



The effects of grazing on the endangered Sinai Thyme (*Thymus decussatus*) in a hyper-arid environment



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ABSTRACT

Herbivores play a key role in determining plant community composition. Historically grazing has been deemed detrimental for plants, but recent theoretical and empirical studies suggest that grazing may in fact be beneficial. Grazing is more likely to improve primary productivity in areas with a grazing history, where the plants are adapted to tolerate grazing, and also in arid environments because water stress and grazing select for comparable plant traits. Sinai Thyme (*Thymus decussatus*) in the arid St Katherine Protectorate of South Sinai has high apparent mortality rates and poor condition, both of which have detrimental consequences for its associated herbivores, particularly the Critically Endangered Sinai Baton Blue (*Pseudophilotes sinaicus*) whose larval stage feeds exclusively upon this plant. One recent conservation action banned grazing but there has been no obvious improvement in the thyme with continued high mortality, and local Bedu claim that grazing is in fact advantageous for plant health. We carried out a factorial experiment that manipulated simulated grazing, fertilizing and watering of thyme. This showed no evidence of any negative response to grazing or that watering or fertilizing had any effect either, presumably their impact is smaller than the current inter-annual variability caused by climatic fluctuations.

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1. Introduction

Grazing has traditionally been considered detrimental for many plant species, reducing photosynthetic area, removing the apical meristem and causing a loss of nutrients stored in the stem (Cingolani et al., 2005; Noy-Meir, 1993; Rutherford and Powrie, 2010). However, the effects of grazing vary with species and ecological conditions, and current theories and studies have shown that grazing can in fact improve productivity (Luo et al., 2012). The removal of old leaves can improve overall quality and prevent senescence (Fulkerson and Donaghy, 2001), whilst moderate grazing has been found to increase species richness, plant cover and biomass when compared to ungrazed or intensely grazed areas (Tadesse et al., 2003). The excretions of herbivores can enhance soil fertility and plant productivity through adding minerals, and can improve soil hydrological properties such as water infiltration: the result is an increase in plant biomass (Tadesse et al., 2003; Willott et al., 2000). The impact of grazing also depends upon grazing history. In areas that are consistently grazed, plants would

be expected to have phenotypic plasticity so as to be able to respond positively to grazing with compensatory growth. This should enhance primary productivity and fitness by initiating new growth and reducing senescence (Klein et al., 2007; Knapp et al., 2012; Noy-Meir, 1993).

Herbivores play a key role in determining species composition in communities, and changes to traditional management practices can trigger rapid reductions in species richness and alterations to species composition (Carmona et al., 2012; Loydi et al., 2012; Spiegelberger et al., 2006). Where there has been a history of grazing, the community is dominated by plants tolerant to grazing, with resistant traits such as small leaves (Komac et al., 2011; Navarro et al., 2006) or unpalatability (Loydi et al., 2012). If grazing ceases then such resistant plants lose their competitive advantage and can be outcompeted by grazing-intolerant species. This process has been noted in the Alps, where long-term pastoral grazing has shaped the environment and community. Grazing has recently declined in the area with considerable effect on species composition (Laiolo et al., 2004).

Milchunas et al. (1988) studied the impact of water availability on grazing. Plants in an arid environment experience high levels of below-ground competition for limited resources such as water, whilst grazing also negatively impacts roots. Therefore water stress and grazing are thought to select for similar traits (Carmona et al.,

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2012; Milchunas and Lauenroth, 1993). As a consequence, plants in arid environments are expected to show either a neutral or positive grazing response (Adler et al., 2004; Milchunas and Lauenroth, 1993; Milchunas et al., 1988). Morphological adaptations include small size, unpalatability and the ability to change chemical composition so as to decrease forage quality or biomass lost to herbivory (Adler et al., 2004). The genus *Thymus* contains species regarded as indicators for degraded landscapes in arid environments with long-standing grazing pressures, because they have favourable characteristics that resist the impact of disturbance. They have small seeds and exposed flowers adapted to temperature stress, whilst small leaves and seeds help limit the effects of drought and grazing (Navarro et al., 2006). In a general review of grazing studies, 17% found a positive correlation between grazing pressure and above-ground productivity; these were studies of unproductive environments with long evolutionary histories of grazing, consistent with Milchunas' theory. Where grazing caused a decline in above-ground productivity, in some studies there can be a positive effect on root mass, indicating that grazing can alter the balance of investment between root and shoot. In general, however, there was no relationship between grazing pressure and root mass (Milchunas and Lauenroth, 1993).

There are studies inconsistent with Milchunas' model, where grazing pressure in resource-poor areas with a long grazing history apparently degrades the environment. An example is in the Mongolian desert, where current grazing levels apparently reduce plant resources and hence flowering, but here climate is a key component of the degradation (Wesche et al., 2010). This study emphasizes that water is the major limiting factor in the majority of arid environments, and water stress can mask the effects of grazing and disturbance (Pueyo et al., 2008). The Simpson Desert of Australia has a light grazing history prior to the past 20 years of heavy grazing by domestic stock; despite this lack of grazing history, a positive relationship was found between grazing pressure and the species richness and diversity of perennial plants, coupled with a lack of any shift to degraded states (Fensham et al., 2010). Plants with a long grazing history in resource-poor areas are more resilient and can quickly recover when grazing ceases (Cingolani et al., 2005). However, irreversible damage can occur if there are drastic changes in local management, or if grazing levels exceed those encountered in evolutionary history: these can result in a rapid decline in biodiversity (Cingolani et al., 2005).

Water is the main limiting factor behind primary productivity in arid environments, with resource pulses associated with sporadic rainfall (Schwinning et al., 2004). Water stress can reduce available resources by lowering the abundance and activity of micro-organisms, with knock-on effects on the levels of available nitrogen (Aguilera et al., 1999). It has a negative impact on nutrient uptake from the soil, and impairs acropetal translocation (Hu and Schmidhalter, 2005). Consequentially in arid environments nutrient movement is often greater after precipitation events, and nitrogen is the second most limiting factor, behind water (Gebauer and Ehleringer, 2000). The response to simulated herbivory is often rapid; significant differences were observed on Sweet Thorn (*Acacia karroo*; Fabaceae) within three months of clipping and additional fertiliser in South Africa (Scogings and Mopipi, 2008), whilst perennial grasses in arid zone of Tunisia showed a response within 6 weeks (Chaieb et al., 1996).

Here we study experimentally the effects of artificial grazing and nutrient additions, and try to assess the success of recent conservation actions on a rare plant growing in the arid mountains of South Sinai. Because the plant is the exclusive host of the Critically Endangered Sinai Baton Blue butterfly (Thompson and Gilbert, 2012), the flagship conservation target of the Protectorate, its response to grazing and conservation techniques is a vital concern of the park management.

2. Materials & methods

2.1. The study system

The endangered plant is Sinai Thyme (*Thymus decussatus* Benham, 1834: Lamiaceae) (James, 2006a), whose flowers constitute the only food of the larvae of the Sinai Baton Blue butterfly (*Pseudophilotes sinaicus* Nakamura, 1975: Lycaenidae), the World's smallest butterfly, categorized as Critically Endangered (Thompson and Gilbert, 2012). The butterfly is one of two species endemic to the St Katherine Protectorate (South Sinai) in Egypt, the most arid country in the world (FAO, 2012; Hoyle and James, 2005; Thompson and Gilbert, 2012). The butterfly has been marooned by post-Pleistocene climate change on mountaintop islands that create a fragmented landscape of host-plant patches (James et al., 2003).

Since 2003 conservation efforts have been focussed upon one key patch of thyme, Farsh Shoeib, a patch found to contain one of the largest butterfly populations with approximately 500 individuals in 2002 (James, 2006a). Water is predominantly the limiting factor in arid environments (Pueyo et al., 2008): from 2002 to 2010 there was a prolonged drought with many years with little or no water, which decreased the quantity and quality condition of the thyme (Thompson, 2013). To rectify this problem, the Protectorate management built dams in Farsh Shoeib to prevent surface run off and to increase water infiltration after flash floods (Thompson, 2013). If these dams are successful then they could be replicated across the park wherever thyme patches occur. The collection of thyme has recently been banned with fines enforced; however there may still be illegal harvesting of the host plant due to its high medicinal value in Cairo. Local support and awareness is essential as this could prevent further anthropogenic habitat damage and discourage the collection of thyme (Thompson, 2013).

Over-grazing by goats of the local Bedouin was identified as a threat by Egyptian botanists in the 1980s (see Gilbert, 2013) and subsequently repeated by Hoyle and James (2005). As a consequence of this apparent grazing threat, a fence was erected around Farsh Shoeib in 2003 to restrict human or animal access. Fences are commonly used to protect wild species from threats, in this case the illegal collection of thyme and grazing damage from livestock (Hayward and Kerley, 2009). The grazing pressure would be greater outside the fence with the park managers predicting a decline in quality and condition of the plants outside the enclosure. However, there are additional environmental variables which may influence the condition of the thyme, such as spatial variation in soil moisture and shelter. There is little evidence regarding the success of fencing because the results of enclosure experiments in the St Katherine Protectorate have never been published. In Farsh Shoeib, no baseline data were collected before the fence was erected, and hence the success of this action can only be evaluated via a comparison of a single fenced area with surrounding unfenced areas (Hayward and Kerley, 2009). The fence was built after the 2002 survey, which did not locate each plant precisely enough to enable their identification with the plants of 2010. Thus it is impossible to get an individual-based measurement for survival inside and outside of the fence between 2002 and 2010 because the precise location of the deaths is unknown.

In the past half-century, Bedouin lifestyles have changed drastically as many have become increasingly settled, abandoning their traditional semi-nomadic lifestyle to live close to towns. The resulting pressure on surrounding grazing has meant that livestock are increasingly fed with imported food and as a consequence herd sizes have declined (Gilbert, 2013). Bedouins are increasingly employed in regular waged work, such as tourism, meaning that herding is now a secondary vocation, only kept as an insurance policy for poor years (Perevolotsky et al., 1989). Although

settlement has the potential to result in a higher local grazing pressure, in fact there is hardly any current grazing around St Katherine because the Bedouin have strongly reduced livestock numbers in response to recent lack of rain. Instead of supplying them with food and profit, their herds actually cost them money because they have to buy imported alfalfa as feed (Gilbert, 2013; Rashad et al., 2003).

The Bedouin maintain that grazing helps rather than restricts many forage plants, so it could certainly be the case that prevention of grazing is exactly the wrong management technique (Murphee et al., 2008). Natural grazers in the protectorate include the Nubian ibex (*Capra nubiana*: Bovidae). In the past this probably would have provided significant grazing pressure; the Himalayan ibex (*Capra sibirica*: Bovidae) definitely feeds upon other thyme species (Awasthi et al., 2003). In the 20th century ibex numbers declined drastically because of the ready availability of guns after the First World War (Alkon et al., 2008). Current grazing pressures are likely to be from local goat herds around the town of St Katherine, inversely proportional to the distance from settlements and altitude (Rashad et al., 2003). Because the patches of thyme are at high altitudes well away from settlements in the wadi bottoms, grazing pressure is likely to be low. Grazing pressure is also very variable across the butterfly's distribution, and the sites with higher grazing intensities have, in fact, increased levels of plant health and vigour (Guenther et al., 2005).

Grazing might indeed be a threat to the thyme and hence to the butterfly, but such a view needs to be seen also as part of an environmental narrative that drives policy in spite of rather than because of scientific evidence (Gilbert, 2013). Research carried out by the Protectorate rangers (Rashad et al., 2003) showed that grazing intensity is higher in open places than on the rough terrain selected by the butterfly. Furthermore, only 10% of grazing occurs at altitudes above 2000 m, while the butterfly only occupies patches above 1900 m (James et al., 2003; Rashad et al., 2003). Observations on the feeding behaviour of goats and sheep for over 250 h detected no feeding upon thyme (Rashad et al., 2003). Local Bedouin say that thyme is unpalatable and their goats avoid it, or take just one bite before moving on, a behaviour also observed in donkeys and camels (Nasr Mansour, 2011, pers. comm.). Taken together, all these lines of evidence suggest that grazing may not be such a large threat to thyme, especially since wild plants are currently such a small secondary component of the diets of livestock. Irrespective of whether goats forage on thyme or not, preventing animal access into Farsh Shoeib could gradually reduce soil fertility and change pH, and hence in the long term negatively impact the condition and quality of the thyme (Taddesse et al., 2003). Soil characteristics such as pH have been found to affect species composition more acutely than grazing (Fensham et al., 2010).

The majority of the fieldwork was carried out in Farsh Shoeib (Fig. 1), found near the summit of Gebel Safsafa on the Mt. Sinai massif, close to the town of St Katherine. It sits at an altitude of approximately 1950 m with an area of 14,000 m², containing 659 thyme plants in 2011. The other site for experimental manipulation was the nearby area of Lower Hammar (Fig. 1), which contained 163 plants in 2011, but has not been the focus of any conservation efforts. They are less than 0.5 km apart. Fieldwork was carried out in three, four-month periods starting in March 2010 and 2011 and April 2012. There are extreme weather fluctuations in the area, an eight year drought was broken in May 2010 when there was heavy rainfall. 2011 was again extraordinarily wet, with heavy rainfall and snow in the winter and spring, whilst 2012 had very little rainfall and was colder than normal. The extent to which these variations are normal for the area is uncertain because of incomplete meteorological records and we are dependent on local Bedouin knowledge. Undoubtedly this will have implications on the quality and condition of the thyme.

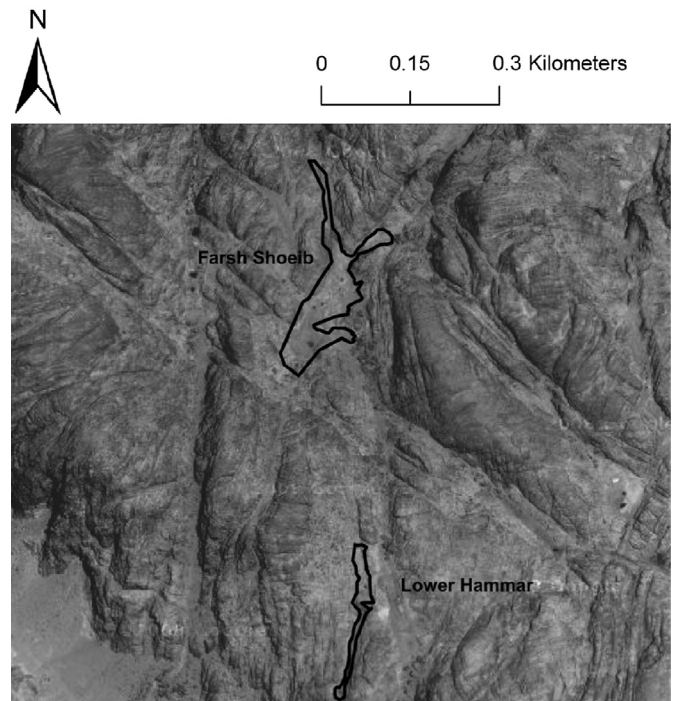


Fig. 1. The locations of the experimental sites; Farsh Shoeib (28.552°, 33.967°) and Lower Hammar (28.547°, 33.966°), note the large differences in topography in the area.

2.2. Experimental manipulations

Sinai Thyme is an endangered plant, and the host plant of a Critically Endangered butterfly: this limited the sample sizes allowed for the experiment under the permission given to us by the Egyptian Environmental Affairs Agency, as conveyed to us by the Protectorate management. We therefore randomly selected ten plants per treatment within both the fenced area of Farsh Shoeib and within Lower Hammar; an additional five plants per treatment were randomly selected from the area of Farsh Shoeib outside the fence – this was smaller because of the low number of plants there. Plants were excluded if they were less than 10% green to reduce the likelihood of natural mortality. Each plant was individually labelled in 2011 when the treatments were carried out, and subsequently measured in 2011 and 2012. Thyme quality was measured using four characteristics; height, two perpendicular widths and condition (percentage green). The 'resource area' for each plant was then calculated from the surface area (assuming each plant was a hemi-ellipsoid) multiplied by the condition (as a proportion).

There were three treatment factors, each with a control and a treated group: simulated grazing, the addition of dry goat faeces and the addition of water. These were factorially combined to create eight treatment groups, each with the sample sizes outlined above. Artificial grazing was simulated by clipping the top 2 cm from 12.5% of the plant before the flowering season, the maximum allowed under our permit. 'Light grazing' is usually simulated by clipping 30% of a plant, but there are many cases where 15% clipping has generated over-compensatory growth (Klein et al., 2007; Oba et al., 2000). Goat faeces have constituted a natural fertiliser for many centuries in South Sinai. We collected fresh pellets from the immediate surroundings on Safsafa: ten pellets were placed under each selected plant. The effect of increased soil moisture was investigated by watering appropriate plants with 150 ml once each week for 12 weeks before and during the flowering season. The treatments began in early March, six weeks before the beginning of the flowering season.

The resources for Sinai Baton Blue larvae are the flowers and flower buds; the response variable was therefore flower density on each plant. To measure this, a 10 × 10 cm quadrat was placed on the most advanced area of flowering on the plant to count the density of flowers. This was done each week for six weeks, commencing the week sepals were noted in the patch. In addition, the phenological state of the thyme was recorded weekly for 13 consecutive weeks, using the phenological scale created by James (2006b). Once a week, from the start of April, five inflorescences were randomly selected from the most advanced area of flowering on the plant and scored phenologically on a scale of 0–7 (Table 1); the average of the five scores represents the phenological state of the plant at that time. This was then repeated from mid-April until the end of June in 2012.

2.3. Analysis of data

To assess the long-term effects of grazing on thyme quality, data for 2010 and 2011 from the plants inside the fenced enclosure of Farsh Shoeib were compared to those outside, using the statistical package R 2.14.1 and models were simplified in accordance to Zuur et al. (2009). Any changes were investigated by testing plant size (assuming the hemi-ellipsoidal shape) and condition as response variables. Since we measured the same individuals, we ran a linear mixed model (*lmer* from the *lme4* package) using year and location (inside & outside) as factors and individual plant as the random measure. Factors were assessed by the change in deviance upon deletion from the model, tested with a χ^2 value. The experiment reduced the number of unmanipulated plants outside the fence to fewer than twenty individuals making it impossible to compare those inside and outside the fence in 2012. To see if there was a significant difference in the proportion of flowering plants inside and outside of the fence, we ran a one-way GLM with whether the plant flowered or not as the response variable and the year (2010 and 2011) and location as factors. The model was run with the R routine *glm*, with a binomial error structure and significance was assessed with a χ^2 value. To compare the location of the mortalities since 2010, we ran a one-way GLM with mortality as the response variable and location (inside or outside the fence) as the factor. The model was run with the R routine *glm*, with a binomial error distribution and significance was assessed with a χ^2 value.

To assess the relatively short-term (two years) effects of the experimental treatments, we used seven response variables: the condition, peak density of flowers, the total number of flowers across six weeks, whether a plant flowered, and the flowering phenology using three summary indices (the average score across the first 13 weeks of surveys; the week where the first flower was seen; and the week of peak flowering). Weeks were counted from the 1st April. When comparing flowering phenology, we removed non-flowering plants from the analysis: fewer plants flowered in 2012, a pattern observed across the whole massif (Thompson, 2013). We ran a linear mixed model (*lmer* from the *lme4* package)

Table 1
Scoring of flowering phenology scale (from James, 2006b).

Phenological score	Appearance of plant
0	100% pre-bud
1	Sepals visible, buds not yet visible
2	Sepals apparent, buds starting to develop
3	Large buds but fewer than 2 flowers open
4	50–90% buds, 10–50% flowers open
5	1–50% buds, 50–100% flowers open
6	1–50% flowers over/seed heads
7	More than 50% flowers over/seed heads

using the year (2011 & 2012) and the three kinds of treatment as fixed factors, with individual plant as the random effect. The error structure for the response variable 'whether a plant flowered' was binomial, and 'condition' was Poisson; all remaining response variables were normally distributed. All factors were assessed by the change in deviance following deletion from the model, tested with a χ^2 value.

3. Results

3.1. Spatial variation within Farsh Shoeib

There was significant spatial variation in mortality across Farsh Shoeib between 2002 and 2010 (Thompson, 2013). The Southern area (outside the fence) had the highest mortality rate (66%), however, the adjacent area (Farsh II) had a similarly high mortality rate (63%), and two-thirds of these individuals would definitely have been located inside the enclosure.

Between 2010 and 2012 there was a significantly higher mortality rate outside the fence ($\chi^2 = 5.37$, $df = 1$, $p < 0.05$); the mortality rate inside the enclosure was 0.02%, whilst it was 0.08% outside. When comparing the size of the plants inside and outside of the fence, there were marginally non-significant differences in size ($\chi^2 = 3.49$, $df = 1$, $p = 0.06$) and condition ($\chi^2 = 3.01$, $df = 1$, $p = 0.08$). The plants were smaller outside the fence with a lower condition across both years. However the large individual variability coupled with the small number of plants found outside the fence may have masked any significance (Fig. 2). Both variables showed temporal fluctuations between years (size: $\chi^2 = 4.1$, $df = 1$, $p < 0.05$; condition: $\chi^2 = 13.81$, $df = 1$, $p < 0.001$) but there was no interaction between year and inside/outside (size: $\chi^2 = 0.001$, $df = 1$, $p = 0.97$; condition: $\chi^2 = 0.03$, $df = 1$, $p = 0.87$). The

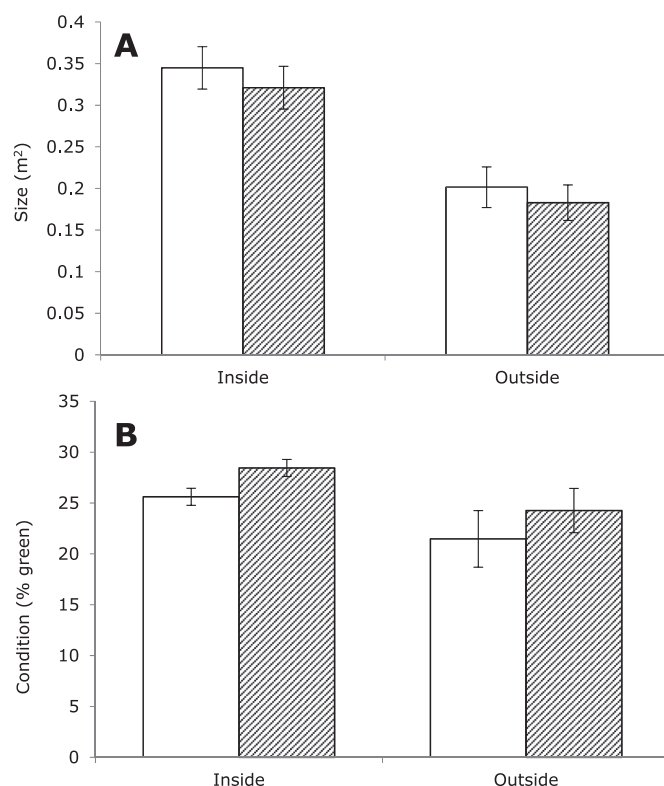


Fig. 2. Differences in a) size and b) condition of the plants inside and outside of the fence in 2010 (white bars) & 2011 (striped). Mean values (\pm SE).

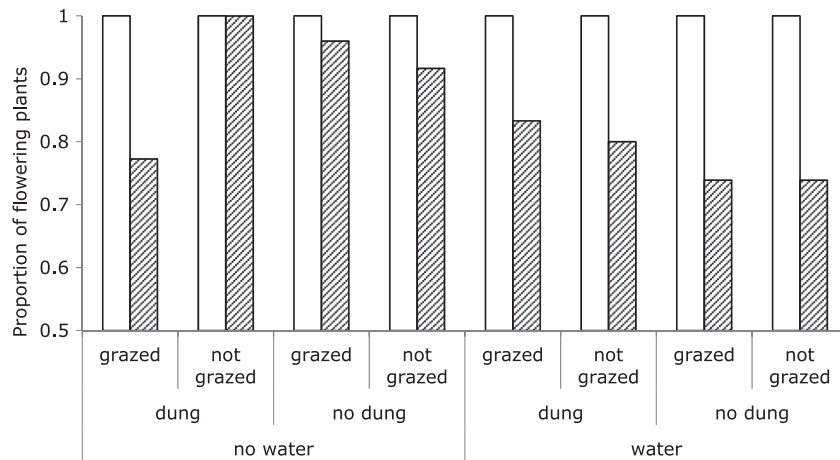


Fig. 3. The proportion of flowering plants in 2011 (white bars) & 2012 (striped) per treatment category.

proportion of flowering plants did not significantly differ between locations ($\chi^2 = 0.379$, $df = 1$, $p = 0.538$) or between years ($\chi^2 = 1.18$, $df = 1$, $p = 0.277$), nor was there an interaction between the two factors ($\chi^2 = 0.364$, $df = 1$, $p = 0.546$), although the flowering rate was higher outside the patch in both years (Supplementary materials).

3.2. Experimental treatments

The treatments were simulated grazing, the addition of dry goat faeces and the addition of water and they were factorially combined to create eight categories. Those with additional water had a significantly lower proportion of flowering plants ($\chi^2 = 6.55$, $df = 1$, $p < 0.01$), but of the watered treatments, those which received all three treatments (clipping, dung and water) had the highest proportion of flowering plants ($\chi^2 = 5.19$, $df = 1$, $p < 0.001$) (Fig. 3). The proportion of flowering plants had significant temporal variation ($\chi^2 = 115.8$, $df = 1$, $p < 0.001$), with every plant flowering in 2011. The peak density of flowers and total density of flowers across 6 weeks did not significantly vary with treatment and showed no interaction with year, only showing yearly variation (peak density: $\chi^2 = 63.3$, $df = 1$, $p < 0.001$; total: $\chi^2 = 67.4$, $df = 1$, $p < 0.001$) (Appendix 1 and Supplementary materials). However the peak number of flowers was slightly lower in the clipped plants than those unclipped ($\chi^2 = 3.124$, $df = 1$, $p = 0.077$) (Fig. 4). The total number of flowers also appears to have an interaction between dung and clipping, with the combination of the two treatments slightly reducing the flowering output. However the difference was

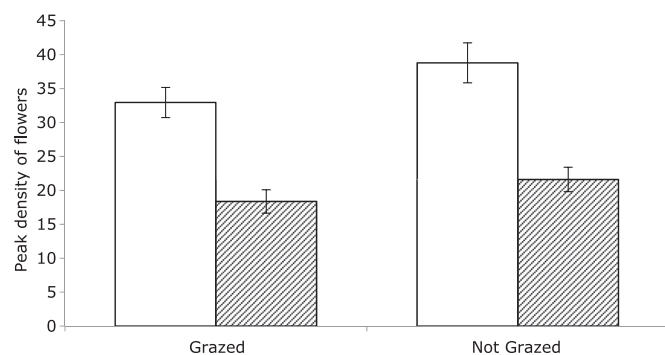


Fig. 4. The peak density of flowers of the grazed and ungrazed treatments in 2011 (white bars) & 2012 (striped). Mean values (\pm SE).

insignificant ($\chi^2 = 2.824$, $df = 1$, $p = 0.093$) (Fig. 5). The condition was significantly affected by an interaction between the year, dung and clipping ($\chi^2 = 4.38$, $df = 1$, $p < 0.05$), but again the other treatments did not have any effect (Fig. 6).

When comparing the phenology there were significant yearly differences in the week of first flower ($\chi^2 = 25.7$, $df = 1$, $p < 0.001$), week of peak flowering ($\chi^2 = 52.6$, $df = 1$, $p < 0.001$) and average score across the thirteen weeks ($\chi^2 = 15.3$, $df = 1$, $p < 0.001$). The average phenological score also had a significant interaction between year, water and clipping ($\chi^2 = 5.16$, $df = 1$, $p < 0.01$), with the average phenology being earlier in 2012 in every group except for the dung only treatment (Supplementary materials). The week of the first flower had a significant interaction with year and dung ($\chi^2 = 4.26$, $df = 1$, $p = 0.039$), whilst there are signs of an interaction between year, water and clipping ($\chi^2 = 3.34$, $df = 1$, $p = 0.068$) (Fig. 7). The remaining treatments did not affect flowering phenology (Appendix 1).

Thus in summary, the plants show a very diverse response to the experimental treatments with no clear trend amongst treatments and responses; for example the water only and water with clipping treatments had low proportion of flowering plants in 2012 yet they had a high average condition in 2012 (Figs. 3 and 6).

4. Discussion

The plants were generally smaller and in a poorer condition where grazing was permitted, however the differences were marginally insignificant and overall treatments had inconsistent effects on the plants' vitality. The response to the treatments did

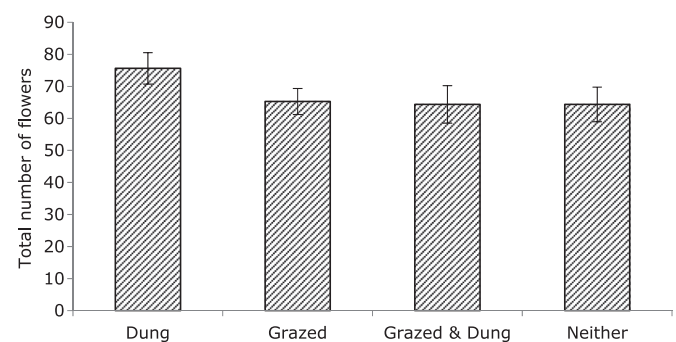


Fig. 5. The total number of flowers of the dung and grazed treatments across both years. Mean values (\pm SE).

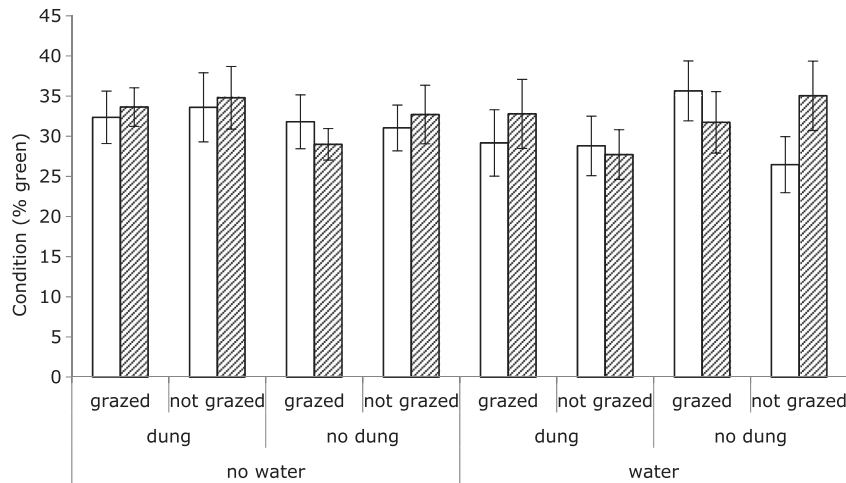


Fig. 6. The condition (% green) of the plants in 2011 (white bars) & 2012 (striped) per treatment category. Mean values (\pm SE).

not mitigate against the inter-annual variability in quality; the large climatic fluctuations and irregular rainfall will undoubtedly impact the vitality of the thyme. This suggests that grazing and disturbances within the natural variation in the thyme might not have negative implications (Lewis, 2001).

It is hard to compare the effectiveness of the fence on plant quality and density because there is only a single fenced area, and there are no base-line data before fencing: thus we can only compare grazed and ungrazed areas. Only a few plants were found outside the enclosure, giving a poor sample size for direct comparisons within Farsh Shoeib, whilst spatial variation across the massif make comparisons with other populations impossible (Thompson, 2013). The plants in Farsh Shoeib where natural grazing is permitted are not significantly different, but they are smaller and in a poorer condition; however, this could be attributed to the collection of thyme (which we observed on multiple occasions despite the current ban, whereas we never observed grazing). Thyme is very slow growing, with very small differences in plant resource area between seasons (Thompson, 2013), so any disparities in size and quality may take longer to become apparent (although it has been almost 10 years!). In 2003 two artificial dams were created inside the enclosure to hold more water in the soil after heavy rainfall, and these dams may also have enhanced plant vigour within the enclosure. The mortality rate was higher outside the enclosure between 2002 and 2010 but this was highly variable

across the whole patch, with the section just inside the fence having a similarly high mortality: thus these deaths cannot solely be attributed to lack of protection from grazing (Thompson, 2013). However, mortality has remained higher outside the patch since 2010.

The experimental plants did not perform worse than the controls, and plants had a variable response to treatments. The groups with the largest decline in the proportion of flowering plants had higher condition in 2012. Overall the thyme plants have large variability in quality; other work showed that Farsh Shoeib has large intra-patch variation in size, condition and flowering output (Thompson, 2013). 2012 had a significantly lower flowering rate compared to 2011, a pattern observed across the whole massif (Thompson, 2013). Flowering entails a high water cost, so presumably this was a response to the dry 2011/2012 winter, with flowering commonly reduced under limited resources (Harrison, 2001). The drought and high variability in plant quality may have masked the effects of the experiment, with the drought being more influential on productivity (Pueyo et al., 2008). Water is predominately the limiting factor in arid environments, with additional nitrogen having a smaller impact on above-ground primary productivity in drier systems (Yahdjian et al., 2011). Consequentially the dry winter may have masked the effects, if they exist, of nitrogen limitation and additional fertiliser on the thyme. Overall flowering phenology was not affected by the treatments. Cues for

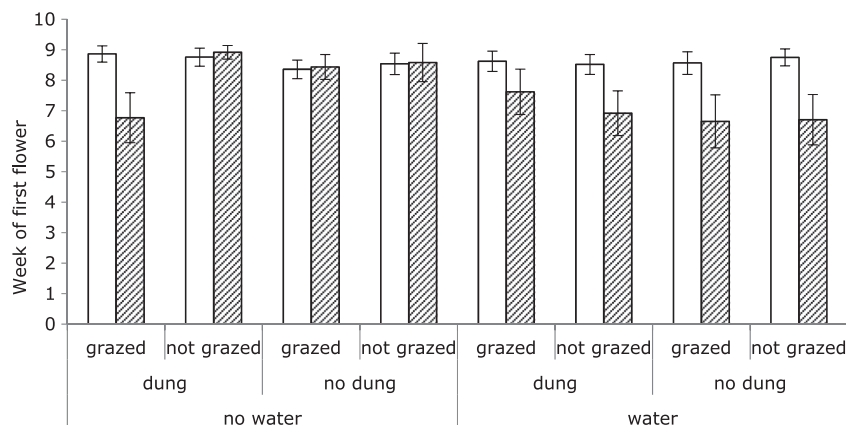


Fig. 7. The week of the first flower in 2011 (white bars) & 2012 (striped) per treatment category. Mean values (\pm SE).

phenological timings are currently unknown for this system, but thyme may be insensitive to changes in water, fertilisation or grazing; air temperature may be the main cue that controls flowering, as in many other plant species (Crepinsek et al., 2006; Matesanz et al., 2009).

Current grazing pressures, if any, are likely to be from local goat herds around the town of St Katherine (Rashad et al., 2003). Any grazing threat coupled with dry conditions would select for grazing-tolerant plants (Carmona et al., 2012; Milchunas et al., 1988; Navarro et al., 2006). However, Sinai's unpredictable weather causes large fluctuations in water availability (Thompson, 2013), creating highly variable herbivory between years. There may have been no consistent selection pressure for grazing-tolerant plants, despite a long evolutionary history. Elsewhere this can result in two sets of plants; grazing-tolerant but less competitive plants, which would succeed under high grazing pressures, whilst less grazing-tolerant plants would dominate during other years (Cingolani et al., 2005; Rutherford and Powrie, 2010).

The state and transition model of rangeland management suggests that a system can be pushed between stable states when thresholds are crossed by natural or management changes in stocking levels (Westoby et al., 1989). This may be occurring here; preventing grazing might result in a shift between states, disturbing species composition, promoting grazing-intolerant or palatable plants (Knapp et al., 2012). If the Bedouin are correct in believing that thyme is unpalatable, this would have negative implications for thyme. Its small leaves and seeds are grazing-tolerant traits (Navarro et al., 2006). Elsewhere in subalpine habitats in Spain, *Thymus praecox* is known to be favoured by grazing (Komac et al., 2011). These adaptations mean if grazing ceases, thyme may lose its adaptive advantage and be outcompeted by grazing-intolerant species. Perhaps this was responsible for the high mortality rates of thyme within Farsh Shoeib.

Further studies need to be carried out on the effects of grazing, especially by native herbivores such as ibex relative to domestic livestock. Rashad et al. (2003) cast doubt on the reality of the grazing threat to high-mountain plants, and this study did not find any evidence of negative consequences of natural or artificial grazing. It may in fact be masked by the climatic fluctuations and the large variability in the quality of the time. The high mortality rates in Farsh Shoeib over the past decade suggest that current conservation strategies may be ineffective. There needs to be more long-term monitoring to get clearer insight into how conservation actions can help to improve the abundance and quality of Sinai Thyme. This paper highlights the need for background research and quantitative analysis before conservation intervention, as grazing may be beneficial within this system which may also be the case in other arid systems.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.jaridenv.2013.09.009>.

Appendix 1. The ANOVA table for the mixed effects model investigating the response of thyme to varying treatments. The levels of significance are * ≤ 0.05 , ** ≤ 0.01 , *** ≤ 0.001 .

Response variable		Chi	df	p
Condition	Year	0.638	1	0.424
	Water*Dung*Graze	0.041	1	0.839
	Water*Dung	1.369	1	0.242
	Water*Graze	0.982	1	0.322
	Dung*Graze	0.032	1	0.858
	Water	0.505	1	0.477
	Dung	0.121	1	0.932
	Graze	0.115	1	0.734
	Year*Water*Dung*Graze	1.473	1	0.225
	Year*Water*Dung	0.300	1	0.584
	Year*Water*Graze	0.092	1	0.762
	Year*Dung*Graze	4.38	1	0.036*
	Year*Water	0.325	1	0.569
	Year*Dung	0.037	1	0.848
	Year*Graze	1.311	1	0.252
	Peak flowers	Year	63.251	1
Water*Dung*Graze		0.921	1	0.337
Water*Dung		0.029	1	0.864
Water*Graze		0.671	1	0.413
Dung*Graze		1.046	1	0.306
Water		2.362	1	0.124
Dung		1.277	1	0.259
Graze		3.124	1	0.077
Year*Water*Dung*Graze		0.013	1	0.910
Year*Water*Dung		0.236	1	0.627
Year*Water*Graze		1.242	1	0.265
Year*Dung*Graze		0.009	1	0.927
Year*Water		0.179	1	0.672
Year*Dung		0.569	1	0.451
Year*Graze		0.518	1	0.472
Total flowers		Year	67.389	1
	Water*Dung*Graze	0.613	1	0.434
	Water*Dung	0.354	1	0.552
	Water*Graze	0.473	1	0.492
	Dung*Graze	2.824	1	0.093
	Water	0.766	1	0.382
	Dung	1.997	1	0.158
	Graze	2.060	1	0.151
	Year*Water*Dung*Graze	0.039	1	0.854
	Year*Water*Dung	0.236	1	0.627
	Year*Water*Graze	0.985	1	0.321
	Year*Dung*Graze	0.211	1	0.901
	Year*Water	0.179	1	0.672
	Year*Dung	0.569	1	0.451
	Year*Graze	0.518	1	0.472
	Proportion of flowering plants	Year	115.840	1
Water*Dung*Graze		5.186	1	0.023*
Water*Dung		1.221	1	0.269
Water*Graze		1.967	1	0.161
Dung*Graze		0.718	1	0.396
Water		6.55	1	0.010*
Dung		0.032	1	0.858
Graze		0.485	1	0.486
Year*Water*Dung*Graze		0.001	1	0.974
Year*Water*Dung		0.003	1	0.971
Year*Water*Graze		0	1	0.995
Year*Dung*Graze		0.001	1	0.993
Year*Water		0.005	1	0.935
Year*Dung		0.208	1	0.742
Year*Graze		0.400	1	0.527
Average phenology		Year	15.28	1
	Water*Dung*Graze	0.542	1	0.462
	Water*Dung	0.437	1	0.509
	Water*Graze	0.460	1	0.497
	Dung*Graze	1.028	1	0.311
	Water	0.026	1	0.871
	Dung	0.007	1	0.934
	Graze	0	1	1
Year*Water*Dung*Graze	1.824	1	0.177	

(continued)

Response variable		Chi	df	p
Week of first flower	Year*Water*Dung	1.271	1	0.260
	Year*Water*Graze	5.162	1	0.023*
	Year*Dung*Graze	0.586	1	0.444
	Year*Water	0.0192	1	0.890
	Year*Dung	2.281	1	0.131
	Year*Graze	0.325	1	0.569
	Year	25.694	1	<0.001***
	Water*Dung*Graze	0.069	1	0.792
	Water*Dung	0.401	1	0.526
	Water*Graze	0.432	1	0.511
	Dung*Graze	1.053	1	0.305
	Water	0.044	1	0.834
	Dung	0.001	1	0.973
	Graze	0.010	1	0.919
	Year*Water*Dung*Graze	0.452	1	0.501
	Week of peak flowering	Year*Water*Dung	1.495	1
Year*Water*Graze		3.343	1	0.068
Year*Dung*Graze		0.346	1	0.555
Year*Water		0.462	1	0.497
Year*Dung		4.265	1	0.039*
Year*Graze		0.089	1	0.765
Year		52.629	1	<0.001***
Water*Dung*Graze		1.02	1	0.312
Water*Dung		0.002	1	0.966
Water*Graze		0.412	1	0.521
Dung*Graze		0.612	1	0.434
Water		0.032	1	0.858
Dung		0.334	1	0.563
Graze		0.310	1	0.578
Year*Water*Dung*Graze		0.265	1	0.607
Year*Water*Dung		2.19	1	0.139
Year*Water*Graze	1.093	1	0.296	
Year*Dung*Graze	0.225	1	0.635	
Year*Water	0.615	1	0.433	
Year*Dung	0.176	1	0.675	
Year*Graze	0.002	1	0.989	

References

- Adler, P.B., Milchunas, D.G., Lauenroth, W.K., Sala, O.E., Burke, I.C., 2004. Functional traits of graminoids in semi-arid steppes: a test of grazing histories. *J. Appl. Ecol.* 41, 653–663.
- Aguilera, L.E., Gutierrez, J.R., Meserve, P.L., 1999. Variation in soil micro-organisms and nutrients underneath and outside the canopy of *Adesmia bedwellii* (Papilionaceae) shrubs in arid coastal Chile following drought and above average rainfall. *J. Arid Environ.* 42, 61–70.
- Alkon, P., Harding, L., Jdeidi, T., Masseti, M., Nader, I., De Smet, K., Cuzin, F., Saltz, D., 2008. *Capra Nubiana* IUCN 2010. IUCN Red List of Threatened Species. Version 2010.3.
- Awasthi, A., Uniyal, S.K., Rawat, G.S., Sathyakumar, S., 2003. Food plants and feeding habits of Himalayan ungulates. *Curr. Sci.* 85, 719–723.
- Carmona, C.P., Azcarate, F.M., De Bello, F., Ollero, H.S., Leps, J., Peco, B., 2012. Taxonomical and functional diversity turnover in Mediterranean grasslands: interactions between grazing, habitat type and rainfall. *J. Appl. Ecol.* 49, 1084–1093.
- Chaieb, M., Henchi, B., Boukhris, M., 1996. Impact of clipping on root systems of 3 grass species in Tunisia. *J. Range Manag.* 49, 336–339.
- Cingolani, A.M., Noy-Meir, I., Diaz, S., 2005. Grazing effects on rangeland diversity: a synthesis of contemporary models. *Ecol. Appl.* 15, 757–773.
- Crepinsek, Z., Kajfez-Bogataj, L., Bergant, K., 2006. Modelling of weather variability effect on fitopenology. *Ecol. Model.* 194, 256–265.
- FAO, 2012. Food & Agriculture Organisation. World Development Indicators: Average Precipitation in Depth (mm per year) [Online]. Available: <http://data.worldbank.org/indicator/AG.LND.PRCP.MM>.
- Fensham, R.J., Fairfax, R.J., Dwyer, J.M., 2010. Vegetation responses to the first 20 years of cattle grazing in an Australian desert. *Ecology* 91, 681–692.
- Fulkerson, W.J., Donaghy, D.J., 2001. Plant-soluble carbohydrate reserves and senescence – key criteria for developing an effective grazing management system for ryegrass-based pastures: a review. *Aust. J. Exp. Agric.* 41, 261–275.
- Gebauer, R., Ehleringer, J.R., 2000. Water and nitrogen uptake patterns following moisture pulses in a cold desert community. *Ecology* 81, 1415–1424.
- Gilbert, H., 2013. Environmental narratives and conservation politics: the enduring ideas of pastoral destruction in South Sinai. *Biol. Conserv.* 160, 59–69.
- Guenther, R., Gilbert, F., Zalat, S., Salem, K.A., 2005. Vegetation and grazing in the St. Katherine Protectorate, South Sinai, Egypt. *Egypt. J. Biol.* 7, 55–66.
- Harrison, R.D., 2001. Drought and the consequences of El Nino in Borneo: a case study of figs. *Popul. Ecol.* 43, 63–75.
- Hayward, M.W., Kerley, G.I.H., 2009. Fencing for conservation: restriction of evolutionary potential or a riposte to threatening processes? *Biol. Conserv.* 142, 1–13.
- Hoyle, M., James, M., 2005. Global warming, human population pressure, and viability of the world's smallest butterfly. *Conserv. Biol.* 19, 1113–1124.
- Hu, Y.C., Schmidhalter, U., 2005. Drought and salinity: a comparison of their effects on mineral nutrition of plants. *J. Plant Nutr. Soil Sci.-Z. für Pflanzenernähr. Bodenkd.* 168, 541–549.
- James, M., 2006a. Metapopulations and the Sinai Baton Blue (*Pseudophilotes sinaicus* Nakamura): an introduction. *Egypt. J. Biol.* 8, 7–16.
- James, M., 2006b. Intra-patch movement in the Sinai Baton Blue butterfly: influence of micro-habitat and individual characteristics. *Egypt. J. Biol.* 8, 51–66.
- James, M., Gilbert, F., Zalat, S., 2003. Thyme and isolation for the Sinai baton blue butterfly (*Pseudophilotes sinaicus*). *Oecologia* 134, 445–453.
- Klein, J.A., Harte, J., Zhao, X.Q., 2007. Experimental warming, not grazing, decreases rangeland quality on the Tibetan Plateau. *Ecol. Appl.* 17, 541–557.
- Knapp, A.K., Hoover, D.L., Blair, J.M., Buis, G., Burkepile, D.E., Chamberlain, A., Collins, S.L., Fynn, R.W.S., Kirkman, K.P., Smith, M.D., Blake, D., Govender, N., O'Neal, P., Schreck, T., Zinn, A., 2012. A test of two mechanisms proposed to optimize grassland aboveground primary productivity in response to grazing. *J. Plant Ecol.* 5, 357–365.
- Komac, B., Alados, C.L., Bueno, C.G., Gomez, D., 2011. Spatial patterns of species distributions in grazed subalpine grasslands. *Plant Ecol.* 212, 519–529.
- Laiolo, P., Dondero, F., Ciliento, E., Rolando, A., 2004. Consequences of pastoral abandonment for the structure and diversity of the alpine avifauna. *J. Appl. Ecol.* 41, 294–304.
- Lewis, O.T., 2001. Effect of experimental selective logging on tropical butterflies. *Conserv. Biol.* 15, 389–400.
- Loydi, A., Zalba, S.M., Distel, R.A., 2012. Vegetation change in response to grazing exclusion in montane grasslands, Argentina. *Plant Ecol. Evol.* 145, 313–322.
- Luo, G.P., Han, Q.F., Zhou, D.C., Li, L., Chen, X., Li, Y., Hu, Y.K., Li, B.L., 2012. Moderate grazing can promote aboveground primary production of grassland under water stress. *Ecol. Complex.* 11, 126–136.
- Matesanz, S., Valladares, F., Escudero, A., 2009. Functional ecology of a narrow endemic plant and a widespread congener from semiarid Spain. *J. Arid Environ.* 73, 784–794.
- Milchunas, D.G., Lauenroth, W.K., 1993. Quantitative effects of grazing on vegetation and soils over a global range of environments. *Ecol. Monogr.* 63, 327–366.
- Milchunas, D.G., Sala, O.E., Lauenroth, W.K., 1988. A generalized-model of the effects of grazing by large herbivores on grassland community structure. *Am. Nat.* 132, 87–106.
- Murphee, M., Hamada, A., Hurst, F., 2008. The Saint Katherine Scenarios 2008–2023. Report on scenario planning workshop May 6–14 2008. Medicinal Plants Project. Global Environment Fund, UNDP.
- Navarro, T., Alados, C.L., Cabezudo, B., 2006. Changes in plant functional types in response to goat and sheep grazing in two semi-arid shrublands of SE Spain. *J. Arid Environ.* 64, 298–322.
- Noy-Meir, I., 1993. Compensating growth of grazed plants and its relevance to the use of rangelands. *Ecol. Appl.* 3, 32–34.
- Oba, G., Mengistu, Z., Stenseth, N.C., 2000. Compensatory growth of the African dwarf shrub *Indigofera spinosa* following simulated herbivory. *Ecol. Appl.* 10, 1133–1146.
- Perevolotsky, A., Perevolotsky, A., Noy-Meir, I., 1989. Environmental adaptation and economic change in a pastoral mountain society: the case of the Jabaliyah bedouin of the Mt. Sinai region. *Mt. Res. Dev.* 9, 153–164.
- Pueyo, Y., Kefi, S., Alados, C.L., Rietkerk, M., 2008. Dispersal strategies and spatial organization of vegetation in arid ecosystems. *Oikos* 117, 1522–1532.
- Rashad, S., Basset, Y.A., Hemeed, M., El Alqamy, H., 2003. A Study Of: Grazing Patterns in High Altitude Mountains Around St Katherine Town. (A GIS Integrated Approach). Nature Conservation Sector (NCS), St Katherine Protectorate.
- Rutherford, M.C., Powrie, L.W., 2010. Severely degraded rangeland: implications for plant diversity from a case study in Succulent Karoo, South Africa. *J. Arid Environ.* 74, 692–701.
- Schwinning, S., Sala, O.E., Loik, M.E., Ehleringer, J.R., 2004. Thresholds, memory, and seasonality: understanding pulse dynamics in arid/semi-arid ecosystems. *Oecologia* 141, 191–193.
- Scogings, P., Mopipi, K., 2008. Effects of water, grass and N on responses of *Acacia karroo* seedlings to early wet season simulated browsing: aboveground growth and biomass allocation. *J. Arid Environ.* 72, 509–522.
- Spiegelberger, T., Matthies, D., Muller-Scharer, H., Schaffner, U., 2006. Scale-dependent effects of land use on plant species richness of mountain grassland in the European Alps. *Ecography* 29, 541–548.
- Tadesse, G., Peden, D., Abiye, A., Wagnew, A., 2003. Effect of manure on grazing lands in Ethiopia, East African highlands. *Mt. Res. Dev.* 23, 156–160.
- Thompson, K., 2013. Assessing the Conservation Status of the Sinai Baton Blue Butterfly (*Pseudophilotes Sinaicus*) (PhD thesis). University of Nottingham.
- Thompson, K., Gilbert, F., 2012. *Pseudophilotes Sinaicus* [Online]. IUCN 2012. In: IUCN Red List of Threatened Species. Available: www.iucnredlist.org. Version 2012.2.
- Wesche, K., Ronnenberg, K., Retzer, V., Miede, G., 2010. Effects of large herbivore exclusion on southern Mongolian desert steppes. *Acta Oecologica-Int. J. Ecol.* 36, 234–241.

- Westoby, M., Walker, B., Noymeir, I., 1989. Opportunistic management for range-lands not at equilibrium. *J. Range Manag.* 42, 266–274.
- Willott, S.J., Miller, A.J., Incoll, L.D., Compton, S.G., 2000. The contribution of rabbits (*Oryctolagus cuniculus* L.) to soil fertility in semi-arid Spain. *Biol. Fertil. Soils* 31, 379–384.
- Yahdjian, L., Gherardi, L., Sala, O.E., 2011. Nitrogen limitation in arid-subhumid ecosystems: a meta-analysis of fertilization studies. *J. Arid Environ.* 75, 675–680.
- Zuur, A.F., Ieno, E.N., Walker, N.J., Saveliev, A.A., Smith, G.M., 2009. *Mixed Effects Models and Extensions in Ecology with R*, second ed. Springer, New York.