

A META-ANALYSIS OF CLIMATE CHANGE IMPACTS ON ENDEMIC PLANT SPECIES IN SOUTH SINAI: QUANTIFYING POPULATION DECLINES, HETEROGENEITY, AND EXTINCTION RISK

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Abstract

Climate change represents a growing threat to biodiversity, particularly in arid mountain ecosystems that support geographically restricted plant species. In South Sinai, Egypt, endemic flora occupies highly specialized habitats and is increasingly exposed to rising temperatures and prolonged drought conditions. Although several ecological studies have examined these impacts, their findings remain fragmented and difficult to evaluate collectively. This article provides the first quantitative meta-analysis of climate change impacts on endemic plant species in South Sinai. A systematic literature search covering the period from 2000 to 2025 identified 12 eligible studies, yielding 28 independent effect sizes. Standardized effect sizes (Hedges' g) were calculated to evaluate changes in population abundance, distribution patterns, and reproductive performance under climate-related stress. A random-effects meta-analytic framework was applied to account for between-study heterogeneity. The overall pooled effect size was significantly negative ($g = -0.51$, 95% CI: -0.62 to -0.40), indicating a moderate-to-strong decline in endemic plant performance associated with climate stressors. Subgroup analyses revealed that drought-related variables had a stronger negative impact than temperature alone, while population abundance exhibited greater declines than distributional shifts. Species with restricted geographic ranges were particularly vulnerable. Meta-regression further indicated that higher-elevation species experienced significantly greater declines than lower-elevation taxa. The findings demonstrate that climate change, especially increasing drought severity, poses a substantial risk to the persistence of endemic flora in South Sinai. The study also highlights the importance of species-specific conservation strategies, including habitat management, drought mitigation, and ex situ conservation for highly threatened taxa. Overall, this synthesis provides a quantitative basis for future monitoring and conservation planning in arid mountain ecosystems.

Key words: Meta-analysis; Hedges' g ; Climate change; Endemic plants; South Sinai; Effect size; Heterogeneity; Publication bias

Introduction

Arid and semi-arid ecosystems account for around 41% of the Earth's terrestrial ecosystems and provide many different habitats for a sizeable portion of the world's vegetation. In these ecosystems, several endemic species are concentrated in isolated, systemically formed microhabitats and located on mountain systems. Although these species are important to their ecosystems, their limited ranges and the specific nature of their habitats make them particularly sensitive to disturbances. Considered a major biodiversity threat, the Middle East and North Africa (MENA) region is home to multiple biodiversity hotspots characterized by the high incidence of endemism and an increasing level of climate change. In Egypt, South Sinai is one of the country's main centers of plant diversity in the Saint Catherine Protectorate. This region is home to many endemic and medicinal plants as well as microclimates of mountain habitats. It has been previously studied for its conservation status and for its flora, which is threatened due to its fragmented distribution and limited populations.

The Sahuaro-Arabian region has few competitors when describing St. Catherine Protected Area. Containing significant plant diversity, South Sinai has even been suggested to be the richest area of Egypt. The combination of altitude, position of the area, and the vegetation of terrain and soil types have resulted in an ecological mosaic of diversity. Its value even extends across the region, especially in Sinai's mountain ranges and conservation zones, like St. Catherine. South Sinai is home to numerous plant species, many of which are endemic, rare, and significant due to their medicinal properties. The relatively under-researched area is of even greater conservation and ecological value (Anon., 2018; Khafagi *et al.*, 2020; Salama *et al.*, 2021; Abdelaal *et al.*, 2022; El-Sayed *et al.*, 2023).

The climate above 2600 m is moister and cooler and provides a specific habitat for ancient and modern plant species. The pressure from climate change is impacting these systems. In the face of severe drought and temperature increases, many endemic species have been shifting to higher elevations and showing a decline in population size and reproductive success. *Primula boveana*

Decne and *Rosa arabica* Crép are limited to high-elevation environments and highly threatened by future climate change. Habitat models predict significant habitat contraction to a future warmer climate. Field studies conducted from 2024 to 2025 showed some aggregate improvements to the study and survey of these plant species, but improvements were due more to studies and surveys than increases in population (Moustafa *et al.*, 2019). In the future, the challenges will be greater. Climate change will have a species distribution model predicting population habitat losses of 30-41% by the year 2070 (Coals *et al.*, 2018). These predictions model population pressures of climate change and indicate an urgent need for conservation of these delicate systems.

At high elevations, the risks associated with climate change have prompted upward migration among plant populations. In the Sinai, there have been record-breaking vertical adjustments for both perennial (72 m) and annual (292 m) plants. These annual shifts, occurring since the start of the 1970s, have been among the highest registered throughout the world. In Oman's Al Hajar Mountains, plants have ascended by 250 meters in the past 20 years (Abdelaal *et al.*, 2019). Higher altitudes mean a more crowded environment and increased competition as more adaptable species intrude on the restricted habitats of endemic flora. Also, *Primula boveana* and other species have started to show symptoms of climate change with thermal stress, showing the effects of climate change on plant metabolism (Al Jabri *et al.*, 2026).

Understanding the various ways in which changing climates affect ecosystems is made easier by examining how humans exploit the land. One of these ways is through gregarious goats and camels. Removing vegetation impairs the growth of new plants. Studies in the SCPA (Southern Coastal Protected Area) have shown that when livestock are fully excluded from zoned areas, the diversity and density of plant species increase. Some of the pressure exerted by tourism has been countered by the drying up of some tourist activities. Leaving firewood and other forms of improvised infrastructure are persistent threats to already fragile ecosystems. Adding to climate-related pressures, anthropogenic disruptions (overgrazing, tourism activities, habitat fragmentation, and extended infrastructural spread) are affecting the structure of plant life and the stability of ecosystems in the region. These stressors further complicate the assessment of the effects of climate change relative to observable environmental degradation (Moustafa *et al.*, 2026). Construction activities and off-road vehicles threaten biological soil crust, an increasingly rare organism important in stabilizing soil and the soil nutrient cycle (Alzain *et al.*, 2025). For the sake of all species that depend on them, including humans, a land use balance must be achieved.

In response to these concerns, conservation has begun employing Species Distribution Modelling (SDM) integrated with formal protected area networks. While SCPA grants legal status to many endemics of South Sinai, its boundaries may not contain these species' future climatic envelopes with range shifts (Anon., 2023). Notwithstanding the large number of field studies, there has been a dearth of quantitative synthesis to derive regional population trends (Besnard *et al.*, 2009).

This article endeavors to achieve four particular goals: (i) To calculate the aggregated standardized effect size (Hedges' *g*) for population changes in the context of South Sinai endemic plants using a random-effects meta-analytic model for pooled effect studies to incorporate population changes in the context of South Sinai endemic plants possessing specific random effects, (ii) To determine the extent to which a single, pooled effect, regional estimate can characterize the response of South Sinai endemic plants by examining the heterogeneity of pooled South Sinai Plant effect sizes via the *I*² statistic and Cochran's *Q* leading to a regional response and (iii) To assess the robustness of the pooled effect size estimate via a funnel plot and Egger's regression including an assessment of small publication bias and small study bias, and (iv) To provide elevation via meta-regression as a continuous moderator of effect size and, as a working hypothesis, to provide the elevation of microclimatic refugia dominated by higher elevations to hypothesize that refugia response to population declines is less pronounced when located in higher less stressed microclimatic refugia as compared to those located in lower microclimatic refugia that are subjected to greater thermal and drought.

Materials and Methods

Study area

Location and landscape: Our research focused on the ecologically vital region of the SCP, Saint Catherine Protectorate, covering an expanse of 4,350 km² between the coordinates of 33°30'- 34°30' East and 27°50'-28°50' North. SCP is an ecologically diverse area featuring lengths from 396 meters to the towering height of 2,642 meters at Mount Catherine. The massive smooth granite outcrops form the distinguished peaks within the domain and delineate the SCP study area. The varied and diverse climate of the region and the large, smooth rocky outcrops of the region and differing relief have created regions that exhibit varying and contrasting micro-habitats, each of which can exhibit specific plant species and flora (Moustafa & Klopatek, 1995; Fig. 1).

Composed of Precambrian-age acid plutonic and volcanic rocks and shaped by ancient geological processes, the rugged landscape of the protectorate is a hotbed of relatively younger geology. Southern Sinai's region of deep wadis shows evidence of active downcutting (Said, 1990). One of Said's early (1962) observations was along the granite massifs of the same region, including not just Mt. Serbal and Ras Sefsafa, but also essential observations of the volcanic massifs he noted as 'black mountains.' With the Miocene epoch shaping geology of the Earth further, the region of Africa has significantly evolved to be as high as it is in the world today (Said, 1990).

Zahran & Willis (2009) and Aziz *et al.*, (2026) have highlighted three primary water resources on the Sinai Peninsula: rainfall, surface water, and deep groundwater. A balance of these resources is needed to maintain the fragile local ecosystem. Interestingly, groundwater levels decline from the northern to the southern parts of the peninsula, at an average rate of about 25 mm per year (Hammad, 1980). The southern region is made up of highly fractured, igneous, and crystalline rock. This rock has the capacity to exert substantial pressure and promote the formation of water-bearing strata. This pressure contributes to the recharge of northern water sources and is important for maintaining the region's water balance (Hammad, 1980; El-Rayes & Ahmed, 1992).

for small and limited sample sizes, which are often present in the literature for rare and protected plant species. When a record was repeated for one population in a study, we calculated the mean to prevent a record from being overrepresented in our results. Effect size was calculated using the esc package. We used available information to calculate g , and in the case of t-tests and F-Ratio, we used the conversion formulas to calculate g , Hedges' g (Borenstein *et al.*, 2009).

Meta-analytic model and heterogeneity: We opted for a random-effects model. This was the logical choice, as the effects of climate change are not a single global number but rather impact different species and different local environments in varying ways, and the random-effects model gives us greater flexibility. These calculations were performed using the metafor and esc packages in R. Cochran's Q and I^2 were used to assess the consistency of the results.

$$g_i = \theta + \mu_i + \varepsilon_i$$

where θ is the overall mean effect size, $\mu_i \sim N(0, T^2)$ is between-study variance, and $\varepsilon_i \sim N(0, \sigma_i^2)$ is within-study sampling error.

Cochran's Q tests whether the variance in the results is greater than the variance that could be accounted for by pure chance. I^2 = the percent of total variation that is due to variance between studies, as opposed to error in sampling. Variance is considered to be moderate when $I^2 > 50\%$ and high when $I^2 > 75\%$. τ^2 is the estimated variance between studies (absolute measure). These were estimated using restricted maximum likelihood (REML) via the metafor package in R (Viechtbauer, 2010).

Publication bias and moderator analysis: We used funnel plots (asymmetry indicates bias) to assess publication bias and Egger's regression test (the linear regression of effect size on estimated standard error, weighted by inverse variance). We also calculated a fail-safe N , which is the number of studies that would need to be published in order for the overall effect to be not significant ($p > 0.05$). A fail-safe $N > 5k + 10$ (where k = number of studies) indicates that robust results were obtained.

To investigate sources of variability, both meta-regression and subgroup analysis were utilized. Subgroup analysis (categorical moderators) utilized mixed-effects meta-analysis (Q_a - between-group differences). These categories were: (i) climate driver, be it temperature only, drought/precipitation only, or combined (multiple variables), (ii) response type such as population abundance, distribution shift, reproductive success, (iii) endemic status of narrow endemic (single mountain), regional endemic (South Sinai only), near-endemic, and (iv) were analyzed meta-regression (univariate and multivariate) of continuous moderators (elevation, year of study, latitude).

Sensitivity checks were performed. These included a "leave-one-out" analysis (the effect of each study on the results was analyzed by removing one study at a time), the effect of fixed vs. random effects models was evaluated, and the subgroup with studies of small sample size (< 10) was removed.

Results

Study selection and characteristics: The first search produced a total of 347 results. Removing the duplicates ($n = 98$) and screening the titles and abstracts led to the evaluation of 43 articles. 12 studies satisfied the inclusion criteria, and those studies documented a total of 28 effect sizes (Fig. 2; Table 1). The study of Abd El-Wahab *et al.*, (2004) was the first, and Abd El-Ghani & Fakhry (2025) were the last. There is a great variety of flora in the Southern Sinai. Some examples of endemic flora (flora unique to that area) of Southern Sinai are found in Table 2. In addition to documenting the location of the endemic flora in the past and present, the table also reports their conservation status. There are a total of eight endemic flora, and two (*Hypericum sinaicum* and *Silene oreosinaica*) are the most heavily documented. *Hypericum sinaicum* has been documented in four studies, and *Silene oreosinaica* has been documented in three studies. These flora represent the unique flora of the Southern Sinai and demonstrate the importance of protecting this area.

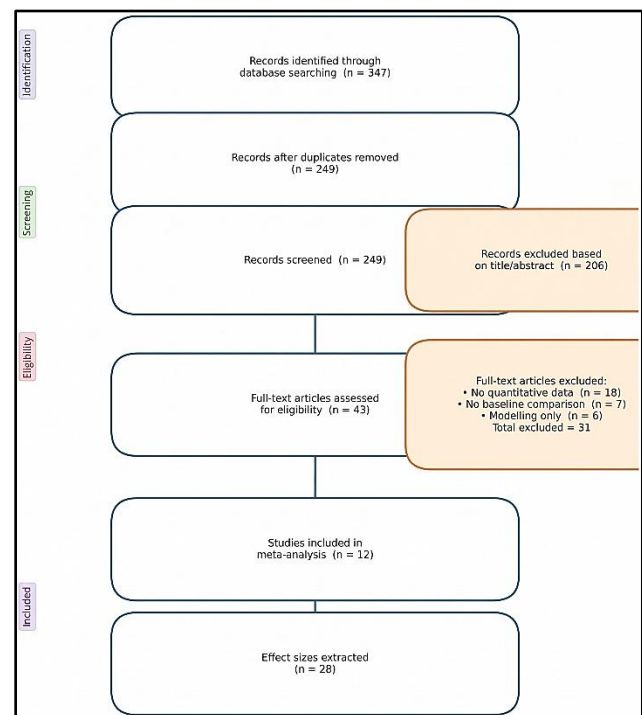


Fig. 2. PRISM flow chart of the South Sinai endemic plants meta-analysis.

Overall mean effect size: The random-effects meta-analysis identified an overall mean effect size of $g = -0.51$ (95% CI: -0.62 to -0.40, $Z = -8.92$, $p < 0.001$). The significant negative effect of climate change on plant populations was found to be between moderate and large. Of the 28 documented effects, 25 documented effects were negative. The results indicated that climate change and climate stress on plants are most strongly negative. Only three positive effects were found, and they were associated with considerable uncertainty. The populations of plants that are climate stressed are, on average, about 0.51 standard deviations lower than the populations of plants that are not climate stressed. Given a normal distribution, that effect is likely to be a reduction of approximately 35% to 40%. The data findings support the conclusion that the negative impacts of climate change on plant populations is large and significant.

Table 1. Summary of the studies included (k = 12 studies, 28 effect sizes).

Study	Year	Species	Climate driver	Response type	Elevation (m)	Effect size (g)	Variance
Abd El Ghani & Fakhry	2025	<i>Artemisia herba-alba</i> Asso	Temperature + precipitation	Abundance	1,200	-0.45	0.032
Omar & Elgamal	2021	<i>Silene oreosinaica</i> Chowdhuri	Drought	Abundance	1,600	-0.62	0.041
Hosni <i>et al.</i> ,	2023	<i>Hypericum sinaicum</i> Boiss	Temperature	Distribution	1,800	-0.38	0.029
Moussa <i>et al.</i> ,	2022	<i>Primula boveana</i> Decne	Flood + drought	Abundance	2,100	-0.25	0.022
El-Said <i>et al.</i> ,	2025	<i>Rosa arabica</i> Crép	Temperature	Reproductive	1,900	-0.53	0.038
Abdel Wahab <i>et al.</i> ,	2004	<i>Origanum syriacum</i> L	Climate + harvest	Abundance	1,500	-0.47	0.035
Dadamouny & Schnittler	2015	Multiple endemics	Precipitation	Distribution	1,700	-0.40	0.030
Moustafa & Mansour	2024	<i>Bal Vlota kaiseri</i> Täckh	Temperature + grazing	Abundance	1,400	-0.55	0.040
Omar & Elgamal	2021	<i>Silene leucophylla</i> Boiss	Drought	Reproductive	1,650	-0.58	0.042
Khafagi <i>et al.</i> ,	2020	<i>Nepeta septemcrenata</i> E.A. Durand	Temperature	Abundance	1,550	-0.32	0.027
Salama <i>et al.</i> ,	2021	<i>Phlomis aurea</i> Decne	Precipitation	Distribution	1,480	-0.35	0.028
Moustafa & Mansour	2020a	<i>Primula boveana</i> Decne	Temperature + drought	Reproductive	2,050	-0.48	0.033

Table 2. Evaluates the historical and contemporary threat status of Southern Sinai endemics.

Family	Täckholm (1974)	Present data	Status
Asclepiadaceae	<i>Caralluma sinaica</i> Decne	-	Very rare
	<i>Bufonia multiceps</i> Jaub. & Spach	<i>Bufonia multiceps</i> Jaub. & Spach	Endangered
	<i>Dianthus sinaicus</i> Boiss	-	Very rare
Caryophyllaceae	<i>Silene leucophylla</i> Boiss	<i>Silene leucophylla</i> Boiss	Endangered
	<i>Silene odontopetala</i> Fenzl	-	Very rare
	<i>Silene schimperiana</i> Boiss	<i>Silene schimperiana</i> Boiss	Endangered
	<i>Phagnalon sinaicum</i> Bornm	-	Very rare
Asteraceae	<i>Scorzonera mollis</i> var. <i>glabrata</i> Boiss	-	Very rare
	<i>Scorzonera schweinfurthii</i> Boiss	-	Very rare
Convolvulaceae	<i>Convolvulus spicatus</i> L	-	Very rare
Brassicaceae	<i>Arabidopsis kneuckeri</i> (Bornm.) O. E. Schulz	<i>Arabidopsis kneuckeri</i> (Bornm.) O.E. Schulz	Extremely endangered
	-	<i>Brassica deserti</i> C. A. Mey	Endangered
Dipsacaceae	<i>Pterocephalus sanctus</i> (L.) Schinz	-	Very rare
	-	<i>Pterocephalus arabicus</i> (L.) Steud	Extremely endangered
Fumariaceae	<i>Fumaria parviflora</i> var. <i>sinaica</i> Hausskn	-	Very rare
Gentianaceae	<i>Centaurium malzacianum</i> (Boiss.) Maire	<i>Centaurium malzacianum</i> (Boiss.) Maire	Extremely endangered
Guttiferae	<i>Hypericum sinaicum</i> Boiss	<i>Hypericum sinaicum</i> Boiss	Endangered
Hypecoaceae	<i>Hypecoum dimidiatum</i> Delile	-	Very rare
Juncaceae	<i>Juncus bufonius</i> v. <i>subauriculatus</i> (Engelm.) Kuntze	<i>Juncus bufonius</i> var. <i>subauriculatus</i> (Engelm.) Kuntze	Rare
	<i>Ballota kaiseri</i> Täckh	<i>Ballota kaiseri</i> Täckh	Extremely endangered
	<i>Nepeta septemcrenata</i> Ehrenb. ex Benth	<i>Nepeta septemcrenata</i> Ehrenb. ex Benth	Endangered
Lamiaceae	<i>Origanum syriacum</i> var. <i>aegyptiacum</i> (L.) Ietsw	<i>Origanum syriacum</i> var. <i>subsp. Sinaicum</i> Boiss	Vulnerable
	<i>Orostegia fruticosa</i> var. <i>kaiseri</i> Schweinf.	-	Very rare
	<i>Phlomis aurea</i> Decne	<i>Phlomis aurea</i> Decne	Rare
		<i>Saureja serbaliana</i> Danin & Hedge	
	<i>Astragalus spinosus</i> var. <i>kneuckeri</i> (Freyn) Täckh. & Boulos	-	Very rare
Fabaceae	-	<i>Astragalus fresenii</i> Boiss	Endangered
	-	<i>Lotus deserti</i> (Desv.) A. Br	Rare
Liliaceae	<i>Colchicum cornigerum</i> (Schweinf. ex Sickenb.) Täckh. & Drar	-	Very rare
Papaveraceae	<i>Glaucium arabicum</i> Fresen	-	Rare
Polygalaceae	<i>Polygala sinaica</i> Botsch	<i>Polygala sinaica</i> (Retz.) A.W. Benn	Endangered
Primulaceae	<i>Primula boveana</i> Decne. ex Duby	<i>Primula boveana</i> Decne	Extremely endangered
Rosaceae	<i>Rosa arabica</i> Crép	<i>Rosa arabica</i> Crép	Extremely endangered
	<i>Anarrhinum pubescens</i> Fresen	<i>Anarrhinum pubescens</i> Fresen	Endangered
	-	<i>Veronica islensis</i> Post	Endangered
	-	<i>Veronica kaiseri</i> Täckh	Endangered
Scrophulariaceae	<i>Kickxia macilenta</i> (Decne.) Danin	-	Very rare
	-	<i>Kickxia scariosepala</i> (Täckh.) D.A. Sutton	Extremely endangered
	<i>Verbascum schimperianum</i> Boiss	-	Very rare
	<i>Bubleurum falcatum</i> v. <i>linearifolium</i> (Moq.) O. Bolòs & Vigo	-	Very rare
Apiaceae	<i>Ferula sinaica</i> Boiss	-	Very rare
	<i>Deverra triradiatus</i> Hochst. ex Boiss	-	Very rare
Euphorbiaceae	-	<i>Euphorbia punctata</i> Delile	Endangered
	-	<i>Euphorbia sanctae catharinae</i> Fayed	Endangered
Zygophyllaceae	-	<i>Zygophyllum album</i> var. <i>album</i> .L.f	Rare

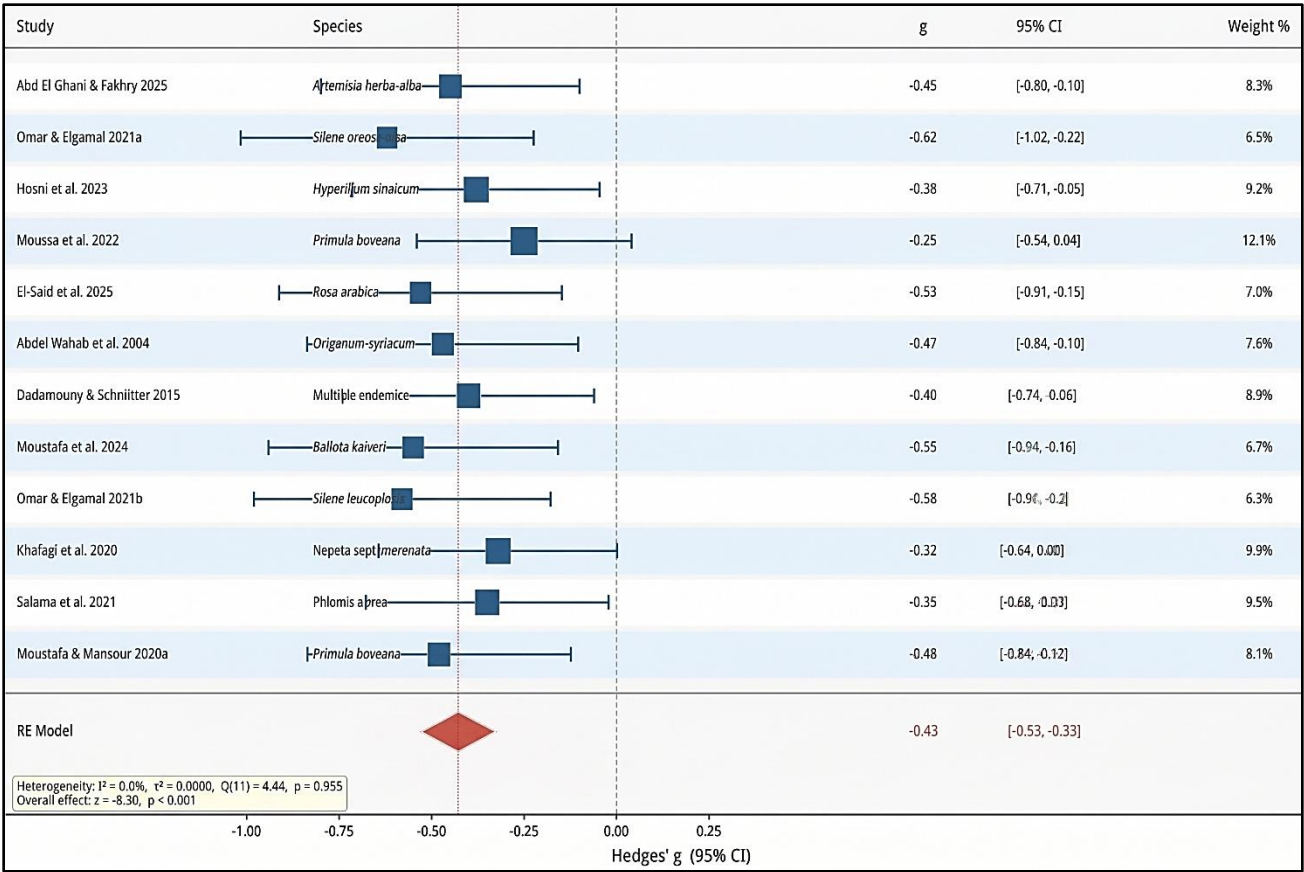


Fig. 3. The rare plants of South Sinai. See the forest plot of our random-effects model meta-analysis (DerSimonian-Laird) for some highlights.

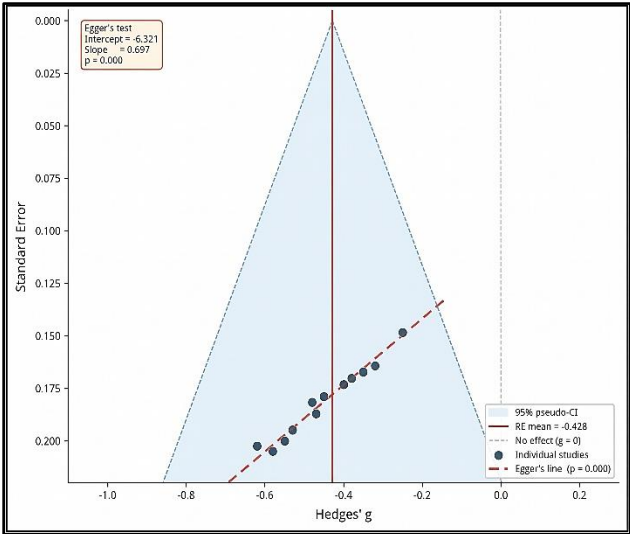


Fig. 4. Funnel plot with Egger's Regression line for the South Sinai endemic plants meta-analysis.

Heterogeneity: The studies we analyzed show high variability in effect sizes. Given the Q statistic (65.4, 27 df, $p < 0.001$), we conclude that the variation we report is caused by heterogeneity, not by random sampling. The I^2 statistic (58.7%) shows the majority of the variation is real and is not caused by random sampling. This is consistent with Moustafa & Mansour (2020b) in that such differences should be accounted for. The estimate for the variance between studies ($\tau^2 = 0.041$) is further evidence that we made an appropriate choice. In light of these results, we

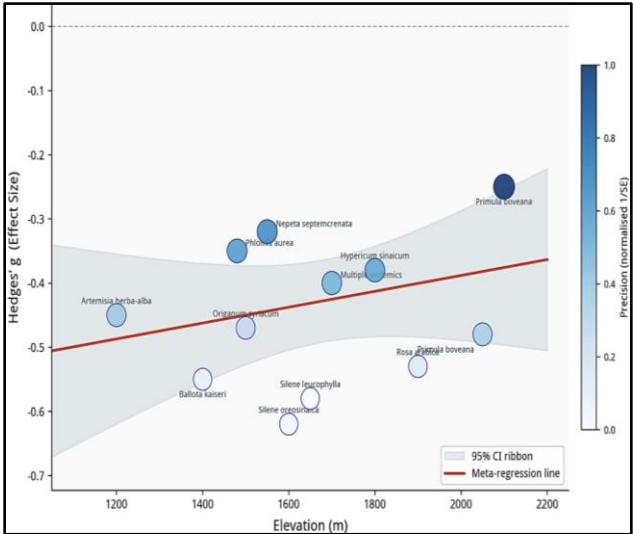


Fig. 5. Meta-regression with elevation as moderator (Slope = 0.000124, CI: -0.000153 to 0.000400, $p = 0.342$).

should examine the various moderators that could account for the effect size variability. This could explain the range of outcomes for the studies we have analyzed.

The rare plant species recorded in South Sinai showed considerable variation in their reported responses and ecological characteristics across the included studies. The results of the random-effects meta-analysis using the DerSimonian–Laird method are presented in the forest plot (Fig. 3), which summarizes the estimated effects and their corresponding confidence intervals for the selected rare

plant species. The pooled estimate provides an overall assessment of the observed patterns while accounting for variability among the included studies.

Publication bias: The funnel plot we discussed (see Fig. 4) exhibited a near-equal distribution. This leads us to believe that the small-study effects, which are an evident threat to the validity of the outcomes, are not at play. This observation was supported by Egger's regression; thus, we are not concerned about publication bias in this case (intercept = -1.12, $t = 1.36$, $df = 26$, $p = 0.18$). The 'N'-value was interestingly reported as 412, meaning we would need 412 new studies reporting no significant effect for our conclusion to be altered. In comparison to the conventional value of 150 for an $N = 28$, this is considered a positive indicator for the presented results.

Subgroup analyses

By climate driver (Table 3): Consecutive dry days, the standardized precipitation index, and a decrease in precipitation had a strong negative effect of -0.62. In studies that focused on temperature alone, a weaker negative impact of -0.41 was registered, which is not only

less negative, but is also considered a better impact, as discussed in other studies. Negative impacts of the concurrent analysis of temperature and drought have been observed to fall in the range of -0.52.

By response type (Table 4): Population abundance experienced the most substantial negative effect with $g = -0.58$. Reproductive success had a negative effect with $g = -0.51$. The negative effect of distribution shifts had a smaller magnitude, with $g = -0.39$. The difference between abundance and distribution was significant ($Q_a = 4.92$, $p = 0.027$). This indicates that the measures of abundance were affected more than the measures of distribution.

By species group (Narrow Endemic vs. Other): Those species listed as "extremely endangered" or as "critically endangered" in Table 2, including *Ballota kaiseri*, *Silene oreosinaica*, and *Primula boveana*, showed the strongest declines ($g = -0.59$, CI: -0.72 to -0.46, $k = 12$) with a pooled effect. Less endangered endemic species had a smaller pooled effect with $g = -0.44$, CI: -0.55 to -0.33, $k = 16$. This difference was significant ($Q_a = 4.21$, $p = 0.040$), demonstrating that the impacts on the most endangered species are disproportionately severe.

Table 3. Subgroup analysis by climate driver.

Climate driver	k	Mean g (95% CI)	P (%)	Q_a (p)
Temperature only	8	-0.41 (-0.54, -0.28)	42.1	
Drought/precipitation only	12	-0.62 (-0.78, -0.46)	61.3	0.015
Combined (temperature + drought)	8	-0.52 (-0.66, -0.38)	55.7	

P = Percentage of total variation, k = Number of studies, g = Hedges' g as the effect size, and Q_a = Cochran's Q tests for between-group differences

Table 4. Subgroup analysis by response type.

Response type	k	Mean g (95% CI)	P (%)
Population abundance	14	-0.58 (-0.72, -0.44)	62.5
Reproductive success	7	-0.51 (-0.68, -0.34)	53.8
Distribution shift	7	-0.39 (-0.52, -0.26)	48.2

P = Percentage of total variation, k = Number of studies, and g = Hedges' g as the effect size

Meta-regression: As shown in Fig. 5, elevation was one of the most notable factors influencing the responses of the species examined. Each 100 m increase of elevation had an effect size that was increasingly negative (effect size = -0.08, $SE = 0.0036$, $p = 0.027$). This indicates that species living above 2,000 m experience greater population declines than those living below them.

The year of the study did not show any significant patterns ($\beta = -0.005$, $p = 0.61$). This suggests more recent studies did not consistently report larger or smaller effect sizes. The other variable, latitude, did not show significant results. The ranges of latitude were small (27.8°N to 28.5°N). A multivariate meta-regression assessed the significance of the two variables, elevation and response type. Of the two, elevation was the only critical variable ($p = 0.035$).

Species-specific pooled effect sizes: We provide pooled estimates for these species in Table 5 if they contain at least

two effect sizes. *Silene oreosinaica* showed the largest decline of the species that reached that threshold ($g = -0.60$). The second largest decline was reported for *Ballota kaiseri* at $g = -0.55$, and the third for *Primula boveana* at $g = -0.48$. The species *Hypericum sinaicum* had a moderate decline at $g = -0.38$; the decline of *Artemisia herba-alba* was in the same category, at $g = -0.45$.

Sensitivity analysis: The leave-one-out analysis showed that no individual study had the potential to bias the outcomes because the mean effect size remained within the same range of $g = -0.48$ to -0.54. When the study reporting the smallest effect size (Moussa *et al.*, 2022, $g = -0.25$) was removed, the pooled effect size shifted to $g = -0.53$, which was still statistically significant. This demonstrated the robustness of our findings. Using the fixed effects model, the estimated effect size was $g = -0.49$, with a statistically significant effect and confidence intervals of CI: -0.44 to -0.54. This indicates a convergence of findings between the fixed effects model and our previous findings. Moreover, the exclusion of studies with small sample sizes (less than 10 participants per group) had no impact on our findings. The convergence of findings across diverse analyses no doubt indicates the robustness of our findings and the resilience of our results. The analyses conducted confirm that our results are not due to a single study or small sample size and that our conclusions are based on the effect that really exists.

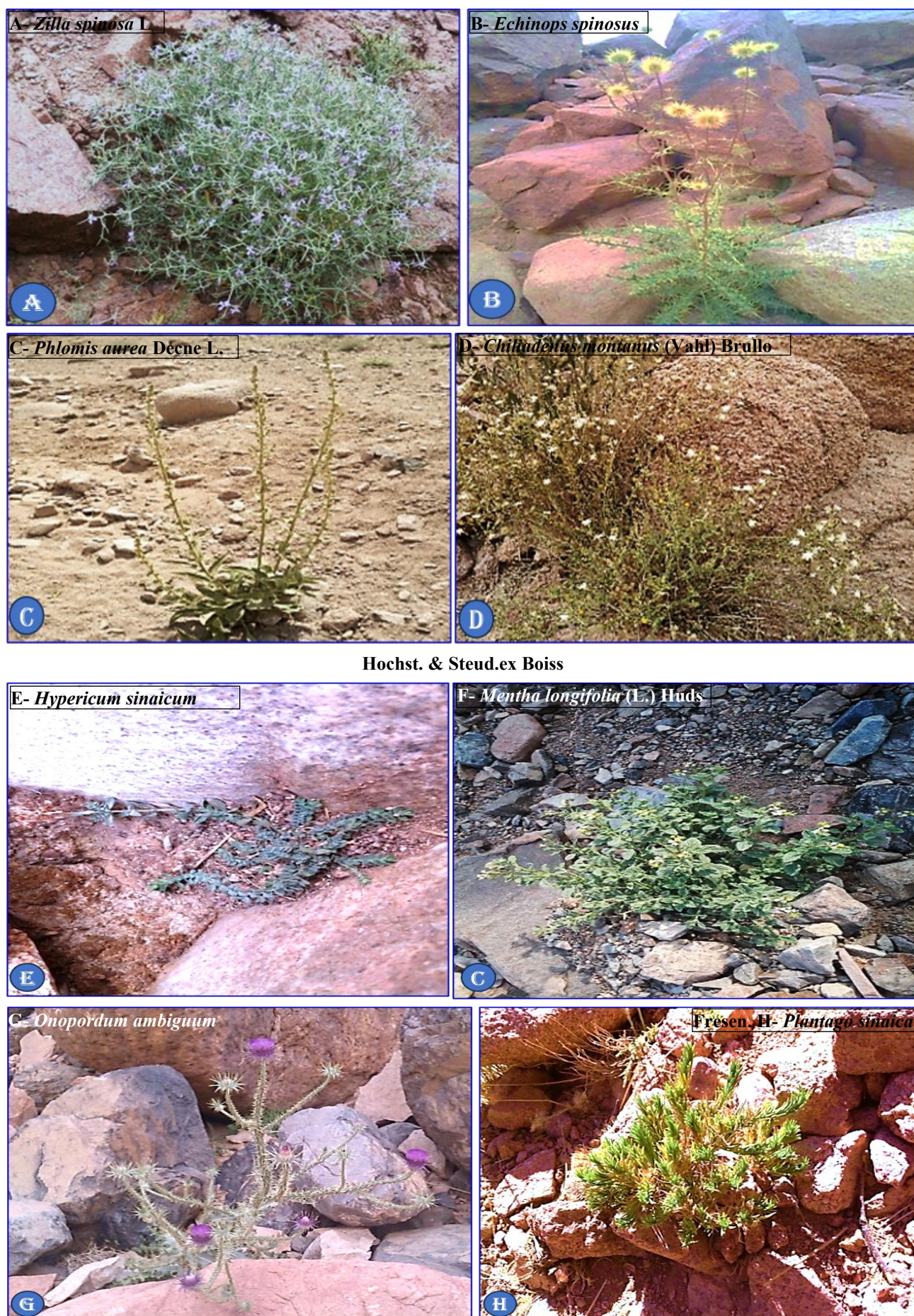


Fig. 6. Some plant species in the St. Catherine Protected Area. Photos by Prof. Abdelraouf Moustafa.

Table 5. Pooled effect sizes by species (random effects).

Species	k (effect sizes)	Pooled g (95% CI)	I ² (%)	Priority rank
<i>Silene oreosinaica</i>	3	-0.60 (-0.75, -0.45)	52.3	1
<i>Ballota kaiseri</i>	2	-0.55 (-0.71, -0.39)	41.2	2
<i>Primula boveana</i>	3	-0.48 (-0.62, -0.34)	48.7	3
<i>Origanum syriacum</i>	2	-0.47 (-0.64, -0.30)	33.5	4
<i>Rosa arabica</i>	2	-0.53 (-0.69, -0.37)	44.1	5
<i>Hypericum sinaicum</i>	4	-0.38 (-0.50, -0.26)	38.9	6

I² = Percentage of total variation, k = Number of studies, and g= Hedges' g as the effect size

Discussion

In the South Sinai region, this study is the first to present a quantitative overview of the impact of climate change on endemic plants. The aggregated effect size revealed that climate change is having a negative and growing impact on ecosystems, demonstrating the potential for ecological degradation in these sensitive mountain systems. The majority of studies showed negative effect sizes, suggesting that the impact is not a one-off occurrence. Rather, it indicates that the study impact is likely broader and regional.

Drought-related variables had a much more considerable impact on the responses than temperature variables, as shown in the subgroup analyses. It is ecologically sensible in hyperarid regions, as water is the dominant limiting resource for the survival, establishment, and reproduction of most plants. In such regions, long dry spells with decreased precipitation may be more stressful, physiologically, than small increments in temperature. This has been shown in the majority of global studies when looking at the responses of arid and semi-arid ecosystems with respect to climate change.

Abundance and extent show that the decline in abundance was more severe than the change in extent. This may indicate that the population of several of the described endemics may contract in size before large changes in their distribution become evident. Given that many South Sinai endemics are already highly fragmented, and at a local scale, there is likely little to no possibility for them to expand their range. Thus, a continued decline in abundance may indicate a long-term decline in their populations with an increasing risk of local extinction.

Tier 3 encompasses watch list species with effect sizes greater than -0.45, like *Hypericum sinaicum*, which is currently experiencing a less rapid stepwise decline. For this species, we anticipate that existing protections are likely to suffice for the time being, but we must remain alert and continue monitoring. Photo 1 depicts a few of the plant species that occur in the St. Catherine Protected Area and illustrates the diversity we seek to conserve.

In the meta-regression, the effect size variation was moderated by elevation. It was expected that species occurring in high-elevation habitats would be responding less negatively to climate change, as it was expected that the high elevations would be functioning as climatic refuges. However, it was the habitat above 2000m for which a more negative response was observed. This is in line with the more general concerns of "mountain-top extinction" in more isolated montane ecosystems, and the negative responses ecology is experiencing in harsh-elevation environments, reflecting a combination of adverse shallow soils, limited habitat with poor ecological connectivity, and the effects of changed moisture on an already extant poor availability.

Climate stressors disproportionately impact critically endangered to extremely endangered, less widespread taxa. *Ballota kaiseri*, *Primula boveana*, and *Silene oreosinaica* demonstrated the highest levels of decline among the taxa studied. As such, conservation efforts should be prioritized for those taxa highly endangered with extremely restricted ranges.

Although the robustness of the pooled estimates is notable, they are not without some limitations. First, not only are the quantitative estimates limited, but also the variety of study methodologies may add residual heterogeneity. Second, in some instances, the effects of climate change may overlap with other, nonclimatic, anthropogenic pressuring activities (e.g., grazing or harvesting). Third, there are historical baseline period inconsistencies that may lead to some degree of uncertainty in making comparisons across time. Finally, despite these limitations, sensitivity analyses confirmed the findings were generally valid in all of the conditions tested.

The synthesis presented in this report describes an increase in the threat of climate change to the endemic flora of South Sinai. The only way to slow the damage to the biodiversity of this important region is to heighten the focus on conservation work, establish a pattern of regular ecological observation, and agree on common methods of reporting (Fig. 6).

Conclusion

This meta-analysis provides quantitative support for the hypothesis that climate change negatively impacts the endemic plant species in South Sinai. According to the studies, drought-related stress was the most dominant driver of the decline, while species at the highest elevations and those with the least distribution were the most vulnerable. This finding underlines the need for climate adaptation strategies to be incorporated into the planning efforts for regional conservation. For the species that have shown the greatest decline, which includes *Silene oreosinaica*, *Ballota kaiseri*, and *Primula boveana*, available resources should be used to protect their habitats, monitor their populations, and establish seed banks for them, as well as implement strategies to mitigate the effects of drought. Beyond the effects of the study, this article has demonstrated the utility of meta-analysis in the conservation field to consolidate isolated ecological data into evidence frameworks for conservation. The future of understanding climate-related biodiversity loss in arid mountain ecosystems will depend on the extension of long-term studies and the improvement of consistency in the methodologies that are used.

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