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Microhabitats Affect Population Size and Plant Vigor of Three Critically Endangered Endemic Plants in Southern Sinai Mountains, Egypt

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Abstract: Endemic species on mountains often have narrow altitudinal ranges and are more threatened at the higher altitudes, especially with climate changes. However, plants could use special microhabitats at the mountain tops as proper places for surviving the climate change (i.e., refugia). We assessed population attributes of three critically endangered endemic species (*Primula boveana* Decne ex Duby, *Rosa arabica* Crep., and *Silene leucophylla* Boiss.) in two growing seasons (2006/2007 and 2013/2014), differing in the received rainfalls in microhabitats at the high mountains of southern Sinai. Both *P. boveana* and *S. leucophylla* had very small population size, but significantly increased in the 2013/2014 growing season which received above average rainfalls. The population of *R. arabica* is the smallest (around 40 individuals) and did not increase, even after the increase in rainfalls. Whereas *P. boveana* is present in fewer sites and grew in small number of specific microhabitats, both *S. leucophylla* and *R. arabica* were recorded in most studied sites and habitat types. Unlike *R. arabica*, both *P. boveana* and *S. leucophylla* were recorded in caves and steep slopes and on the top of the mountains. This indicates that these sheltered mist microhabitats are the best for future conservation of these species after climate change.

Keywords: endangered species; climate change; population size; conservation

1. Introduction

Mountains harbor a unique and large portion of the world's biodiversity. Many species at high elevations are isolated, and consequently, have limited number of climatic niches as compared to lowland vegetation communities. Consequently, greater portion of endemic species are present in the plant communities of mountains than the lowland communities [1,2]. In addition, mountains are more susceptible to the impacts of rapid climate changes [3]. As endemic species often have narrow altitudinal ranges of distribution, they are more threatened at the higher altitudes [4]. The high-altitude ecosystems are largely controlled by climatic constraints, and many plants reside close to their climatic limits of survival [2–5].

The geography of the Sinai Peninsula has a special importance and uniqueness. Sinai is the meeting point of Asia and Africa, and therefore, its flora has evolved in isolation. Floristically, it is one of the richest of all phytogeographical regions of Egypt [6]. Sinai supports about 1285 species, of which about 800 species are recorded in southern part [6]. Moustafa and Klopatek [7] stated that more than 61 rare species were recorded in southern Sinai, with some of them being endangered or threatened endemics and near endemics. Khedr et al [8] analyzed a database for the flora the Egyptian flora book of Tackholm [9] and stated that 34 of the southern Sinai plants (4.3% of Egypt flora) are endemics. *Primula boveana* Decne ex Duby, *Rosa arabica* Crep., and *Silene leucophylla* Boiss. are three endemic species recorded as very rare and critically endangered endemics in their narrow range of distribution at the high mountains of South Sinai, Egypt [6]. After the last glacier retreatment, these species, as most of the other endemic species in the region, remained and grew in either mesic or cooler habitats, such as the top of the mountains [6]. As a result, these species became critically endangered. For example, according to the IUCN Red List of threatened species, *R. arabica*, which is nano-phanerophyte shrub, has been listed as one of the world's 100 most threatened species [10]. Similarly, *P. boveana*, which is a perennial hemicryptophyte, has been reported as one of the rarest plant species worldwide [11,12]. Furthermore, the population size of *S. leucophylla*, another perennial hemicryptophyte in Saint Katherine protectorate, is about 50 individuals distributed over seven locations [13–15]. The high environmental pressures expected from future global warming place these endemic species in fragile ecological habitats. Global warming would increase the rate of evapotranspiration, and this might put these species under more environmental pressures that would lead to their extinction. It has been reported that Egypt, including the Saint Katherine Mountains, showed overall mean annual temperature increases of 0.62 °C per decade during the period 1971—2000 [16], which is greater than the average global increase of 0.17 °C per decade [17].

Temperature decreases with the increase in altitude. Therefore, an upslope movement for mountainous species is expected after climate change [18,19]. Several studies have reported movements of mountain biota upward as a result of global climate warming [2,20–22]. For example, Harsch et al [23] analyzed a global dataset of 166 mountainous sites around the world for which tree line dynamics had been recorded since 1900 and reported upward advances of tree lines. In addition, Kelly and Goulden [18] reported that the average elevation of the dominant plant species rose by ≈ 65 m during 30 years in a 2314 m elevation gradient in southern California's Santa Rosa Mountains. They attributed this shift to changes in regional climate. In South Sinai, Coals et al. [24] indicated a significant overall upslope shifts in mean upper altitudinal limits in the high-mountain flora. In addition, climatic change is expected to be associated with drought. The high rate of evapotranspiration is expected to be higher with the increase in global warming, even at the high altitudes of the mountains. Therefore, these factors would threaten critically endangered species at the top of the mountains. The presence of the critically endangered endemic species of the mesic habitats at the top of the Saint Katherine Mountains of southern Sinai might accelerate their extinction. This is particularly possible with climate change scenario, which will be associated with an increase in the temperatures and a reduction in rainfalls (i.e., increase the repeated drought). The aim of the present study, therefore, was to assess the changes in population sizes, individual sizes, and vitality of the three endemic *P. boveana*, *R. arabica*, and *S. leucophylla* during a seven-year period in different habitats with varying amounts of received rainfall. In addition, the study aimed at determining the environmental factors associated with the distribution of individuals of the three species in the different habitat types (e.g., caves, gorges, wadi beds, and terraces) and topographic microclimates (e.g., slope, aspect, and altitude) of the mountains. This would help determine the important environmental factors limiting the distribution of these endemic species. This would also determine the most suitable habitats that could be used as refugia for their conservation after climate change.

2. Study Area

The study area is located at the Saint Katherine Mountains, which is situated in the southern part of Sinai and is a part of the upper Sinai massif. It is located between 28°30′ to 28°35′ North and 33°55′ to 34°30′ East. The arid to hyper-arid climate of the Saint Katherine Mountains is characterized by an ecological uniqueness due to its diversity in landforms, geologic structures, and climate [25].

The high elevation and diversity of mesic habitats in the ecosystem of the Saint Katherine Mountains support the incidence of a big proportion of endemic and rare plants. The soil has granitic origin, as it is formed mainly from mountains weathering. The regular run-off creates shallow soils with bedrock close to the surface [26]. The characters of land surfaces, altitudinal gradient, and landform types offer microhabitats dominated by vegetation that is very specialized to grow in the mountain habitats. This vegetation is sparse and characterized by a variety of chasmophytic and xerophytic plant species [7].

The annual precipitation (rain and snow) in the Saint Katherine Mountains over 25 years (1970—1994) is 45 mm per year. The higher elevations receive more precipitation (100 mm per year) [27]. This indicates the hyper-aridity of the Saint Katherine Mountains region. Precipitation occurs as a snow on the mountaintops and usually lasts two to four weeks. Based on the meteorological data of the Saint Katharine Protectorate weather station, the highest amount of rainfall received in the Saint Katherine Mountains during the period of the study was in growing season October 2013—May 2014 (145.6 mm, Table 1). However, the growing season October 2006—May 2007 received only 22.2 mm, which is below the long-term average (45 mm). In years that receive above average rainfall, floods resulting from convective rains have been observed during the winter and spring. In addition, the mean air temperature ranged from 5.4 °C to 25.1 °C. The lowest temperature is in January and February, and the highest in July and August [28]. In a recent nine-year record (2006—2014) in the Saint Katharine Protectorate weather station, the mean air temperature ranged from 5.2 ºC to 25.2 ºC, with the lowest temperature in January and the highest in August (Table 1).

Table 1. Monthly variation in average temperatures (°C) and rainfall (mm) in the Saint Katherine area from 2006 to 2014, except for 2011 (Saint Katharine Protectorate Weather Station). Temp: Average temperature, RF: Sum rainfall.

Mon	2006		2007		2008		2009		2010		2012		2013		2014	
	Temp	RF	Temp	RF	Temp	RF	Temp	RF	Temp	RF	Temp	RF	Temp	RF	Temp	RF
Jan.	7.5	0.0	6.8	2.6	5.7	2.2	7.9	0.0	11.5	0.5	5.2	9.0	10.0	50.5	10.0	2.0
Feb.	9.2	6.0	9.3	8.0	8.9	0.0	11.8	0.0	12.6	0.4	9.4	0.0	10.5	87.0	10.0	10.0
Mar.	12.4	1.2	11.7	1.0	16.2	0.0	12.1	0.2	15.4	0.0	10.7	0.8	14.1	0.0	13.0	2.4
Apr.	16.2	1.0	16.4	5.8	19.8	0.0	16.7	0.0	18.3	0.0	18.3	0.0	15.6	0.0	18.4	6.9
May	20.4	0.4	22.8	0.0	19.6	0.0	19.8	0.0	21.6	10.5	21.7	0.4	21.4	0.0	20.8	11.7
Jun.	22.9	0.0	24.3	0.0	25.2	0.0	23.7	0.0	26.4	0.0	26.6	0.0	25.3	0.0	24.9	0.0
Jul.	24.4	0.0	23.8	0.0	23.9	0.0	23.4	0.0	24.3	0.0	25.3	0.0	24.0	0.0	23.9	0.0
Aug.	25.4	0.0	24.5	0.0	25.2	0.0	24.0	0.0	27.6	0.1	24.9	0.0	24.6	0.0	25.3	0.0
Sep.	22.7	0.0	21.6	0.0	24.1	0.8	20.6	0.0	24.6	0.0	23.9	0.9	22.5	0.0	22.0	0.0
Oct.	18.8	0.0	20.1	0.0	17.5	0.0	18.4	0.0	22.9	0.0	19.5	0.0	17.3	0.0	17.9	0.0
Nov.	11.3	0.0	13.9	0.0	13.1	0.0	14.9	0.0	17.0	0.0	13.1	23.9	14.0	0.0	12.9	0.0
Dec.	7.4	4.8	10.4	0.0	12.9	0.0	8.2	0.2	11.4	0.3	9.2	3.3	6.6	8.2	11.2	18.6
Total	16.6	13.4	17.1	17.4	17.7	3.0	16.8	0.4	19.5	11.8	17.3	38.3	17.1	145.6	19.0	41.6

3. Materials and Methods

In 2007, 38 sampling plots (stands) distributed in 16 sites were surveyed. These plots were selected to cover the distribution of the three endemic species (*P. boveana*, *R. arabica*, and *S. leucophylla*) in the different habitat types of the populations in the Saint Katherine Protectorate in South Sinai. The plots represented five major types of habitats (wadi beds, gorges, slopes, terraces, and caves). A Global Positioning System was used to record the positions of the plots. The survey was conducted between the end of March and June 2007. The plot size was 5 m × 5 m. For each plot, the following topographic environmental factors were recorded: (a) Elevation (ranged between 1645 and 2014 m above sea level (asl); (b) slope angle, which was estimated using clinometer; (c) aspect, which is the direction that a slope faces. It identifies the steepest downslope direction from each cell to its neighbors. Here, aspect was measured using digital elevation model (DEM) from ArcGIS 10.2. The aspect map of a certain site that is resulted from the Arc map program displays the aspect of each raster cell grouped into compass directions that the surface faces at that site. It is measured clockwise in degrees from 0 (due north) to 360 (again due north), coming full circle. Flat areas having no downslope direction are given a value of −1. We categorized slope aspect into seven directions (west, northeast, northwest, southeast, southwest, and flat); and (d) extent of occurrence, which is the area located within the shortest continuous imaginary boundary that can be drawn to encompass all the known, inferred, or projected sites of occurrence, excluding cases of vagrancy. Arc View GIS 10.2 was used to plot the study sites and estimate the extent of occurrence.

The growth and reproductive parameters of the three studied endemic plants (e.g., canopy height and diameters, and numbers leaf, inflorescences, and fruits) were recorded. In addition, size index was calculated as average of plants heights and diameters. Plant density was estimated as number of rooted plants per 100 m^2. Plant vitality was measured as a ratio between number of leaves and plant size. Size of the photosynthetic organs (leaves) was suggested to be a good indicator for plant vitality [29]. Typically, vigorous plants have more leaves for doing photosynthesis, compared to weaker plants.

Frequency of occurrence was calculated as the number of stands in which a species occurred over the total number of survived plots. Density was calculated as the number of plants of a certain species per 100 m^2. Despite using 25 m^2 (5 m × 5 m) stands, density was calculated per 100 m^2 to give reasonably bigger values. Relative change (RC) in a certain variable was calculated as a percentage of the difference between 2007 and 2014 to the value of that variable in 2007.

In 2014, we increased the number of plots based on the increase in area of occurrence of the three species. Therefore, 58 sampling plots distributed in 18 sites were surveyed, including the 38 plots that were surveyed in 2007. The selected plots covered the distribution of the three species by 2014. Surveys were carried out between the end of March and June 2014 as described above. All measurements and calculations were conducted as described above.

One-way ANOVA was used to assess each of the main factors (year, altitude, habitat, slope, and aspect) on the following variables: Population size (number of individuals), plant size (size index), and vitality (leaf number/size) of the three endemic species. Number of individuals was square root transformed, but both size index and vitality were log-transformed. These transformations improved the normality of the distribution of the data. Tukey's test (Honestly significant differences, HSD) was used to estimate the least significant differences between the means at $P = 0.05$. All statistical methods were performed using SYSTAT, version 13.0.

4. Results

4.1. *Primula boveana*

The population size of *P. boveana* is very small. It is significantly affected by year, altitude, and slope of the mountains (Table 2). The total population size increased from 176 plants recorded at five locations in 2007 to 1065 plants at six locations in 2014, which is more than a five-fold increase. The total areas occupied by this species in the different locations were 225 and 250 m^2 in 2007 and 2014, respectively. The density per 100 m^2 significantly increased from 78 in 2007 to 426 in 2014 plants. Interestingly, most of the plants of 2014 were newly recruited seedlings (Table 3).

The population of *P. boveana* was distributed into five and six subpopulations (locations) in 2007 and 2014, respectively. The subpopulation sizes were significantly increased during the seven years in four locations ($P < 0.001$), but insignificantly decreased in only one (Sad Abo Hebake, $P > 0.05$). The highest increases were in Wadi Graginya (multiplied by 8.61) and Maen Shinara (multiplied by 6.14, Table 4).

Table 2. Results of one-way ANOVA (F-values) showing the effects of year, altitude, habitat, slope, and aspect on population size, plant size, and vitality of three endemic species in the Saint Katherine Protectorate Mountains.

Species	Variable	Year	Altitude	Habitat	Slope	Aspect
Primula boveana	No of individuals	28.150 ***	20.080 ***	2.350	9.920 **	2.680
	Size index	7.940 **	0.288	1.438	0.156	0.435
	Plant vitality	0.700	2.549	0.546	0.365	0.296
Rosa arabica	No of individuals	0.018	7.329 **	3.104 *	0.093	2.400 *
	Size index	3.506	2.646	0.328	4.024 *	0.469
	Plant vitality	1.172	11.111 ***	2.071	7.328 **	2.765 *
Silene leucophylla	No of individuals	0.794	0.807	0.871	5.824 **	3.168 **
	Size index	0.767	4.793 **	6.341 **	2.590	2.544 *
	Plant vitality	15.591 ***	10.586 ***	9.096 ***	4.033 *	5.802 ***

* $p \leq 0.05$, ** $p \leq 0.01$, and *** $p \leq 0.001$.

Table 3. Relative change over seven years (2007—2014) in number of individuals and population attributes in three endemic species growing in the Saint Katherine Protectorate Mountains.

Species	Variable	2007	2014	RC
Primula boveana	No of subpopulations	5	6	20.0
	No of habitats	3	3	0.0
	Number of recoded plots	9	10	11.1
	Frequency of occurrence	23.7	17.2	−27.2
	Total No of individuals	176	1065	505.1 ***
	Density (plants/100 m^2)	78.2	426	444.7 ***
	Total areas occupied (m^2)	225	250	11.1
	Size index (cm)	18.0	14.9	−17.2 ***
	Vitality	2.53	2.53	0.0
Rosa arabica	No of subpopulations	10	11	10.0
	No of habitats	4	4	0.0
	Number of recoded plots	19	20	5.3
	Frequency of occurrence	50.0	34.5	−31.0
	Total No of individuals	40	42	5.0
	Density (plants/100 m^2)	8.4	8.2	−2.4
	Total areas occupied (m^2)	475	500	5.2
	Size index (cm)	321.5	466.8	45.2
	Vitality	36.3	29.7	−18.2
Silene leucophylla	No of subpopulations	8	10	25.0
	No of habitats	3	3	0.0
	Number of recoded plots	10	28	180 **
	Frequency of occurrence	26.3	48.3	83.4
	Total No of individuals	33	109	230.3 ***
	Density (plants/100 m^2)	13.2	15.6	18.2
	Total areas occupied	250	700	180 ***
	Size index (cm)	6.5	20.8	220.0
	Vitality	3.5	25. 8	634.2 ***

* $p \leq 0.05$, ** $p \leq 0.01$, and *** $p \leq 0.001$, according to one-way ANOVA testing the difference between 2007 and 2014.

Table 4. Relative change over seven years (2007—2014) in number of plants, sizes, and plant vitality in three endemic species growing in different regions of the Saint Katherine Protectorate Mountains.

Region	*Primula boveana*			*Rosa arabica*			*Silene leucophylla*		
	No of plants	Size	Vitality	No of plants	Size	Vitality	No of plants	Size	Vitality
Abo Giefa							50	39.5	91.3 *
Abo Twaita				57.1	0.4	−53.4 *			
Abo-Hamman							−100.0 **	−100.0	−100.0
El-Maeen				0	4.2	2.4	400	48.0	−27.2
Farsh El Romana				−50	−31.7 ***	−98.1 ***			
Farsh El Sefsafa							<u>100.0</u> ***	100.0	<u>100.0</u>
Farsh Elia							<u>100.0</u> ***	100.0	<u>100.0</u>
Farsh mesela							−100.0 *	−100.0	−100.0
Gebel El-Ahmar	<u>100.0</u> ***	100.0	<u>100.0</u>	−40	112.0 ***	−30.3 **	<u>100.0</u> ***	100.0	<u>100.0</u>
Kahf El Gholah	86.1 ***	−62.1 ***	83.6	−14.3	−33.8 ***	182.7			
Maen Shinara	614.3 ***	−69.3 ***	236.8				300	−12.7 *	−5.6 ***
Mousa Mountain							<u>100.0</u> *	100.0	<u>100.0</u>
Musa Gorge	364.3 ***	115.7	−50.1	0	4.3	22.7	<u>100.0</u> **	100.0	<u>100.0</u>
Sad Abo Hebake	−33.3	−76.3 *	69.7	10	68.0 ***	−70.5			
Shag Tinia				−50	469.9 ***	−92.7*	−100.0	−100.0	−100.0
Shaq Saqr				0	18.5	−14.7	−28.6	12.5	−2.1
Sheqeaf Mislla				<u>100.0</u>	100.0	<u>100.0</u>			
Wadi Elshak							50	18.0	7.4
Wadi Graginya	861.5 ***	63.4 **	−7.7				500.0 ***	84.8 *	563.6 ***
Wadi Tinia				50	117.1***	−38.4			

<u>100.0</u> and <u>−100.0</u> means that a variable was not recorded in 2007 and 2014, respectively. * $p \leq 0.05$, ** $p \leq 0.01$ and *** $p \leq 0.001$, according to one-way ANOVA testing the difference between 2007 and 2014.

The presence of *P. boveana* was restricted to three habitat types at the different locations. The number of plants was significantly increased during the seven years in both gorges (multiplied by 3.12) and slopes (multiplied by 6.35, Table 5). The presence of *P. boveana* depended on slope aspect, as plants were recorded only in east- and northeast-facing aspects. The number significantly increased during the seven years of the study in the two aspects. This species was not recorded in the gentle slope (<55°). The occurrence of *P. boveana* was significantly greater at the steeper slopes (>85°), as compared with the gentle slopes (55–85°). The increase between 2007 and 2014 was much greater in steeper slope (7.1 fold) than in the gentle slope (1.34 fold). In addition, *P. boveana* preferred the highest altitudes. The total number plants increased from 91 in 2007 to 650 in 2014 at >2000 m asl, but from 45 to 73 at <1800 m asl (Table 5).

The size index of *P. boveana* plants was significantly affected by the year, but not by the other ecological factors (Table 2). It decreased by 17.2% during the seven years (Table 3). This might be attributed to the big number of newly recruited plants in 2014 that had smaller sizes. The plant sizes significantly decreased in three sites, but significantly increased in Wadi Graginya and was not affected in Musa Gorge. Plant vitality, as a measure of number of leaves per plant size, did not significantly change during the seven years ($P > 0.05$), (Tables 2 and 5).

4.2. *Rosa arabica*

Rosa arabica has a very small, but stable population size. A total of 40 and 42 individuals were recorded in 2007 and 2014, respectively. The population size was significantly affected by habitat, altitude, and aspect of the mountains ($P < 0.05$, Table 2). However, this small number of individuals were evenly distributed in a larger number of locations (10 and 11 locations in 2007 and 2014, respectively, Tables 3 and 4) and habitat types (four in both 2007 and 2014, Tables 2 and 5). In addition, the total areas covered the distribution range of *R. arabica* were 475 and 500 m^2 in 2007 and 2014, respectively. The density per 100 m^2 was 8.4 in 2007 and 8.2 in 2014 (Table 3).

Table 5. Relative change over seven years (2007—2014) in number of plants, sizes, and plant vitality in three endemic species growing in different habitats and topographic features of the Saint Katherine Protectorate Mountains.

Microhabitat type		*Primula boveana*			*Rosa arabica*			*Silene leucophylla*		
		No of plants	**Size**	**Vitality**	**No of plants**	**Size**	**Vitality**	**No of plants**	**Size**	**Vitality**
Habitat	Caves	50	−12.8	−46.1	-	-	-	-	-	-
	Gorges	312.5 ***	−12.4	9.8	5.6	57.6 ***	−16.4	−37.5	40.3	0.7
	Slopes	634.9 ***	−34.7	71.9	0	−35.4 **	202.5	910.0 ***	20.3 ***	174.2 ***
	Terraces	-	-	-	0	12	−77.0**	−100.0*	−100.0	−100.0
	Wadi Bed	-	-	-	13.3	47.5 ***	−43.0 ***	-	-	-
Aspect	E	161.1 ***	−34.6	−6.3	−11.1	−5.6	−62	50	18	8.3
	Flat (no aspect)				20	−21.6 ***	−50.8 ***	-	-	-
	NE	607.9 ***	−11	1.7	21.4	31.6 ***	−15.5	266.7 ***	123.1 ***	571.7 ***
	NW	-	-	-	100.0	100.0		333.3 ***	219.8 ***	−33.2
	SE	-	-	-				−100.0	−100.0	−100.0
	SW	-	-	-	−33.3	149.8 ***	−80.9 ***	100.0	100.0	100.0
	W	-	-	-	−20	248.7 ***	−4.3	100.0	100.0	100.0
Slope	<55°	-	-	-	17.9	49.8 ***	−23.8 ***	20	271.8 **	88.4 *
	55–85°	133.9 ***	−58.2 ***	−14.5	−15.4	30.2 ***	−43.5*	800.0 ***	368.2 ***	930.3 ***
	>85°	709.4 ***	13.3	11.2	-	-	-	83.3 *	27.4	373.0 ***
Altitude (m asl)	<1800	62.2 **	−79.7 ***	−2.2	−9.1	52.1 ***	−62.4 ***	−37.5	−22.8	−49.0
	1800–2000	805.0 ***	186.0 ***	−8.4	33.3	47.3 ***	−20.8 **	330.8 ***	230 **	602.9 ***
	>2000	614.3 ***	−69.3 ***	39.1	-	-	-	2150.0 ***	1906.3 ***	1333.1 ***

100 and −100 means that a variable was not present in 2007 and 2014, respectively. * $p \leq 0.05$, ** $p \leq 0.01$ and *** $p \leq 0.001$, according to one-way ANOVA testing the difference between 2007 and 2014

The size index of *R. arabica* plants was not affected significantly by any factor ($P > 0.05$) except slope of mountains ($P < 0.05$, Table 2). The plant sizes were significantly greater in 2014 than in 2007 in four locations ($P < 0.001$), but significantly decreased in other two ($P < 0.001$) and were not affected in five locations ($P > 0.05$, Table 4). In addition, size index significantly increased ($P < 0.001$) in two habitats (gorges and wadi bed), but significantly decreased ($P > 0.01$) in the slopes. During the seven years, plant sizes of *R. arabica* were significantly increased in three aspects (northeast, west, and southwest, $P < 0.05$), but significantly decreased ($P < 0.001$) in the flatlands (Table 5).

R. arabica was recorded in all aspects of the mountains except the southeast. The species was recorded only in the gentle (<55°) and gentle (55–85°), but not in the steepest slope (>85°). During the seven years, the population size increased at the gentle slope (<55°) but decreased at the gentle (55–85°) slopes. In addition, *R. arabica* was recorded in up to 2000 m asl, but the gentle altitudes were the best for its occurrence (Table 5).

The vitality of *R. arabica* plants was significantly affected by all topographical factors (slope, aspect, and altitude, $P < 0.05$, Table 2). The average vitality insignificantly decreased by 18.2% between 2007 and 2014 (Table 3). Vitality significantly decreased during the seven years in four locations (Abo Twaita, Farsh El Romana, Gebel El-Ahmar, and Shag Tinia, Table 4) and in two habitats (terraces and wadi beds). In addition, the significant decreases in plant vitality were recorded in two aspects (flat summit and southwest), in gentle slopes (<55°), and in low altitudes (<1800, Table 5).

4.3. *Silene leucophylla*

Silene leucophylla had a small population size that grew significantly during the seven years of the study. The total population increased from 33 plants in 2007 to 109 plants in 2014 (the increases were more than 2.3-fold). The population size was not affected by year, altitude, or habitat ($P > 0.05$), but was significantly affected by slope and aspect of the mountains ($P < 0.01$, Table 2). In addition, the total number of plots in which *S. leucophylla* was recorded increased significantly during the seven years, increasing from 10 in 2007 to 28 plots in 2014. However, the increase in plant density during the same period was not significant. The total areas occupied by *S. leucophylla* in its distribution range almost tripled during the seven years, from 250 m^2 in 2007 to 700 m^2 in 2007 (Table 3).

Subpopulations of *S. leucophylla* were found in eight locations in 2007 and increased to 10 locations in 2014. However, three subpopulations of 2007 disappeared in 2014 (Abo-Hamman, Farsh mesela, and Shag Tinia). Instead, other five subpopulations appeared in 2014 (Farsh El Sefsafa, Farsh Elia, Gebel El-Ahmar, Mousa Mountain, and Musa Gorge). Their sizes significantly increased in 2014 in the subpopulation Wadi Graginya (Table 4)

The number of plants of *S. leucophylla* increased significantly ($P > 0.001$) between 2007 and 2014 in one habitat types (slopes; multiplied by 9.1 increase), in two aspects (northeast and northwest; multiplied by 2.67 and 3.33 increases, respectively). Low numbers of *S. leucophylla* were recorded in gentle slopes and at lower altitudes. Most of the plants were present in steep slopes (>55º) and higher altitudes (>1800 m). The increase during the seven years was higher at 55–85º (eight-fold), compared with the steepest slopes (>85º, 0.8-fold). In addition, the increase was much greater at the highest altitudes (>2000 m asl, 21-fold) than that at moderate altitude (1800–2000 m asl, 3.3-fold). *S. leucophylla* was recorded in all aspects except flatlands. However, it disappeared from some aspects and appeared in others in 2014 (Table 5).

Size and vitality of *S. leucophylla* were significantly affected by most of the factors ($P < 0.05$, Table 2). Vitality increased during the seven years by 6.34-fold (Table 3). During the study period, both size and vitality significantly increased in one subpopulation (Wadi Graginya), but significantly decreased in another subpopulation (Maen Shinara, $P < 0.05$). Vitality also increased in Abo Giefa (Table 4). Similarly, both size index and vitality significantly increased ($P < 0.001$) in one habitat types (slopes). In relation to aspects, size increased during the seven years in two aspects (northeast and northeast), but vitality increased in one (northeast, Table 5).

Plant vitality was increased during the study periods in all slope categories, but size index increased in slopes up to 85º, but not at the steepest slopes (>85º). In addition, both plant size and vigor significantly increased in altitudes above 1800 m asl (Table 5).

5. Discussion

There are six habitats in Saint Katherine Protectorate, each has its own specific environmental conditions, landscapes, and flora. These habitats are caves, gorges, slopes, terraces, basins, and wadi beds [30]. Several studies have reported habitat specificity for endemic species of Southern Sinai [6,31–34]. These microhabitats are shaped by altitude, aspect, and degree of slope, which in turn shape the spatial distribution and patterns of vegetation [35,36]. Our results showed that the three studied endemic taxa are growing in different types of specific microhabitats. The three species were recorded in the gorges and slopes. In addition, two species were recorded in terraces (*R. arabica* and *S. leucophylla*), and one species in the caves (*P. boveana*) and wadi beds (*R. arabica*).

The IUCN has categorized *P. boveana* as globally critically endangered. It has been reported as one of the rarest plant species worldwide [11,12]. It was also reported that the population of *P. boveana* was abundant in the year 1832 at the Saint Katherine Mountains [11]. However, the population was reduced to around 2000 individuals in 1991 [37], and 336 in 2007 [12]. In the present study, we recorded only 176 individuals in 2007, but this number increased significantly to 1065 individuals in 2014. Our results showed that the distribution of this species is limited to few locations and grows in small number of specific microhabitats, particularly the sheltered mountain areas, such as cliffs and caves of the steep slopes in the northeast mountain direction. Similarly, Moustafa and Kamel [38] recorded *P. boveana* among the plants that grow in caves and shaded gorges, mainly on rocky outcrops of high-moisture content (wet and shaded rocks) with very low temperatures (3—10 °C) at elevations of 2200—2400 m. Zaghloul [39] recorded *P. boveana* only in few water springs in north-facing cliffs at high elevations in Saint Katherine. This author found that *P. boveana* was restricted to the caves and sheltered wet crevices of slopes, which is shaded most of the year. The distribution of *P. boveana* in cooler and mist microhabitats indicates that it is very sensitive to climate changes that would increase the temperatures.

However, as the cliffs and caves receive less solar radiation, they would be less vulnerable to warming associated with climatic changes. These sites could be perfect future conservation refugia.

The high increase in population size and plant density of *P. boveana* in 2014 could be attributed to the higher amount of rainfall received in 2013/2014. Most of the individuals of *P. boveana* recorded in 2014 were newly recruited seedlings. According to Moustafa [25], the 2013/2014 growing season showed the highest recorded annual precipitation in the whole history of Sinai (>200 mm). However, the smaller population size of *P. boveana* in 2007 (176 individuals) could be attributes to the lower amount of rainfalls received during 2006/2007 season (<20 mm; [25]).

The small population size of *P. boveana* could be attributed to natural and/or anthropogenic effects. For example, several human activities have been considered among the factors that threaten the presence of *P. boveana* in the natural habitats [40,41]. These include, for example, overcutting, overgrazing, and reduction in water available to the plants [42]. In addition, the habitats of this species are facing several natural threats. Floods and cyclic drought are among these natural threats. The shallow soils of the very steep slopes maintain little water and consequently dry years might significantly increase plant mortality. In addition, plants in shallow soils could be uprooted with the floods in years receive more rainfalls. The Saint Katherine Mountains region receives destructive floods every seven to 10 years [40,41].

The Sinai endemic wild rose, *R. arabica*, was qualified by the IUCN Red List of threatened species as critically endangered. It has been listed as one of the world's 100 most threatened species [10]. In the present study, *R. arabica* had very small population size (40 and 42 individuals in 2007 and 2014, respectively). Interestingly, the small number of *R. arabica* is distributed in more diverse sites and habitats as compared to *P. boveana* and *S. leucophylla*. It grows in most studied sites and habitats, except the very specific habitats, which are caves and high altitudes. According to [25], *R. arabica* grows in mountainous wadis and gorges with rocky grounds (40%) and northwest-facing, steep granite slopes of up to 90° on west. They were not recorded in the caves. The absence of *R. arabica* in the caves could be attributed to its large sizes, as it is a big shrub with a height up to 3 m. In addition, the light intensity and quality inside the caves might not be suitable for the photosynthesis process. The absence of *R. arabica* from the caves would deprive them from advantages of the sheltered moist sites that might protect them from the higher temperatures and droughts of climate change. However, the absence of *R. arabica* from the top of the mountains might give them the chance to shift upslope after climate change. Our results also showed a significant decrease in vitality of mature individuals between 2007 and 2014. In addition, among the important threats that would reduce the plant numbers of *R. arabica* are overgrazing and over collection for the exploitation of the medicinal active constituents that are present in different organs of the plant [25]. The evaluation of the status of the protected populations of *R. arabica* showed that there is no real conservation plan for that species and it needs more protection, restoration, and reintroduction [25].

S. leucophylla is an endangered endemic perennial that grows in the rocky habitats of the St. Katherine Protectorate in southern Sinai, Egypt. We recorded a very small population size of *S. leucophylla*. The total number of individuals increased from 33 in 2007 to 109 in 2014. The significant increase was recorded in northeast and northwest steep slope habitats (>55º) and higher altitudes (>1800 m). The results of the present study also highlighted the disappearance of three subpopulations from 2007 to 2014 (Abo-Hamman, Farsh Mesela, and Shag Tinia), but other five subpopulations appeared in Farsh El Sefsafa, Farsh Elia, Gebel El-Ahmar, Mousa Mountain, and Musa Gorge in 2014. This indicates that the population of *S. leucophylla* is very dynamic. It can appear and disappear according to environmental conditions. This indicates that individuals of this species are sensitive to environmental stresses but could be also recruited easily upon the availability of the favorable conditions. Individuals of the new five populations appeared with the extraordinary high rainfall received in 2013/2014.

As mountains usually have conical shapes, upslope movement certainly results in range loss and may even lead to extinction of the plants at the top of the mountains [43]. It has been reported that range-restricted species and mountaintop species show severe range contractions [22–44]. Mountaintop species respond to global warming by shifting their range boundaries toward higher altitudes. For example, Lenoir et al. [20] showed that climate warming has resulted in a significant upward shift in species optimum elevation, averaging 29 m per decade in their comparisons of the altitudinal distribution of 171 forest plant species during 100 year in West Europe. In addition, Parmesan [21] provided evidence that woody plants at their upper altitudinal range boundaries have responded to global warming by dispersing to higher elevations. Consequently, global warming would negatively affect endemic plants growing in mesic microhabitats at high elevations of the Saint Katherine Mountains of southern Sinai. In Egypt and the Middle East, in general, the overall mean annual temperature has increased with 0.62 °C per decade during the period 1971—2000 [25]. This increase is greater than the overall average global trend, which is 0.17 °C per decade [17]. In addition, the average warmest daily maximum temperatures of the Middle East has been increased by more than 1 °C since the 1970s [16–45]. In our study, the increase in the overall mean annual temperature affected the local distribution of the studied species, especially *P. boveana* and *S. leucophylla*, which could have been moved upslope. Both are growing better and have higher vitality at the higher altitudes. In high mountains of southern Sinai, Coals et al. [24] also showed a significant overall upslope shift of plants in mean upper altitudinal limits. Many of the perennial herbs, trees, and small and big shrubs expanded their altitudinal ranges and showed long-term shifts in altitudinal range in the hyper-arid desert mountains of South Sinai [25]. The upslope movement of studied species, especially *R. arabica,* could be attributed to biotic stresses, especially overgrazing and overcutting that are higher at low and mid-elevations as compared to top mountains. The accessibility of the plants of these species could be less at the top mountains (Hatem Shabana, personal observation).

6. Conclusions

Both *P. boveana* and *S. leucophylla* grow at the top of the mountains. Therefore, their extinction under the global warming scenario is higher as compared to plant of the lower elevations. However, the tendencies of these species to grow in specific habitats that provide them shelter is a real advantage after global warming. The presence of species of the present study in specific microhabitats of the caves and sheltered wet cervices of slopes, which are shaded most of the year, indicates that these sites are the best for their conservation after climatic changes. The smaller areas of sheltered habitats make them more feasible for conservation. Consequently, conservation of mesic habitats should receive more priority. However, the few individuals of the critically endangered *R. arabica* are distributed in wider varieties of habitats, not including the moist and sheltered ones. As this species is exposed to overgrazing and overcutting, their conservation in enclosures would be a more practical option.

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