	0.004
Tetrapogon villosus Desf.	97	29.8	0.002
Chrysopogon plumulosus Hochst.	97	29.3	0.012
Euryops arabicus Steud. ex Jaub. and Spach	55	38.7	0.002
Sageretia thea (Osb.) M.C. Johnst.	37	35.3	0.005
Phoenix dactylifera L.	16	33.3	0.003
Pycnocyla prostata Hedge and Lamond	17	27.4	0.008
Olea europaea–Fingerhuthia africana group (18 significant indicator species)			
Fingerhuthia africana Lehm.	94	92.2	0.000
Heteropogon contortus (L.) Roem. and Schultes	100	85.5	0.000
Olea europaea L. subsp. *cuspidata* (Wall. ex G. Don) Ciferri	55	53.6	0.000
Lantana petitiana A. Rhich.	69	80.6	0.000
Ochradenus arabicus Chaudhary, Hillc. and A.G. Mill.	45	70.6	0.000
Farsetia aegyptiaca Turra	50	69.6	0.000
Enneapogon persicus Boiss.	69	66.7	0.000
Helichrysum makranium (Rech.f.) and Esfand Rech.f.	90	62.7	0.000
Helianthemum lippii (L.) Dum.-Cours.	94	48.4	0.000
Ebenus stellata Boiss.	31	44.4	0.001
Fagonia bruguieri DC.	67	41.3	0.001
Ziziphus spina-christi–Nerium oleander group (29 significant indicator species)			
Ziziphus spina-christi (L.) Desf.	78	80.2	0.000
Nerium oleander L.	65	58.3	0.000
Cynodon dactylon (L.) Pers.	83	37.0	0.021
Oxalis corniculata L.	48	54.0	0.000
Spergula fallax (Lowe) Krause	30	50.0	0.000
Pupalia lappacea (L.) A.L. Juss. var. *velutina* (Moq.) Hook.	40	45.8	0.000
Sisymbrium erysimoides Desf.	52	43.9	0.000
Astragalus corrugatus Bertol.	35	41.7	0.000
Saccharum spontaneum L.	52	41.6	0.000
Plantago afra L.	52	38.9	0.001
Dyerophytum indicum (Gibs. ex Wight) Kuntze	44	34.9	0.003
Moringa peregrina–Pteropyrum scoparium group (11 significant indicator species)			
Moringa peregrina (Forssk.) Fiori	45	74.4	0.000
Pteropyrum scoparium Jaub. and Spach.	63	71.6	0.000
Zataria multiflora Boiss.	38	47.1	0.001
Filago desertorum Pomel	65	30.0	0.020
Cheilanthes fragrans (L f.) Sw.	44	40.7	0.001
Teucrium mascatense Boiss.	81	34.8	0.002
Taverniera glabra Boiss.	38	29.5	0.008
Euphorbia arabica Hochst and Steud. ex Boiss.	38	36.1	0.002
Rhus aucheri Boiss.	25	30.1	0.004
Acridocarpus orientalis A. Juss.	26	20.0	0.048
Caralluma arabica N.E. Br.	44	27.0	0.020
Acacia gerrardii–Leucas inflata group (13 significant indicator species)			
Leucas inflata Benth	75	47.7	0.000
Acacia gerrardii Benth	86	38.1	0.001
Solanum incanum L.	65	34.6	0.003
Grewia erythraea Schweinf.	64	29.3	0.028
Euphorbia larica Boiss.	57	25.3	0.042
Aerva javanica (Burm.f.) J.A. Schult.	43	44.0	0.001
Abutilon fruticosum Guill. and Perr.	40	38.6	0.003
Blepharis ciliaris (L.) B.L. Burtt	40	32.4	0.004
Morettia parviflora Boiss.	40	30.6	0.011
Plectranthus rugosus (Wall). ex Benth	32	43.7	0.001
Boerhavia diffusa L.	33	25.5	0.023

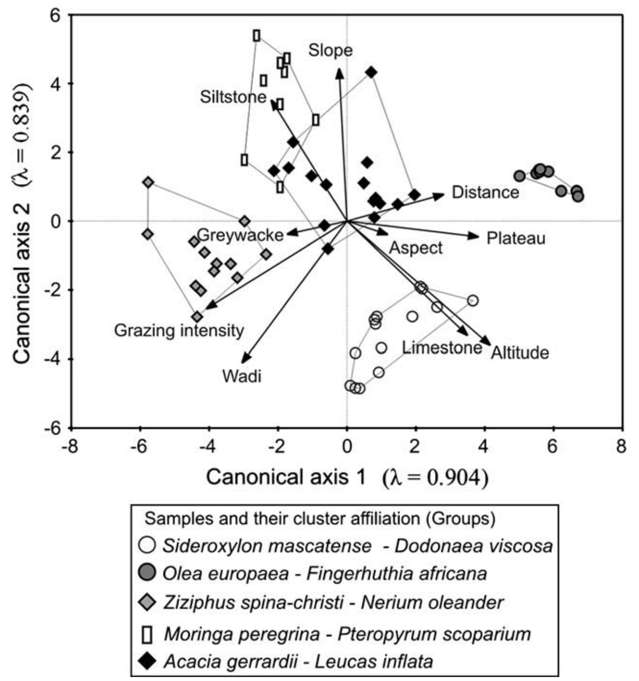

Fig. 3. Canonical variate analysis Biplot of the 62 samples classified into the five vegetation groups. Only the environmental variables selected by forward selection and included in the final model are shown. The first ($\lambda = 0.904$) and second canonical variates ($\lambda = 0.839$) explain 60% of the variation in the relationship between clusters.

3.2. Plant species richness, functional diversity and animal grazing damage

The animal grazing damage to plants (=proportion of species that were heavily grazed with an extent of grazing damage >40%) decreased with increasing distance from human settlements and with proximity to the steep, inaccessible slopes at the peripheries (Fig. 4a). The height of the ground layer (including herbs, grasses and semi shrubs) decreased significantly with increasing animal grazing damage ($r = -0.64$, Fig. 4b), whereas species richness and animal grazing damage were only weakly correlated ($r = -0.30$, Fig. 4c).

There was a unimodal relationship between species richness and altitude (Fig. 4d). The highest number of species per sample was found for the *Acacia gerrardii–Leucas inflata* group on the common pasture of Qasha' at an altitude of 1700 m a.s.l.

We used a main-effects ANOVA (Table 4) to test the effects of altitude, aspect, grazing intensity (no grazing, low, medium and high grazing intensity) and landform (wadi and plateau sites) on the diversity and stand structure. The environmental factors considered in the main-effects ANOVA explained only a small portion of variability in species richness (*S*), diversity (*D*, FD), cover and height of the ground and tree layer (adjusted $R^2 < 0.5$ for all variables). There were no significant differences between the south- and the north-facing sites. The most significant differences in the cover of the tree layer ($F = 45.27^{***}$), the height of the tree layer ($F = 15.34^{**}$), the functional diversity ($F = 17.15^{**}$) and the Simpson diversity ($F = 33.10^{***}$) occurred on the two landforms. The stand structure present on the wadi and plateau sites was highly variable. The mean tree layer cover on wadi sites amounted to 6.5% with a mean tree height of 4 m, whereas on plateau sites the mean tree height was less than 2 m and the tree layer cover only 3%.

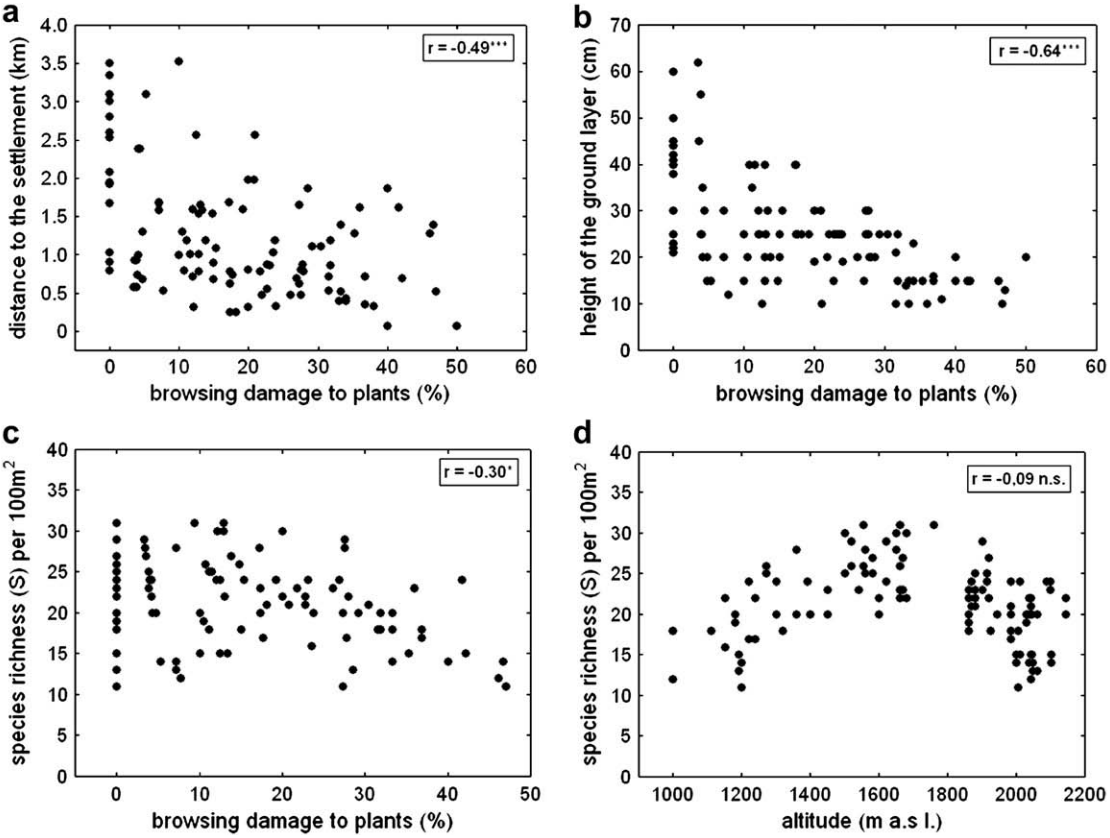

Fig. 4. Relationship between altitude, grazing intensity and distance to the settlement as well as plant species richness (100 m^2) and height of the ground layer (cm) on the Jabal al Akhdar.

The height of the ground layer and the diversity indices decreased with increasing grazing intensity. The ANOVA confirmed the high variation in plant species richness along the altitudinal zoning ($F = 10.86^{**}$). The cover and height of the tree layer decreased with altitude. The height of the ground layer differed most significantly along the grazing intensity gradient ($F = 14.94^{**}$).

4. Discussion

4.1. Vegetation groups along the environmental gradients

Overall, the present results correspond to earlier vegetation descriptions of Al Jabal al Akhdar (Mandaville, 1977; Sankary, 1980; Ghazanfar, 1991b; Kuerschner, 1998). The structure and pattern of the vegetation in the study area indicated a close relationship to the Jabal Shams area studied previously (Mandaville, 1977; Sankary, 1980; Ghazanfar, 1991b), the mountainous regions of south west Iran (Zohary, 1973) and south west Pakistan (Rafi, 1965). Ghazanfar (1991b) delimited four plant communities along an altitudinal gradient spanning 650 m to 2820 m on the Jabal Shams which forms the highest part of the Hajar range. Her results also showed a strong influence of altitude on the structure of the vegetation. The *Euphorbia larica* zone between 1100 and 1500 m altitude and the *Sideroxylon–Olea–Dodonaea* zone at 1500–2000 m were common in the study area featured here. The first two vegetation groups, distinguished by a two-way cluster analysis and an indicator species analysis, were the *Sideroxylon mascatense–Dodonaea viscosa* group and the *Olea*

Table 4
Results of the main-effects ANOVA for the diversity indexes, cover and height of the ground and tree layer (Aspect: 1 = southerly exposed sunny sites, 2 = northerly exposed shady sites; Altitude: 1 = ≥1400, 2 = 1400–1800, 3 = $<$1800 m a.s.l.; Location: 1 = Wadi sites, 2 = Plateau sites. Grazing intensity: 0 = no grazing, 1 = low, 2 = medium, 3 = high).

	Adj. R^2	Aspect (df = 1)		Altitude (df = 2)		Location (df = 1)		Grazing intensity (df = 3)	
		F	*p*	*F*	*p*	*F*	*p*	*F*	*p*
Species richness (*S*)	0.34	2.46	n.s	10.86	**	1.11	n.s.	3.42	*
Simpson diversity (*D*)	0.42	2.54	n.s	7.70	*	33.10	***	3.82	*
Functional diversity (FD)	0.28	1.57	n.s	0.58	n.s.	17.15	**	1.32	n.s.
Cover of the ground layer (%)	0.16	1.07	n.s.	3.90	*	0.01	n.s.	0.84	n.s.
Height of the ground layer (cm)	0.39	2.24	n.s.	2.07	n.s.	0.26	n.s.	14.94	**
Cover of the tree layer (%)	0.41	2.08	n.s.	0.19	n.s.	45.27	***	0.17	n.s.
Height of the tree layer (m)	0.22	0.65	n.s.	1.47	n.s.	15.34	**	0.56	n.s.

europaea–Fingerhuthia africana group. These can be taxonomically classified into the *Sideroxylon mascatense–Oleetum cuspidatae* (Patzelt, submitted for publication) and correspond to earlier descriptions of the *Sideroxylon–Olea–Dodonaea* zone (Ghazanfar, 1991b) and in part to the *Reptonia–Olea* woodland (Mandaville, 1977).

Within the *Euphorbia larica* zone between 1100 and 1500 m altitude (Ghazanfar, 1991b), which is also described as *Euphorbia larica* community on the rocky outcrops of the Hajar mountains (Deil and Al Gifri, 1998; Kuerschner, 1998), the cluster analysis distinguished the *Moringa peregrina–Pteropyrum scoparium* group and the *Acacia gerrardii–Leucas inflata* group. The first group is related to the *Moringa peregrina* community type described by Frey and Kuerschner (1986).

The wadi vegetation is of an azonal type, dependent on the prevailing water regime, and is highly influenced by man and livestock (Deil and Al Gifri, 1998; Kuerschner, 1998). In this study the main indicator species of the vegetation group on wadi sites were *Ziziphus spina-christi* and *Nerium oleander*, which were previously described by Kuerschner (1998) and Deil and Al Gifri (1998) as typical phanerophytes present in the wadis and wadi fans. This group is related to the Saccharo-Nerietum oleandro (Deil and Müller-Hohenstein, 1996), which occurs in the canyon like wadis of the mountains of the eastern United Arab Emirates and northern Oman with *Saccharum spontaneum* and *Ficus cordata* subsp. *salicifolia* as further indicator species.

This study and the previously published results of Ghazanfar (1991b) are the first quantitative attempts to classify the rangeland vegetation of the Jabal al Akhdar Mountains, using a range of complementary methods and current best-practice in statistical techniques. The present study concentrated on the vegetation between 1100 and 2300 m a.s.l. Data for the *Juniperus* zone (Ghazanfar, 1991b) above 2300 m a.s.l., recently described and classified syntaxonomically as *Teucrio mascatense–Juniperetum excelsae* (Patzelt, submitted for publication), were not collected. Only a few individuals of *Juniperus excelsa* subsp. *polycarpos* were found in the sheltered gullies and wadi fans on the common pastures of the Sayq plateau. This species is generally the dominant component of the woody vegetation at altitudes above 2100 m in the northern mountains of Oman (Mandaville, 1977; Ghazanfar, 1991b). Below 2400 m, however, there is an apparent die-back and poor regeneration of *Juniperus* in many of the woodlands (Fisher and Gardner, 1995).

Several relatively short-lived species that emerge soon after a rainfall event may be missing from the analysis. The occurrence of rain seems to be the key factor determining species richness in the area in any one year (Ghazanfar, 1997, 1992). For this reason the field work was conducted during a season in which the phenological development of annuals was optimal. Heavier rainfall events (>10 mm) occurred in the study area in the late summer months and again in December 2006, just before the second field survey was conducted. It was assumed that annual and biennial plant species were well represented in the present vegetation survey, as their proportion was relatively high (37%).

Legendre and Legendre (1998) emphasised the necessity of validation of the results of hierarchical clustering, because this method will always reveal groups even when the dataset is essentially unstructured (Pillar, 1999). We used a MRPP test with environmental variables to analyse the separation between the groups. The advantage of this non-parametric method is that it does not require assumptions (such as multivariate normality and homogeneity of variances) that are seldom met by ecological community data (McCune et al., 2002).

Vegetation patterns are determined by environmental factors that exhibit heterogeneity over space and time, such as climate, topography, geology and soil, as well as human disturbances (Alexander and Millington, 2000). To test which linear combinations of environmental variables discriminate best between the defined vegetation groups we performed a CVA. The results of the CVA revealed a good separation of the five defined groups of the cluster analysis, particularly for the ungrazed samples. There were three main gradients within the vegetation data sets. The most important factors were the landform and the altitudinal gradient. These topographic parameters have been described as indirect variables according to Austin and Smith (1989), which usually replace a combination of different resources and direct gradients in a simple way, such as climatic and moisture conditions. Wadi fans and plateau sites revealed the greatest variation in stand structure and functional diversity. As in any arid country, low-lying sites and wadi sites receive runoff water, and water- and windborne sediments, resulting in deeper soil layers, which provide a continuous supply of moisture for the deep roots of perennials (Batanouny and Baeshin, 1983). By contrast, elevated sites always have limited water resources and more shallow soils. Hence, the number of annual plant species, as well as the height and cover of trees and shrubs are greatly affected by the landform and were significantly higher on wadi sites.

Within the environmental gradients the vegetation samples were separated according to their different grazing intensities. Samples with the lowest (class 0 on ungrazed rangelands) and highest grazing intensity (class 3) were found at the same altitudinal belt at approximately 2000 m a.s.l. (Fig. 1).

4.2. Diversity and grazing pressure

The vegetation samples collected along the altitudinal gradient ranges from 2150 m a.s.l. at the highest point to 1000 m a.s.l. at the lowest point, reflecting the environmentally changes in plant species composition and species diversity. Above 1500 m a.s.l., a total of 329 plant species occurred, thirty-four being included into the Red List, representing 10% of the regional flora (Patzelt, submitted for publication). The plant species richness in the study area followed a unimodal distribution along the altitudinal gradient, with the highest number of species in the *Acacia gerrardii–Leucas inflata* group at altitudes between 1600–1750 m a.s.l. Similar diversity–altitude relationships with the highest species richness and diversity in the intermediate altitudinal belt were also described by other studies from arid mountains (Abd El-Ghani and Abdel-Khalik, 2006; Al-Sodani et al., 2003; Ghazanfar, 1991b; Hegazy et al., 1998) as well as from temperate and tropical regions (Rahbek, 2005). Altitudinal gradients encompass several gradients in climatic and environmental factors that are often correlated, making hypothesis testing problematic and controversial (Bravo et al., 2008). As elevation increases, temperature on the slopes as well as evapotranspiration decreases. The mean annual temperature along the altitudinal gradient varies between 18 °C at 2000 m a.s.l., 25 °C at 1070 m a.s.l. and 29 °C at sea level (Luedeling et al., 2007). The variation of mean annual precipitation ranges from 75 mm in the lowlands to 300 mm in the higher reaches of the mountains (Fisher, 1994). Consequently, the climate is distinctly cooler at the upper altitudes of Al Jabal al Akhdar, with frost events in winter times and more humid than in the lowlands (Siebert et al., 2007). The more balanced climate and the higher diversity of the topography in the intermediate zone probably accounted for the higher numbers of plant species. Ghazanfar (1991b) found the highest species richness between 950 and 1400 m, with a decrease both below and above this zone.

As in many other arid regions, rangelands and woodlands in the rural areas of Oman still represent the major source of feed for livestock, which constitute a major source of rural community income. In the past, the use of rangeland was regulated by rotational herding at selected locations, allowing grazing areas to regenerate (Anonymous, 1982). In some areas access was also controlled by the traditional "hema" system, whereby plants were only cut for fodder from an otherwise "closed" area when grazing conditions were poor (Lancaster and Lancaster, 1990). Such conservation practices have now been largely abandoned and as a consequence, together with the increase in domestic livestock holdings, rangelands are over utilised. Dickhoefer et al. (submitted for publication) recently estimated the stocking rates per settlement at Al Jabal al Akhdar. Generally, the resulting mean rates per settlement of 0.25 goats and sheep are not very high, but overlapping use of grazing grounds may lead to five-fold higher use intensity. Furthermore, large numbers of feral donkeys have greatly added to the overgrazing problem. With the introduction of a well-developed network of roads since 1970, donkeys, formerly used to transport merchandise across the mountain ridges, have been released into the wild and are now multiplying and grazing in uncontrolled herds. In a recent study the total number of feral donkeys were estimated at about 2000 (Schlecht et al., 2009) of which a high proportion has been observed at the Sayh plateau whereas the steep slopes south of Quasha' were seldom grazed by these animals. However, the precise numbers of feral donkeys and their distribution are still unknown and no measures have yet been taken to reduce the grazing pressure, such as controlled hunting.

Altogether, 27% of the plant species recorded in this study showed a high degree of grazing damage. While the proportion of species that were heavily grazed decreased with increasing distance from human settlements, there was only a weak correlation between species richness and animal grazing damage as expressed by the proportion of heavily grazed species. The relationship of plant species richness and grazing often depends on the palatability of particular species and the relationship between palatability and competitive ability (Pacala and Crawley, 1992) but it also varies across environmental gradients of soil fertility and precipitation (Olff and Ritchie, 1998). Hence, the altitudinal gradient overlaid the grazing effects on plant species richness. This was also confirmed by the results of the ANOVA indicating highly significant differences in species diversity (S and D) between the altitudinal zones, whereas the differences between the four grazing intensity classes were relatively low. Moderate or small changes to the composition of plant communities in response to grazing are expected in semi-arid rangelands with low biomass productivity in which plant growth is usually limited by the availability of water and soil-borne nutrients (Osem et al., 2004). In such areas, the adaptations to aridity such as shorter plants, small leaves, basal meristems and short life cycle, increase tolerance, or avoidance, of grazing ("convergent selection"; Milchunas et al., 1988).

However, heavy grazing over a longer period of time will probably result in the creation of monospecific stands of those perennial species most able to survive grazing pressure (Oatham et al., 1995), or those escaping grazing through high concentration of secondary compounds unpleasant or toxic to animals. In 1981, a detailed survey of the rangelands of northern and central Oman concluded that these are highly degraded (Anonymous, 1982), and recent work suggests that if the present trend continues most rangelands will become completely treeless and weed-infested within the next 20–30 years (Ghazanfar, 2003).

The highest browsing intensity in this study was found on the Sayh plateau near Sayh Qatanah, the central settlement of the Jabal al Akhdar, reflected by the stunted development of the ground layer and a severely impoverished species composition. A sharp decline in the populations of the most palatable annual plant species, especially of grasses, has been observed for that area, as well as the establishment of invasive species (Anonymous, 1982; Ghazanfar, 1998), such as *Dodonaea viscosa* and *Euryops arabicus*.

The results of the multivariate analysis confirmed this observation. For similar abiotic site conditions, the cluster analysis illustrated a clear floristic separation between grazed and ungrazed plots on the limestone plateau at 2000 m a.s.l. The ungrazed sites (Ras al Kabul plateau and the studied exclosure) are characterised by the *Olea europaea–Fingerhuthia africana* group, which is particularly well defined with a high number of indicator species, including many grass species. The floristic composition of the ungrazed areas differed significantly from that of the grazed areas described as *Sideroxylon mascatense–Dodonaea viscosa* group, although the exclosure was fenced off only ten years ago. This indicates the relatively fast and high regeneration potential of the local vegetation which confirms reports of Thalen (1979) that the vegetation cover on desert rangelands protected from grazing increases after only one or two seasons. This is also supported by data of Oatham et al. (1995) and Shaltout et al. (1996) for Saudi Arabia.

5. General conclusions

The rangeland vegetation in the present study showed different vegetation types along an altitudinal and a grazing gradient. As such it mirrors particularly the effects of altitude, grazing intensity and landform on plant species composition and diversity. The identified vegetation groups and plant species compositions are typical for the whole Al Jabal al Akhdar region and correspond to the results of Patzelt (submitted for publication) who investigated plant community aspects for a broader area, including Jabal Shams and the upper Wadi Mistal. The latter study indicates a relict situation of the mountain flora of northern Oman with high endemism and a strong link to the Irano-Turanian geoelement and the vegetation of the mountains in southern Iran, Afghanistan and southwest Pakistan.

Remote parts of the northern mountains are still poorly investigated and future work is needed to study the distributions of plant communities and threatened species in more detail, particularly in relation to grazing effects of goat and sheep herds but also of feral donkeys on natural vegetation. As demonstrated by the data obtained from the ungrazed sites, there seems great potential for recovery of the vegetation of these rangelands if the grazing pressure is reduced on the mid- to long term. Given Oman's policy to increase local production and to reduce dependence on imports of food such as goat meat, it is clear that the grazing pressure will continue to increase in the future, requiring the development of sustainable management strategies.

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References

Abd El-Ghani, M.M., Abdel-Khalik, K.N., 2006. Floristic diversity and phytogeography of the Gebel Elba National Park, South-East Egypt. Turkish Journal of Botany 30, 121–136.

Al-Sodani, Y.A., Shehata, M.N., Shaltout, K.H., 2003. Vegetation along an elevation gradient in Al Jabal al Akhdar, Lybia. Ecologia Mediterranea 29, 35–47.

Alexander, R., Millington, A., 2000. Vegetation Mapping: From Patch to Planet. John Wiley and Sons, Chichester.

Anonymous, 1982. Range and Livestock Survey. Ministry of Agriculture and Fisheries, Oman (unpubl.).

Austin, A.T., Smith, T.M., 1989. A new model for the continuum concept. Vegetatio 83, 35–47.

Batanouny, K.H., Baeshin, N.A., 1983. Plant communities along the Medina-Badr road across the Hejaz mountains, Saudi Arabia. Vegetatio 53, 33–43.
Béchennec, F., Roger, J., Le Métour, J., Wyns, R., 1992. Geological Map of Seeb. Explanatory Notes. Ministry of Petroleum and Minerals, Sultanate of Oman.
Beyer, H.L., 2004. Hawth's Analysis Tools for ArcGIS. Available at http://www.spatialecology.com/htools.
Botta-Dukát, Z., 2005. Rao's quadratic entropy as a measure of functional diversity based on multiple traits. Journal of Vegetation Science 16, 533–540.
Bravo, D.N., Araujo, M.B., Romdal, T., Rahbek, C., 2008. Scale effects and human impact on the elevational species richness gradients. Nature 453, 216–220.
CBD (Convention on Biological Diversity), 1997. First National Report. Ministry of Regional Municipalities and Environment, Sultanate of Oman. http://www.cbd.int/doc/world/om.
Cope, T.A., 1988. The flora of the sands. In: The Scientific Results of the Royal Geographical Society's Oman Wahiba Sands Project 1985–1987. Journal of Oman Studies Special Report Vol. 3, 305–312.
part 1 Cope, T.A., 2007. In: Knees, S.G., Miller, A.G. (Eds.), Flora of the Arabian Peninsula and Socotra, Vol. 5. Edinburgh University Press, Edinburgh.
Curtin, C.G., 2002. Livestock grazing, rest, and restoration in arid landscapes. Conservation Biology 16, 840–842.
Deil, U., Müller-Hohenstein, K., 1996. An outline of the vegetation of Dubai (UAE), in: Verhandlungen der Gesellschaft für Ökologie ZDB-Info zu diesem Werk, Band 25, 77–96.
Deil, U., Al Gifri, A.N., 1998. Montan and Wadi Vegetation. In: Ghazanfahr, S.A., Fisher, M. (Eds.). Vegetation of the Arabian Peninsula, Kluwer, Dordrecht, pp. 125–174.
Dietvorst, P., van der Maarel, E., van der Putten, H., 1982. A new approach to the minimal area of a plant community. Vegetatio 50, 77–91.
Dickhoefer, U., Buerkert, A., Brinkmann, K., Schlecht, E. The role of pasture management for sustainable livestock production in semi-arid subtropical mountain regions. Journal of Arid Environments, submitted for publication.
Dufrêne, M., Legendre, P., 1997. Species assemblages and indicator species: the need for a flexible asymmetrical approach. Ecological Monographs 67 (3), 345–366.
Fisher, M., 1994. Another look at the variability of desert climates, using examples from Oman. Global Ecology and Biogeography Letters 4 (3), 79–87.
Fisher, M., Gardner, A.S., 1995. The status and ecology of a *Juniperus excelsa* subsp. *polycarpos* woodland in the northern mountains of Oman. Vegetatio 119, 33–51.
Frey, W., Kuerschner, H., 1986. Masquat area (Oman). Remnants of vegetation in an urban habitat, in: Kuerschner, H. (Ed.), Contributions to the Vegetation of Southwest Asia. Beih. TübingerAtlas des Vorderen Orients, Reihe A, Nr. 24, Wiesbaden, pp. 201–221.
Gebauer, J., Luedeling, E., Hammer, K., Nagieb, M., Buerkert, A., 2007. Mountain oases in northern Oman: An environment for evolution and in situ conservation of plant genetic resources. Genetic Resources and Crop Evolution 54, 465–481.
Ghazanfar, S.A., 1991a. Floristic composition and the analysis of vegetation of the Sultanate of Oman. Flora et Vegetatio Mundi 9, 215–227.
Ghazanfar, S.A., 1991b. Vegetation structure and phytogeography of Jabal Shams, an arid mountain in Oman. Journal of Biogeography 18, 299–309.
Ghazanfar, S.A., 1992. An Annotated Catalogue of the Vascular Plants of Oman. Scripta Botanica Belgica, Vol. 2. National Botanic Garden of Belgium, Meise, 153 pp.
Ghazanfar, S.A., 1997. The phenology of desert plants: a 3-year study in a gravel desert wadi in northern Oman. Journal of Arid Environments 35, 407–417.
Ghazanfar, S.A., 1998. Status of the flora and conservation in the Sultanate of Oman. Biological Conservation 85, 287–295.
Ghazanfar, S.A., 2003. Flora of the Sultanate of Oman. Vol. 1: Piperaceae to Primulaceae. Scripta Botanica Belgica 25, 262 pp.
Ghazanfar, S.A., 2007. Flora of the Sultanate of Oman, Vol. 2: Crassulaceae—Apiaceae. Scripta Botanica Belgica 36, 220 pp.
Hegazy, A.K., El-Demerdash, M.A., Hosni, H.A., 1998. Vegetation, species diversity and floristic relations along an altitudinal gradient in south-west Saudi Arabia. Journal of Arid Environments 38, 3–13.
Jongman, R.H.G., ter Braak, J.F., van Tongeren, O.F.R., 1987. Data Analysis in Community and Landscape Ecology. Pudoc, Wageningen, 321 pp.
Khan, M.I.R., 1982. Management, conservation and development of agricultural resources in the United Arab Emirates. Emirates Nat. Hist. Group (Abu Dhabi) Bull. 16, 9–19.
Kharbotly, A.E., 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.
Kuerschner, H., 1998. Die aktuelle und natürliche Vegetation der Masqat-Region (Nord-Oman) mit einem Versuch der Rekonstruktion der spät-steinzeitlichen Vegetationsverhältnisse, in: Hannss, C. and Kuerschner, H. (Eds.), The Capital Area of Northern Oman, Teil II. Beih zum Tübinger Atlas des Vorderen Orients, Reihe A (Naturwissenschaften) Nr. 31/2, pp. 159–187.
Lancaster, W., Lancaster, F., 1990. Desert Devices: The pastoral system of the Rawala Bedu. In: Galety, J.C., Johnston, D.L. (Eds.), The World of Pastoralism. Guilford Press, New York, pp. 177–194.
Legendre, P., Legendre, L., 1998. Numerical Ecology, second ed. Elsevier, Amsterdam, 870 pp.
Lepš, J., de Bello, F., Lavorel, S., Berman, S., 2006. Quantifying and interpreting functional diversity of natural communities: practical considerations matter. Preslia 78, 481–501.
Lepš, J., Šmilauer, P., 2003. Multivariate Analysis of Ecological Data Using CANOCO. Cambridge University Press, Cambridge, 282 pp.
Lomolino, M.V., 2001. Elevational gradients of species-density: historical and prospective views. Global Ecology and Biogeography 10, 3–13.
Luedeling, E., Buerkert, A., 2008. Effects of land use changes on the hydrological sustainability of mountain oases in northern Oman. Plant and Soil 304, 1–20.
Luedeling, E., Siebert, S., Buerkert, A., 2007. Filling the voids in the SRTM elevation model—A TIN-based delta surface approach. Journal of Photogrammetry and Remote Sensing 62 (4), 283–294.
Madeira, S.C., Oliveira, A.L., 2004. Biclustering Algorithms for Biological Data Analysis: A Survey. IEEE/ACM Transactions on Computational Biology and Bioinformatics 1, 24–45.
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, vol. 1, pp. 229–267.
Mandaville, J.P., 1985. A botanical reconnaissance in the Musandam region of Oman. Journal of Oman Studies 7, 9–28.
McCune, B., Grace, J.B., Urban, D.L., 2002. Analysis of Ecological Communities. MjM Software Design, Oregon, 300 pp.
Milchunas, D.G., Sala, O.E., Lauenroth, W., 1988. A generalized model of the effects of grazing by large herbivores on grassland community structure. The American Naturalist 132, 87–106.
Miller, A.G., Cope, T., 1996. Flora of the Arabian Peninsula and Socotra, Vol. 1. Edinburgh University Press, Edinburgh, 586 pp.
Miller, A.G., Nyberg, J., 1991. Patterns of endemism in Arabia. Flora et Vegetatio Mundi 9, 263–279.
Oatham, M.P., Nicholls, M.K., Swingland, I.R., 1995. Manipulation of vegetation communities on the Abu Dhabi rangelands. I. The effects of irrigation and release from long-term grazing. Biodiversity and Conservation 4, 696–709.
Olff, H., Ritchie, M.E., 1998. Effects of herbivores on grassland plant diversity. Trends in Ecology and Evolution 13 (7), 261–265.
Olson, D.M., Dinerstein, E., 2002. The Global 200: Priority ecoregions for global conservation. Annals of the Missouri Botanical Garden Volume 89, 199–224.
Osem, Y., Perevolotsky, A., Kigel, J., 2004. Site productivity and plant size explain the response of annual species to grazing exclusion in a Mediterranean semi-arid rangeland. Journal of Ecology 92, 297–309.
Pacala, S.W., Crawley, M.J., 1992. Herbivores and plant diversity. The American Naturalist 140, 243–260.
Patzelt, A., 2004. Flora and vegetation of Juzur al Hallaniyat (the Kuria Muria Islands) with a report of additional species. Journal of Oman Studies 13, 139–153.
Patzelt, A., 2008. Oman Plant Red Data Book. Diwan of Royal Court, Office for Conservation of the Environment, Muscat, Sultanate of Oman.
Patzelt, A. The mountain vegetation of northern Oman: Ecology, phytosociology and biogeography of Olea europaea and Juniperus excelsa woodlands and of weed vegetation on cultivated terraces, in: Victor, R., Robinson, M. (Eds.). Al Jabal Al Akhdar Monograph, submitted for publication.
Petchey, O.L., Gaston, K.J., 2006. Functional diversity: back to basics and looking forward. Ecological Letters 9, 741–758.
Pillar, V.D., 1999. How sharp are classifications? Ecology 80, 2508–2516.
Riggs, R.A., Urness, P.J., 1989. Effect of goat browsing on gambel oak communities in northern Utah. Journal of Range Management 42, 354–360.
Radcliffe-Smith, A., 1980. The vegetation of Dhofar. Journal of Oman Studies, Special Report 2, 59–85.
Rafi, M., 1965. Vegetation types of Baluchistan Province. Pak. Govt. Printing Press, Punjab. Lahore, Pakistan.
Rahbek, C., 1995. The elevational gradient of species richness: a uniform pattern? Ecography 18, 200–205.
Rahbek, C., 2005. The role of spatial scale and the perception of large-scale species-richness patterns. Ecology Letters 8, 224–239.
Sankary, M.N., 1980. Ecology and phytogeography of Jabal al-Akhdar, Oman. 20th science week. ACSAD, Damascus.
Schlecht, E., Dickhoefer, U., Gumpertsberger, E., Buerkert, A., 2009. Grazing itineraries and forage selection of goats in the Al Jabal al Akhdar mountain range of northern Oman. Journal of Arid Environments 73 (3), 355–363.
Siebert, S., Nagieb, M., Buerkert, A., 2007. Climate and irrigation water use of a mountain oasis in northern Oman. Journal of Agricultural Water Management 89, 1–14.
Shaltout, K.H., El-Halawany, E.F., El-Kady, H.F., 1996. Consequence of protection from grazing on diversity and abundance of the coastal lowland vegetation in Eastern Saudi Arabia. Biodiversity and Conservation 5, 27–36.
Thalen, D.C.P., 1979. Ecology and Utilization of Desert Shrub Rangelands in Iraq. Dr W. Junk Publisher, The Hague, 448 pp.
Zohary, M., 1973. Geobotanical Foundations of the Middle East, Vol. 1. Gustav Fischer Verlag, Stuttgart, Germany.