Distribution of Sideroxylon Mascatense (A.DC.) T.D.Penn. and Associated Perennial Plant Communities in Oman

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Research article

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Abstract

Background

Oman is located on the south-eastern tip of the Arabian Peninsula and is characterized by an arid climate with a vast and varied landscape. *Sideroxylon mascatense* is a fruit-producing species growing in the arid mountainous regions of North Africa, The Middle East, and Asia. To date, there are no studies describing the population distribution of *S. mascatense* and the plant communities associated with it in Oman. This study fills this gap.

Results

A series of botanical field surveys was carried out between June 2018 and August 2019 to describe the distribution and associated plant communities of *S. mascatense* in the Western Hajar Mountains. Sample units were surveyed in the months of June, July, and August as this is the optimal fruiting period of *S. mascatense* in the Western Hajar Mountains of Oman. Throughout the surveys, 54 perennial non-cultivated species from 32 families were observed growing with *S. mascatense*. Two-way cluster analysis and indicator species analysis found two main plant communities associated with *S. mascatense* along an altitudinal gradient. These were the *Acridocarpus orientalis*-*Euphorbia larica* community and the *Olea europaea*-*Euryops arabicus* community. There was species overlap in the transitional area between the communities where the environmental factors allowed for continuation along the altitudinal gradient. There was no recruitment of *S. mascatense* observed during the surveys.

Conclusions

The lack of recruitment, along with the threats of overgrazing and habitat destruction, point to an uncertain future for the *S. mascatense* populations in Oman. As *S. mascatense* is associated with threatened key species in the Western Hajar Mountains, *S. mascatense* should be protected and included in conservation projects. This could allow for the establishment of natural recruitment of *S. mascatense*, t*hereby preserving the fragile ecosystem of the Western Hajar Mountains and ensuring the future survival of S. mascatense and its associated communities.*

Background

Oman is located on the south-eastern tip of the Arabian Peninsula and has a vast and varied landscape with an arid climate. The rugged and steep Hajar Mountains dominate the north with peaks reaching about 3000 meters (m) above sea level (a.s.l.) (Fig. 1); there is a vast central desert in the middle, and the south has coastal mountains with monsoon cloud forests. Within this variety of terrain, Oman hosts over 1400 native wild plant species with 191 of them being range-restricted and 72 being rare and threatened [1, 2]. Of all the flora of Oman, 703 of the 1407 species are found in the mountains of northern Oman [1]. Of the 703 species, 298 species belonging to 73 families are found above 1500 m a.s.l. in the Western

Hajar Mountains, of which, 22 are range-restricted and 33, while not range-restricted, are classified as threatened, near-threatened, or data-deficient [1, 2].

The Western Hajar Mountains exhibit a variety of seasonal microclimates that are in general more temperate and Mediterranean in nature than compared to those occurring in the rest of Oman. The Saiq meteorological station on Jebel Akhdhar, a mountain in The Western Hajar Mountains, has recorded average temperatures that are 12°C cooler than those in Muscat. Further, the mountains had an average rainfall over the last two decades of 210 millimeters (mm) while the meteorological station in Muscat recorded only 68 mm [3]. The data from this station also shows that over the last 20 years, there have been increases to the minimum temperature of 0.6°C/decade and mean temperature of 0.1°C/decade [3]. Al-Kalbani et al.[4] found increases of minimum temperatures of 0.79°C per decade and mean temperatures of 0.27°C per decade, with a decrease in precipitation of 9.42 mm per decade at the Saiq meteorological station data from 1979–2012. Al-Sarmi and Washington[5] found an increase in mean temperature of 0.85°C per decade, an increase in minimum temperature of 1.20°C per decade, and a decrease in precipitation of 67.71 mm per decade at the Saiq meteorological station data from 1980–2008. In Oman, temperatures are predicted to increase, with average minimum temperatures increasing more than average maximum temperatures with rainfall decreasing [6]. Data loggers placed in the study area over the course of the study revealed that the weather in the Western Hajar Mountains during the period in which the surveys were conducted was similar to the trends set in the past 30 years of weather data. The average rainfall was 156 mm in 2018 and 325 mm in 2019 compared to the 221 mm 10-year average between 2010 and 2019 from the Saiq weather station on Jebel Akhdhar [3]. According to the data loggers placed in the field, the hottest months were June, July, and August of 2018, where the mean temperatures were 25.5 °C, 25.1 °C, 24.3 °C respectively. The hottest temperatures were recorded in August 2018 at 45.7 °C on Jebel Hat at 2300 m a.s.l. The coolest months were December 2018 and January 2019, which had mean temperatures of 0.5 °C and − 2.2 °C respectively. The highest mean relative humidity occurred in November 2018, December 2018, and January 2019 at 67%, 63%, and 54% respectively. All months had occurrences of maximum relative humidity between 90–100% except June of 2018 which peaked at 84%. It is clear that the flora of Oman is under threat from climate change. In addition to threats from climate change, plants in Oman also face threats due to overgrazing and impacts from human activities. The basis of knowledge to establish conservation zones to protect plant populations, wildlife, and natural resources comes from field research such as habitat and community surveys.

Botanical surveys in Oman are limited. However, notable work includes regional surveys on plants such as the study by Al-Harthy and Grenyer [7], which classified the plant communities in the Eastern Hajar Mountains above 1000 m a.s.l. The coastal vegetation of Oman has also been studied and the communities were classified [8]. Field surveys in Oman’s central desert have been utilized to study endemic and rare plant populations. These studies along with environmental factors were then used to model the extents of these populations [9]. Surveys were also utilized to determine the population structure of woody plants in Wadi Garziz in the Dhofar region of Oman [10]. Specific areas in the Western

Hajar Mountains have been studied with plant surveys as well, including Jebel Akhdhar, Jebel Shams, and a few representative mountain oasis farms [11–13].

Surveys on specific plant species and their associated communities have also been conducted in Oman. *Juniperus polycarpos* var. *seravschanica* (Kom.) Kitam. has been the subject of many studies as it is a key species in the Western Hajar Mountains [14–17]. In another species-of-special- concern survey, *Dracaena serrulata* Baker was studied in the Dhofar mountains in southern Oman by Vahalík et al. [18]. The authors studied the population density and distribution from 255 viewpoints located throughout the species range. These data were then used to map the distribution to highlight the most vulnerable populations and areas. Models of plant populations have also been created and tested to ease the estimation of populations in difficult-to-reach areas like the Hajar Mountains in Oman [19].

S. mascatense is a fruit-bearing species found growing throughout the arid mountainous regions in North Africa, The Middle East, and Asia. Two distinct morphotypes produce markedly different colored fruit. The dark purple-black colored fruit is found in Pakistan and a yellow-brown fruit can be found in Somalia [20, 21]. In Oman, both morphotypes are known to coexist, although the purple-black morphotype is dominant over the less prevalent yellow-brown morphotype[22–25] (Fig. 2). *S. mascatense* in Oman can be found between 1000–2500 m a.s.l. predominantly in the Western Hajar Mountains, with small populations scattered throughout the Eastern Hajar Mountains and in Dhofar [7, 10, 23]. In the Western Hajar Mountains the fruit is widely collected by local inhabitants and sold at markets for consumption [23]. While not cultivated, some wild specimens are incorporated into developed landscapes to increase harvest yields [24].

In general, there is a lack of research on *S. mascatense* in the wild with only general descriptions in country-specific flora volumes [21, 23], one study on its habitat and associated plant communities in Pakistan [20], one including it as an associated species in a plant community survey in Ethiopia [26], and one molecular characterization study [25]. However, there has been extensive research on the nutritional and medicinal qualities of the fruit, leaves, and stems, with most studies focusing on the purple-black morphotype found in Pakistan [27–34]. The lack of habitat and population distribution research, especially in Oman where both morphotypes coexist, is an obstacle both for programs focused on conservation strategies, and the development of *S. mascatense* as a commercially-cultivated fruit crop [24]. The current study aims to address this knowledge gap by defining the population distribution throughout Oman and classifying the plant communities associated with *S. mascatense* in the Western Hajar Mountains in Oman.

Results

- Population distribution

In order to map the full habitat of *S. mascatense* in Oman, herbarium records from the Royal Botanic Garden Edinburgh (E), the Oman Botanic Gardens (OBG), the Oman National Herbarium (ON), and the

Sultan Qaboos University College of Science Herbarium (SQUH) were added to records from previous studies, unpublished work, and the quadrat locations from the current study (Fig. 3 and Appendix A). The bulk of the population distribution is in the Western Hajar Mountains between Jebel Akhdhar in the east and Jebel Shams to the west. Small isolated populations exist on Jebel Aswad and are scattered elsewhere throughout the Eastern Hajar Mountains. In Dhofar, southern Oman, several scattered populations have been documented on Jabal Al Qamar and Jabal Samhan. No specimens are known to exist in the Western Hajar Mountains from Jebel Misht north to Musandam.

The surveys took place between June of 2018 and August of 2019. Quadrats were surveyed in June, July, and August as this is the optimal fruiting period of *S. mascatense* in the Western Hajar Mountains. However, one lower elevation quadrat was visited in April of 2019 in an area known for early fruiting. There were 6 quadrat locations that were impossible to physically access, so three accessible locations located in the appropriate strata were chosen to ensure that a minimum of 17 quadrats were surveyed in each stratum not including the quadrats of yellow-brown morphotype specimens. Actual elevations of the 114 quadrats surveyed in this study ranged in altitude between 1134 and 2419 m a.s.l. There were some specimens of *S. mascatense* found at elevations as low as 800 m a.s.l.; however, they were rare and located in protected areas with northern aspects. Throughout the study, 14 specimens of the yellow-brown morphotype were located in nine quadrats.

During the survey, the quadrats with the largest populations of *S. mascatense* were found at elevations of 1360–2350 m a.s.l. in the eastern half of the study area on Jebel Akhdhar (Fig. 4). Overall, a total of 513 specimens of *S. mascatense* were located. Of these, only 34% (172) had mature fruit. Of those 172 fruiting specimens, 92% (158) were the purple-black morphotype, and 8% (14) were the yellow-brown morphotype (Fig. 5). *S. mascatense* specimens ranged from 0.5-5 m in height and with driplines from 0.25-4 m in diameter.

- Vegetation Analysis and Associated Plant Communities

Throughout the survey, 54 perennial non-cultivated species from 32 families were observed growing with *S. mascatense*. The three most species-abundant families were Asteraceae, Fabaceae, and Lamiaceae with 13.6%, 11.4% and 11.4% representation respectively. Of the species associated with *S. mascatense*, eight are regionally endemic, three are endemic to Oman, and two are considered rare and threatened [2]. The five most common species found were *Dodonaea viscosa* (L.) Jacq., *Olea europaea* subsp. *cuspidata* (Wall. & G.Don) Cif., *Euryops arabicus* Steud. ex Jaub. & Spach, *Sageretia thea* (Osbeck) M.C. Johnst., and *Grewia erythraea* Schweinf which were found in 80%, 63%, 56%, 51%, and 48% of the quadrats respectively. Average species richness across all quadrats of the study was 7.4. The average species richness had a weak yet highly significant negative correlation with elevation ($r = -0.27$) with a p-value of 0.003. Shannon's diversity index followed a similar trend, with an average of $H' = 1.192$ and a weak yet highly significant negative correlation with elevation ($r = -0.23$) with a p-value of 0.013. Plant names follow that of The Plant List [37], and plant family delineation came from the Angiosperm Phylogeny Group (APG IV) [38]. Phytosociological nomenclature was not used to describe the plant communities.

The first division of the TWCA was utilized for the community study. The first division produced two groups accounting for 87.5% of the variation in the data (Appendix B). With these two groups the ISA gave the most significant indicator species with the lowest average significance level. These two groups are the two main plant communities associated with *S. mascatense*, and fall along an altitudinal gradient. The communities were named after the two species with the highest IV in the group (Table 1). These were the *Acridocarpus orientalis*-*Euphorbia larica* community and the *Olea europaea*-*Euryops arabicus* community. Quadrats aligning with the *Acridocarpus orientalis*-*Euphorbia larica* community were found from 1134–1925 m a.s.l. where quadrats aligning with the *Olea europaea*-*Euryops arabicus* community were found between 1320–2419 m a.s.l. Both communities had instances of continuation along the altitudinal gradient due to other influencing environmental factors such as water availability, slope, aspect, and geological features present. TWINSPAN analysis corroborated the TWCA grouping. The top eight significant indicator species by IV according to ISA were the same species as those shown by the ISA of the TWCA. The only differences were the IVs and p-values for those eight significant indicator species. The dendrogram from the TWCA (Appendix B), a table of indicator species and average p-values (Table 1), and a table of indicator species from the first division of TWCA and TWINSPAN (Appendix C) are shown for reference. Using the groups indicated by TWCA, MRPP showed a highly significant difference between groups using the main matrix of presence-absence data ($A = 0.20$, $T = 53.54$, $p < 0.00000001$) and using the matrix of environment variables ($A = 0.43$, $T = 55.73$, $p < 0.00000001$). Ordination with NMDS also grouped the same two main plant communities along the altitudinal gradient (Appendix D). A two-dimensional solution was chosen for the final solution for NMDS because the mean stress in the Monte Carlo test with 250 runs was 16.91 at a p-value of 0.012. The best solution had final stress of 17.07 after 55 iterations.

Table 1
List of the 8 indicator species with the highest indicator values for the two plant communities associated with *S. mascatense* in the Western Hajar Mountains of Oman.

Species	**IV**	**p***
Group 1. Acridocarpus orientalis-Euphorbia larica community		
(17 significant indicators)		
Acridocarpus orientalis A.Juss.	78.2	0.0002
Euphorbia larica Boiss.	77.0	0.0002
Polygala mascatensis Boiss.	58.9	0.0002
Grewia erythraea Schweinf.	57.4	0.0002
Tephrosia apolina (Delile) DC.	50.8	0.0002
Vachellia gerrardii Benth. subsp. *negevensis*	50.6	0.0002
Fagonia indica Burm.f.	48.0	0.0002
Ochradenus arabicus Chaudhary, Hillc. & A.G.Mill.	45.5	0.0002
Group 2. Olea europaea-Euryops arabicus **community**		
(8 significant indicators)		
Olea europaea subsp. *cuspidata* (Wall. & G.Don) Cif.	80.2	0.0002
Euryops arabicus Steud. ex Jaub. & Spach	75.3	0.0002
Dodonaea viscosa (L.) Jacq.	73.0	0.0002
Teucrium mascatense Boiss.	50.6	0.0002
Sageretia thea (Osbeck) M.C. Johnst.	48.8	0.0006
Helianthemum lippii (L.) Dum.Cours.	32.9	0.0008
Juniperus polycarpos var. *seravschanica* (Kom.) Kitam.	32.9	0.0014
Ephedra pachyclada Boiss.	18.8	0.0238
* p is the significance level of the indicator species according to the Monte Carlo test.		

- Acridocarpus orientalis-Euphorbia larica community

The *Acridocarpus orientalis-Euphorbia larica* (*Ao-El*) community describes most of the lower *S. mascatense* habitat range with an average elevation of 1345 m a.s.l. The habitat ranges from steep shale-covered hillsides, rolling hills and summits, as well as the occasional wadi (dry river bed). The soil structure of this community varies from very rocky in places to rocky-clay-silt packed in runnels between exposed rock slabs. Quadrats surveyed at the higher elevation limits of the *Ao-El* community were located on steep hillsides with little access to ground water. This was the most diverse community associated with *S. mascatense* with an average species richness of 8.7 and a Shannon's diversity index of H' = 2.08. It also held the most diverse quadrat surveyed in the study with a species richness of 17 and a Shannon's diversity index of H' = 2.83. The top five species in the *Ao-El* community are *Grewia erythraea*, *Acridocarpus orientalis*, *Euphorbia larica*, *Polygala mascatensis*, and *Vachellia gerrardii* subsp. *negevensis* which occurred in 83%, 79%, 79%, 69%, and 62% of the sample plots respectively.

- Olea europaea-Euryops arabicus community

The *Olea europaea-Euryops arabicu*s (*Oe-Ea)* community, with an average elevation of 2067 m a.s.l., associates with *S. mascatense* at the higher elevation limits of its habitat. The habitat ranges from gently rolling hills, hillsides with moderate to steep slopes, to areas near or in wadis. Many of the quadrats at the lower elevation limits of the *Oe-Ea* community were located in wadis or on steep protected north-facing hillsides. The soil varied from very rocky, rocky gravel, to rocky-clay-silt packed in runnels between exposed rock slabs. The average species richness for the *Oe-Ea* community was 6.96 with a Shannon's diversity index of H' = 1.86. The top five species according to their relative frequency in the *Oe-Ea* community are *Dodonaea viscosa*, *Olea europaea* subsp. *cuspidata*, *Euryops arabicus*, *Sageretia thea*, and *Teucrium mascatense* which occurred in 96%, 84%, 75%, 62%, and 51% of the sample plots respectively.

Discussion

The habitat range of *S. mascatense* in the Western Hajar Mountains allows for the growth of a variety of associated flora. In the current study, the perennial plant communities produced by TWCA and ISA, validated by MRPP and NMDS, fall in line with previous research on plant communities in the Western Hajar Mountains. However, the current study area exceeds the areas described in detail in previous research [11, 13, 19]. On Jebel Shams, Ghazanfar[13] describes four plant communities along an altitudinal gradient from 650–2820 m a.s.l. Species found in the first and second communities are those found in the *Acridocarpus orientalis-Euphorbia larica* (*Ao-El*) community, while species found in the third and fourth communities are those found in the *Olea europaea-Euryops arabicus* (*Oe-Ea*) community. Similar results are found on Jebel Akhdhar in communities described by Brinkmann et al. [11]. These communities varied in composition due to grazing patterns and topographical positioning along an altitudinal gradient of 1100–2000 m a.s.l. According to the species present, the two higher-elevation communities both fall in line with *Oe-Ea* community, while the lower and mid-elevation communities fall in line with the *Ao-El* community. Brinkmann et al.[19] used environmental variables to model the vegetation patterns on Jebel Akhdhar. They used previous research along with verification samples to create their vegetation model for the central zone of Jebel Akhdhar from 640–2560 m a.s.l. The model focused on two main plant communities, the *Sideroxylon-Oleetum* and the higher elevation *Teucrio-Juniperetum*, each subdivided into two variants. They also included two lower-elevation communities along with others classified as rank-less plant communities. The Brinkmann et al.[19] model was utilized to compare with the communities described here. Quadrats from the current study were overlayed on top of the model created by Brinkmann et al.[19] (Fig. 6). Quadrats belonging to the *Oe-Ea* community fell within upper two communities of the model 91% of the time, with the other 9% falling in the lower elevation community. Only two quadrats from *Ao-El* community were located within the model's extent. One quadrat aligned with the *Acacia gerrardii-Leucas inflata* community and the other aligned with the *Moringa peregrina-Pteropyrum scoparium* community. Patzelt[1] described three plant communities along an altitudinal gradient in the Wester Hajar Mountains, the *Euphorbia larica-Moringa peregrina* community, the *Sideroxylon mascatense-Olea europaea* community, and the *Teucrium mascatense-Juniperus seravschanica* community. *S. mascatense* was present in all three communities [1]. The *Ao-El* community aligns with upper elevations of the *Euphorbia larica-Moringa peregrina* community as well as the lower elevations of the *Sideroxylon mascatense-Olea europaea* community. The *Oe-Ea* community aligns with the upper elevations of the *Sideroxylon mascatense-Olea europaea* community and the *Teucrium mascatense-Juniperus seravschanica* community.

Grazing, commonly by goats, sheep, and donkeys, is a major biotic stress to plant species found in the Western Hajar Mountains. This level of grazing pressure has changed over time. Brinkmann et al.[11] describe the vegetation along a gradient of grazing pressure. They describe a community subset that had little or no grazing presence. Throughout the current study, which encompasses the areas surveyed by Brinkmann et al. [11], all quadrats had some presence of grazing pressure. Al-Harthi et al.[39] found that *S. mascatense* was heavily consumed by goats, sheep, and donkeys. They state that the current level of animal overstocking was unsustainable and was leading to a stressed ecosystem. *S. mascatense* was found to be the most frequently-occurring plant species in goat feces [39]. Unsustainable overgrazing has been linked to the decline of recruitment, and as a threat of several plant populations including *Olea europaea* subs. *cuspidata* and *Dracaena serrulata* in Oman [40, 41]. Kouba et al.[42] found that short-term exclusion was an appropriate conservation management system to protect vegetation during periods of drought, which would allow native plant species to recover without being grazed in an arid steppe ecosystem.

Climate change has been shown to threaten the populations of *Olea europaea* subs. *cuspidata*, and *Juniperus polycarpos var. seravschanica* in the mountains of Oman [14–17, 41]. Both of these species are associated with *S. mascatense* higher elevation communities. As the climate and weather patterns change in the mountains of Oman, restricting the growth and distribution of these two species, *S. mascatense* growth and distribution will be affected as well. This could mean a limitation of growth with the dieback of individuals in the upper and lower elevation limits of *S. mascatense* distribution.

Conclusion

This study is the first to describe the habitat and plant communities associated with *S. mascatense.* In the Western Hajar Mountains of Oman, *S. mascatense* is a dominant key species. It is associated with many species including *Acridocarpus orientalis*, *Euphorbia larica, Olea europaea* subsp. *cuspidata*, *Dodonaea viscosa*, and *Juniperus. polycarpos* var. *seravschanica*. Major threats to the habitat of *S.*

mascatense include climate change, human encroachment, and grazing pressure by domesticated and feral animals. There was no recruitment observed in the quadrats themselves, and no recruitment observed while trekking the over 200 km to and from the quadrats. The lack of recruitment, along with the threats of overgrazing and habitat destruction, point to an uncertain future for the *S. mascatense* populations in Oman. There are *in-situ* preservation projects ongoing to protect the habitat of *Juniperus polycarpos var. seravschanica* in the Western Hajar Mountains. As this species is associated with *S. mascatense* at higher elevations, *S. mascatense* exists in these protected habitats as well. These areas should be protected from the encroachment of settlement projects and closed against grazing pressures of domesticated animals. This could allow for the establishment of natural recruitment of *S. mascatense*, thereby preserving the fragile ecosystem of the Western Hajar Mountains and ensuring the future survival of *S. mascatense* and its associated communities. Future research should focus on propagation and cultivation techniques to allow for replanting in areas damaged by construction as well as for commercial agricultural projects. Research into the habitat, phenology, and associated species of *S. mascatense* in the cloud forests of Dhofar is also recommended as the seasonal monsoon climate changes the seasonality of this unique fruit-producing wild plant in Oman.

Methods

- Development of Study Area

During a preliminary literature review, the main *S. mascatense* locations were determined to be within elevations of 1400 to 2400 m a.s.l. [22]. With this information, using a high-resolution digital elevation model (DEM) (5m) obtained from the National Survey Authority in Oman and ArcGIS software, the study area of the Western Hajar Mountains from the Samail Gap to Jebel Sarah was stratified into three elevation classes: 1150–1650 m a.s.l., 1651–2150 m a.s.l., and 2151–2650 m a.s.l. These elevation classes allowed for equal distribution of the study area with a buffer above and below the elevation limits found in the literature. The elevation classes were further stratified into the north side of the mountain range (facing the Sea of Oman) and the south side of the mountain range (facing the Central Desert). These six total strata allowed for the factoring of elevation and any rain shadow effect into the research model. Using the DEM in ArcGIS, a 30 m x 30 m grid with center points was produced and clipped to the study area. Using the ArcGIS software Random Generator tool, the 30 m x 30 m quadrat center points were selected randomly to eliminate bias. ArcGIS with Basemap Imagery, along with satellite images from Google Earth was used to visually assess sample units for accessibility. Quadrats were either rejected or accepted based on their accessibility, ensuring that the overall slope of the quadrat was less than 35° and keeping each quadrat within a six-kilometer (km) hike round trip from a vehicle-accessible road. 18 samples from each of the six strata were selected. As mentioned previously, the yellow-brown morphotype is much less common in the mountains of Oman. Given the infrequency of occurrence of the yellow-brown morphotype, when specimens of this morphotype were located, an extra study quadrat was added around them.

- Botanical survey

A botanical field survey on *S. mascatense* as the species of special concern was conducted and all information was recorded in a custom spreadsheet. *S. mascatense* fruits during the dry hot months of the summer during which, as Al-Harthy and Grenyer[7] state, the presence of ephemeral annual, biennial, and grass species is inconsistent in this arid mountainous region. Due to the inconsistent presence of ephemeral annual, biennial, and grass species during the summer months in the Western Hajar Mountains, the presence-absence data of only perennial species was used to analyze and describe the communities associated with *S. mascatense*. The survey included recording the number of *S. mascatense* specimens within the quadrats, as well as aspect, slope, and elevation of the quadrat. Global positioning system (GPS) coordinates, heights, and dripline diameters of some of the *S. mascatense* specimens within the quadrats were also recorded. All perennial plant species located within the quadrat were recorded. Any unidentifiable non-target species plant specimens found within the quadrat were collected and pressed, with their location recorded by GPS. Formal identification of the samples collected was done by Darach Lupton at the Oman Botanic Garden Herbarium (OBG). Voucher specimens have yet to be deposited in a publicly available herbarium. No permission for the collection of samples was required. The general phenological cycles of the *S. mascatense* specimens in the quadrat were recorded at the time of the survey. Digital photographs of target specimens, as well as other plant species located nearby, were taken at the time of the survey. Stages of the *S. mascatense* specimens' phenological cycles were also be documented by digital photography with a Nikon D5300. Temperature and relative humidity data were recorded by data loggers placed at three selected sites across the study area and monitored bi-monthly throughout one year. A handheld Garmin→ GPSMAP 64S with an accuracy of ±3 meters was used to locate quadrat center points, mark target specimens' locations, and mark the locations of any unknown or unusual species present.

Data Analysis

Plant community data were analyzed with PC-ORD 7.03 (MjM Software, OR, USA). The presence-absence of perennial plant species within the quadrats was summarized to remove any species that only occurred in one quadrat. *S. mascatense* was also removed as it occurred in all quadrats. These two steps were taken to reduce sparsity in the dataset [43]. The data were then analyzed with the hierarchical cluster analysis method of two-way cluster analysis (TWCA) using the Sørensen distance measure, flexible beta linkage, and relativized maximum, to produce the grouping for plant communities. The Sørensen distance measure was chosen because of its functionality with the use of presence-absence binary data of the current study as well as quantitative data [43]. Groups from the TWCA were then used for indicator species analysis (ISA)[44] to define indicator species with indicator values (IV) and significance levels for the groups with the Monte Carlo test at 4999 permutations and time of day for the random number seed. ISA was used to determine the relevant and significant cut level for the TWCA groups by choosing the division with the most significant indicator species with the ultimate lowest average p-value [44]. Two-way indicator species analysis (TWINSPAN)[45] was used to verify grouping in TWCA. The multi-response permutation procedure (MRPP) was then utilized to test the significance between the groups delineated by TWCA using the Sørensen distance measure. Nonmetric multidimensional scaling (NMDS)[46, 47] was then used to analyze the plant community data against the environmental variables and gradients with the Sørensen distance measure and a Monte Carlo test with a random starting configuration on 250 runs with real data to access the probability of similar final stress being obtained by chance for the NMDS. Temperature and relative humidity data retrieved from the data loggers were analyzed with Microsoft Excel for basic descriptive statistics. This included seasonal minimum and maximum temperatures as well as average day and night temperatures, with relative humidity and dew point. After surveying all of the accessible quadrats, GPS and relevant data were entered into the ArcGIS software (Esri, Redlands, CA) for analysis and mapping.

Abbreviations

°C	Degrees Celsius
A	Within Group Agreement
a.s.l.	Above Sea Level
DEM	Digital Elevation Model
E	Royal Botanic Garden Edinburgh
Ao-El	*Acridocarpus orientalis-Euphorbia larica* Community
GPS	Global Positioning System
H'	Shannon's Diversity Index
ISA	Indicator Species Analysis
IV	Indicator Value
km	Kilometer
m	Meter
MRPP	Multi-Response Permutation Procedure
NMDS	Nonmetric Multidimensional Scaling
OBG	Oman Botanic Garden
Oe-Ea	*Olea europaea-Euryops arabicus* Community
ON	Oman National Herbarium
SQUH	Sultan Qaboos University College of Science Herbarium
T	Test Statistic
TWCA	Two-Way Cluster Analysis
TWINSPAN	Two-Way Indicator Species Analysis
UPGMA	Unweighted Pair Group Method with Arithmetic Mean

Declarations

Ethics approval and consent to participate

Not Applicable

Consent for publication

Not Applicable

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

EH: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – Original Draft, Visualization. RAY: Conceptualization, Methodology, Writing – Review & Editing, Supervision, Funding acquisition. DL: Conceptualization, Methodology, Writing – Review & Editing, Supervision. All authors have read, revised, and approved this manuscript.

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Figures

Figure 1

A view from Jebel Hat around 2000 m a.s.l., and located between Jebel Shams and Jebel Akhdhar in the Western Hajar Mountains of Oman

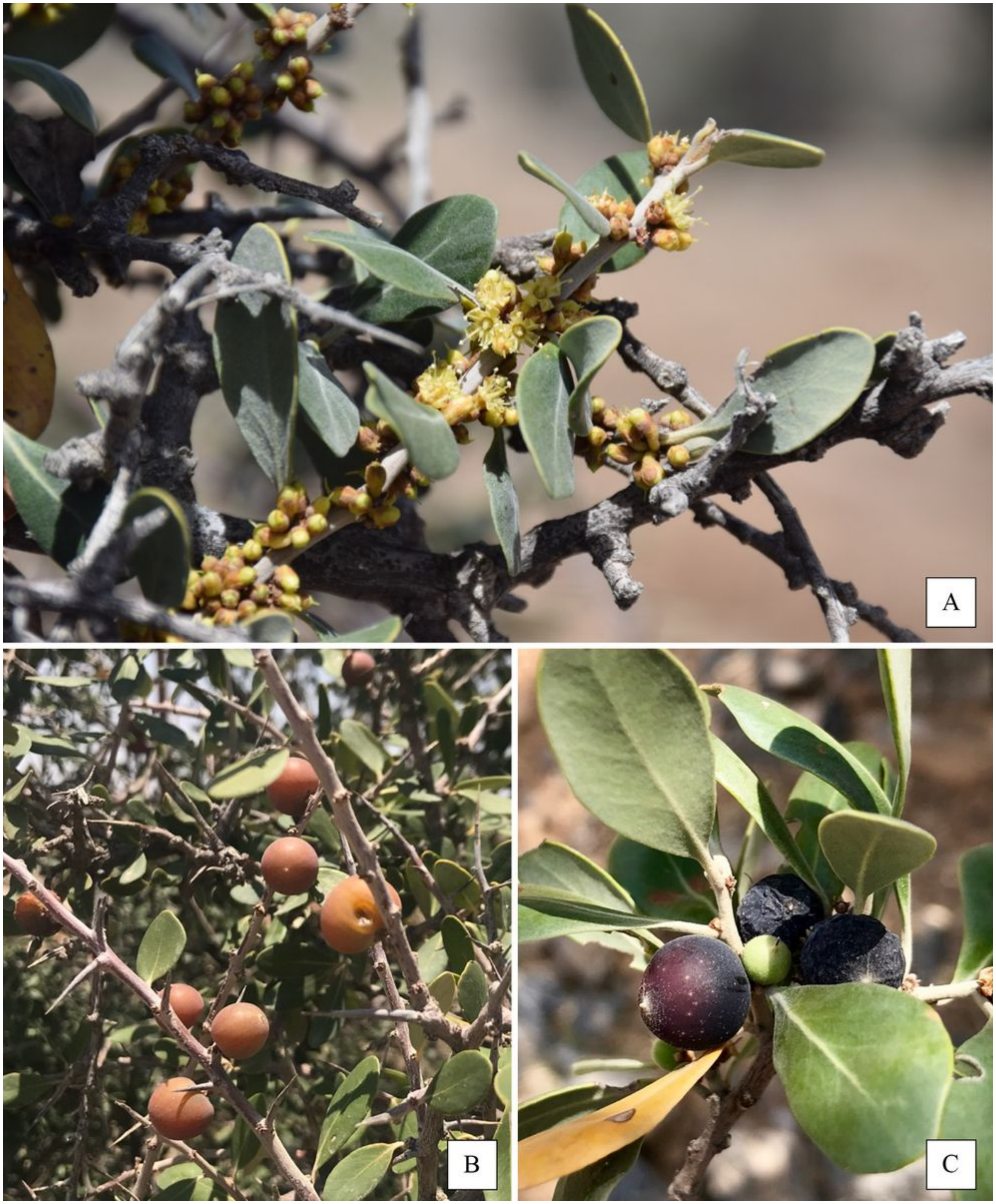

Figure 2

A. Flowering branch of S. mascatense. B. Fruit from the yellow-brown morphotype of S. mascatense. C. Fruit from the purple-black morphotype of S. mascatense.

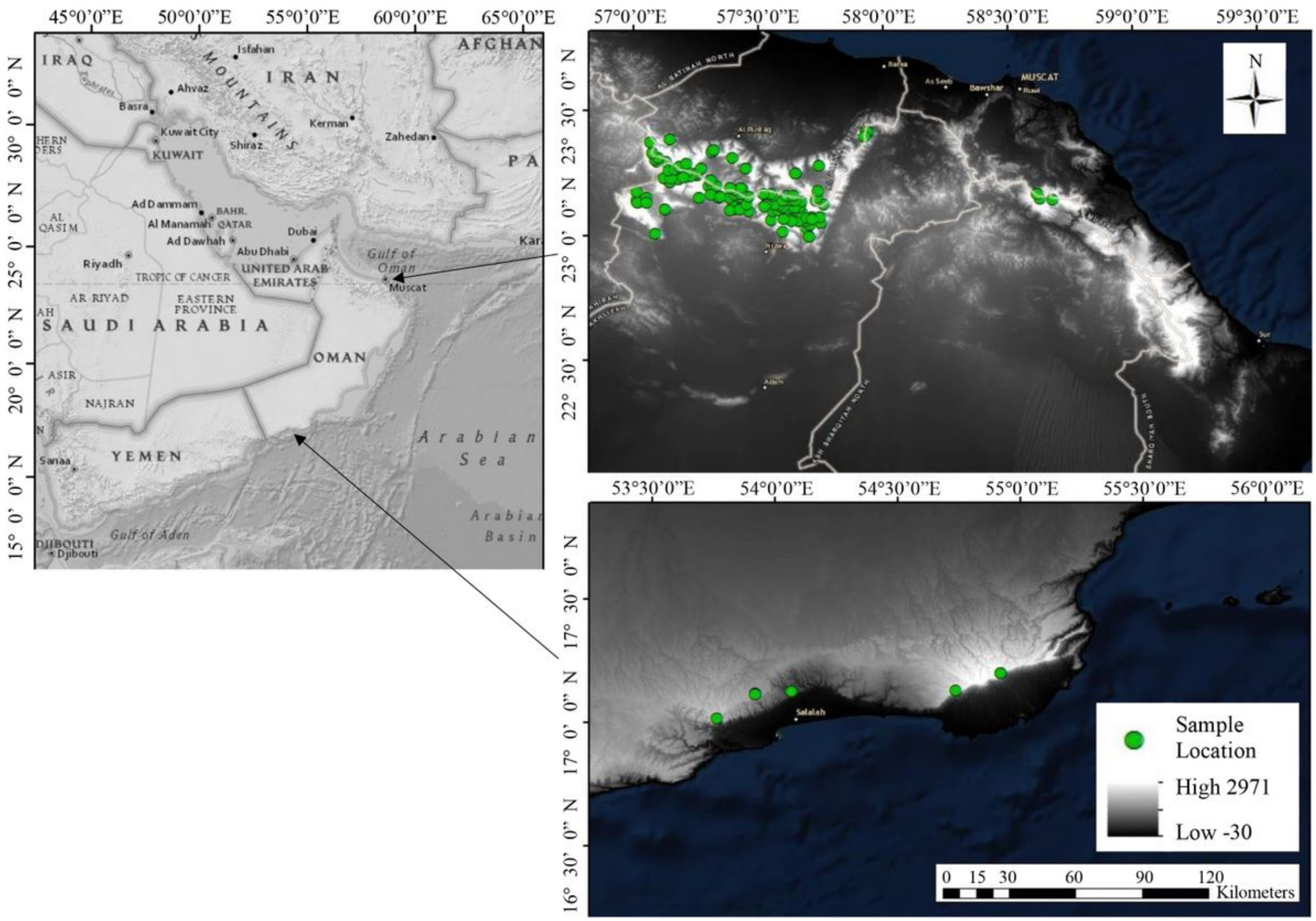

Figure 3

Distribution map of S. mascatense in Oman, the upper showing populations in the Eastern and Western Hajar Mountains, and the lower showing populations in Dhofar (Southern Oman). Green dots represent locations where S. mascatense either currently exists or was previously reported. Elevation in meters above sea level is represented in grayscale from the DEM. Sources: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community. National Geographic, Esri, DeLorme, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, iPC [35,36]. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

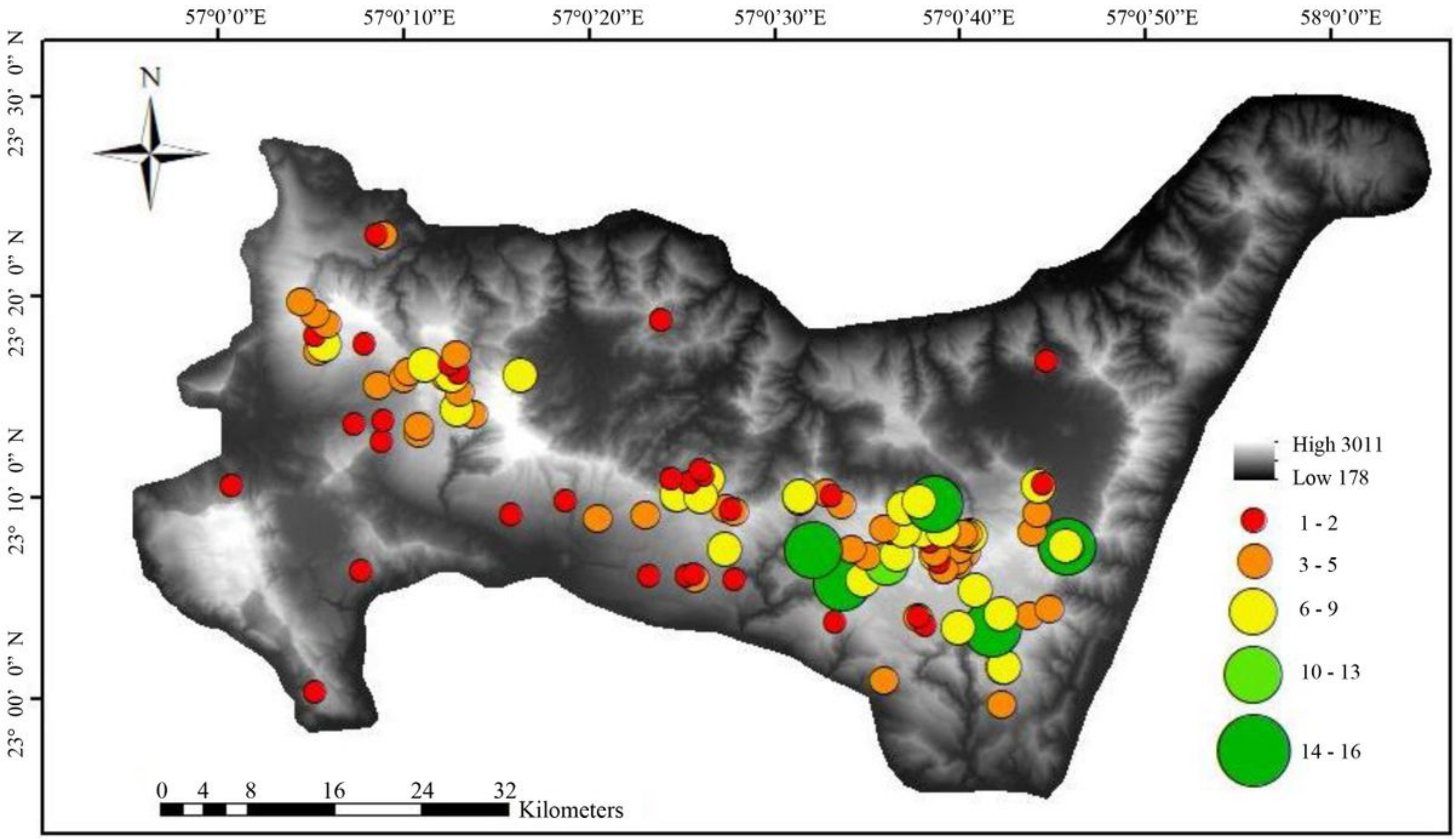

Figure 4

Map of the study area in the Western Hajar Mountains of Oman. The populations of S. mascatense specimens per quadrat location were classified into five size classes. The elevation in meters above sea level is represented in the grayscale of the DEM. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

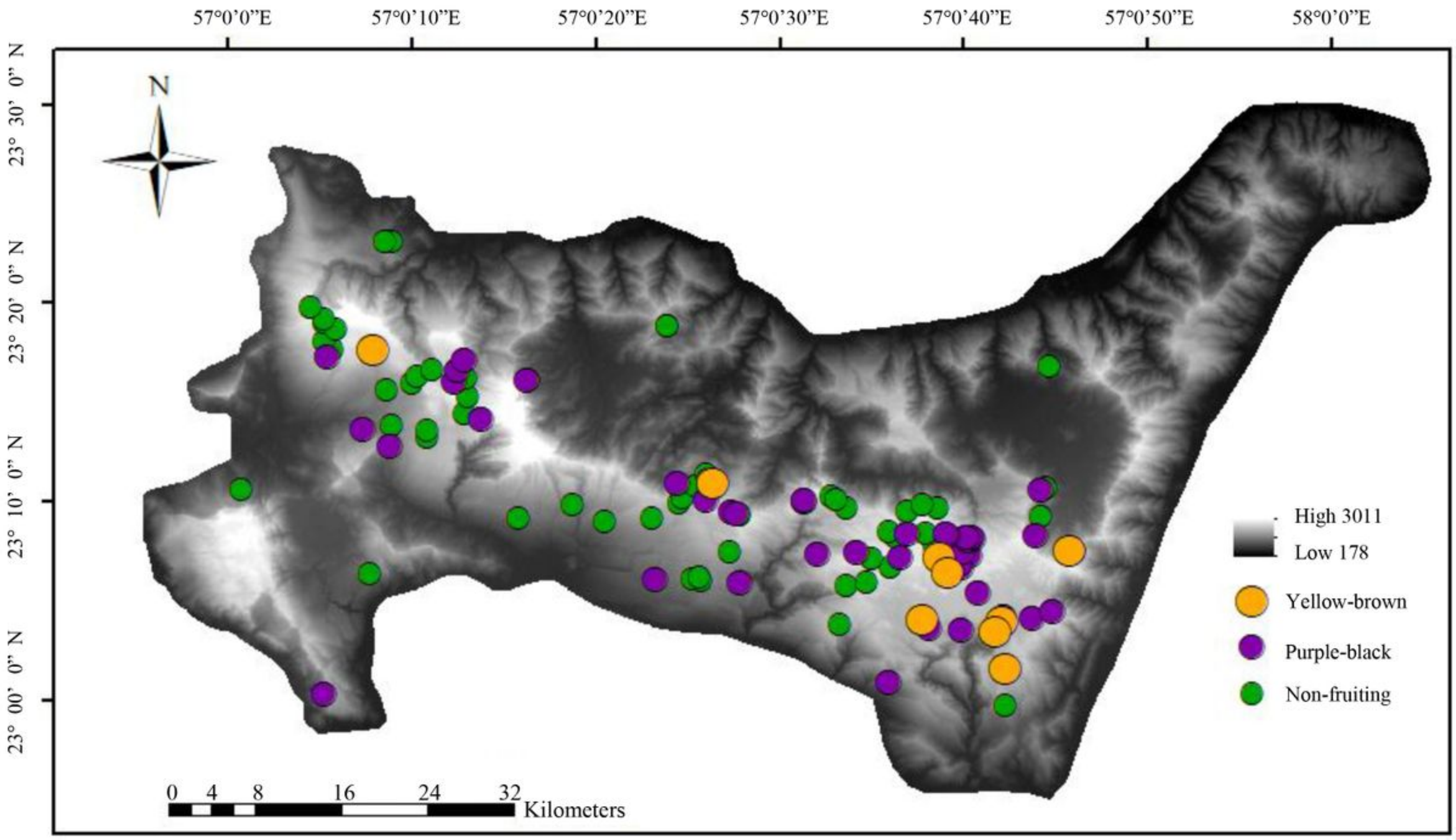

Figure 5

Map of the study area in the Western Hajar Mountains of Oman. The circles represent the quadrats with different colors representing the morphotypes of fruiting S. mascatense specimens observed. If no mature fruit were present at the time of survey, the quadrats are indicated as no fruit. The purple-black morphotype was present in all but one quadrat where the yellow-brown morphotype was observed. The elevation in meters above sea level is represented in the grayscale of the DEM. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

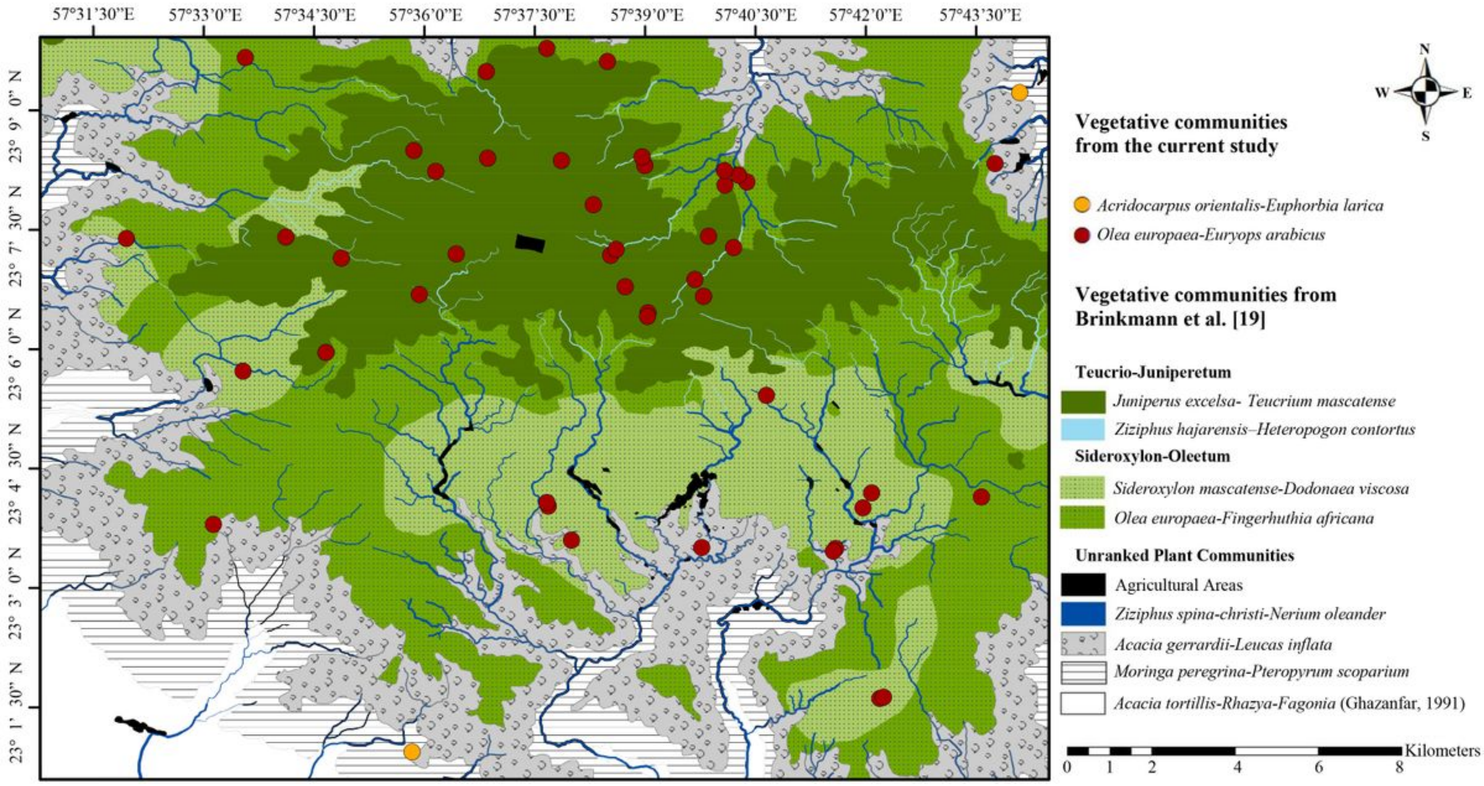

Figure 6

Map of quadrats from the two communities in the current study overlayed on the model created by Brinkmann et al. [19]. Used with permission from the authors. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.