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Journal of Insect Conservation
An international journal devoted to the conservation of insects and related invertebrates

ISSN 1366-638X
Volume 18
Number 6

J Insect Conserv (2014) 18:1017-1025
DOI 10.1007/s10841-014-9707-8

Springer

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ORIGINAL PAPER

Nowhere left to go: the Sinai Hairstreak *Satyrium jebelia*

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Received: 9 June 2014 / Accepted: 1 October 2014 / Published online: 11 October 2014

Abstract High-mountain endemics with very restricted ranges are likely to have a high risk of extinction under the various scenarios of global warming. Endemic to the high mountains of the St Katherine Protectorate in South Sinai (Egypt), the Sinai Hairstreak *Satyrium jebelia* is just such a species. For the first time, its population size was estimated and its distribution and that of its larval food plant (*Rhamnus dispermus*) were mapped. The total world population in 2012 was estimated to be 1,010 individuals, perhaps divided into six smaller sub-populations of varying size. Its moderate dispersal ability and the relatively close proximity of the sub-populations may indicate metapopulation structure, but more data are needed. Aspects of host-plant and habitat quality were significant predictors of the presence of Sinai Hairstreaks on individual trees. No immediate threats are evident except global warming: if current climate-change predictions for Egypt are correct, the quality of habitat and plant diversity will decrease in the St Katherine Protectorate, with obvious long-term conservation implications.

Keywords Butterfly conservation · Mountain habitat · Monophagous herbivore · Red Listing · Population size

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Introduction

Species with narrow environmental niches often have small or very small ranges ('endemics') and low local abundances (Rabinowitz 1981), although in some ancient specialized species abundances can be high (Williams et al. 2009). Changes in climate over thousands and millions of years are important drivers of the distribution of endemics (Ohlemüller et al. 2008; Dirnböck et al. 2010): the Pleistocene glaciations and post-Pleistocene warming are well known to have caused range contractions down to survival refugia, followed by range expansions by some but not all taxa (Hewitt 2000). In mountain regions, significantly associated with high biodiversity and endemicity (Myers et al. 2000; and even human linguistic diversity: Axelsen and Manrubia 2014), past climate changes have forced many species to higher altitudes in order to track their climate niche (Wilson et al. 2007; Dirnböck et al. 2010). Such species can become isolated on 'mountain-top islands', out of which migration is very difficult or impossible: since migration then becomes non-adaptive, many mountain endemics have evolved low powers of dispersal (Thomas et al. 2004). As anthropogenic global warming continues, these species are being pushed even higher, restricting their available habitat even more: thus mountain endemics face a heightened risk of extinction because of these factors (Thomas et al. 2004; Ohlemüller et al. 2008; Dirnböck et al. 2010).

Even within the naturally small ranges of mountain endemics, the sizes of patches of potential habitat are important for explaining their occurrence (Aarts et al. 2013). Understanding the spatial structure of patches and the dynamics of their populations is crucial to a successful conservation strategy (Guiney et al. 2010), especially since by no means all sets of patchy populations function as metapopulations (Fronhofer et al. 2012). The risks of habitat loss are important, since habitat destruction decreases habitat area as well as the connectivity between suitable sites, making it more difficult to move between and colonise suitable areas of habitat, and increasing extinction risk for most (but not all) species (Rueda et al. 2013). Such considerations may be especially important in arid environments, which are patchy and fragmented due to the limited and patchy natural resources available, especially water (Sheffer et al. 2011).

This study concerns a high-mountain Egyptian endemic butterfly, the Sinai Hairstreak *Satyrium jebelia* (Nakamura 1975; Lepidoptera: Lycaenidae: Theclinae), now probably Egypt's only known endemic butterfly species after the recent discovery of a population of the Sinai Baton Blue *Pseudophilotes sinaicus* in Saudi Arabia (Dr Samy Zalat, *pers. obs*.). Before this study the Sinai Hairstreak was known only from three small sites above 2,000 m altitude in the South Sinai mountains, all within a 10-km radius of the town of St Katherine, in the heart of the St Katherine Protectorate. These data highlight it as a species urgently needing reliable assessment, likely to be Critically Endangered under the IUCN categorisation. As of 2007, there were only fourteen known records, the latest from 2001 (Gilbert and Zalat 2007). The original collector and describer, Nakamura (1975), stated that the Sinai Hairstreak is on the wing between late May and early July, and is not uncommon in areas where its larval food plant, Sinai Buckthorn *Rhamnus dispermus*, occurs. The dioecious Sinai Buckthorn is found more widely on mountaintops in the Middle East (Boulos 2000), but before our study it was unknown whether *R. dispermus* is under threat in the St Katherine Protectorate.

Thus here we address two questions: (a) what is the distribution of both butterfly and host-plant in the St Katherine Protectorate; and (b) how large is the total population, and how do butterflies move among host-plants?

Materials and methods

Study system

The Sinai Hairstreak is probably most closely related to the Blue Spot Hairstreak *Satyrium spini* (Schiffermüller) of the subgenus *Satyrium* (Nakamura 1975), found throughout western Europe as far east as Iran (Tshikolovets 2011). There have not been any recent studies on the phylogeny of *Satyrium*, and the current attribution of the Sinai Hairstreak to the subgenus *Superflua* is not well supported (Gian Christophoro Bozano, *pers. comm*.). The Blue Spot Hairstreak has a similar wing pattern and egg structure, as well as being relatively close geographically. In the mountains of the West Bank (Palestine), it uses the same larval food plant as the Sinai Hairstreak (Nakamura 1975). As well as differences in wing morphology, the size of the male genitalia of the Sinai Hairstreak is different.

The eggs of both the Blue Spot and Sinai Hairstreaks are said to go through a diapause with a delayed emergence until the following spring. In the former, caterpillars hatch in spring and feed on emerging flower buds and young leaves; its caterpillars secrete a sugary substance and are tended by ants (Settele et al. 2008). Myrmecophilous relationships are common in lycaenid butterflies, with about 75 % of species having an association with ants (Pierce et al. 2002). However, the genus *Satyrium* has fewer species with ant associations than other genera (Fiedler 1991). Tending ants may provide protection to the caterpillars from parasites or predators, but the benefits of myrmecophilous relationships are likely to be species-specific (Pierce et al. 2002). It is unknown if the larvae of the Sinai Hairstreak are tended by ants.

Study site

The St Katherine Protectorate is one of Egypt's largest protectorates, situated in South Sinai and spanning an area of 4,350 km^2 (Grainger and Gilbert 2008). Known as the 'Roof of Egypt' the area contains all of Egypt's highest mountains (up to Mt St Katherine at 2,643 m), with deep extensive networks of dry valleys ('wadis') cut throughout the landscape. The igneous Pre-Cambrian Ring Dyke encompassing 640 km^2 and lying at the centre of the national park was classified by UNESCO as a world heritage site in 2002 for its cultural and religious importance. The massif is 600 million years old and is comprised mainly of red granite (UNESCO 2002). Our study sites are found around the high mountain peaks around the city of St Katherine within the Ring Dyke.

The mountain massif is a local hotspot of biodiversity: the flora contains Turano-Iranian relicts of the last 10,000 years of drying of the Sahara (Boulos 2000). South Sinai has a Sahara-Mediterranean climate with hot summers (up to 36 °C) and cold winters, and is the coolest area in Egypt (UNESCO 2002). On average the area receives 62 mm of rainfall a year (Zahran and Willis 2009). The high mountains are sometimes covered in snow during the winter, and snow melt provides the area with more water throughout the rest of the year (Grainger 2003). The relatively high amount of water available compared to the rest of Egypt has resulted in a relatively high diversity of plants and animals, among the richest in the country, if not the richest.

Host-plant and butterfly distribution

The mountains and wadis around the city of St Katherine were searched for the presence of *R. dispermus* in April and

Table 1 The features of *R. dispermus* recorded, and the instruments used

Larval food plant/habitat feature	Instruments used
Tree size; height and two perpendicular widths	Measuring tape (in m)
Percentage of 'green' healthy leaves	Subjective estimation
Presence of fruit	Observation (presence or absence)
Slope where the tree grows	Clinometer
Aspect where the tree grows	Compass
Shelter/shade	Scored according to the following scale: (1) tree in the open with nothing shading it on any side; (2) sheltered on one side or partial shelter on two sides; (3) a lot of shelter on two sides or partial shelter on three sides; (4) a lot of shelter on three sides or partial shelter on four sides.
Number of different plant species within 2 m of larval food plant	Observation
Number of plant individuals within 2 m of larval food plant	Observation
Altitude	Recorded with global positioning satellite receiver (GPS) (Garmin, eTrex Venture HC)

May 2012 before the main flight period of the Sinai Hairstreak. Throughout the study, the detailed local knowledge of the highly skilled Bedouin guides was utilised to find trees, given the extremely difficult steep terrain of hyperarid rocky mountains. Trees were also searched from vantage points with binoculars. Given the lack of a tree line and the ultra-sparse distribution of vegetation, the trees were easily located. While there may be some trees on other higher (unvisited) mountains of the massif (Serbal, Um Shomar), Sinai Buckthorn has never been recorded by any botanical expeditions, or recognised by our Bedouin guides, anywhere else other than the locations recorded here. The location of each tree was recorded with a portable global positioning satellite receiver (GPS) (Garmin, eTrex Venture HC, accurate to ±5 m) and a map of all the sites produced. All the sites and all discovered trees were revisited once during the main flight period to search for the presence/absence of adult Sinai Hairstreaks, to see which trees were used by the butterflies.

To assess the apparent selectivity of the butterflies (and hence their requirements in terms of habitat and probably larval food plants), eleven features of the larval food plant and its location were recorded (see Table 1 for feature details and instruments used). Because of the great difficulty and effort required to reach the sites, some sites (particularly Jebel Bab) had to be visited much later in the season when flowering had finished. This made it impractical to use the presence of flowers as a predictor, and instead we use the presence of fruit. Butterflies visited trees even if no flowers were present, flying around them and sitting on the leaves.

After the flowering period the leaves of *R. dispermus* begin to senesce (Boulos 2000), so attention was paid to this feature. An estimate of the state of leaf senescence (% of leaves that were green) was taken for each tree to try to determine what stage of the life cycle of *R. dispermus* is preferred by the Sinai Hairstreak.

Population and movement estimates

Population estimates for adult Sinai Hairstreaks were carried out at each site in June and July 2012. A 5-day Mark-Release-Recapture (MRR) experiment was carried out at each of the four sites (Jebel Katherine 2–6 June, Abu Druce 17–21 June, Abu Towaita 24–28 June and Jebel Bab 7–11 July). Every tree at each site was visited multiple times to search for butterflies following a rough transect. Butterflies were caught with a large butterfly net from 08:00 to 16:30 (local time, GMT +2) for five consecutive days. Each butterfly captured was given an individual mark with a felt-tip pen through the net and released as quickly as possible. These sub-population sizes were estimated using Eberhardt's geometric model (Pollard 1977). An MRR was attempted in Wadi El-Freya on the 3rd of July, but there were no butterflies present, and the *R. dispermus* trees were in bad condition in comparison to previous visits. The transect count of adult butterflies on the 10 of May was used to estimate the population.

Given the large size of the Wadi Ahmar region and its apparently high population of Sinai Hairstreaks, a different method was used here (8 and 12 June). A pre-determined transect route through Wadi Ahmar was walked on the 8 of June encompassing as many of the larval food plants as possible. Adults were caught and given a site-specific mark and released quickly. The site was revisited on the 12th of June, a period of time likely to give the marked individuals time to redistribute into the population at random. The same transect route was used, unmarked individuals were given a different mark and recaptured individuals were re-marked to avoid double counting. Marking took place between 0800 and 1600 (local time). The population size of this site was estimated using a simple Lincoln index.

The location, behaviour and time were recorded for each capture or subsequent recapture to allow us to reconstruct the minimum movement distances of individual butterflies (as straight lines between successively recorded locations). The main aim of the work was to record the distribution and to estimate population size; given the extreme nature of the terrain making human movements among sites very slow and logistically difficult, the design does not make it easy to record butterfly dispersal among sites.

Statistical analysis

All statistical tests were performed using R v.3.0.2 (R Core Team 2014). The eleven features of each larval food plant (n = 553 trees) were entered as explanatory variables (including all interactions) into a mixed-effects Generalized Linear Model with *site* as a random factor (with six levels) to account for spatial variation. The presence/absence of Sinai Hairstreaks was entered as the (binomially distributed) response variable. Factors were removed singly and the change in deviance assessed using χ^2; non-significant factors were omitted sequentially, leaving the minimal sufficient model (when the AIC was at a minimum; see Zuur et al. 2009).

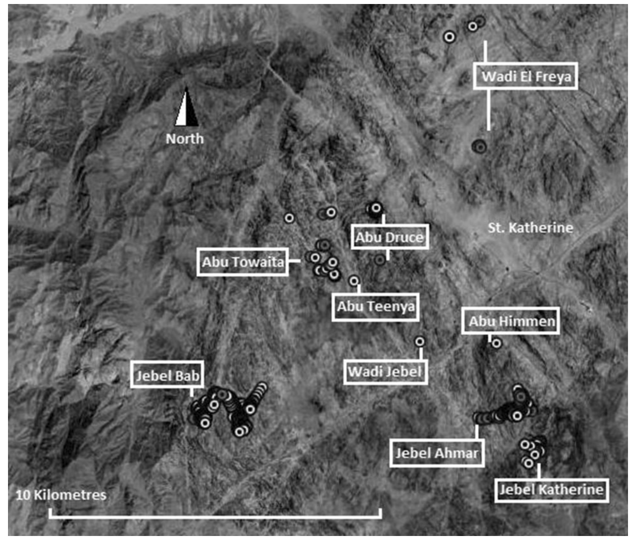

Fig. 1 Map of St Katherine Protectorate showing distribution of *R. dispermus* and Sinai Hairstreak (*white symbols* show *Rhamnus* trees where no Sinai Hairstreak were recorded during the study, *grey symbols* show *Rhamnus* trees where Sinai Hairstreaks were present during study)

Results

General observations

The tree is known to expert Bedouin guides as 'orontol', but many Bedu are unfamiliar with it and do not distinguish it from other thorny bushes (such as the Sinai Hawthorn *Crateagus* × *sinaica*, known locally as 'zah-rur'). The tree does not seem to play any role in Bedouin culture, unlike the Hawthorn. Butterflies are not distiguished to species by the Bedouin, all being called 'farasha'.

Host-plant and butterfly distribution

590 *R. dispermus* trees were discovered in nine discrete 'sites' at altitudes between 1,584 and 2,368 m above sea level. Site boundaries were assigned using the natural topography of the landscape (Fig. 1) and contained varying numbers of trees within the main six areas (see Table 2); single trees were discovered high up near Abu Himmen, in a tributary valley off Wadi Jebel, and in Abu Teenya (see Fig. 1). Tree size varied greatly, with heights ranging from 0.02 to 5.90 m (overall mean 1.29 ± 4 m). Fruit was recorded on a total of 187 trees out of 553 mature trees. Most trees had a high percentage of green leaves during the study period and hence during the flight season of the Sinai Hairstreak.

Trees in April had bright-green leaves and many buds, some with the characteristic light green/yellow flowers. By early May many trees had green and some red fruits, and some flowers were withering and leaf condition was beginning to decline. The last flowers were recorded on 21 June on just two of the 42 trees of Abu Druce. By early July almost all trees had withered leaves in the lower-altitude sites, and some were beginning to wither in Jebel Bab and Wadi Ahmar, the sites a't the highest altitude. By mid-August fruit was still present on the trees of these two high-altitude sites, but many leaves had withered.

Although occasionally landing on other plant species (*Origanum*, *Mentha*, *Teucrium*, *Crataegus*), hairstreak butterflies were almost exclusively seen on or around the host-plant. Not all trees were visited, however: they were seen on a total of 130 trees across all six main sites (Table 2), but not on the three single isolated trees in Abu Himmen, Wadi Jebel and Abu Teenya. They were first observed on 10 May in Wadi El-Freya (six individuals), while the last individual was seen on 27th July in Wadi Ahmar. The main flight period was from late-May to mid-July. They were active from 0700 (GMT +2) until 1900 hours, with a broad peak from 1100 to 1400 hours. Butterflies (presumably the males) were highly territorial and aggressive, chasing off other species (commonly the Long-tailed Blue *Lampides boeticus*, but also Painted Lady *Vanessa cardui*, Pomegranate Playboy *Deudorix livia*, Clouded Yellow *Colias croceus* and an unidentified red parasitic wasp). One was attacked by a Rock Martin *Ptyoprogne fuligula* on two separate occasions, and several insectivorous birds (Scrub Warbler *Scotocerca inquieta*, Blackcap *Sylvia atricapilla*, Redstart *Phoenicurus phoenicurus*, White-crowned Wheatear *Oenanthe leucopyga*) and a praying mantis foraged on *Rhamnus* and could eat butterflies.

In predicting the occurrence of Sinai Hairstreaks on individual trees of the six main sites, there were three

Table 2 The number and density of *R. dispermus* trees in each site, together with their measured characteristics

Site	Area (km^2)	No. of trees	Trees per km^2	Tree height (cm)	Tree vol. (m^3)	% Green	% Fruiting	No. of trees with butterflies
Jebel Katherine	0.2	33	165	139 ± 12	4.5 ± 1.2	61.1 ± 4.3	54.5	9
Abu Druce	0.1	42	420	171 ± 19	16 ± 4.9	83.2 ± 3.8	26.2	24
Abu Towaita	2.3	27	12	146 ± 22	12.7 ± 4.3	69.4 ± 4.4	22.2	7
Wadi El-Freya	1.3	6	5	155 ± 32	11 ± 3.2	53.3 ± 16.4	33.3	3
Jebel Bab	2.2	330	150	117 ± 4	5.6 ± 0.6	69.5 ± 1.3	38.0	25
Wadi Ahmar	0.7	145	207	134 ± 9	15.9 ± 3.5	75.7 ± 1.9	25.5	62

"% Green" is the percentage of the leaves of an individual tree that were green (not senescing); "% fruiting" is the percentages of trees of a site that had fruit at any time during the study. All means are ±SE. The host-plant density was calculated from the tree coordinates using MapSource™

Table 3 Minimum sufficient model of a generalized linear mixed model explaining the presence/absence of *S. jebelia* on individual host trees, using the R routine *lmer* (from the library *lme4*) with binomial errors

Factor	Estimate	χ^2	Df	p
Intercept	−4.09 ± 0.79			
Tree height	0.0097 ± 0.0017	41.89	1	≪0.001
% Green leaves	0.012 ± 0.007	3.01	1	0.08
Slope	0.013 ± 0.008	2.63	1	0.10
Presence of fruit on tree	0.97 ± 0.29	11.51	1	<0.001
Local plant spp richness	0.40 ± 0.09	20.89	1	≪0.001

Site was the random factor (variance 0.6513, n = 6). The model was not a perfect fit (residual deviance = 385, df = 541; log likelihood = −192.5). χ^2 was calculated from the change in deviance on dropping the factor from the model

highly significant predictors (tree height—positively, local plant species richness—positively, and the presence of fruit—positively). There were also two marginal predictors where the change in deviance was not quite significant ($0.05 \leq p \leq 0.01$) yet the model AIC increased when they were dropped from the model (state of leaf senescence—positively, and slope—positively; see Table 3). None of the interactions with the random effect (site) was significant.

Population and movement estimates

The number of captures and recaptures during the five-day MRR in Jebel Katherine, Abu Druce, Abu Towaita and Jebel Bab can be seen in Table 4. The attempted MRR in Wadi El-Freya failed because no butterflies were present and the *R. dispermus* trees were senescing: the minimum of six individuals recorded there previously on the 10th of May was taken to be the population estimate. Estimates for the sizes of the sub-populations (excluding Wadi El-Freya; Table 4) range from 57 to 403, with the total estimated population size of 1,010.

Movement distances were available for three sites (Jebel Katherine 62 ± 34; Abu Druce 52 ± 11 and Jebel Bab 193 ± 88—all in m), differences close to significant (Kruskal–Wallis $\chi^2 = 5.66$, df = 2, $p = 0.059$). The overall average minimum distance travelled between recaptures was 104 m, with a maximum of 938 m by a butterfly in Jebel Bab. The frequency distribution of these distances (Fig. 2) was leptokurtic. No marked butterflies were seen in any site other than where they were first marked.

Age estimation was not an objective of this study, which concentrated on estimating population size. However, a Sinai Hairstreak was observed on the 2nd of July in Wadi Ahmar which had been marked in the same location on the 8 of June: at 25 days, this time gap was the largest recorded.

Discussion

The dispersal ability of a species and the spatial structure of available habitat determine its population structure (Fronhofer et al. 2012). Basing a conservation strategy on the wrong population structure may waste valuable resources and may not be of benefit (Fronhofer et al. 2012). This is the first study on this rare and highly restricted species, and therefore its detailed distribution together with that of the host-plant and its powers of dispersal are important.

Host-plant and butterfly distribution

Both the butterfly and its host-plant appear to be confined to a tiny area within the St Katherine Protectorate. The population of Sinai Hairstreaks in 2012 was estimated to be between 745 and 1,275 individuals spread across six sites

Table 4 Population estimates for each site

Site	Method used	Total no. of captures	Total no. of recaptures			Population estimate
Wadi Ahmar	Lincoln index	54	11 (of 82 captured)			403
			Once	Twice	Thrice	
Jebel Katherine	Eberhardt's model	19	7	1	0	57
Abu Druce	Eberhardt's model	66	15	4	2	214
Abu Towaita	Eberhardt's model	25	3	2	0	111
Jebel Bab	Eberhardt's model	45	9	1	0	225
Wadi El-Freya	Transect count	–				6
Total						1,010
	95 % confidence interval					745–1,275

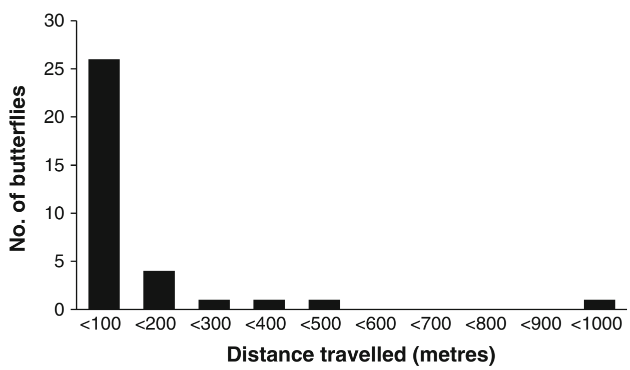

Fig. 2 Frequency distribution of total distances travelled by all butterflies recaptured

enclosed within a minimum convex polygon of roughly 83 km^2. This is likely to represent a large proportion, if not all, of its worldwide population and distribution, since it is as yet unrecorded from any other location, although as with the Sinai Baton Blue, it is possible that other populations exist wherever *R. dispermus* occurs, i.e. in Lebanon and Palestine (Boulos 2000), and also eastern Syria (Chikhali 2009), Jordan (Ateyyat and Abu-Darwish 2009) and northwestern Saudi Arabia (Ghazanfar and Fisher 1998: 129). Benyamini (2000) looked for them on *R. dispermus* trees in southern Jordan, but none were found. Only 590 trees were found in the high mountains of the St Katherine Protectorate: because of the expertise of the Bedouin guides, although more may exist we are fairly confident of having surveyed nearly all of them. The trees only grow at very high altitudes, suggesting that for both plant and butterfly, global warming will be a serious issue in the future.

The main flight period appeared to be from late May to early/mid July, much longer than Nakamura's (1975) estimate of late May to early June. The life-cycle closely mirrored that of the host-plant. The young larvae presumably hatch in spring and feed on emerging young buds and leaves in April (Nakamura 1975), with adults emerging in May when the main flowering period began. The peak emergence of adult butterflies in Sinai extended from May to mid-June, and then the butterfly flight season declined and ended as *R. dispermus* trees began to wither in late-July and August.

While tied to the presence of the host-plant, predictors of individual tree and local habitat quality were clearly important for the presence of Sinai Hairstreaks: tree height, the presence of flowers/fruit, and high local plant diversity, with perhaps the state of leaf senescence and landscape slope also contributing. These are all indicators of good-quality habitat that can support vigorous plant growth: nutrient-rich soil and higher water availability are probably important elements for the growth of large healthy plants and high floral diversity. Female trees require more nutrients than males to grow both fruit and flowers (Yu and Lu 2011), and hence such places are probably even more important for female trees. The role of leaf senescence may be significant since many butterflies select younger or greener leaves for oviposition (Prokopy and Owens 1983). However, although we did not study oviposition here, there seems to be no a priori reason for female Sinai Hairstreaks to make such a choice, because we think the eggs over-winter and hatch when the new leaves of the following year are unfurling—thus the current state of old leaves should not be relevant.

Population and movement estimates

The data suggest the Sinai Hairstreak has a propensity to move (8 of 34 moves [24 %] were more than 100 m) and an ability to disperse reasonable distances. This is in sharp contrast to the other endemic of St Katherine, the Sinai Baton Blue, which rarely moves further than 100 m (James 2006a). Some Sinai Hairstreaks covered impressive distances: the champion was a butterfly caught in the Jebel Bab region and subsequently recaptured a day later almost 940 m away as the crow flies. The landscape between these two locations is difficult to navigate, showing that hairstreaks are capable of travelling reasonable distances quickly, and certainly have the ability to move between sites (although this was not detected). However, the mean distance moved (104 m) is not very large compared to the scale of the study (ca. 10^4 ha). Schneider (2003) recorded an excellent relationship between study scale and mean distance moved, but on her plot our butterfly comes out as a relatively poor mover.

As to the maximum observed distance moved (938 m), the Wadi Ahmar and Jebel Katherine regions are separated by the same distance, as are those of Abu Towaita and Abu Druce, apparently well within reach of a dispersing hairstreak. A series of interconnecting wadis in the St Katherine Protectorate link most areas together, and a dispersing individual could use these wadis as corridors where there is less wind resistance and where flowers can be found from which to feed. Some male butterflies can sense female pheromones from great distances (Nieberding et al. 2008), encouraging movement of males between sites. Butterflies may also learn where larval food plants are. Coupled with a probable relatively long lifespan (cf. the record of 25 days), the ability to travel a kilometre in one day means that we can predict movers from patch to patch. Despite this, none were seen in the year of study.

Without further information it is difficult to assign a population structure to the Sinai Hairstreak. A true metapopulation is defined by a number of criteria: habitat patches must be able to support a breeding population; these populations must be vulnerable to extinction, and persist in a stochastic balance between local extinction and re-colonisation; the dynamics should be asynchronous, preventing the entire metapopulation becoming extinct; and there should be limited dispersal between populations (Harrison 1991; Hanski et al. 1995; Fronhofer et al. 2012). If the sites discovered in this study represent separate populations, it seems likely that the smaller sites are too small to be capable of supporting their own breeding populations. Dispersal among sites was not observed, and average movement distances are moderate compared to distances among sites, so it is possible for there to be a metapopulation. It is also possible that there is a single 'patchy population', a set of habitat patches linked together by levels of dispersal that prevent local extinction (Harrison 1991) by a rescue effect (Fronhofer et al. 2012). Incorrect assumptions about population structure can lead to the implementation of unnecessary and wasteful conservation strategies (Fronhofer et al. 2012).

Conservation implications

Short-term threats to the Sinai Hairstreak are less evident than those of the Sinai Baton Blue (cf. Thompson and Gilbert, 2012). The larval food plant is not collected by the Bedouin. All the sites where *R. dispermus* was found are isolated and remote. The town of St Katherine is expanding, but according to local information the number of people living near *R. dispermus* sites is decreasing as they move to the town, and was in any case initially very low. Given the remoteness of some of the sites, there is a very low risk of habitat destruction from human development. *R. dispermus* trees are long-lived and large, and are hence less likely to be affected by grazing than other plants: few signs of grazing animals were discovered in the study sites.

Considering the small amount of potential habitat currently available to the Sinai Hairstreak, the most significant threat facing the Sinai Hairstreak is likely to be global warming. The climate of the South Sinai has been predicted to become hotter and drier (Hulme et al. 2001; Giannakopoulos et al. 2009), and thus has the potential to disrupt the interaction between the Sinai Hairstreak and its larval food plant and possibly adult food plants. The existence of monophagous butterfly species is dependent on synchronisation of the life-cycle with their larval food plants, for example in the Sinai Baton Blue (Thompson and Gilbert 2014). Another example is Edith's Checkerspot butterfly *Euphydryas editha* in North America, whose range is contracting: it is believed that increasing temperatures are causing the host-plants to dry prematurely before the caterpillars hatch, depriving them of a food source (Parmesan 1996). A drier climate would reduce the resources available for *R. dispermus* and affect other plants too: during a dry year the number of flowering Sinai thyme plants *Thymus decussatus* can be reduced by 40 % (James 2006b). Host-plant size, fruiting, and perhaps condition are important determining factors for the presence of Sinai Hairstreaks, all probably dependent on water availability, already a limited resource in the St Katherine Protectorate and increasingly a problem due to increased human water demand from both local people and tourism (Abdulla et al. 2003; Hilmi et al. 2012). There is an increasing number of butterfly species being forced to higher altitudes as average temperatures increase. A study of Spanish butterflies suggested that 16 species have shifted their ranges upwards by more than 200 m over the past 30 years (Wilson et al. 2005). Eventually such species run out of higher altitudes: like the Sinai Hairstreak, the Uncompahgre Fritillary *Boloria acrocnema* is a rare relict found in the San Juan Mountains of Colorado (USA) that survives by clinging to cooler habitats at the highest altitudes from where it cannot move up any more (Britten et al. 1994).

Microclimate selection becomes more important under global warming. Most of the eggs of the Blue Spot Hairstreak are laid on plants growing in the warmest conditions (Loeffler et al. 2013), fully exposed to the sun on steep south and west-facing slopes: 80 % of egg batches were on the upper surface of a twig fork close to the ground (<1 m;

Loeffler et al. 2013) where the air temperature was higher and the wind speed lower (Porter 1992). Warm microclimates are very important for the egg and larval stages of many species of thermophilous butterflies (García-Barros and Fartmann 2009), especially for populations at high altitudes, such as the Blue Spot Hairstreak, which in the Pyrenees lays its eggs even closer to the ground and selects plants near warm bare ground (Stuhldreher et al. 2012). Conservation strategies for the Blue Spot Hairstreak focus on protecting the host-plant, coupled with management of the surrounding habitat by using traditional rough-grazing methods (Stuhldreher et al. 2012; Loeffler et al. 2013). The oviposition preference of the Sinai Hairstreak is likely to be similar. It also lives at high altitudes where it is cold in the winter months, so it would be beneficial to oviposit in warm microclimates. Grazing is probably less important as a threat or a management tool, because the hyper-arid mountain climate of the Saint Katherine Protectorate results in naturally low vegetation cover compared to Europe, and therefore shading would not be as problematic.

Our data suggest that this species should be classified as Vulnerable (from criterion D2 of the IUCN Red Listing: IUCN 2012), since there may be fewer than 1,000 individuals in a restricted area of occupancy and number of locations. Under B1 of the criteria it might qualify as critically endangered (since the Extent of Occurrence is <100 km^2), but only one of the three co-criteria is true (fewer than ten locations): there is no information available about continuous decline, or yet of extreme fluctuations in distribution or population numbers (although butterfly populations are typically very variable). Similarly under criterion C it would qualify as Endangered (fewer than 2,500 mature individuals), if there were evidence of continuing decline. *Rhamnus dispermus* trees were found in nine discrete sites in the St Katherine Protectorate, and the Sinai Hairstreak in six of these sites. The sites where the butterfly was not recorded each contained only one single very small tree, and hence these cannot be considered suitable habitats for Sinai Hairstreaks. Within the six main sites, there were many individual trees where the Sinai Hairstreak was never observed.

This study confirms that the Sinai Hairstreak has an extremely small population size and a greatly restricted range at the highest altitudes in Egypt; it is therefore highly susceptible to extinction. More information about its biology is clearly needed, and the populations of both the hairstreak and *R. dispermus* need to be monitored in the future so that we can understand long-term population trends and changes in habitat. Future studies should concentrate on the behaviour and life-cycle of the Sinai Hairstreak. It is imperative that the small number of *R. dispermus* trees remain protected to ensure the survival of this extremely rare and beautiful butterfly.

Acknowledgments We thank the Egyptian Environmental Affairs Agency and Mr. Mohamed Qotb, manager of the St Katherine Protectorate, for permission to do the work. Dr. Sabrine Rashed of the St Katherine Protectorate generously shared her knowledge of the butterfly and host-plant, as did our expert local Bedouin guides Nasr Mansour and Suleiman Abusada. We are grateful to Brian Power, Peter Cutler and Féaron Cassidy for help with the fieldwork, and Dubi Benyamini for advice on finding the butterflies. We thank Luke McLeod, Olivia Norfolk, Stine Simensen and Katy Thompson for field support and companionship, and Farag Mahmoud and everyone at Fox Camp for logistical help. We thank two anonymous referees for their comments which greatly improved the manuscript.

References

Aarts G, Fieberg J, Brasseur S, Matthiopoulos J (2013) Quantifying the effect of habitat availability on species distributions. J Anim Ecol 82(6):1135–1145

Abdulla H, Ghodeif K, El-Shatoury S, Dewedar A (2003) Potential contamination of groundwater in the world heritage site of the St. Katherine Protectorate, Egypt. Egypt J Biol 5:1–9

Ateyyat MA, Abu-Darwish MS (2009) Insecticidal activity of different extracts of *Rhamnus dispermus* (Rhamnaceae) against peach trunk aphid, *Pterochloroides persicae* (Homoptera: lachnidae). Span J Agric Res 7(1):160–164

Axelsen JB, & Manrubia S (2014) River density and landscape roughness are universal determinants of linguistic diversity. Proc R Soc Lond B Biol Sci 281, 20133029

Benyamini D (2000) *Pseudophilotes jordanicus*, a new relict species of the S.E. Mediterranean (Lepidoptera: lycaenidae). Linneana Belg 17:359–370

Boulos L (2000) Flora of Egypt, vol 2. Al Ghoneimy, Cairo

Britten HB, Brussard PF, Murphy DD (1994) The pending extinction of the uncompahgre fritillary butterfly. Conserv Biol 8(1):86–94

Chikhali, M. 2009. Flora of Syria on-line. http://www.florasyria.com

Dirnböck T, Essl F, Rabitsch W (2010) Disproportional risk for habitat loss of high-altitude endemic species under climate change. Glob Change Biol 17(2):990–996

Fiedler K (1991) European and North West African Lycaenidae (Lepidoptera) and their associations with ants. J Res Lepid 28(4):239–257

Fronhofer EA, Kubisch A, Hilker FM, Hovestadt T, Poethke HJ (2012) Why are metapopulations so rare? Ecology 93:1967–1978

García-Barros E, Fartmann T (2009) Butterfly oviposition: sites, behaviour and modes. In: Settele J, Shreeve T, Konvicka M, van Dyke H (eds) Ecology of butterflies in Europe. Cambridge University Press, Cambridge, pp 29–42

Ghazanfar, S.A. & Fisher, M. (eds) (1998) Vegetation of the Arabian Peninsula. Geobotany 25. Kluwer, The Netherlands

Giannakopoulos C, Le Sager P, Bindi M, Moriondo M, Kostopoulou E, Goodess CM (2009) Climatic changes and associated impacts in the Mediterranean resulting from a 2 C global warming. Glob Planet Change 68:209–224

Gilbert F, Zalat S (2007) Butterflies of Egypt: atlas, red data listing and conservation. Cairo, Nature Conservation Sector, EEAA

Grainger J (2003) 'People are living in the park'. Linking biodiversity conservation to community development in the Middle East region: a case study from the Saint Katherine Protectorate, Southern Sinai. J Arid Environ 54:29–38

Grainger J, & Gilbert F (2008) Around the sacred mountain: the St Katherine Protectorate in South Sinai, Egypt. In: Mallarach JM (ed) Protected landscapes and cultural and spiritual values. Volume 2 in the series values of protected landscapes and seascapes, IUCN, GTZ and obra social de caixa catalunya. kasparek verlag, Heidelberg. p 21–37

Guiney MS, Andow DA, Wilder TT (2010) Metapopulation structure and dynamics of an endangered butterfly. Basic Appl Ecol 11:354–362

Hanski I, Pakkala T, Kuussaari M, Lei G (1995) Metapopulation persistence of an endangered butterfly in a fragmented landscape. Oikos 72:21–28

Harrison S (1991) Local extinction in a metapopulation context: an empirical evaluation. Biol J Linn Soc 42:73–88

Hewitt G (2000) The genetic legacy of the Quaternary ice ages. Nature 405:907–913

Hilmi N, Safa A, Reynaud S, Allemand D (2012) Coral reefs and tourism in Egypt's Red Sea. Top Middle East Afr Econ 14:416–434

Hulme M, Doherty R, Ngara T, New M, Lister D (2001) African climate change: 1900–2100. Clim Res 17:145–168

IUCN. 2012. IUCN Red List categories and criteria. Version 3.1, 2nd edn. IUCN, Gland, Switzerland & Cambridge, UK

James M (2006a) Intra-patch movement in the Sinai Baton Blue butterfly: influence of micro-habitat and individual characteristics. Egypt J Biol 8:51–66

James M (2006b) The natural history of the Sinai Baton Blue: the smallest butterfly in the world. Egypt J Biol 8:67–83

Loeffler F, Stuhldreher G, Fartmann T (2013) How much care does a shrub-feeding hairstreak butterfly, *Satyrium spini* (Lepidoptera: lycaenidae), need in calcareous grasslands? EurJ Entomol 110(1):145–152

Myers N, Mittermeier RA, Mittermeier CG, de Fonseca GAB, Kent J (2000) Biodiversity hotspots for conservation priorities. Nature 403:853–858

Nakamura I (1975) Descriptions of two new species of butterflies (Lepidoptera, Lycaenidae) from the South Sinai. J Entomol Ser B-Taxon Syst 44:283–295

Nieberding CM, De Vos H, Schneider MV, Lassance JM, Estramil N, Andersson J, Bång J, Hedenström E, Löfstedt C, Brakefield PM (2008) The male sex pheromone of the butterfly *Bicyclus anynana*: towards an evolutionary analysis. PLoS ONE 3:e2751

Ohlemüller R, Anderson BJ, Araujo MB, Butchart SHM, Kudrna O, Ridgley RS, Thomas CD (2008) The coincidence of climatic and species rarity: high risk to small-range species from climate change. Biol Lett 4:568–572

Parmesan C (1996) Climate and species' range. Nature 382:765–766

Pierce NE, Braby MF, Heath A, Lohman DJ, Mathew J, Rand DB, Travassos MA (2002) The ecology and evolution of ant association in the Lycaenidae (Lepidoptera). Annu Rev Entomol 47:733–771

Pollard E (1977) Method for assesing changes in abundance of butterflies. Biol Conserv 12:115–134

Porter K (1992) Eggs and egg-laying. In: Dennis RLH (ed) The ecology of butterflies in Britain. Oxford University Press, Oxford, pp 46–72

Prokopy RJ, Owens ED (1983) Visual detection of plants by herbivorous insects. Annu Rev Entomol 28:337–364

R Core Team. (2014) R: a language and environment for statistical computing. Vienna, Austria. http://www.R-project.org

Rabinowitz D (1981) Seven forms of rarity. In: Synge H (ed) The biological aspects of rare plant conservation. Wiley, New York, pp 205–217

Rueda M, Hawkins BA, Morales-Castilla I, Vidanes RM, Ferrero M, Rodriguez MA (2013) Does fragmentation increase extinction thresholds? A European-wide test with seven forest birds. Glob Ecol Biogeogr 22:1282–1292

Schneider C (2003) The influence of spatial scale on quantifying insect dispersal: an analysis of butterfly data. Ecol Entomol 28:252–256

Settele J, Kudrna O, Harpke A, Kühn I, Van Swaay C, Verovnik R, Warren M, Wiemers M, Hanspach J, Hickler T (2008) Climatic risk atlas of European butterflies. Pensoft, Sofia

Sheffer E, Yizhaq H, Shachak M, Meron E (2011) Mechanisms of vegetation-ring formation in water-limited systems. J Theor Biol 273(1):138–146

Stuhldreher G, Villar L, Fartmann T (2012) Inhabiting warm microhabitats and risk-spreading as strategies for survival of a phytophagous insect living in common pastures in the Pyrenees. Eur J Entomol 109(4):527–534

Thomas CD, Cameron A, Green RE, Bakkenes M, Beaumont LJ, Collingham YC, Erasmus BFN, De Siqueira MF, Grainger A, Hannah L (2004) Extinction risk from climate change. Nature 427:145–148

Thompson K & Gilbert F (2012) *Pseudophilotes sinaicus*. In: IUCN 2013. IUCN Red list of threatened species. Version 2013.2. www.iucnredlist.org

Thompson K, Gilbert F (2014) Phenological synchrony between a plant and a specialized herbivore. Basic Appl Ecol 15:353–361

Tshikolovets VV (2011) Butterflies of Europe and the Mediterranean area. Tshikolovets, Pardubice

Unesco (2002) Nomination of the St Catherine area, Sinai, Egypt as a mixed world cultural and natural heritage site [Online]. http://whc.unesco.org/en/list/954/documents/

Williams SE, Williams YM, VanDerWal J, Isaac JL, Shoo LP, Johnson CN (2009) Ecological specialization and population size in a biodiversity hotspot: how rare species avoid extinction. Proc Natl Acad Sci USA 106(S2):19737–19741

Wilson RJ, Gutiérrez D, Gutiérrez J, Martínez D, Agudo R, Monserrat VJ (2005) Changes to the elevational limits and extent of species ranges associated with climate change. Ecol Lett 8(11): 1138–1146

Wilson RJ, Gutierrez D, Gutierrez J, Monserrat VJ (2007) An elevational shift in butterfly species richness and composition accompanying recent climate change. Glob Change Biol 13: 1873–1887

Yu L, Lu J (2011) Does landscape fragmentation influence sex ratio of dioecious plants? A case study of *Pistacia chinensis* in the Thousand-Island lake region of China. PLoS ONE 6:e22903

Zahran MA, Willis AJ (2009) The vegetation of Egypt. Springer, London

Zuur AF, Ieno EN, Walker NJ, Saveliev AA, Smith GM (2009) Mixed effects models and extensions in ecology with R. Springer, New York