Climate change drives decline of Juniperus seravschanica in Oman

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CLIMATE CHANGE DRIVES DECLINE OF *JUNIPERUS SERAVSCHANICA* IN OMAN

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ABSTRACT

The southernmost population of Zeravschan juniper *(Juniperus seravschanica)* is found in Oman's Hajar Mountains. This is an iconic tree, important to wildlife and local people. However, Oman's juniper population is in decline: many trees have sparse, unhealthy foliage and few saplings can be found. Climate change, over-grazing, and over-harvesting have been suggested as possible causes. In this study, Zeravschan juniper were surveyed across the Jebel Akhdar-Shams range, Oman's largest juniper woodland. Generalised linear models were used to explore tree foliage status and relative abundance of saplings in relation to habitat characteristics, grazing and harvesting. Habitat characteristics associated with temperature and moisture explained patterns in percent living foliage and sapling abundance, but grazing and harvest data did not, suggesting climate change as the main cause of decline. Records of recent local temperature rises and reduced precipitation support this conclusion. Optimal habitat for juniper is now limited to areas near the summit of Oman's tallest mountain, and at lower elevations juniper with healthy foliage are only found in shallow depressions and on shaded north-facing slopes. These areas may offer climatic refugia, and protecting these habitats from other threats will be key to conserving Oman's junipers in the face of climate change.

KEYWORDS

Juniperus seravschanica; Juniperus excelsa subsp. *polycarpos;* Oman; climate change; refugia; elevational shift.

1. INTRODUCTION

The peaks of the Hajar Mountains of northern Oman host a unique ecosystem. Above 2000m, the mountains are more than 10°C cooler than the surrounding lowlands (Jebel Akhdar Initiative, 2007), and receive approximately three times as much rain (Meteorological Affairs Oman, 2009). This relatively cool, moist climate supports a range of plants which are found nowhere else in Arabia (Ghazanfar, 1991). Almost one quarter of Oman's flora can be found in these mountains, including nine endemic species (Jebel Akhdar Initiative, 2007). The Hajars represent a centre of relict diversity (Hampe and Petit, 2005): they have strong floristic ties to southwest Asia (Ghazanfar, 1991), but have long been isolated by the Arabian Gulf and the lowland deserts. The most iconic species of the Hajar Mountains is Oman's juniper. These trees were originally thought to be a population of the Persian juniper, *Juniperus excelsa* subsp. *polycarpos* (Miller and Cope, 1996), but have recently been confirmed to be the Zeravschan juniper, *Juniperus seravschanica* (Adams et al, 2014). The Zeravschan juniper is distributed from Kazakhstan to Iran, and the isolated population in Oman is the southernmost population of this species (Adams et al, 2014).

Within the Hajar Mountains, the Zeravschan juniper occurs along the Jebel Akhdar-Jebel Shams range, and also on Jebel Khawr. The lower altitudinal limit of the tree is around 2000m.a.s.l (sometimes lower on north-facing slopes), and its range extends upwards to the summit of Jebel Shams, which is the tallest mountain in Oman at 3009 m.a.s.l. (Gardner and Fisher, 1996). The junipers are dominant trees of the sparse montane woodlands, and as such play a role in providing habitat for wildlife (Eriksen, 2008), and are likely important contributors to ecosystem services such as hydrological regulation and soil conservation (Ingraham and Matthews, 1988; Körner, 2004; Pugnaire et al, 2011). To the local people, the junipers represent a resource of firewood, timber, and local medicine (Matwani, 2011; Mandaville, 1978). The montane woodlands are also an important tourist attraction for both domestic and international tourists (Times of Oman, 2014).

In recent decades, concern has grown that the juniper woodlands of the Hajar Mountains are becoming increasingly degraded. Gardner and Fisher (1996) assessed the range and status of the juniper in Oman, and identified that some stands of juniper were in very poor condition, with little remaining foliage. Consistently healthy juniper were only found above 2400m, and seedlings were found only rarely during their study. Juniper tended to be in better condition in shaded wadis and at higher elevations, indicating that exposed sites at lower elevations have become less suitable for juniper, and the authors suggest this could be due to climate change (Fisher and Gardner, 1995; Gardner and Fisher, 1996). As the world's southernmost population of Zeravschan junipers, these trees are probably already at the warmer, drier limit of their climatic tolerance (Hampe and Petit, 2005; Franco et al, 2006).

In addition to climate change, several other theories have also been presented for the decline of Oman's junipers. Some authors have suggested that grazing by livestock and human harvest of wood and branches may be posing a problem, with the Jebel Akhdar Initiative (2007) concluding that grazing on the mountain is at unsustainable levels, based on the poor condition of the rangelands and the dominance of unpalatable plant species. Diet analysis studies (Jebel Akhdar Initiative, 2007; Schlect et al, 2009) have found that juniper remains were sometimes present in the scat of both domestic goats and feral donkeys, suggesting that these animals may impact juniper, and this may particularly be an issue for young juniper within reach of browse. There have also been many reports of cut and burnt junipers on Jebel Akhdar, many of which are thought to have been damaged by tourists (e.g. Victor, 2008; Eriksen, 2008). Locals are also known to harvest branches for medicinal products (al Haddabi, pers. comm.). Another potentially damaging human activity on Jebel Akhdar is the removal of soil from areas of the woodlands for use in local agroindustry, which involves extensive destruction of vegetation across areas up to 1ha in size (pers. obs.; Victor, 2008).

Declines have also been reported for several juniper populations in other arid and semi-arid areas of the Middle Eastern-Mediterranean region, including *Juniperus communis* in southern Spain (Garcia et al, 1999), *Juniperus thurifera* in Spain and Morocco (Gauquelin et al, 1999), *Juniperus excelsa* in Greece (Milios et al, 2007), and *Juniperus procera* in Saudi Arabia (Fisher, 1997; El-Juhany, 2009) and in Ethiopia (Aynekulu et al, 2009). Human activities such as timber harvest, wood and foliage collection, and overgrazing are often cited as causes for these declines (Gauquelin et al, 1999; Milios et al, 2007), but in other regions climate conditions appear to be driving juniper dieback (Fisher, 1997; Garcia et al, 1999). Droughts and heat stress associated with climate change have been identified as a cause of much recent forest mortality worldwide (Allen et al, 2010).

The current status of the junipers of Oman's Hajar Mountains remains uncertain. Gardner and Fisher (1996) completed their evaluation of the junipers almost 20 years ago, and little monitoring has been undertaken since. This study presents an up-to-date and geographically comprehensive survey of the juniper on Jebel Akhdar and Jebel Shams. Percent living foliage and the relative abundance of saplings are used to assess the current status of the juniper population, and infer future trends. This study aims to identify threats to the junipers, and to gather evidence to support or discredit the range of theories previously suggested for juniper decline in Oman: grazing, climate change, or human harvest. It is hoped that these findings will contribute to the conservation of Oman's junipers, and increase our understanding of potential threats to long-lived tree species in arid regions.

2. METHODS

2.1 Study area and layout

Data were collected from 86 sites located across the Jebel Akhdar-Shams range (Figure 1). Jebel Akhdar and Jebel Shams are two peaks of the same massif, connected by a narrow saddle, and Jebel Shams is the highest peak in Oman at 3009 m.a.s.l. This massif is an anticline of limestone and dolomite (Gerner, 2013), approximately 80km in length. The landscape is primarily exposed rock, although sandy soils and gravels have built up in depressions and basins. Vegetation cover is sparse. The weather station on Jebel Akhdar at 1755 m.a.s.l. records an annual average temperature of 23.5^{o}C, while at the summit of Jebel Shams the annual average temperature is 15^{o}C (Meteorological Affairs Oman, 2009; Weather Online, 2014). The average annual rainfall on Jebel Akhdar is 310mm per year (no rainfall data is available for Jebel Shams).

Several villages are situated along this mountain range. Many people from these villages commute to towns and cities for work, but some traditional livelihood activities still take place on the mountains, of which raising goats is the most common (Roe, 2014; unpublished data). There are three or four hotels on each mountain, and both mountains are also popular for picnics and camping.

All survey sites were located within the juniper woodlands, which extend from the summits of Jebel Shams and Jebel Akhdar down to 2100 m.a.s.l on southern slopes and 1600 m.a.s.l on northern slopes (Gardner and Fisher, 1996). Data collection was undertaken during 95km of walked routes within the study area; these routes were situated to maximize geographical coverage of the woodlands (excluding areas that we could not gain permission to access). Sample sites were located along these routes to represent the full range of elevations and topographical features present within the woodlands, because both elevation and topography were expected to be important for juniper health (Fisher and Gardner, 1995; Gardner and Fisher, 1996). Sampling was conducted at the centre of areas of homogenous topography (i.e. in the middle of a hillside, a wadi bed, etc.) to minimise environmental variation within the site. As such, site placement was not strictly random, so the potential for selection bias has been addressed in the data analysis. Cliffs and ravines were not included in the survey due to their inaccessibility. Sites with no juniper present were excluded from the study. Sites were always placed at least 300m away from one another. Locations were recorded using a handheld GPS device (Garmin eTrex 10), and all sites were located between the coordinates UTM 40N 510276, E2579639 and UTM 40N 577736, E2554374.

2.2 Juniper percent living foliage and age class

At each sample point, the nearest five juniper trees within a 40m radius were assessed. The trees grow very sparsely so it was not always possible to find five trees within a 40m radius, but this limit was placed to prevent the sample spanning an area large enough to become significantly environmentally heterogeneous. The percent of potential living foliage on each tree was visually estimated as an indicator of tree health, with each tree categorised into the following scores: 0% (no foliage/dead), 25%, 50%, 75% or 100% (full, dense foliage with no sign of yellowing) (Figure 2). This measure was chosen to be consistent with previous assessments of juniper health in Oman (Matwani, 2011; Fisher and Gardner, 1995; Gardner and Fisher, 1996). Juniper trees were also recorded as belonging to one of two size classes, either ‘saplings’ (less than 2.5m with a trunk width of 20cm or less and adult foliage), or adults (taller than 2.5m or had a trunk width greater than 20cm).

2.3 Environmental and human activity data collection

The environmental and human activity variables used in this study were chosen to provide further evidence for or against the various hypotheses for juniper decline described in the introduction: overgrazing, damage through human harvest, and climate change. Environmental data were collected in the field or using a digital elevation model (DEM) of the study area in ArcMap 10.2 (ESRI, 2013). Estimates for levels of grazing, and of harvesting of juniper by local people, were based on a household survey undertaken at all villages within the study area (Roe, 2014: unpublished data).

2.3.1 Environmental variables

Each site was categorized as either a ‘hillside’, ‘wadi’, or ‘depression’. These three categories reflect the main topographical features present within the woodlands, and differ in their hydrological characteristics. Data on soil moisture was unavailable for this research, so topography was used provide an insight into the importance of hydrology for junipers. Previous research has shown that juniper health differs between wadi and non-wadi habitats (*wadi* is the Arabic term for a non-permanent river channel; Fisher and Gardner, 1995; Gardner and Fisher, 1996), but the effect of depressions has not been explored. ‘Depression’ was the term used in this study to describe the shallow bowl-shaped features that occur in a few places along this mountain range. They are not a common habitat feature, and their shallow slopes contrast with the exposed plateaus and deep wadis which characterise most of the landscape. The shape of these depressions suggests that water would drain to these areas during rainfall, but that flow rates through these areas would not be high, and moisture would be retained well after the rainfall event. In contrast, ‘wadis’ were steep-sloped valleys where water flow could become torrential after heavy rain, but would subsequently drain away rapidly *(wadi* is the Arabic term for a non-permanent river channel). ‘Hillsides’ were exposed upper slopes, ridges and plateaus from which water could drain freely.

The elevation, slope and annual incident solar radiation of each site were calculated from a DEM with a 30m resolution, using ArcMap 10.2 (ESRI, 2013). An increase in elevation is associated with a decrease in temperatures, and higher elevations in the Hajar Mountains are thought to receive higher precipitation (Stanger, 1986). Slope can affect how much soil and water a site retains; soil tends to erode more from steeper slopes, and water drains faster from steeper slopes. Incident solar radiation affects light availability, and also temperatures and evaporation rates. The percent soil cover of each site was visually estimated to the nearest 10% for a 10x10m quadrat around the sample centre point; this quadrat size was chosen as it was considered large enough to represent the sample area but small enough fit in one’s field of view for the visual estimate. Substrate was considered soil (as opposed to gravel or stones) if most particles were <1mm across. The presence or absence of donkey droppings in the site was also recorded as a proxy for whether feral donkeys visited the area to graze.

The longitudinal coordinate, or easting, for each site was included in the analysis. Spectral analysis of satellite imagery by Khalefa (2014) using the Normalized Difference Vegetation Index (NDVI), indicated lower vegetation densities on the western end of the range (Jebel Shams), suggesting that the western areas are drier. This can also be expected from prevailing wind and rain patterns (Stanger, 1986), and may have an impact on the junipers. The easting was included as a variable to capture this gradient.

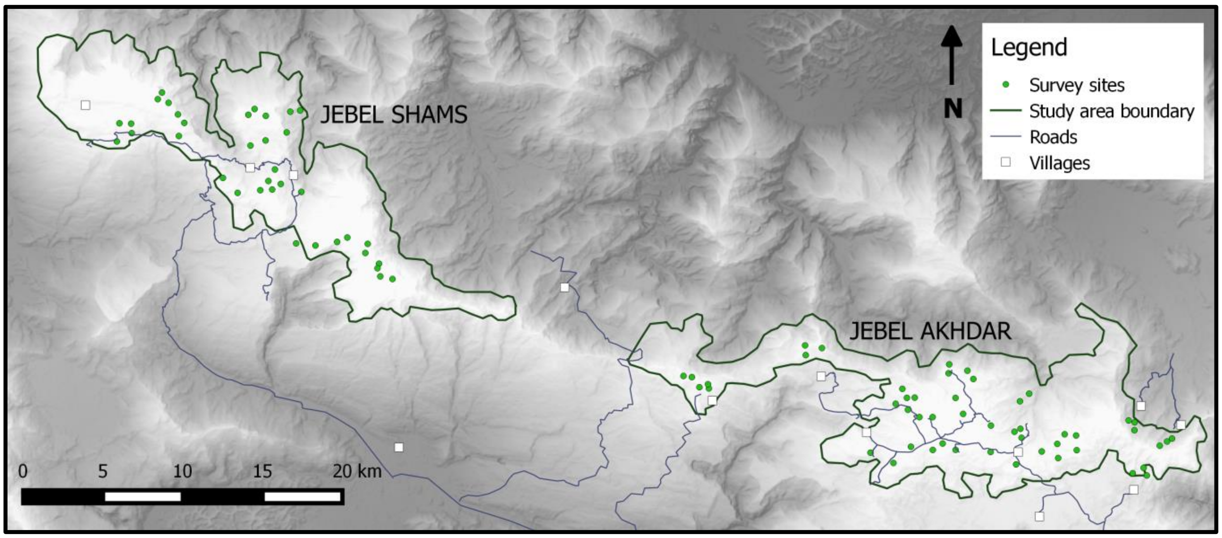

Figure 1: The locations of the survey sites within the study area on Jebel Shams and Jebel Akhdar. Whiter shading represents higher elevations.

Figure 2: The percent living foliage of each tree was visually assessed From left to right, these photos show living foliage values of 0%, 50% and 100%.

2.3.2 Livestock grazing and harvest variables

Scores for grazing and juniper harvest intensity across the study area were based on information collected during a household survey of local people (Roe, 2014; unpublished data). Locals were asked how many goats they owned, and where they took them to graze and for how long. They were also asked if they harvested juniper branches, fruits, or foliage, and where they went for this. The locations given in this survey were based on a map of the study area divided into 11 topographically recognisable zones, so that respondents could indicate which areas they visited. Grazing and harvest scores were calculated for each zone, and each juniper survey site was assigned the score from the zone in which it was located. The grazing score was calculated as 'goat hours per hectare': the number of goats taken to each zone, weighted by how many hours per day they spend there, and by the area of the zone. Eighty-seven livestock owners were surveyed. The harvest score is the proportion of the 108 respondents who stated that they harvested juniper for either firewood or medicinal use in each zone, weighted by the area of the zone.

2.4 Data analysis

Generalized linear models were used to estimate the effects of the environmental and human variables on juniper percent living foliage and the relative abundance of saplings. All modelling was undertaken in R version 3.1.2 (R Core Team, 2014), using functions from the package 'The R Stats Package'. For the model of percent living foliage, the response variable was the average foliage score of the five trees at each site. A generalized linear regression model (GLiM) was used, with a Gaussian distribution because the response variable had a normal distribution. To investigate the relative abundance of saplings, a GLiM with a Binomial distribution was used because the response variable in this model was the number of saplings present (out of the total 5 trees) at each site. The scales of the explanatory variables included in these models varied widely, so variables were standardized to a mean of zero and a standard deviation of one before they were entered into the model.

For each response variable, an initial model was created containing site topography, elevation, easting, incident solar radiation, grazing score, harvest score, and presence of donkey droppings. Slope and soil cover were initially excluded because they were correlated with topography (depressions tended to have higher percent soil cover and shallower slopes than either hillsides or wadis), and slope also correlated with solar radiation (Appendix A). Alternate models containing these variables in place of topography were explored. The explanatory power of these alternate models was compared to the initial models using the Akaike Information Criterion (AIC), a measure of goodness-of-fit that balances information loss between observed and predicted values with a penalty for models that have a higher number of parameters (to avoid over-fitting; Burnham and Anderson, 2002). The AIC of all models were also compared to a null model of the response variable and the intercept only, to ensure that adding the explanatory variables improved model fit over a null model.

Because sample sites were non-randomly located throughout the woodlands, a subset resampling analysis was used to check the model coefficient estimates for the effects of any site selection bias, as suggested by Guisan and Zimmerman (2000) for cases when a formal random-stratified sample design could not be achieved. For both models, the dataset was randomly resampled 1000 times (without replacement), to create subsets of 57 sites for the foliage model (66%, two thirds of the original dataset), and of 70 sites (81%) for the sapling model (to ensure at least 3 sites in any subset contained saplings, because only 19 out of the original 86 sites contained saplings). The models were then fitted for the data for each of the 1000 subsets. If any selection bias had biased the observed coefficient estimates of the full dataset model, we would expect the model to fall at one extreme of the range of estimates given by the subset models. Therefore, if the observed coefficient estimates for the full set model fell within the central 95% of the range of coefficient estimates given by the subset models, we were confident that selection bias had not significantly affected the results of the full dataset model.

2.5 Comparison with the 1996 survey

The results of this study were compared with those of Gardner and Fisher (1996) who completed the last survey of Oman's junipers on the Jebel Akhdar-Shams range over 20 years ago. The same survey sites could not be revisited during this study, but the survey designs were similar so the results are comparable. Of particular interest was Gardner and Fisher's (1996) finding that juniper consistently scored well for percent living foliage above 2400m, but below that trees with high foliage scores were generally only found in more sheltered sites. Examining changes to this pattern in the last twenty years can help to deepen our understanding of causes and patterns of decline.

3. RESULTS

3.1 Environmental modelling

3.1.1 Juniper percent living foliage

The model for juniper percent living foliage showed that all variables associated with environmental variation and microclimate were significantly related, whilst variables reflecting local human activities and feral donkeys were not (Table 1). Of the significant variables, topography had the greatest impact, with a change from a depression to a hill habitat associated with a 34% decline in average living foliage, and a change from a depression habitat to a wadi habitat was associated with a 23% decline in average living foliage. Elevation had a positive relationship with percent living foliage (Figure B.1), with trees at higher elevations tending to have higher foliage scores. Easting was also positively associated with percent living foliage (Figure B.1), indicating that for a given elevation and habitat type, trees further east retained more foliage than those further west. Solar radiation was negatively associated with juniper percent living foliage (Table 1) with trees exposed to higher levels of solar radiation typically retaining less foliage than trees in more shaded areas (Figure B.1).

Variable	**Coefficient (S.E)**	***t*-value**	***P***
Easting	11.6 (2.60)	4.483	<0.001
Elevation	14.8 (2.74)	5.414	<0.001
Topography – hill	-33.7 (8.49)	-3.965	<0.001
Topography – wadi	-22.9 (8.99)	-2.544	0.013
Incident solar radiation	-5.6 (2.51)	-2.244	0.028
Graze score	3.9 (2.53)	1.550	0.125
Harvest score	3.7(2.48)	1.470	0.146
Donkey droppings	-3.1(5.05)	-0.616	0.540

Table 1: The model estimates for the relationship between the juniper percent living foliage and the environmental and human activity variables (model AIC = 770.59 with 77 degrees of freedom; null model AIC = 805.81 with 85 degrees of freedom).

Alternate models using different collinear variables were explored by replacing the topography variable with first soil and then slope (and when slope was added solar radiation was also removed). In both cases the AIC value was higher in the alternate models: the original model had an AIC of 770.59, while the AIC for the model containing soil was 781.96, and the AIC for model containing slope was 782.86. As these models contained either the same number of variables or one fewer (in the slope model), these higher AIC values would not be related to a penalty for additional parameters, and so are a direct reflection of decreases in goodness-of-fit. When the difference between the AIC values of two comparable models is greater than 10, this is considered grounds to reject the model with the higher AIC as significantly worse than the other (Burnham and Anderson, 2004). The high AICs of both the soil and slope models suggest that neither soil cover nor slope alone can explain why depression habitats are associated with higher percent living foliage, and that other characteristics of these depressions may also be important to junipers.

The resampling analysis of the model showed that all observed coefficient estimates lay well within the central 95% range of randomised model estimates; thus, we can therefore be confident that any selection bias amongst the sample sites has not significantly affected the outcomes of the model.

3.1.2 Presence of seedlings and saplings

Only four seedlings were found during this study; too few for any data analysis. All seedlings were found near the summit of Jebel Shams, and three of them in a small, shallow depression. Of the 348 trees included in this survey, thirty-four were saplings (<10%), and all were found within 19 of the total 86 survey sites. The model of sapling presence indicated that topography had a significant impact on the number of saplings, with depressions more likely to contain a greater relative abundance of saplings than either hillsides or wadis (Table 2; Figure B.2). The grazing score was also significantly associated with the abundance of saplings, but the effect was both small and positive (Table 2; Figure B.2). It is possible that a higher intensity of grazing reduces competition with other plants and promotes juniper regeneration. However, it is also likely that better forage grows in areas which are also suitable for sapling growth, and thus the shepherds favour these areas for their livestock.

Alternate models were used to explore the collinear variables of soil and slope in place of topography. Again, the difference between the AIC value of the original model and the two alternate models was greater than ten, indicating that the original model describes the data much better than either of the two alternate models (original model AIC = 103.23; AIC for model containing soil = 115.98, AIC for model containing slope = 128.64) (Burnham and Anderson, 2004). The resampling analysis of the sapling model containing topography also indicated no effect of selection bias: all coefficient estimates from the model were within the central 95% range of subset model estimates.

Variable	**Coefficient (S.E)**	***z*-value**	**P**
Easting	0.62 (0.38)	1.643	0.100
Elevation	0.70 (0.47)	1.498	0.134
Topography – hill	-3.29 (0.69)	-4.760	<0.001
Topography – wadi	-2.36 (0.65)	-3.599	<0.001
Incident solar radiation	-0.38 (0.23)	-1.619	0.105
Graze score	0.65 (0.27)	2.426	0.015
Harvest score	0.51 (0.27)	1.879	0.060
Donkey droppings	-0.12 (0.58)	-0.198	0.843

Table 2: The model estimates for the relationship between the relative abundance of saplings and the environmental and human activity variables (model AIC = 103.25 with 70 degrees of freedom; null model AIC = 128.55 with 78 degrees of freedom).

3.2 Comparison with 1996 survey

Gardner and Fisher's (1996) survey identified that juniper in Oman were consistently found to have healthy amounts of living foliage above 2400 m.a.s.l. Below that, juniper with high scores for living foliage tended to be found in more shaded areas (Figure 3). In this study, juniper were only found to have consistently high levels of percent living foliage above 2650 m.a.s.l (Figure 3), whereas at lower elevations, juniper in shallow depressions, further to the east, and in areas with lower incident solar radiation (more shaded areas) tended to retain more living foliage. The patterns in juniper foliage status identified in these two studies are therefore very similar: above a certain elevation, juniper have consistently high levels of living foliage, whereas below a certain elevation, juniper living foliage depends upon variation in environmental variables that affect temperature and moisture. The key difference between these two studies is the elevation above which juniper were found to be in consistently good condition. In 1996 this elevation was 2400 m.a.s.l, while in this survey that elevation is 2650 m.a.s.l. This suggests an upward range shift of 250 metres in 20 years, which is associated with a major decline in the area of optimal habitat remaining for the juniper (Figure 4).

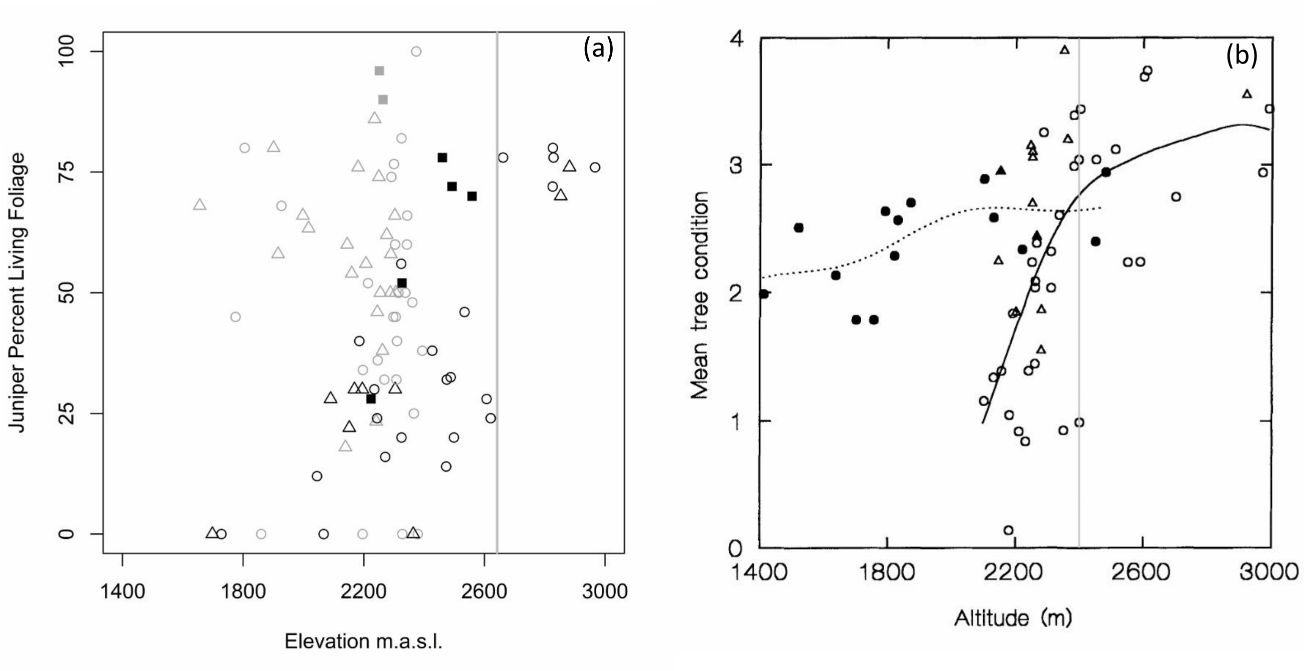

Figure 3: The relationship between elevation and juniper percent living foliage in this survey (a) and in the 1996 survey (b) (reproduced from Gardner and Fisher, 1996). For this survey (a), triangles represent wadi sites, circles represent hill sites, and filled squares represent depression sites. The shades in this plot illustrate the effect of easting, as sites on eastern Jebel Akhdar (grey) tended to have juniper in higher conditions at lower elevations compared with western Jebel Shams (black). The outlying group of sites in the top left of the plot with elevations between 1800 m.a.s.l and 2200 m.a.s.l were all from sites on the mountains' steep northern slopes, and thus are likely to explain the effect of incident solar radiation in the models. A vertical grey line has been placed at 2650 m.a.s.l, above which all sites contained juniper with high living foliage scores, and below which juniper foliage depends on easting, topography and incident solar radiation. For Gardner and Fishers' survey (b), triangles

represent wadi sites while circles represent non-wadi sites, and filled shapes indicate a site that was at least partially shaded during the day. Gardner and Fishers' 'mean tree condition' is equivalent to this study's use of estimated percent living foliage. A vertical grey line has been placed at 2400 m.a.s.l, above which all sites contained juniper with high living foliage scores, and below which juniper foliage depended largely on shading. The black lines indicate differences in foliage condition trends between shaded and unshaded sites (Gardner and Fisher, 1996).

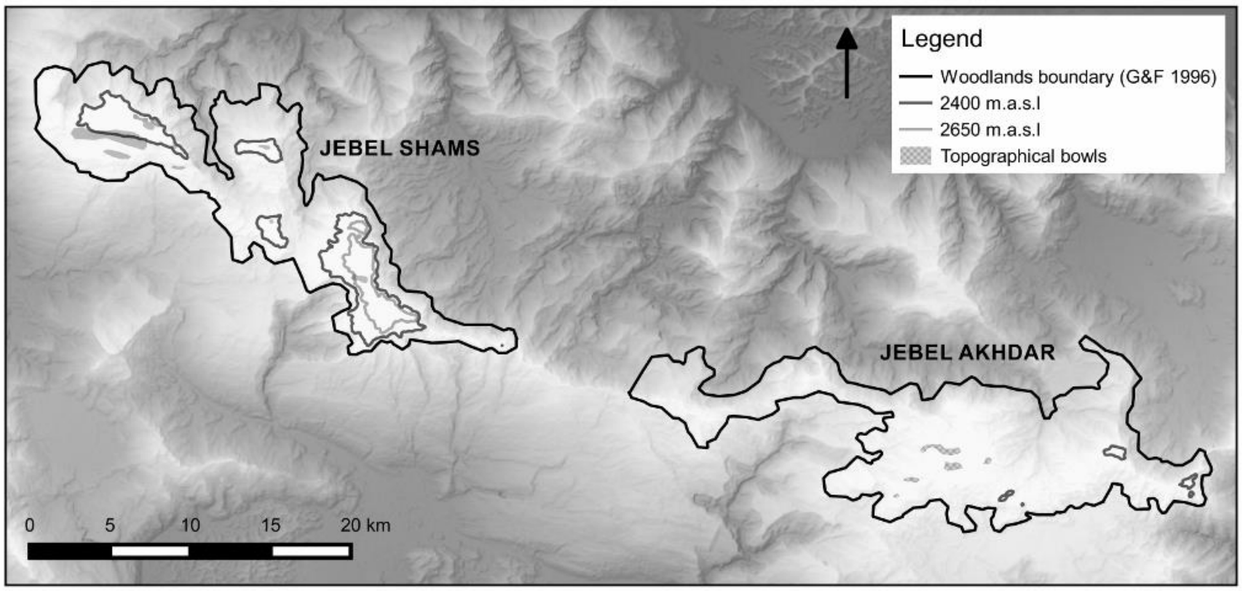

Figure 4: Recent shifts in the elevation limit at which juniper with consistently high foliage scorescan be found. The outer black line is the boundary of the juniper woodlands described by Gardner and Fisher in 1996 (down to 2100 m.a.s.l on southern slopes and 1600 m.a.s.l on northern slopes). The dark grey line is the 2400 m.a.s.l contour line, above which Gardner and Fisher (1996) found the juniper to be consistently high levels of living foliage. The inner light grey line delimits the 2650 m.a.s.l contour, above which juniper were found to have consistently high foliage scoresin this survey. The locations of topographical depressions are shown as shaded grey areas: these sites provide habitat where juniper usually retained more foliage even at lower elevations, and these are also the areas where most saplings were found. This map does not illustrate variation in solar radiation nor any change with easting, which also affect juniper percent living foliage (Table 1), so there are a few sites further east and in more shaded areas where juniper retain high levels of foliage but which are not marked on the map.

4. DISCUSSION

4.1 Patterns in juniper condition and regeneration

Throughout the montane woodlands of Jebel Akhdar and Jebel Shams, juniper trees in with high levels of percent living foliage could only be found in small areas of their range (Figure 4). Evidence of regeneration was extremely limited, with only four seedlings observed during this study. Less than 10% of the trees surveyed were saplings, whilst in other parts of its range, populations of Zeravschan juniper can have up to 50% saplings (Økland et al, 2008). In this study, juniper with more living foliage tended to be found in cooler, moister conditions: at higher elevations, further east (where more precipitation is thought to occur), and in areas with lower incident solar radiation (Table 1). Topography had the greatest impact on both percent living foliage and the relative abundance of saplings, with both found significantly more often in depressions, rather than on hillsides or in wadis (Tables 1 and 2). Due to their shallow basin shape, these depressions collect more soil than either hillsides or wadis, and are expected to retain moisture for longer after rainfall events than either hills or wadis (Figure 5).

Neither human harvest nor grazing were found to play a significant role in the overall patterns of juniper foliage condition and relative abundance of saplings. It is true that some human harvest does occur, and in a few locations it can be severe (pers. obs.), but overall patterns in foliage and saplings were not related to harvest patterns. It is known that goats and donkeys may occasionally feed on juniper foliage (Jebel Akhdar Initiative, 2007; Schlect et al, 2009), but any impact appears to be small given that juniper percent living foliage was not related to grazing pressure, and no browse lines were observed on juniper trees. In contrast, browse lines were obvious throughout the study site on the co-dominant wild olive trees *(Olea europaea,* a species known to be favoured by livestock in arid montane ecosystems; Anthelme et al, 2008; Aynekulu et al, 2009). The abundance of juniper saplings was found to be slightly higher in more heavily grazed areas, but this may simply be an association between areas where good forage is found and areas which are suitable for sapling growth. Both are likely to be promoted by higher moisture availability in this arid ecosystem.

4.2 Climate change and juniper decline

The finding that juniper tended to have more living foliage in cooler, moister areas, and that saplings were also mostly found in these locations, suggests that juniper decline is primarily driven by climate change. The relationship found between juniper percent living foliage and elevation indicates a pattern typical of climate-stressed montane plant species: health reduces and mortality increases in the lower parts of the species' range (Breshears et al, 2008). Plants growing near the lower altitudinal limits of their range are near their temperature tolerance limit, so when regions become warmer then lower areas become less hospitable to survival, and the species' range shifts upwards (Walther et al, 2005; Parmesan, 2006). For species such as the Zeravschan juniper in Oman, which have a range that already includes the mountain summit, then this upward shift in range also coincides with a reduction in available habitat *(*Figure 4): there is simply no more mountain at climatically suitable elevations (Gottfried et al, 2012).

Figure 5: This photo of Hayl Juwari on Jebel Shams illustrates the effect of depression habitats on juniper health: junipers with higher levels of living foliage and juniper saplings are often found in the centres of gently sloping basins. Hayl Juwari is the largest depression habitat within the study area.

A comparison of the results of this survey with the 1996 survey by Gardner and Fisher suggests that the lower boundary of optimal habitat for Oman's junipers has shifted upwards by 250 metres in the last twenty years (Figures 3 and 4). 'Optimal habitat' is used here to refer to parts of the landscape where juniper consistently retain high levels of living foliage, and are believed to be in good health. Juniper can survive below the elevation of this optimal habitat, but their health and reproduction is dependent on habitat characteristics that promote cooler temperatures and higher moisture levels (Figure 3). This results in a mosaic at lower elevations of pockets of juniper with high levels of foliage, between areas with trees of deteriorating condition with little remaining foliage. Similar patterns in plant vigour and mortality are often observed near the lower range boundaries of species responding to climate change in montane habitats (Breshears, 2008; Anthelme et al, 2008; Scherrer and Körner, 2011).

The upward elevational shift in optimal habitat can be attributed to the rapid local climate change observed in the area in recent decades. According to Al Sarmi and Washington (2012), who analysed data from the Saiq weather station not far from the boundary of the juniper survey area, Jebel Akhdar has experienced an increase in average annual temperature of 0.45^{o}C per decade between 1980 and 2008, and a decrease in average annual precipitation of 69mm/decade in the same time period. Al Sarmi and Washington (2012) do not state what the average annual temperature nor precipitation was in the 1980s, but some rough estimates can be made, given that the Oman Department of Meteorological Affairs reports an average annual precipitation of 310mm and an annual average temperature of 23.5^{o}C for the same weather station, between 1986 and 2009. A decrease of 69mm/decade in annual precipitation between 1980 and 2008 would therefore equate to a change from around 380mm/year in the 1980s to 240mm/year in the 2000s, a severe reduction in rainfall. Likewise, an increase in average annual temperature of 0.45^{o}C/decade between 1980 and 2008 implies a change from approximately 23^{o}C in the 1980s to 24^{o}C in the 2000s. If these trends in precipitation and temperature continue, and the rate of upward shift remains constant, we would expect the lower boundary of optimal habitat to rise above the summit of Jebel Shams at 3009 m.a.s.l around the year 2040.

4.3 Shallow depressions and shaded northern slopes as climate refugia for Zeravschan juniper in Oman

The effect of climate change on available habitat for montane species can be mitigated where habitat features maintain suitable conditions at lower elevations, despite rising regional temperatures (Anthelme et al, 2008; Scherrer and Körner, 2011). Temperature differences across montane landscapes caused by shading from topographical features and other vegetation can be greater than forecasted temperature change for the next 100 years, and these cool refugia may be able to sustain many montane species despite increases in average temperatures (Scherrer and Körner, 2011). In this study, juniper experiencing lower levels of incident solar radiation, and therefore lower temperatures, tended to be in better condition. The steep north-facing slopes of Jebel Akhdar and Jebel Shams seem able to provide sufficient shading to support juniper in relatively healthy levels of foliage below the elevation of optimal habitat (Figure 3). However, there was no evidence that shading promotes a higher number of saplings (Table 2).

Variation in moisture levels can also create refugia in a landscape that is becoming increasingly arid. There is evidence that a dramatic reduction in rainfall has occurred over Jebel Akhdar and Jebel Shams in recent decades (Al Sarmi and Washington, 2012) and in this study it is apparent that the most critical habitat feature for Oman's junipers are the shallow depressions These host both saplings and mature trees with high levels of living foliage, even at lower elevations. This suggests that the moisture retention capacity of the depressions outweighs the decreases in precipitation and any increases in evaporation caused by rising temperatures.

Depressions (Figure 5) and shaded northern slopes may offer refugia to Zeravschan juniper in Oman in the face of climate change. The junipers have a lifespan of hundreds to possibly thousands of years (Saas-Klaasen et al, 2006), and so may be able to withstand prolonged periods of reduced or absent regeneration, if the mature trees survive (Garcia et al, 1999). The patterns in juniper percent living foliage found in this study suggests that current climate change is increasing mature tree mortality in most of the range, but trees located in depressions and on shaded northern slopes remain in good condition even at relatively low elevations. There is also a significantly higher proportion of saplings in depressions than in other habitat types, suggesting that these depressions therefore offer the best hope of survival for Oman's junipers.

To provide the Zeravschan juniper in Oman with the best possible chance of surviving climate change, these key refugia habitats will need to be protected from other adverse pressures. Although this study shows that current harvesting does not have an impact on the overall patterns of juniper decline, harvesting has been observed to reach high levels around the Khab Hayl Mahlab area of Jebel Akhdar, which is easily accessible and is favoured by tourists. This area contains several small depressions as well as a flat plateau with many juniper trees in reasonable condition. Khab Hayl Mahlab has also suffered substantial damage from soil removal to supply local agroindustry, with areas up to 1ha in size denuded of vegetation and topsoil (Victor, 2008; pers. obs.). Such activities need to be limited or prevented within depression habitats to give the junipers the highest chance of survival in the face of climate change. The shaded northern slopes are currently less impacted by human activities due to their relative inaccessibility, and care should be taken to ensure they remain protected.

4.4 Conclusions and conservation implications

This article has presented evidence to show that climate change is the main cause of decline of Zeravschan juniper in Oman. Conservation strategies for this iconic tree can now be adapted to reflect this threat, and to take into account the value of shallow depressions and shaded northern slopes as climate refugia for juniper. These findings may also have implications for the conservation of other plant species in the Hajar Mountains, as the junipers are probably only the most visible impact of climate change. Many less obvious species are also thought to be shifting upwards (El-Keblawy, 2014). Climate refugia offered by certain habitat features may also exist for many of these other species (Anthelme et al, 2008; Scherrer and Körner, 2011), yet little is currently known about the fine-scale distribution and habitat requirements of most plants within the Hajar Mountains. Such knowledge will be critical to ensure the protection of habitat features which are most likely to conserve a high species diversity in the face of climate change.

A focus on habitat heterogeneity could be important for the conservation of vulnerable montane species worldwide. The Hajar Mountains are not alone in their recent dramatic temperature and precipitation shifts, and global data suggests that average annual temperatures for mountain environments will increase a further 2 - 3^{o}C by 2055 (Nogués-Bravo et al, 2007). This study on Oman's junipers has shown that topographical features can have a significant impact on the regeneration and survival of a climatically vulnerable tree, despite strong warming trends. Improving our understanding of the relationships between habitat heterogeneity, microclimate and species survival will help to optimize conservation strategies for global montane diversity in the face of climate change.

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9. APPENDIX A: Collinearity in explanatory variables

Collinear explanatory variables were not included in the same GLiMs in this study. Quantitative explanatory variables were considered collinear if the Pearson's correlation coefficient (R) between a pair of variables was greater than 0.4 or less than -0.4. Pairs of collinear quantitative variables in this study were slope and percent soil cover (R = -0.46) and slope and incident solar radiation (R = -0.77). Collinearity amongst categorical variables was judged using boxplots. Topography was collinear with both slope and percent soil cover: depressions had consistently lower slopes and higher soil covers than either wadis or hillsides (Figure A.1).

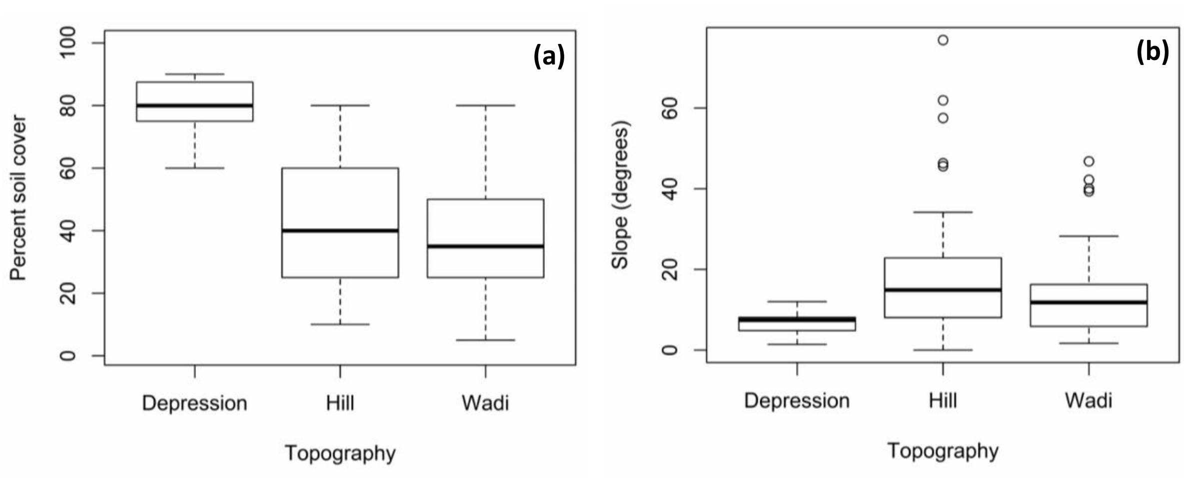

Figure A.1: Boxplots illustrating collinearity between topography and slope (a), and topography and percent soil cover (b).

10. APPENDIX B: Relationships of significant explanatory variables with the response variables

This appendix illustrates the relationships of the explanatory variables found to be significantly associated in the generalised linear models with juniper condition (Figure B.1), and with the relative abundance of saplings (Figure B.2).

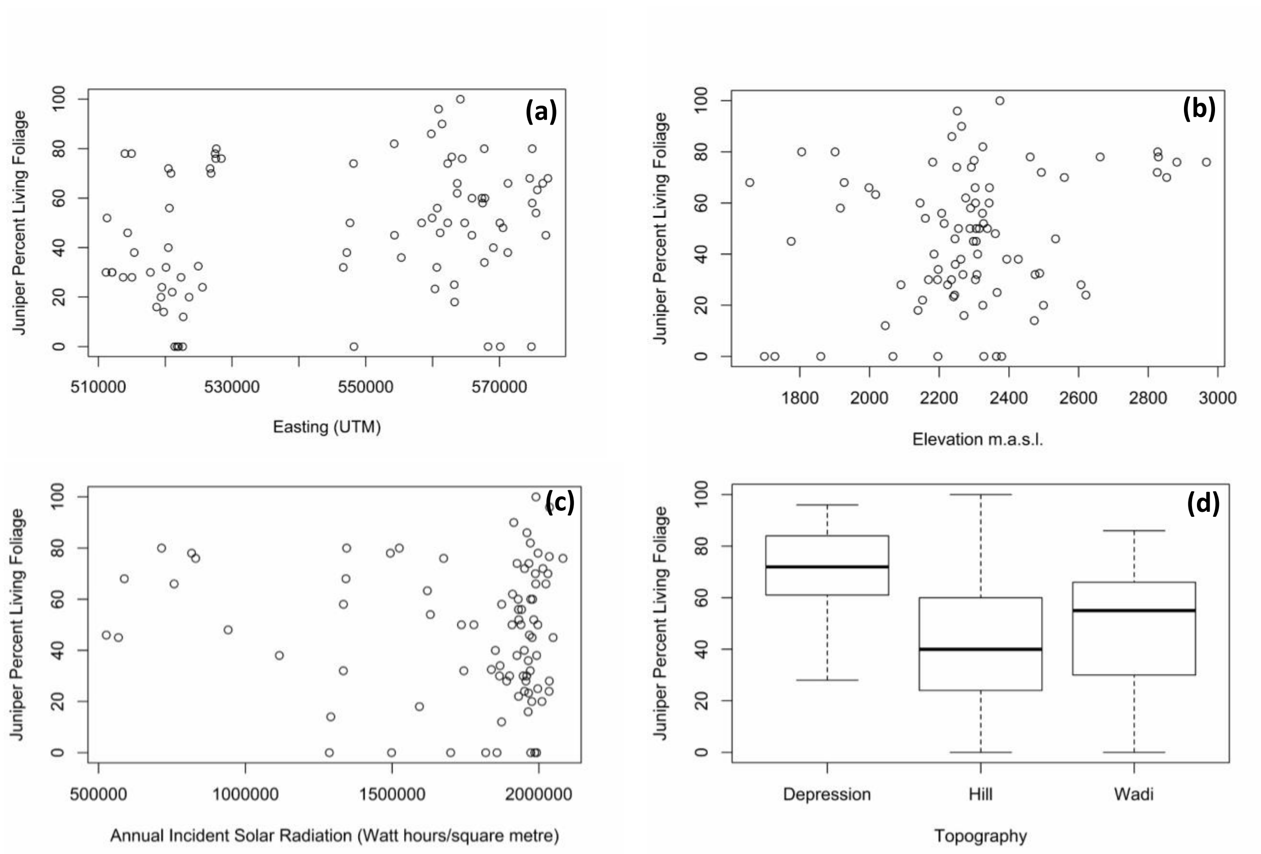

Figure B.1: The relationship between juniper condition and easting (a), elevation (b), incident solar radiation (c), and topography (d).

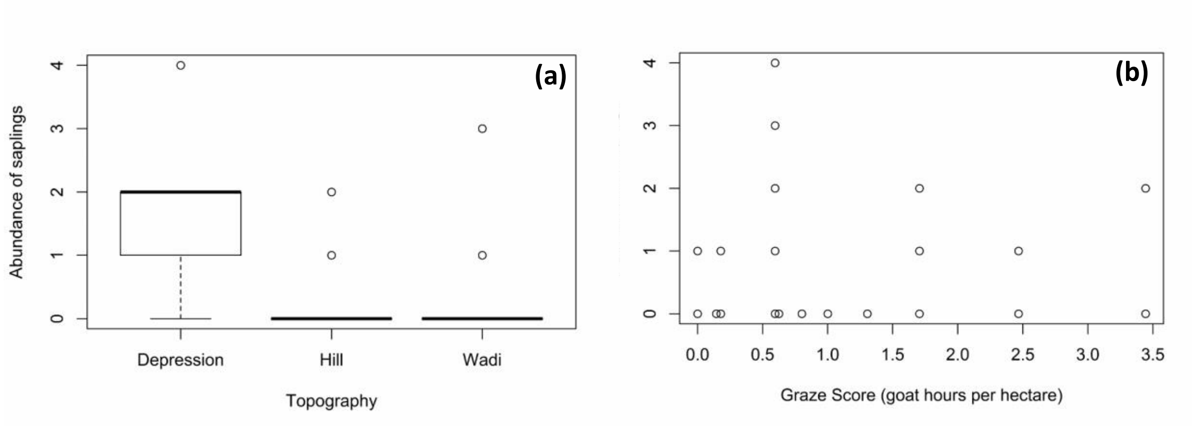

Figure B.2: The relationship between the relative abundance of saplings and topography (a), and graze score (b).