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Analysis of GPS trajectories to assess goat grazing pattern and intensity in Southern Morocco

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Abstract. The assessment of grazing intensity is important for making adequate management decisions on rangelands. Using GPS collars, tended goat herds from three villages in southern Morocco were studied. The aim was to characterise their spatio-temporal movement patterns, i.e. the seasonal variation in grazing intensities, and daily trajectories of the herds. Furthermore, the effect of recording interval on recorded daily walking distances and the relationship between grazing intensities and distance was assessed. Grazing intensities were calculated within 4-ha grid cells for areas around settlements. The highest grazing intensities were found in the 250 m nearest the settlement. Some directions were totally avoided due to either community boundaries or adverse topography. The daily and maximum walking distances were significantly different between seasons. In the arid ecosystems the longest mean daily walking distance were found to be in the spring whereas in semiarid ecosystems it was in summer. It is argued that this variation in grazing pattern is mainly driven by varying fodder availability and its nutritive value, weather conditions and the length of day. The distances were longer in periods when fodder of high nutritive value was available, while cold temperatures and short days in winter limited the distances walked. The relationship between GPS recording interval and recorded trajectory length was described well by an exponential function, which in turn allows extrapolation from data with longer intervals to the actual distances travelled. Using non-linear regressions, the decay of grazing intensity with increasing distance was described better with power functions. The exponents ranged from –1.69 to –2.18, demonstrating that the goats were clumped around the settlements. The description of the grazing patterns of goats in this study provides valuable data for the parameterisation of grazing models.

Additional keywords: distance decay, GPS collar, grazing concentration, grazing intensity, non-linear regression, recording interval.

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Introduction

Dry rangelands cover large areas worldwide and constitute a source of subsistence for millions of people (World Resources Institute 2005). About 15% of these dry rangelands are affected by degradation, mostly through overgrazing (Steinfeld *et al*. 2006), which leads to a decrease in biodiversity and productive capacity. In Morocco, 82% of the drylands are used as rangelands and contribute to the subsistence of thousands of people (Mahyou *et al*. 2010). In recent years, however, these rangelands have suffered from severe degradation and reduced production (Fikri Benbrahim *et al*. 2004). For instance, in the Central and Oriental High Atlas 45% of the rangelands show symptoms of desertification (Mahyou *et al*. 2010). Overgrazing has been identified as one of the main drivers of this degradation. To deal with this situation, an evaluation of grazing intensities, the key management variable in the development of management strategies (Dumont *et al*. 2007) of these arid rangelands, should be a priority.

Grazing intensity, as defined by Holechek *et al*. (1998), is the cumulative effect of grazing animals on rangelands during a particular time period. Its assessment is very complex in the open collective rangelands of southern Morocco, due to the difficulty of quantifying the number of grazing animals and their spatio-temporal movement patterns. The rangelands of southern Morocco are used by sedentary and transhumant pastoralists (Akasbi *et al*. 2012*a*). Customary laws regulate the utilisation of rangelands by the herders, both between villages and within the same village (Bourbouze and Gibon 2000; Saqalli *et al*. 2002). However, the legal status of collective rangelands is often not clearly defined. Differences between administrative and tribal territories impede management decisions and block revenues resulting from collective lands. Ambiguity in the legal status of collective lands often favours long-term strategies for individual land claims that might block sustainable management decisions (Finckh and Kirscht 2008). Furthermore, the abandonment of traditional pastoral practices can accelerate the deterioration of rangeland conditions (Werner 2004).

Given the urgency for conservation and sustainable utilisation of these rangelands, there is a need for researchers to contribute to the development and implementation of management strategies by evaluating current land use practices and intensities. For this purpose, Global Positioning System (GPS)-collar techniques are effective tools for tracking livestock over time (Biggs *et al*. 2001). Several authors have used them for the determination of herd and flock itineraries and grazing areas (Rutter *et al*. 1997; Schlecht *et al*. 2006), or for the quantification of grazing intensities and the study of the behaviour of livestock (Kawamura *et al*. 2005; Tomkins and O'Reagain 2007; Putfarken *et al*. 2008).

Since 2000, the positioning error of GPS collar data has declined from ~30 to ~4 m due to the cancellation of Selective Availability (Adrados *et al*. 2002; Frair *et al*. 2004; Tomkiewicz *et al*. 2010). However, the limited battery power of GPS collars creates a trade-off between long recording periods without battery change and high temporal recording resolution. As temporal resolution influences the perceived distance walked by the animals (Pépin *et al*. 2004; Johnson and Ganskopp 2008), adequate statistical approaches are needed if one wants to combine extended recording periods with accurate data.

Despite some recent studies on rangeland management in southern Morocco (Finckh and Goldbach 2010; Freier *et al*. 2011; Akasbi *et al*. 2012*a*), there is still a lack of empirical baseline data on spatio-temporal grazing patterns in this region. There is no reliable information concerning the grazing intensity on common grazings, the grazing radius of tended goats, and the mean length of their daily itineraries.

No information on the physical and social factors delimiting the spatial extension of the grazing areas is available for southern Morocco. Interviewing the herdsmen on daily itineraries can help to understand the general background of grazing itineraries but it does not yield precise spatial information. A better understanding of spatio-temporal grazing patterns in addition to vegetation data would allow the development of spatially explicit models of livestock impacts on rangeland vegetation and improve decision-making about rangeland management (Rutter 2007).

The aim of the present study was to provide a detailed description of spatial and temporal grazing patterns of goat herds. Three tended sedentary goat herds in southern Morocco were tracked using GPS collars in order to understand their spatio-temporal pattern. The following questions were addressed: (i) how do herds use the space around their settlements during the course of the year, (ii) what are the grazing intensities on the three sites studied and could they be described according to a general model, and (iii) do the daily trajectories of the goats follow certain patterns? In order to derive data from GPS records of relatively low temporal resolution, an additional question was addressed: (iv) what is the effect of recording interval on perceived daily walking distance? A statistical approach was developed to deal with this latter issue.

Materials and methods

Study area

The study was conducted at three villages in the province of Ouarzazate in southern Morocco along an altitudinal gradient (Fig. 1). The village, Ameskar, is situated at ~2200 m a.s.l. in a narrow valley on the southern slopes of the main range of the Central High Atlas. The second village, Taoujgalt, is located at ~2000 m a.s.l. at the periphery of a large intra-montane basin in the southern ranges of the Central High Atlas. The third site is the small settlement of Azorz, close to the mines of Bou Skour, situated at 1420 m a.s.l. in the rocky hills of the northern Jebel Saghro, which is the eastern range of the Anti-Atlas. This site is subsequently referred to as Bou Skour.

The village, Ameskar, lies at the bottom of a deep west–east valley. In the lower mountain belt of Ameskar, the vegetation is an open juniper–sagebrush steppe dominated by three *Juniperus* species, three *Artemisia* species and several *Stipa* species, as well as *Teucrium* species (Schulz *et al*. 2010). The soils are skeletic Calcisols and calcaric Leptosols on the slopes, whereas Fluvisols occur on the floor of the valley (Miller 2002).

The village, Taoujgalt, lies in the foothills of the Atlas chain on a small plateau. The vegetation in the plains corresponds to a sagebrush steppe dominated by dwarf shrubs such as *Artemisia herba-alba* Asso, *Artemisia mesatlantica* Maire and *Teucrium mideltense* (Batt.) Humbert. On the slopes north-west of the village, the vegetation is similar to that of Ameskar. In terms of soil types, the plain is characterised by calcaric Leptosols and lepti-calcaric Regosols, whereas leptic Calcisols occur on the slopes (Miller 2002).

The site of Bou Skour lies on a slightly undulating plain that is dissected by several dry riverbeds. The vegetation corresponds to a semi-desert dominated by the Saharan dwarf shrubs *Hammada scoparia* (Pomel) Iljin and *Convolvulus trabutianus* Schweinf. & Muschl., accompanied by other dwarf shrubs. In spring, a large number of therophytic grasses and herbs produce a short boost of fresh biomass (Nedderhof 2009). Predominant soil types are calcaric Regosols as well as lithic and chromic Leptosols (Weber 2004), interspersed with basaltic outcrops (Schulz *et al*. 2010).

The three sites represent a climatic gradient from semiarid and relatively cold conditions in Ameskar to peri-arid and much warmer conditions in Bou Skour [Table 1, Supplementary materials (Appendix 1) as available on the journal's website]. The areas around the three settlements are used by transhumant and sedentary goat and sheep herds, but sedentary and mobile herders normally do not go into direct resource competition by avoiding each other's current rangelands (Akasbi *et al*. 2012*a*). The herds selected for the current analysis were sedentary and consisted exclusively of goats. They grazed from morning to evening in the surroundings of the settlements, always guided and kept together by herdsmen. Overnight, they were kept inside within the respective settlements.

Data collection

In each village, a healthy female goat was selected from one of the tended herds (Table 1) for GPS tracking during the whole study period. The selected goats were from the local race with a black body and a white face and ears, with an average liveweight of 18 kg (White House 2004). All collared goats had offspring within the monitoring period. The collared goats were supposed to indicate the daily itinerary of their tended herds. For the village, Ameskar, the selected herd was assumed to be representative for the whole village because it was logistically not possible to

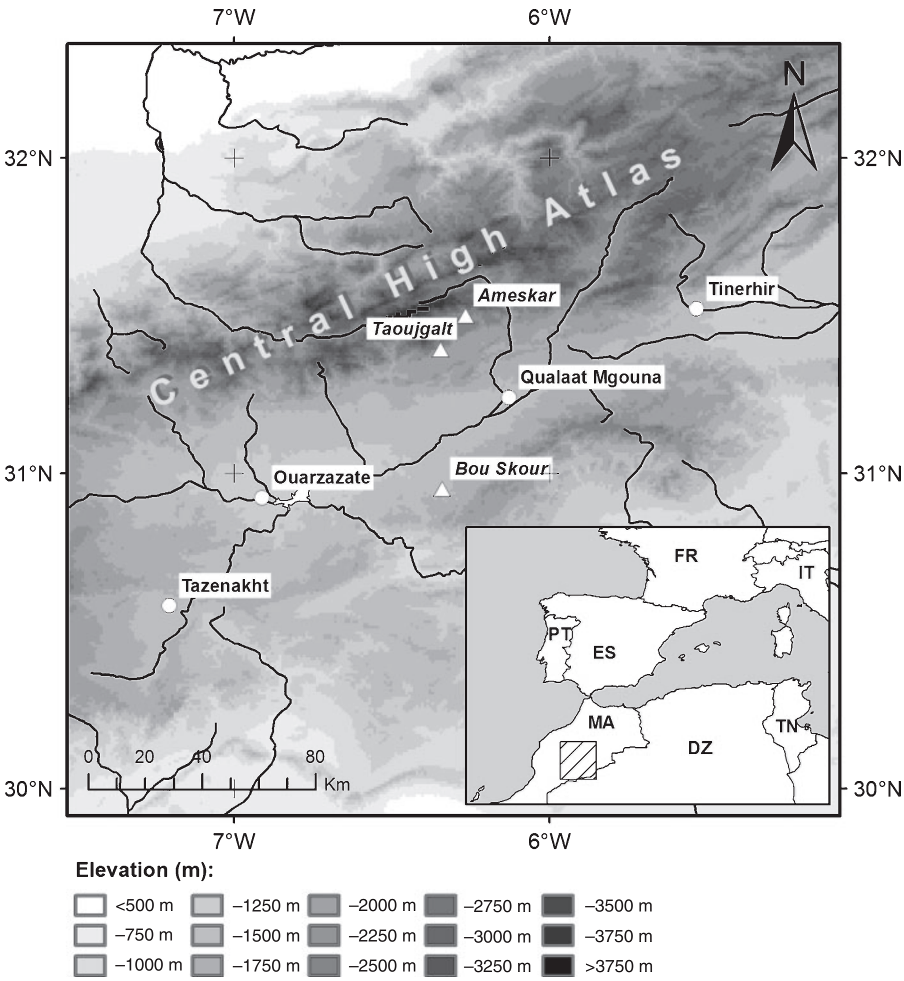

Fig. 1. Location of the study area in southern Morocco.

monitor all herds. A GPS PLUS-1 Store On Board Collar (Vectronic Aerospace, Berlin, Germany) was used. The GPS collar recorded the *x*/*y*/*z*-coordinates of the goat (i.e. longitude, latitude and altitude) from 0600 to 2200 hours. Two different time resolutions (15 min and 2 h) were used in order to (i) analyse the effects of temporal resolution and (ii) maximise battery life.

In Ameskar, the data covered the periods from April 2007 to January 2008 and from November 2008 to January 2009. The recording interval was set to 2 h for the first period and to 15 min for the second period. In Taoujgalt, data recording covered the periods from April to October in both 2007 and 2008. Here, a recording interval of 2 h was used. Data recording was interrupted from October 2007 to April 2008 by a short-circuit in the GPS device. In Bou Skour, data recording covered two periods: from March to October 2007 and from November 2008 to June 2009. A recording interval of 2 h was used during the first period and 15 min in the second.

Data analysis

Effect of the temporal resolution on the recorded distance

To analyse the effect of the recording interval (I) on the recorded daily walking distance (D), the GPS data of Bou Skour were chosen since they contained the longest time series with a resolution of 15 min ($n = 14\,570$). From this dataset, lower resolution subsets were created corresponding to recording intervals of 30, 45, 60, 75, 90, 105 and 120 min by omitting records. The recorded daily walking distance was then calculated using *x*/*y* coordinates for each day and averaged over the whole study period for each of the resolution subsets. In order to determine the functional relationship between recorded distance and recording interval, non-linear regressions were applied with STATISTICA 8.0 (StatSoft Inc. 2007). Three different function types were compared: inverse, power and exponential, all continuously falling and approaching a lower limit, and each in two variants with the lower limit being either zero or a constant c (Table 2). The default setting of the program was used [loss function = (OBS – PRED)^2; estimation method = quasi-Newton; convergence criterion = 0.0001; step width for all parameters = 0.5; starting values for all parameters = 0.1]. When these settings did not lead to convergence, starting values previously established in similar situations were used until the iterations yielded a result. As the models differed in their complexity (1–3 fitted parameters + estimated variance), the Akaike Information Criterion corrected for small n was used (AIC$_c$; Burnham and Anderson 2002) for model selection, calculated in the ordinary

Table 1. Overview of climate and land use data for the three study sites
If no source is given, the information is based on the authors' observations

	Settlements Ameskar	Taoujgalt	Bou Skour
(a) Location	31°30′N, 6°14′W, 2 205 m a.s.l.	31°23′N, 6°19′W, 2 088 m a.s.l.	30°57′N, 6°20′W, 1 420 m a.s.l.
(b) Climate			
Mean annual precipitation from 2001 to 2006 (Schulz *et al.* 2010)	341 mm	238 mm	135 mm
Mean annual temperature (Schulz *et al.* 2010)	13.0°C	14.2°C	19.1°C
Bio-climate (Oldeland *et al.* 2008)	Semiarid cold	Semiarid cold	Per-arid cool
Vegetation growth period	May–June	March–April and September–October	March–April
(c) Land use			
General	Silvo-pastoral use for sheep and goats, firewood collection	Pastoral use for sheep and goats, firewood collection	Pastoral use for goats
(d) Herds			
Total number of sheep and goats in the studied villages	1000	350	370
Number of herds per village	17	2	2
Number of goats in the study herd	50	50	120
Identity of the herder	A member of the family (adult man)	Study herd: a member of the family (adult man) Other herds: several families join their animals and share the herding	A member of the family (shared between adult men and children)
(e) Standing biomass			
Mean standing biomass (kg DM ha^{-1})	3500[A]	2599 ± 394	3004 ± 197.64
Author	Bryl (2009)	Ben-Najim (2009)	Nording (2008)
Years of data collection	2006–08	2009	2007
Number of plots	2 plots of 100 m^2 each	126 plots of 4 m^2	124 plots of 4 m^2

[A]Only two measurements were available, thus no standard error of the mean is calculated.

Table 2. Regression functions used for the analysis of the relationships between recorded daily walking distance (*y*) and recording interval (*x*) (all models) and between grazing intensity (*y*) and distance from the settlement (*x*) (models with *)
The letters *a*, *b*, and *c* denote fitted parameters

Function name	Formula	Number of parameters
Inverse function*	$y = a/x$	1
Inverse function with constant	$y = a/\times + c$	2
Power function*	$y = a\,x^b$	2
Power function with constant	$y = a\,x^b + c$	3
Exponential function*	$y = a \exp(b\,x)$	2
Exponential function with constant	$y = a \exp(b\,x) + c$	3

least-squares framework. As a goodness-of-fit measure, Akaike weights (w_i), which are the probability that a given model is the best among those compared, are presented (Burnham and Anderson 2002).

Spatial patterns of the grazing herds

For each site, circular vector grids of radius 3900 m were created around the settlement using ArcGIS 9.3 (ESRI 2010). This defined radius corresponds to the maximum grazing distance at a 2-h interval found for any of the villages. The grid cells were 200×200 m (4 ha) in size and the settlement was positioned in the centre of the vector grid. Then, the number of recorded GPS positions in each grid cell was counted. Finally, the grazing intensities in each grid cell were calculated using the formula:

$$GI_{\mathrm{herd},\,i} = n_i \times N_{\mathrm{herd}} \times R \times D^{-1} \times GP^{-1} \times S^{-1}$$

with $GI_{\mathrm{herd},i}$ (goats ha^{-1}) being grazing intensity of the herd in grid cell i; n_i is the number of records within grid cell i; N_{herd} is the number of goats in the herd; R is the GPS recording interval (2 h); D is the daily grazing period (for this purpose a standard period of 12 h was used); GP is the total grazing period (number of days recorded); and S is the area of the grid cell (4 ha).

The spatial grazing patterns of each of the three studied herds (GI_{herd}) were visualised using ArcGIS, both for the whole study period and for the separate seasons. The seasons were defined as follows: spring (March–May), summer (June–August), autumn (September–November) and winter (December–February). In Taoujgalt, due to a lack of data from the winter months, only three seasons were analysed: spring, summer, and autumn. To help interpretation, additionally the topography of the study area was plotted with a 90-m digital elevation model provided by the

National Aeronautics and Space Administration's Shuttle Radar Topography Mission (Jarvis *et al*. 2006).

Grazing intensities around the villages

While GI_{herd} was used to describe the spatio-temporal grazing pattern of a particular herd, $GI_{village}$ was applied to characterise the grazing intensities for the village as a whole. This allowed comparison between the three study sites as well as with published data. Underlying the calculation of $GI_{village}$ is the assumption that the different village herds, while potentially using different sectors around the village, essentially follow the same distance decay function of grazing intensity.

Accordingly, the interest was in the distance of the grid cells, not in their direction. The distance from the cell centroid to the settlement was used, and assigned a value of 50 m to the central grid cell (instead of 0 m) as here the mean distance from the settlement to edge was ~50 m. $GI_{villages}$(animals ha^{-1}) was calculated as follows:

$$GI_{\mathrm{village},\,i} = GI_{\mathrm{herd},\,i} \times N_{\mathrm{village}} \times N_{\mathrm{herd}}{}^{-1}$$

with $N_{village}$ being the total number of goats and sheep in the village (Table 1). In order to make the grazing intensities per village comparable, the grid cells were grouped into five distance classes (0–250, 250–500, 500–1000, 1000–2000 and 2000–4000 m) and mean $GI_{village}$ values for each distance class were calculated. Then, the distance decay in *GI* was modelled with the same modelling approach and set of functions as those used for recorded distance *v.* recording interval (see Table 2). The comparison was only restricted to the three model variants without constants as $GI_{village}$ should always approach zero for very large distances.

Daily trajectories of the goats

The daily trajectories of the goats were analysed based on the GPS-measured *x*/*y*/*z* coordinates, using all recording periods, which were standardised to a recording interval of 2 h. In order to assess the daily walking distance, the linear distances were summed between each pair of successive *x*/*y* coordinates for each day, including the settlement as the starting and end point of each daily trajectory. Likewise, the daily maximum distance from the settlement was determined by calculating the linear distance of each point to the settlement and then selecting the maximum distance. For the vertical distance, the linear distance between the *z*-values of the GPS collar and the altitude of the settlement was calculated, and then selected the maximum distance for each day. For all distances, one-way ANOVA were used to analyse whether distances differed between seasons, implemented in STATISTICA 8.0 (StatSoft Inc. 2007), followed by HSD *post hoc* tests for unequal *N* with $\alpha = 0.05$. Furthermore, within-day trajectories, i.e. how the time of day influenced the distance from the settlement, were analysed using ANOVA.

Results

Effect of the temporal resolution on the recorded distance

Smaller GPS recording intervals (*I*) led to a significant increase in the recorded daily walking distance (*D*; Fig. 2). For instance, the calculated distance increased by 18% when the recording interval was reduced from 2 to 1 h. Among the six models compared, the exponential function with constant explained the relationship best ($w_i = 94.6\%$), followed by the power function ($w_i = 4.8\%$), while the four other functions were unsuitable. The equation of the best model was: $D = 3340 \exp^{(-0.0177 \times I/\mathrm{min})} + 3953$. Using this function to extrapolate to a recording interval of 0 min (i.e. continuous recording) yielded a distance of 7293 m. The actual distance thus becomes 68% longer than the one recorded at 2-h intervals.

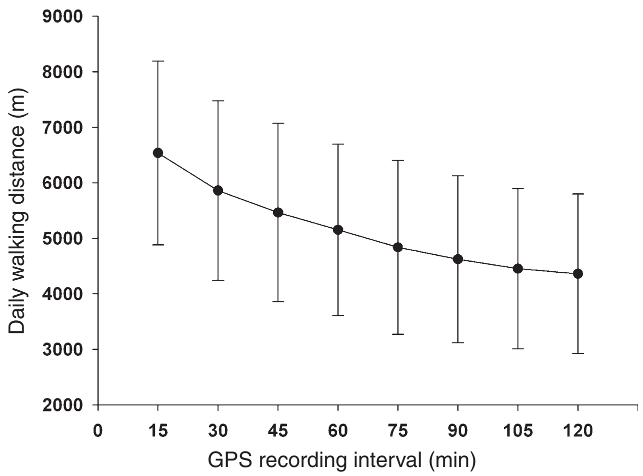

Fig. 2. Relationship between the recording interval (*I*) (min) and the recorded daily walking distance (*D*) (m) for the collared goat in Bou Skour. The error bars show the standard deviation. The best-fitting regression function according to AIC$_c$ was $D = 3340 \exp^{(-0.0177 \times I/\mathrm{min})} + 3953$ ($R^2 = 99.8\%$).

Spatial patterns of the grazing herds

Grazing patterns were distributed around the settlements in the three villages (Fig. 3). Generally, grazing intensities were highest in the immediate vicinity of the settlements and showed a strong decline with distance. In both mountainous villages, Ameskar and Taoujgalt, grazing stretched up to the hills but not on the other side of the hilltops, while in Bou Skour grazing was more concentrated south of the riverbed (see KMZ files in Supplementary materials, Appendix 2). In Ameskar, the grazing pattern showed only a slight deviation from a radial distance decay, while in the other two villages, grazing was concentrated in certain directions, mainly north–south, while other directions were completely avoided.

In Ameskar, the grazing range stretched further to the north and north-west, while visits to the south and south-east seemed to be avoided (Fig. 3). The area visited by the herd differed little between seasons (Supplementary materials, Appendix 3). During autumn and summer, the herd was scattered over a slightly larger area than in winter and spring, with little variation in grazing intensity.

In Taoujgalt, the grazing intensity was highest in the valley north of the settlement, while the rangelands east of the settlement were mostly avoided by the herd (Fig. 3). The grazing pattern varied between the seasons such that, in summer, longer trajectories northwards and southwards were covered than in autumn and spring (Supplementary materials, Appendix 4). In spring, the herd moved mostly to the north and rarely to the south.

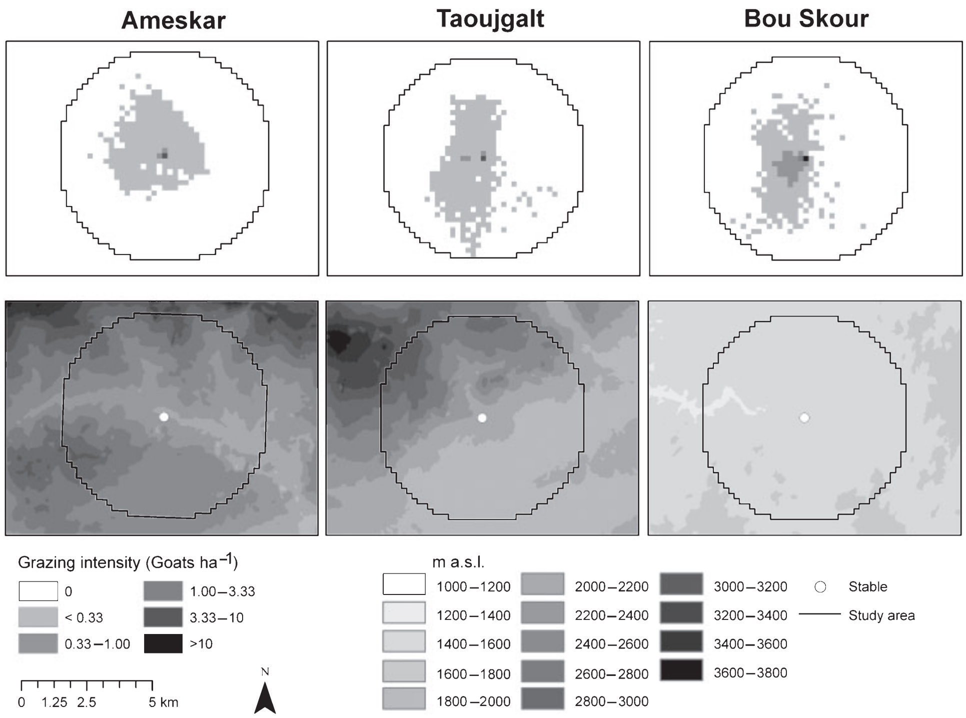

Fig. 3. Grazing intensity patterns of the studied herds (GI_{herd}) of the three villages Ameskar, Taoujgalt, and Bou Skour (top row and left-hand legend) in comparison with the topography of the sites (bottom row and right-hand legend). For a 3D view in Google Earth, please see KMZ files in Supplementary materials (Appendix 2).

In Bou Skour, the grazing pattern extended in the north–south direction with the highest grazing intensities in the west and south of the settlement while the areas east were mostly avoided (Fig. 3). The grazing area varied between the seasons, whereas little variation in grazing intensity was observed (Supplementary materials, Appendix 5). The areas visited in winter were limited in comparison to the other seasons and the northern part was mostly avoided.

Grazing intensities around the villages

At all three villages, $GI_{village}$ decreased continuously with distance from the village (Table 3). For all distance classes, grazing intensities were highest in Ameskar. Grazing intensities were similar in Bou Skour and Taoujgalt, but differed across the distance classes. They were more than twice as high for Bou Skour within the first distance class (250 m radius around the settlement), but then declined steeply to slightly lower levels than for Taoujgalt in the more distant areas.

For all three villages, the power function was the best among the three models compared (w_i = 67.8–80.7%), followed by the exponential function (w_i = 19.3–32.2%), while the inverse function (i.e. a power function with fixed exponent of –1) performed poorly (w_i = 0.001–0.5%; Table 4). The exponent of the power function was highest for Taoujgalt (–1.69) and lowest for Bou Skour (–2.18) (Table 4), indicating the strongest distance decay of grazing intensity in the latter site.

Daily trajectories of the goats

The mean daily walking distance was 3580 m in Ameskar, 3480 m in Taoujgalt, and 4460 m in Bou Skour, based on the 2-h GPS recording interval. The daily walking distances varied significantly with season in all the three sites according to the ANOVA ($P < 0.001$; Fig. 4). However, the *post hoc* test revealed different homogenous groups within each site. In general,

Table 3. Mean grazing intensities in different distance classes around the goat shed (village), calculated for all animals (goats and sheep) of the respective village ($GI_{village}$)

Distance from the goat shed (m)	$GI_{village}$ (animals ha^{-1}) Ameskar	Taoujgalt	Bou Skour
0–250	22.030	6.187	13.099
250–500	1.603	0.673	0.658
500–1000	0.809	0.436	0.495
1000–2000	0.387	0.141	0.132
2000–4000	0.012	0.009	0.004

Table 4. Best fitting regression functions of $GI_{village}$ (goats ha^{-1}) on distance D (in m)

Among the three compared models (inverse function, power function, exponential function), the power function always performed best

Study site	Function	R^2	w_i
Ameskar	$GI_{village} = 157\,287\ D^{-1.91}$	0.9767	80.7%
Taoujgalt	$GI_{village} = 17\,012\ D^{-1.69}$	0.9356	78.5%
Bou Skour	$GI_{village} = 291\,488\ D^{-2.18}$	0.9808	67.8%

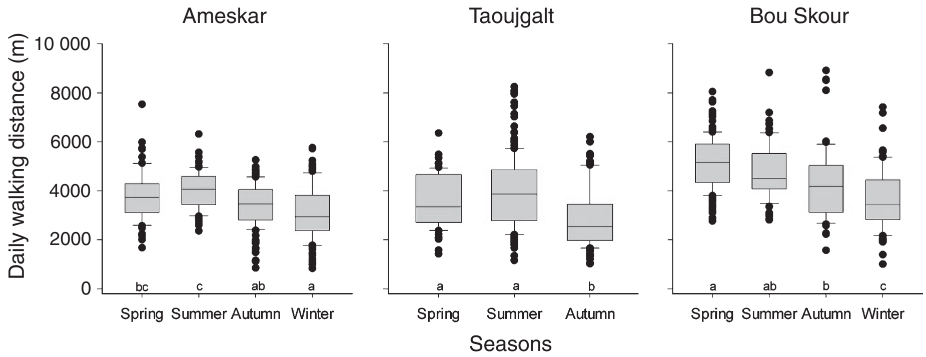

Fig. 4. Seasonal variation in the daily walking distance recorded at a 2-h recording interval for each of the three sites. Medians, interquartile ranges, total ranges without outliers, and outliers are shown. All sites showed a significant variation between seasons according to ANOVA ($P < 0.001$). The same letters under the box plots denote homogeneous groups according to the *post hoc* test.

distances in spring and summer as well as in autumn and winter were more similar. The many outliers indicate that the distances also varied strongly within the seasons.

In Ameskar and Taoujgalt, the mean daily walking distance was longest in summer and shortest in winter and autumn. At both villages, it reached a maximum of 4000 m (June) and decreased to a minimum of 3130 m in Ameskar and to 2880 m in Taoujgalt. In Bou Skour, the mean daily walking distance showed a continuous decrease from spring to winter. The longest mean daily walking distance of 5130 m was registered in spring while the shortest distance of 3680 m was registered in winter (note that these are the uncorrected values at a 2-h resolution; the true values are higher, see subsection *Effect of the temporal resolution on the recorded distance* in the Results section).

The maximum daily walking distance from the settlement varied significantly between seasons at all three sites (Supplementary materials, Appendix 6). The patterns were quite similar to those of the mean daily walking distances at Ameskar and Taoujgalt (Fig. 4). However, the patterns differed at Bou Skour where the mean daily walking distance showed a decrease during the year while highest maximum distances from the settlement were found in autumn. In Ameskar, the mean maximum distance reached its highest seasonal value of 1700 m in summer and its lowest value of 1340 m in winter. In Taoujgalt, the maximum distance from the settlement was also greatest in summer at 1700 m and least in autumn at 1250 m. In Bou Skour, the maximum distance from the settlement reached the highest seasonal mean of 1760 m in autumn and the lowest mean value of 1450 m in spring.

The daily trajectories of the goats in the three villages started in the morning at ~0800 hours (or between 0600 and 0800 hours in the case of Bou Skour) and ended at ~2000 hours (Fig. 5). Distances to the settlement over time followed a unimodal distribution in Ameskar and Taoujgalt with a peak at 14 h. The longest mean distance from the settlement during the day reached ~1500 m in Ameskar and Taoujgalt. In Bou Skour, the distance from the settlement reached a plateau of ~1000 m between 1200 and 1600 hours. While the mean trajectories followed a clear pattern, there was much variation between days at all three sites, indicated by the high standard deviations. For example, in Ameskar at 1200 hours, the distance from the settlement ranged from less than 700 m to more than 1500 m.

The maximum vertical distance from the settlement varied significantly between seasons in Ameskar and Taoujgalt according to the ANOVA ($P < 0.001$), while it was not significant in Bou Skour ($P = 0.747$; Fig. 6). The maximum vertical distance from the settlement was longest in Taoujgalt in spring with a mean of 302 m and shortest in summer with a mean of 141 m, while in Ameskar it was longest in summer with a mean of 285 m and shortest in winter (177 m). In Bou Skour, the maximum vertical

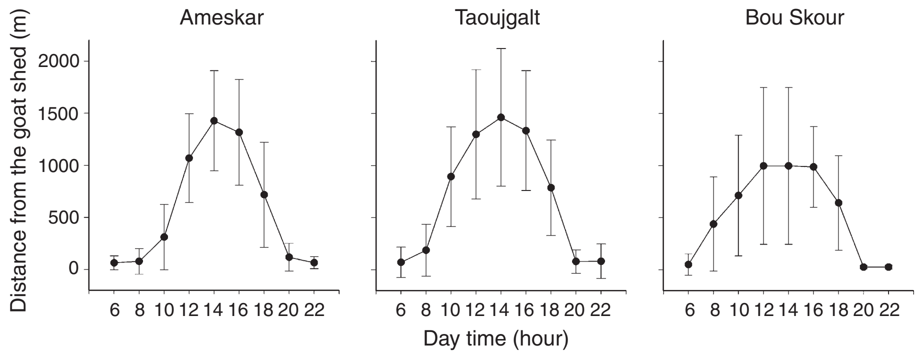

Fig. 5. Mean within-day trajectories of the studied goat herds in the three sites. The error bars represent the standard deviation. For all three villages, the ANOVA yielded significant temporal pattern ($P < 0.001$).

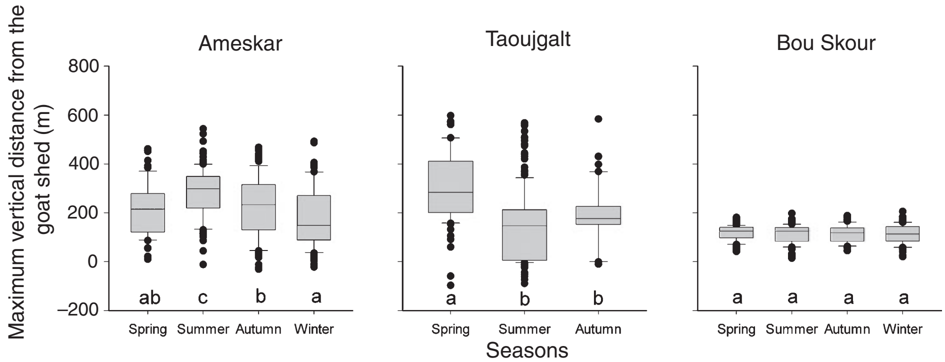

Fig. 6. Seasonal variation in the maximum vertical distance from the goat shed recorded at 2-h recording interval for each of the three sites. Medians, interquartile ranges, total ranges without outliers, and outliers are shown. The same letters under the box plots denote homogeneous groups according to the *post hoc* test.

distance from the settlement did not show any significant difference between seasons and varied between 112 and 117 m. The *post hoc* test showed that summer differed from the other seasons in Ameskar while, in Taoujgalt, spring was different from the other seasons (Fig. 6).

Discussion

Our results are based on the analysis of movement patterns of a single goat representing a herd from a specific village. This could potentially bias our results because the movements of one single goat might not be representative for the whole herd. However, we observed that the herds we studied were rather small (see Table 1) and that these were kept close together by herders. Another potential bias could be that our comparisons of grazing patterns between seasons of different years were influenced by the specific weather conditions. A comparison of the weather data for the time periods of the analysis did not show strongly different pattern between the years at the study sites (Supplementary materials, Appendix 7). In general, temperature values varied less than precipitation. However, autumn precipitation in Bou Skour and Taoujgalt showed highest variation between 2007 and 2008 with higher precipitation values for 2008. Hence, the results for this season should be interpreted carefully. Winter precipitation in Ameskar also showed high variation between the years 2007 and 2008. However, this variation does not influence the movement pattern of the herd because in winter movement is mainly limited by low temperatures, which were similar between the years (Supplementary materials, Appendix 7, see subsection on *Spatial patterns of the grazing herds*).

Effect of the temporal resolution on the recorded distance

The detected negative effect of lower temporal resolution (i.e. higher recording interval) on the recorded walking distance was expected as the trajectories are inevitably shorter when fewer GPS points are connected (see also Pépin *et al.* 2004; Johnson and Ganskopp 2008). For cattle in the Great Plains, USA, Johnson and Ganskopp (2008) found a decrease of more than 50% in the estimated walking distance between recording intervals of 5 and 160 min. Based on the regression function developed in this study, the decrease would be slightly more than 40% for the same recording intervals (5 and 160 min) for the goats in Bou Skour: a remarkably similar result given the different livestock species and countries. As in Johnson and Ganskopp (2008), the exponential decay function with a constant proved to be the best model. These authors did not explicitly state which functions they compared and which statistics they used for model selection. The approach in this study, however, allows us to have confidence in the results, using information criteria and taking into consideration six possible decay functions. The best fitting functions in both cases had a constant. This constant corresponds to the limit of spatial distance between two points of the trajectory as the temporal distance increases. This value of 3953 m, therefore, represents the mean distance between two random points within the grazed area (weighted by the frequency of visit).

Determining the regression function between GPS resolution and recorded daily walking distance of livestock is important since it allows extrapolation from discontinuously recorded data to continuous data which is the length of the actual trajectory. Furthermore, this regression approach allows the comparison of data produced in different studies of varying temporal resolution (see subsection *Daily trajectories of goats* in the Discussion section). It is recommended that similar pilot studies should be conducted on the effect of temporal resolution on recorded walking distance before any GPS-based investigation on the length of walking trajectories by livestock. The establishment of regression functions from such pilot studies provides reliable estimates of actual trajectory lengths even with rather long recording intervals, thus enabling longer recording periods without battery change.

Spatial patterns of the grazing herds and flocks

Grazing intensity varies according to the movements of the livestock and their spatial distribution, which depend on many factors such as the availability, distribution and composition of forage (Adler and Hall 2005; van Beest *et al.* 2010). High grazing intensities around water points have been found in many studies of livestock behaviour and vegetation analyses are often regarded as sacrifice zones (Andrew 1988; Adler and Hall 2005; Kawamura *et al.* 2005; Todd 2006; Wesuls 2011). In this study it was found that the surroundings of settlements showed comparable patterns of sacrifice zone.

The spatial grazing patterns differed between the herds in this study. In Ameskar, grazing was more extended to the north and limited to the south. This is due to rugged topography i.e. steep slopes limiting access to the southern areas. In contrast, the northern areas consist of moderate slopes with vegetation, including many chamaephytes of high nutritive value for goats (Le Houérou 1980; Ben Salem *et al*. 2000). The eastern limit of the grazing area is defined by the boundary of the neighbouring village. In Taoujgalt, grazing occurred mainly in a north–south direction from the upper slopes to the north and west to the plain in the south. On the northern and western hill slopes browse for goats, i.e. many dwarf shrub species, are found while in the plain *Artemisia* and *Teucrium* species provide valuable biomass (Akasbi *et al*. 2012*b*). The eastern part was avoided because it was used by sedentary herds of the neighbouring village, Ait Youb, and some transhumant herds. In Bou Skour, grazing also showed a north–south direction with a higher grazing intensity in the west to south-west. This pattern arose due to the fact that the herder preferred this area for grazing, especially in winter. This core rangeland is sharply demarcated by a large dry riverbed. The area to the south-east and east (on the other side of the riverbed) is used by different sedentary community members. The herder avoided grazing his goats on a neighbour's land following the grazing rules in this village.

Several factors could influence the seasonal changes in the distribution of grazing such as precipitation, temperature and fodder availability (e.g. Güsewell *et al*. 2007; Putfarken *et al*. 2008). In Ameskar, a slight seasonal variation was observed in grazing areas and grazing intensities. During summer and autumn, the herd used a slightly larger area than in spring and winter. This limited movement in winter could be due to the harsh weather conditions on the mountain ridges in winter, with daily mean temperatures around 5°C and strong winds (Supplementary materials, Appendix 7). In Taoujgalt, the herd visited an area twice as large during summer in comparison to the other seasons. In spring, the herder used the slopes offering abundant shrub species rather than the sagebrush plain south of the village, because the plain is used in spring by transhumant pastoralists as transition rangeland before they are allowed to migrate into the high mountain rangelands at the end of May (Akasbi *et al*. 2012*a*). In contrast, during summer and autumn, when the transhumant pastoralists are using the high mountain rangelands, the herder also used the plain which offers a biomass peak of flowering *Teucrium mideltense* (in early summer) and *Artemisia herba-alba* (in autumn) (Gresens 2006). This would be in line with the herder's general tendency to avoid direct competition for forage between sedentary and transhumant herds.

The larger areas, used for grazing in the summer than the autumn, could thus be explained by extension of the competition-free rangeland available in this season. In Bou Skour, by far the most arid of the studied sites, the grazing area was larger during summer than in other seasons probably due to a reduction in forage available in the dry season. The northern part was mostly avoided in winter, due to the temporary presence of some transhumant pastoralists north of the riverbed who use this territory as winter rangeland (Akasbi *et al*. 2012*a*) and the sufficient availability of herbs and shrubs in the families' 'core-rangelands' south-west of the riverbed.

Grazing intensities around the villages

Grazing intensities were generally higher in Ameskar than in the other sites, reflecting the fact that this herd was almost 3 times larger and that the mean annual precipitation is ~2.5 times as high as in Bou Skour (Table 1). Grazing intensities ranged from 0.004 goats ha^{-1} at distances greater than 2000 m from the settlements, and up to 22 goats ha^{-1} within a 250-m radius around the settlements (Table 3). In the sacrifice zone in close proximity to the settlement, it was even higher (Table 4). Kawamura *et al*. (2005) reported for Inner Mongolia, China (with a mean annual precipitation of 350 mm) a grazing intensity between 0 and 72 048 SU ha^{-1} (SU = sheep unit), using for 5 days a 1-min recording interval in grid cells of 6.25 ha. From their daily recording time of 15 h, the 60 records per hour, and assuming that one goat corresponds to 0.8 SU, it can be calculated that their maximum grazing intensity value corresponds to 20 goats ha^{-1}. Thus, the maximum grazing intensity in Inner Mongolia is similar to that of Ameskar (with 341 mm precipitation), twice that of Bou Skour and 4 times that of Taoujgalt (Table 3). A study of comparable ecosystems in southern Africa, Soebatsfontein and Gellap Ost, with mean annual precipitations of 146 and 153 mm yielded grazing intensities of 0.07 and 0.06 SSU ha^{-1} (SSU = small stock unit, i.e. one sheep or goat), respectively, (Haarmeyer *et al*. 2010), which is much lower than for the 2-km radius of the climatically similar area of Bou Skour (135 mm). However, these grazing intensities were based on average grazing intensity within larger commonages of 15 000–20 000 ha. The average grazing intensity in this study, based only on the total area of the visited grid cells of 950–1120 ha, was calculated to be 1.13 SSU ha^{-1} in Ameskar, 0.37 SSU ha^{-1} in Taoujgalt and 0.57 SSU ha^{-1} in Bou Skour. In south-eastern Spain, Robles and Passera (1995) studied the carrying capacity of a farm in a mountainous area with mean annual precipitation of 324 mm. They found values ranging between 0.63 goats ha^{-1} and 0.92 goats ha^{-1}. This shows that the average grazing intensity is high in Ameskar and moderate to low in Taoujgalt and Bou Skour in relation to comparable rainfall areas. This is further supported by the investigation of Alaoui (1985) on the effect of three grazing intensities on sagebrush steppe in the upper Moulouya, being an area very similar (altitude, 1800 m a.s.l.; mean annual precipitation, 226 mm; and mean annual temperature, 14.1°C) to the general conditions at the Taoujgalt site in this study. Alaoui (1985) considered grazing intensities of 0.7 ewes ha^{-1} as low, 1 ewe ha^{-1} as moderate and 3 ewes ha^{-1} as high. Consequently, it is concluded that the grazing intensity around the settlement is very high within a radius of 250 m at Ameskar and Taoujgalt, moderate in the zone of 250–500 m in Ameskar and low at more than 500 m distance in Ameskar and at more than 250 m in Taoujgalt (Table 3). This classification scheme is not applicable in the arid rangelands of Bou Skour. Here, the very high grazing intensities around the settlement include resting times around the settlement during the morning and evening and should, therefore, be interpreted with caution.

Manthey and Peper (2010) mathematically derived a null model for grazing intensity around settlements, assuming that livestock generally move in a radial fashion and at constant pace away from and back to the settlement and thus that grazing intensity will be an inverse function (i.e. a power function with exponent –1). Manthey and Peper (2010) measured grazing intensity indirectly as dung density in the mountain rangelands of Azerbaijan, comparing the inverse and three other functions, and reported best fits for the inverse function. While their paper did not include the general power function – the best for the data in this study – in their comparison, their data indicate that in their case a power function with exponent –1 was indeed a reasonable model. However, in this study, the inverse function was not at all adequate. The exponents determined for the best-fit power models with values ranging from –1.69 to –2.18 indicate that here the distance decay is much stronger than expected by the null model. This means that the goats' presence is extremely clumped around the settlements and, as mentioned above, was probably due to resting time in the morning and evening. With this in mind, the ratio of the actual exponent to the theoretical exponent from the null model (–1) is proposed as a measure of grazing concentration (*GC*) around settlements and similar hotspots. A *GC* above 1 thus indicates unexpected clumping and a *GC* below 1 indicates an over-dispersion. With $GC = 2.18$, the strongest clumping of livestock activities was detected around the settlement in Bou Skour. This might be due to the fact that the owner of the herd in Bou Skour lived some distance from his neighbours. The herder let the goats rest and roam freely around his settlement from sunrise before the tended daily itinerary started at ~0800 hours while in Taoujgalt and Ameskar the herdsmen directly left the village with the herds and flocks.

Daily trajectories of the goats

In Ameskar and Taoujgalt, the mean daily walking distance and the maximum distance from the goat shed were longest in summer, while in Bou Skour the pattern was different. This could be explained by the difference in weather conditions (Supplementary materials, Appendix 1*a*–*c*) and the resulting forage availability in each village. In Ameskar, higher forage availability upslope in the oro-Mediterranean vegetation zone, together with longer days, led to larger distances in summer. In Taoujgalt, longer distances in summer were mainly due to the length of the day and less competition by other herds in this season, which led to bi-directional grazing trajectories to slopes and plain. The shortest distances in winter are mainly due to (i) the very cold weather in this season (as low as −4°C in Taoujgalt) and to (ii) the short daylength that shortened the herding time. In Bou Skour, longer walking distances in spring were mainly due to favourable weather conditions and availability of sparse but highly preferred herbs in this season (Nording 2008). In summer, heat makes a mid-day break indispensable and thus reduced the daily walking distances. The fact that the longest maximum distance from the settlement occurred in autumn rather than in spring can be explained by the fact that the herd in Bou Skour had to reach distant areas to find sufficient fodder in autumn when no herbs remained (Nording 2008). Other studies in other semiarid ecosystems also found such seasonal differences in walking distances. Lachica *et al*. (1999) found in southern Spain that the distances travelled by goats were longest in summer and shortest in autumn due to forage availability. Schlecht *et al*. (2009) found in northern Oman that walking distances of goats in spring were longer than those in autumn. Similarly to this study, these authors reported that the distance was longer with higher forage availability. Hence, within the herders' territory, availability of preferred forage and weather conditions controlled the mean daily walking distances in different seasons.

The mean daily walking distances were between 3480 and 4460 m for the three study sites, based on the 2-h temporal resolution. Applying the ratio of trajectory length under continuous recording *v*. the 2-h interval from Bou Skour of 1.68, these values would translate to actual daily walking distances of 5840–7490 m. In northern Oman (Schlecht *et al*. 2009), as well as in western Niger (Schlecht *et al*. 2006), the daily walking distances of goats were higher than in Morocco. In the first case, they varied between 10 500 and 16 700 m and in the second case between 6200 and 11 800 m based on a 5-s GPS recording interval in both studies. The high values in northern Oman were due to the fact that goats had to walk 4000–5000 m before they reached the first grazing area (Schlecht *et al*. 2009). By contrast, the values found in this study are higher than those of Sharma *et al*. (1998) from northern India, who reported daily walking distances for goats of between 3800 and 5000 m. In this case, the lower values are probably due to differences in the grazing system which was free-ranging in India while it was herded grazing in this study and that of Schlecht *et al*. (2006, 2009). This is in line with other studies that showed that free-grazing livestock walk shorter distances than herded ones (Schlecht *et al*. 2006). It seems that the differences in trajectory lengths between the different regions are driven by many factors. The most important are varying forage availability and quality, weather conditions for herders and animals (i.e. temperature) and the grazing system. Hence, the difference between ecosystems, i.e. seasonal variation in fodder availability and climatic constraints, should be taken into account in order to provide the most adequate management strategies for each region.

The mountainous topography of the valley of Ameskar explains the high values of the maximum vertical distance from the settlement. The mild temperature in summer and the very low temperature in winter are the main reasons that could explain the seasonal pattern in vertical distance (Fig. 6). The village of Taoujgalt is located between mountains in the north and a plain to the south (Fig. 3). The herder preferred the mountains in spring and the plain in summer and autumn as shown in Supplementary materials (Appendix 4) and this explains the seasonal pattern of the maximum vertical distance. The herder's preference is mainly due to the seasonal fodder availability and avoidance of competition with transhumant herders (see paragraph 3 in the subsection *Spatial patterns of the grazing herds* in the Discussion section).

The mean distance from the settlement at midday was much lower in Bou Skour than in the other two sites (see Fig. 5) despite the longer daily trajectories there. This can be explained by the fact that, in Ameskar and Taoujgalt, the herds left the settlement and did not return during the day until evening, whereas in Bou Skour in summer the herder (in many cases the children of the family) frequently returned home with the herd at mid-day for lunch and to avoid the peak of hottest temperatures. This is in line with Schlecht *et al*. (2009) who showed that during the dry season the trajectories of the goats were shorter and the resting periods were longer at Al Jabal Al Akhdar in northern Oman. It is concluded that horizontal and vertical trajectory length of the tended herds depends on the climatic conditions of the respective ecosystem, fodder availability, daylength and herders' routines.

Conclusions

This study provided first comprehensive and detailed description of the spatial and temporal grazing pattern and intensity of tended goats in southern Morocco. Grazing trajectories showed significant differences between seasons due to the difference in weather conditions, fodder availability and daylength. Furthermore, a statistically sound proposal for how to derive actual trajectory lengths from GPS records of different resolution was developed and a statistical framework for the assessment of the distance decay of grazing intensity around hotspots (such as settlements or water points) was described, proposing *GC* as a metric to assess the deviation from the null model proposed by Manthey and Peper (2010). Specifying the temporal pattern of grazing behaviour of the goats (feeding, resting and ruminating) as a next step would be of high importance to further quantify the grazing intensity of the studied herds. In order to confirm the findings and to generalise them to the whole region, analyses of grazing patterns of other herbivore species, such as sheep, would be helpful in identifying both differences and similarities in grazing patterns. For a better interpretation of grazing pattern and intensity data, measurements of vegetation or biomass data are a next step. This would help assess grazing pressure on these rangelands and develop sustainable utilisation and management plans.

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