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SHORT COMMUNICATION

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High mortality of beetle migrants along the Eastern Mediterranean Flyway

Will L. Hawkes[1,2] | Özge Özden[3,4] | Olivia Forster[1] | Teddy Walliker[1] | Katharine Lacey[1] | Boya Gao[5] | Jason W. Chapman[1,5] | Karl R. Wotton[1]

[1]Centre for Ecology and Conservation, University of Exeter, Penryn Campus, Cornwall, UK

[2]Swiss Ornithological Institute, Sempach, Switzerland

[3]Department of Landscape Architecture, Near East University, Nicosia, Cyprus

[4]Cyprus Herbarium and Natural History Museum, Near East University, Nicosia, Cyprus

[5]Department of Entomology, Nanjing Agricultural University, Nanjing, China

Correspondence
Will L. Hawkes, Centre for Ecology and Conservation, University of Exeter, Penryn Campus, Cornwall, UK.
Email: w.l.s.hawkes@exeter.ac.uk

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Abstract

1. Migration is costly in terms of increased energy expenditure and exposure to risks encountered *en route*. These factors can lead to a higher mortality among migrants compared with more sedentary life history stages.
2. Insect migrants are incredibly numerous, but as they are less conspicuous than vertebrate migrants and as migration often occurs at high altitude and over a broad front, it can be difficult to study migration-related mortality. A major source of information on migration-related mortality comes from cadavers found on the strandline following unsuccessful sea crossings.
3. Here, we analyse strandline mortality following a 100 km crossing of open ocean along the Eastern Mediterranean Flyway from the Middle East mainland to the island of Cyprus by tens of millions of insects.
4. All strandline recordings were of two species of beetles, the seven-spot ladybird *Coccinella septempunctata* and the carabid beetle *Calosoma olivieri*, whereas only nine individuals of *C. septempunctata* were caught successfully arriving with the rest of the insect assemblage over the ocean.
5. Major strandings were associated with easterly winds, suggesting origins from the Middle East mainland, with the individuals documented as extremely weak and unable to fly or dead.
6. Our results suggest that beetles are weaker migrants than other members of the migratory insect assemblage, with the sea crossing too far for the great majority to fly, leading to high mortality. The impact of this high mortality on the marine ecosystems is discussed.

KEYWORDS
arthropods, *Coccinella septempunctata*, Coccinellidae, Cyprus, insect migration, migration-related mortality

INTRODUCTION

Every year, huge numbers of animals undertake seasonal migrations (e.g., Alerstam & Bäckman, 2018; Satterfield et al., 2020). Often, these journeys are to obtain increased reproductive success through the exploitation of seasonal resources (Dingle, 2014), yet the associated cost may be high as the journeys are full of risks. Studies of raptors and songbirds have shown that increased mortality occurs during periods of migration (Alerstam & Bäckman, 2018; Klaassen et al., 2014). These deaths often have important impacts on the ecosystem within which they occur, which may be far removed from development or feeding grounds. This is particularly true for short-lived migrants such as insects or for species like migratory Salmon (*Oncorhynchus* spp.) that die after spawning in freshwater rivers and so provide nutrients to the surrounding riparian ecosystem (Bartz & Naiman, 2005; Bauer & Hoye, 2014; Holtgrieve & Schindler, 2011). The impacts of the mortality of insect migrants, however, have been rarely studied.

Insects migrate in incredible numbers annually, moving to exploit seasonal resources, to increase reproductive output or to escape the deterioration of their current habitat, for example, due to disease risk, food quality or temperature (Chapman et al., 2015; Dingle, 2014). Their numbers surpass the movements of vertebrates both in abundance and biomass, whereas their ecological roles (e.g., pollination, pest control and nutrient transfer) make the phenomena a crucial component of many ecosystems (Chapman et al., 2015; Doyle et al., 2020; Hu et al., 2016; Satterfield et al., 2020). The variety of species found migrating through any flyway, known as the 'migratory insect assemblage', is often diverse (Chapman et al., 2004; Hawkes et al., 2022). While Lepidoptera are the most apparent and best studied members, and Diptera the most numerous components, the ladybirds (Coccinellidae) are perhaps the most well-known beetle migrants with various historical records of their migration. Evidence of large-scale migrant mortality often is recognised when the insects are washed up on beaches, for example, in 1952, there was a 'very great migration' of *Coccinella septempunctata* to the south Lincolnshire coast, United Kingdom, where the high tide mark was a 'pink band [of ladybirds] … extending for about forty miles' (Williams, 1957). Sea crossings are likely hazardous for migrating insects. If conditions become unfavourable, then the insects will become trapped over the water and may fall into the sea leading to death (Fisler & Marcacci, 2022). Islands may well be important stepping stones for migrants, helping them avoid this fate (Hawkes et al., 2022).

The island of Cyprus sits 105 km from the Middle Eastern coast and acts as a stepping stone for migrants colonising Europe from the east during the springtime (Hawkes et al., 2022). Research in spring 2019 revealed at least 39 million insects making landfall at the tip of the Karpaz Peninsula in the northeast of Cyprus, with an estimated 6.9 billion insects emigrating from the Middle East towards southeast Europe during the same period (Hawkes et al., 2022). Given the distance of the sea crossing and the number of insects involved, we predicted that migration-related mortality would occur among the weaker fliers of the migratory assemblage. We utilise strandline counts, netting and transects to document mortality and the species involved before discussing the ecological impacts of this phenomenon.

MATERIALS AND METHODS

Cyprus is an island situated in the east of the Mediterranean Sea. The study site was situated at the northeastern tip of the Karpaz Peninsula (coordinates: 35.692824° N, 34.584572° E) (Figure S1a,b). The narrow peninsula stretches out into the ocean where the nearest off-island landmasses are Turkey (83 km northeast) and Syria (105 km east). The Karpaz Peninsula is one of the most important areas for biodiversity in Cyprus (Özden, 2013). The area has recently received official legal protection as an important natural resource for the northern part of the island and was declared a 'Special Environmentally Protected Area' according to Environment Law (21/97) article 11 by the Turkish Cypriot authorities (Özden, 2013).

Observations of insect migration were made between 28 March and 5 May 2019 as part of a whole assemblage insect migration study (Hawkes et al., 2022). The migrant species were recorded in four different ways: (1) bi-hourly hand-netting of migrant insects arriving across the sea from the southeast (Figure S1b, orange circle and blue arrows indicating migratory insect arrival bearing); (2) strandline surveys on the local 45 m beach (Figure S1b, red dashed line at location [ii]); (3) daily wildflower transects 100 m in length (Figure S1b, red dashed line at location [i]) and (4) on an ad hoc basis around the field site. All insects encountered were noted and identified using field guides and keys.

In method (1), hand-netting, small insects were noted to make landfall by flying up a gulley situated at the tip of the peninsula (Figure S1b, orange circle): for 2 min every 2 h between 10:00 AM and 16:00 PM, the net was swiped across the gulley. The insect catch was then emptied into a mesh cage before being identified in the field. In method (2), strandline surveys, a 45 m beach close to the peninsula tip (Figure S1b, blue dashed line) collected washed up migratory insects after being stranded at sea. The beach was walked daily at 16:30 PM and all species encountered were counted and collected. This collection ensured no double counting was performed in subsequent days. The insects stranded on the beaches were seen to be very weak, unable to fly, but mostly alive, suggesting that they had spent some time in the water although not long enough for them all to drown. This suggests that they had fallen into the water relatively close to the shore. For analysis, we reasoned that these stranded insects had fallen into the sea while migrating the previous day. For method (3), daily wildflower transects, we also utilised a 100 m transect close to where the insects made landfall and first had a chance to feed upon the abundant wildflowers. The transect was walked at 16:00 PM each day at a regular pace, the insects were counted and identified by eye. Finally, method (4) consisted of ad hoc recordings of beetles as they were spotted around the field site. Further records of ladybirds were noted during the spring 2022 migration season, but no systematic counts were made. Daily wind directions were taken from Ventusky (ventusky.com) at an elevation of 250 m above sea level.

RESULTS

Only beetles were recovered from the strandline surveys (Figure 1a–c; Table S1). A total of 74 individuals of the carabid beetle *Calosoma olivieri* were identified from the strandline survey and wildflower transect. A second beetle species, *C. septempunctata*, was the most abundant numbering 1160 in the combined surveys,

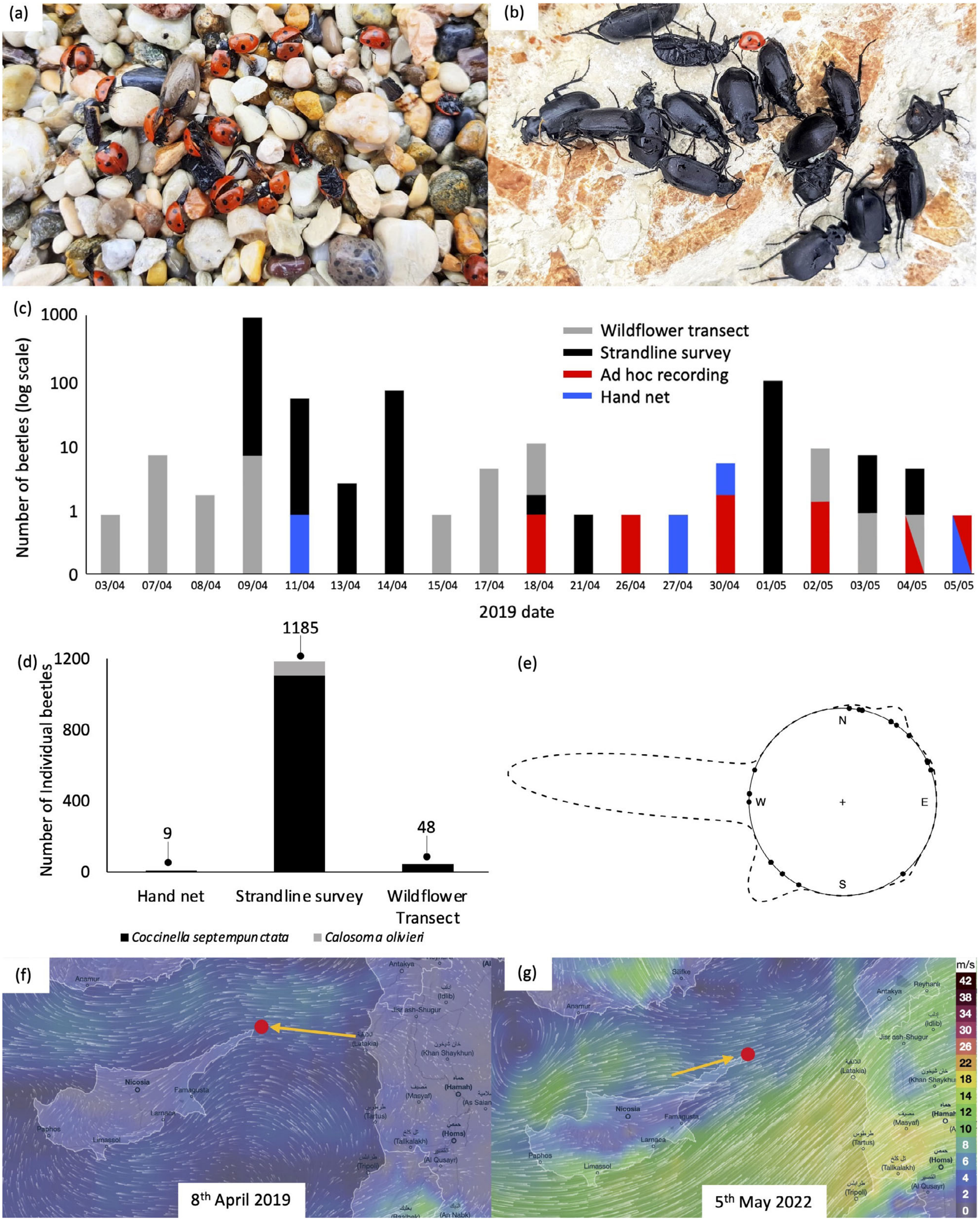

FIGURE 1 (a) and (b) Beetles identified on the Karpaz Peninsula. (a) Image of stranded *Coccinella septempunctata* ladybirds. (b) Image of stranded *Calosoma olivieri* ground beetles. (c) The phenology of beetle captures and arrivals across the 2019 season. The data are displayed with a log-scale to allow for ease of viewing. For specific species data and phenologies, see Table S1. (d) Total number of C. *septempunctata* and C. *olivieri* documented from strandline surveys, hand netting and transects. (e) Circular plot showing beetle numbers (dotted line indicates the number of beetles; largest peak equates to 930 individuals) and wind directions associated with their arrival (black dots) during 2019. (f) and (g) Wind directions and wind speeds for the largest mass arrival events of beetles (>100 individuals) to the tip of the Karpaz Peninsula, Cyprus (red dot). In 2019, the migrating beetles were found stranded, so the wind directions from the day before are displayed (f). In 2022, the mass arrival event occurred with live beetles, and so wind conditions on the day are displayed (g). Yellow arrow represents wind direction. Map colours represent wind speeds (m/s).

outnumbering the other beetles by nearly 15-fold, and was the only species caught crossing the sea by hand net (Figure 1c; Table S1). The largest stranding events occurred on 9 April 2019 with 930 *C. septempunctata* (Figure 1a,c,d; Table S1), whilereas *C. olivieri* were found in greatest numbers (70) in the late season (1–4 May). Two further Coccinellidae, *Coccinella undecimpunctata* and *Harmonia quadripunctata*, the latter recorded new to Cyprus, were also recorded but only appeared during ad hoc recordings. No direct evidence for migratory behaviour was documented for these two latter species (Table S1), though we note large-scale strandings of *C. undecimpunctata* have previously been recorded on the northern coast of Egypt (Oliver, 1943).

The majority (91% of total) of beetles in 2019 arrived on winds from the east (Figure 1e,f). Major beetle arrivals were identified when the number recorded exceeded 100 individuals. This occurred twice in 2019 (9 April and 1 May) with the beetles recorded being weak (unable to fly), near death or dead on the beach strandline. Analysis of the wind directions on the day preceding the stranding events suggests that the beetles had their origins towards the east in countries such as Syria, Turkey or Lebanon (Figure 1f). During spring of 2022, a further observation of ladybird beetles was made at the field site. A rough estimate of 500–900 *C. septempunctata* were recorded on 5 May 2022 (Table S1). In contrast to 2019, these beetles were recorded alive and flying, covering the high points of the peninsula's tip. The wind direction on this day was from the west, suggesting these beetles had their origins more locally from Cyprus (Figure 1g).

DISCUSSION

Between 28 March and 5 May 2019, migration-related mortality of insects was recorded at the tip of the Karpaz Peninsula of Cyprus. Of the millions of insects that made the >100 km over-sea crossing to Cyprus during 2019 (Hawkes et al., 2022), only beetles were recorded during strandline surveys. A total of 1252 beetles were recorded, of which two species showed migratory behaviour: the abundant 7 spot ladybird (*C. septempunctata*) and the carabid beetle *C. olivieri*. Both these species were recovered during the strandline surveys, but only *C. septempunctata* was recorded successfully making the crossing, albeit in small numbers. *C. olivieri* was observed to have undergone a 'population explosion' in Israel, Saudi Arabia and Jordan, the day prior to their arrival in Cyprus (Nir Sapir, *Pers. comms*.). These beetles were likely part of a much larger movement of migratory insects (numbering at least 39 million) with their origins in the Middle East (Hawkes et al., 2022). However, of the beetles recorded, 95% were found stranded on the beaches either very weak and unable to fly or dead, indicating a high level of mortality during the crossing. Analysis of wind directions and speed the day before the strandings revealed that the beetles likely had their origins to the east. While beach strandings of other migratory insects are known to occur, for example, because of bad weather at sea (Fisler & Marcacci, 2022), no other taxa were found on the strandline, nor were bad weather events recorded here. Rather, the lack of other insects suggests poorer flight capability than the millions of other insect migrants that successfully made the crossing in this period, primarily species of Diptera, Lepidoptera and Odonata (Hawkes et al., 2022). The single instance where ladybirds were found flying in large numbers occurred in 2022; however, wind analysis from this arrival event indicated a local origin of the beetles.

Interestingly, mortality of large numbers of migratory hoverflies were also recorded at the tip of the Karpaz Peninsula in 2019 (Hawkes et al., 2022). However, in contrast to the beetles, the hoverflies appear to have made the sea crossing before succumbing to infection to *Entomophthora* sp. pathogenic fungi, which causes the flies to climb to prominent locations (e.g., the top of grass stems) so that the fungi can release their spores (Elya & de Fine Licht, 2021; Hawkes et al., 2022 (Figure 6d)). Interestingly, despite thorough searches, no hoverflies were recorded washed up on the strandline like the beetles, suggesting that, despite the infection, they were still able to make the sea crossing.

Migratory insects are known to have large-scale impacts on terrestrial ecosystems through ecological roles such as pollination, pest control, decomposition and nutrient transfer (Doyle et al., 2020; Ecodiptera, 2009; Pérez-Bañón et al., 2003; Satterfield et al., 2020; Wotton et al., 2019). Beetles play important ecological roles, with both the ladybirds and the *Calosoma* ground beetles being important biocontrol agents. A single *C. septempunctata* is known to eat more than 5000 aphids per year (Majerus et al., 1989), and so when moving in large numbers, it can have highly beneficial consequences to agricultural crops. The *C. olivieri* beetle is known to be a voracious generalist predator of caterpillars, presumably including those that do harm to crop plants. Moreover, as ladybirds also feed on pollen, they are known to have pollination capabilities (Bertolaccini et al., 2008); this coupled with their migratory behaviour has the potential to link geographically isolated plant populations (Doyle et al., 2020; Lysenkov, 2009; Meyer et al., 2009; Rader et al., 2020).

Despite these known roles in terrestrial ecosystems, the effects on marine ecosystems of high insect mortality during over-sea migratory flights are unknown. The stranding events recorded in the current study likely represent a small percentage of the number of beetles migrating, suggesting that large quantities of nutrients from the beetles' bodies could end up in the sea and, therefore, be available for the marine ecosystem. For example, autopsies performed on loggerhead and green turtles during spring 2019 revealed that migratory invertebrates, such as painted lady butterflies (*Vanessa cardui*) and migratory Orthoptera, had been ingested (Palmer et al., 2021). Other marine residents, such as fish and marine invertebrates, no doubt also feed on the migrant insects falling into the ocean. Studies collecting insects from the surface of the Black Sea found nine different insect orders, with an estimation of 10 metric tons of insects on the surface of the Black Sea at any one point during the summer (Zaitsev, 1970). This nutrient flow from terrestrial to marine ecosystems by the migrating insects may have considerable importance to low productivity areas of the ocean such as in ocean gyres (Johnson, 1976). However, much more research is needed to fully understand this phenomenon.

Avenues to explore could involve monitoring of marine organism stomach contents for migratory insects during the migratory seasons or looking for correlations between the movements of migratory marine organisms and the flow of insects along flyways.

This study is one of the few to quantify mortality and migratory insect movements at the same location. Regular systematic monitoring programmes of insect migration hotspots, such as the tip of the Karpaz Peninsula, Cyprus, will help to reveal if the occurrence of stranded beetles alongside groups of other migratory insects is a regular event and the extent to which beetles might successfully make the crossing under different conditions. Further studies into migration-related mortality will be important to better understand the movement capabilities of the varied taxa found within migratory insect assemblages and the impacts of this mortality on the wider ecosystems.

AUTHOR CONTRIBUTIONS

Will L. Hawkes: Conceptualization; investigation; writing – original draft; methodology; visualization; writing – review and editing; formal analysis; data curation; validation. **Özge Özden:** Writing – review and editing; project administration; investigation; conceptualization; data curation. **Olivia Forster:** Investigation; methodology; writing – review and editing. **Teddy Walliker:** Conceptualization; investigation; methodology. **Katharine Lacey:** Investigation. **Boya Gao:** Investigation. **Jason W. Chapman:** Conceptualization; methodology; writing – review and editing; supervision; funding acquisition; project administration; resources. **Karl R. Wotton:** Conceptualization; methodology; funding acquisition; writing – review and editing; data curation; supervision; resources; project administration.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in the supplementary material of this article.

ORCID

Will L. Hawkes https://orcid.org/0000-0003-0661-7864

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Figure S1. The fieldwork location on Cyprus and its position relative to the wider area. (a) The position of Cyprus in the Mediterranean. The red circle represents the location of (b) the study site situated on the Karpaz peninsula. Orange circle indicates migratory insect netting site, red dashed lines: (i) indicates location of the 100 m long wildflower transect, (ii) represents the 45 m strandline survey. Blue arrows represent the arrival bearings of the migratory insects recorded in Hawkes et al, 2022. Base images taken from Google Earth.

Table S1. The species and relative abundance of beetles recorded migrating onto Cyprus during spring 2019 and the different survey techniques during which they were recorded. Abbreviations: *C.7* = *Coccinella septempunctata*, *C.11* = *Coccinella unidecimpunctata*, *H.q.* = *Harmonia quadripunctata*, *Ch.b.* = *Chilocorus bipustulatus*, *O.c.* = *Oenopia conglobata*, *Hi.v.* = *Hippodamia variegata*, and *Ca.o.* = *Calosoma olivieri*.

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