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An "alien" species on the loose: new records and updated distribution of the black soldier fly *Hermetia illucens* in the Western Palearctic

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Abstract

The black soldier fly *Hermetia illucens* (L.) (Diptera Stratiomyidae) is renowned around the globe as a bioconverter reducing organic matter as well as an important source of protein in aquaculture and livestock farming. In this publication, *H. illucens* is recorded for the first time in Austria, Belgium, Cyprus, Israel, Lebanon and the United Kingdom utilizing museum and personal collection specimens, citizen-science data and authors' personal records. Eastern Mediterranean records are suspected to reflect on rather recent introduction events whereas new records from Central European countries and the United Kingdom may correspond to individuals introduced from already invaded neighbouring countries. The industrial use of the black soldier fly is implied to have contributed to the species spread around countries where insect farming facilities are operating. The species' known distribution and impacts on human welfare and the environment are summarized.

Key words: alien species, biological invasions, citizen science, first record, updated distribution, Western Palearctic.

Introduction

The number of "alien" (i.e. exotic or non-native) species across the globe has been steeply climbing for the past centuries and is yet to show any signs of saturation (Seebens *et al.*, 2017). In Europe, the number of exotic terrestrial invertebrates has been growing exponentially since the 15th century and particularly since the second half of the 20th century (Roques *et al.*, 2009). This unprecedented rise in species translocations has been amplified by globalization and the continuously expanding international trade (Hulme, 2009). A significant proportion of alien species tends to become invasive (IAS) that is, according to EU Regulation 1143/2014, species that threaten native biodiversity and related ecosystem services. Invasive species have been deemed as one of the main causes of biodiversity loss around the globe, forcing governments to implement ambitious biodiversity strategies aiming towards their rapid identification, control and eradication (UNEP/CBD/COP/6/20; EU Reg. 1143/2014). IAS have also been associated with human health risks (Schindler *et al.*, 2015; Peyton *et al.*, 2020) and adverse socioeconomic impacts (Kettunen *et al.*, 2009; Manachini, 2017).

Early detection and monitoring of IAS has been acknowledged as a crucial step towards effective management strategies (Simberloff *et al.*, 2013). Recent technological advancements (e.g. in photographical equipment, smartphones and public data storage software) alongside the global surge in social media platforms usage have facilitated public participation in scientific research, providing vast datasets on non-native species biology and impacts (Miller-Rushing *et al.*, 2012; August *et al.*, 2015). Citizen scientists have proved to be a valuable source of information assisting surveillance efforts and supplementing data on the occurrence and distribution of alien species, mainly throughout the provision of photographic occurrence records (Chandler *et al.*, 2017; Johnson *et al.*, 2020). Citizen-science data have demonstrated the presence of numerous alien insects in the Western Palearctic, both widespread (e.g. feather-legged fly *Trichopoda pictipennis* Bigot; Kazilas *et al.*, 2020; Dios *et al.*, 2021) and taxa previously unnoticed by the scientific community (e.g. *Erthesina* sp.; Lupoli *et al.*, 2020; 2021). Regarding alien flies, the black soldier fly *Hermetia illucens* (L.) (Diptera Stratiomyidae) stands out due to its large size and distinctive morphology, enhancing detection possibilities and easy identification. Thus, public engagement in scientific research can be harnessed towards its detection and distribution mapping.

The black soldier fly has received a great deal of attention due to both its beneficial and negative effects on human well-being and the environment. At the larval stage, it is considered as an efficient bioconverter because of its well-known property of reducing organic matter (Gao *et al.*, 2019). In combination with its worldwide distribution, it has been utilized to establish a sustainable organic-waste management system on a global scale. In addition, significant interest has been shown in protein production, in order to keep up with the global protein consumption needs (Li *et al.*, 2011; Müller *et al.*, 2017; Gao *et al.*, 2019). However, the species has been also linked to health-related issues, such as cases of myiasis in humans and domestic animals (Adler and Brancato, 1995; Yang, 2014; Mulieri *et al.*, 2019). Furman *et al.* (1959) argued that in manure where multiple larvae of *H. illucens* were abundant, *Musca domestica* (L.) flies were scarce. Thus, the black soldier fly could act as a biological control measurement against the common house fly, not via active predation, but rather via interspecific competition for the available food sources; an act that was commented as "trading one pest for another" (Furman *et al.*, 1959). However, adverse impacts on other saprophagous invertebrates (e.g. beetles, flies, millipedes, woodlice) or soil community structures have yet to be addressed.

H. illucens is a polysaprophagous cosmopolitan species presumably of Nearctic origin (Ståhls *et al.*, 2020), presently distributed in the majority of the warmer parts of the world (Marshall *et al.*, 2015). In the Western Palearctic, the species has been first reported from Malta in 1926 (Lindner, 1936), followed by Spain (Peris, 1962), the Canary Islands (Báez, 1975), France (Chevin, 1986), Albania (Beschovski and Mannasieva, 1996), Croatia (Beschovski and Mannasieva, 1996), Portugal (Carles-Tolrá, 2001), Switzerland (Üstüner *et al.*, 2003), Turkey (Üstüner *et al.*, 2003), Germany (Ssymank and Doczkal, 2010), Slovenia (de Groot and Veenvliet, 2011), Czechia (Roháček and Hora, 2013), Italy (Mason, 2013), Montenegro (Roháček and Hora, 2013), Greece (Tsagkarakis *et al.*, 2015), Morocco (Maquart P. O. personal communication), Sweden (Jonsell, 2017), Russia (Gladun, 2019), the Netherlands (Smit *et al.*, 2019) and Algeria (Koutsoukos and Kazilas, 2021). Oddly, a larval specimen found in the sarcophagus of Duchess Isabella d'Aragona (1470-1524 CE) in Naples (Italy) was identified as *H. illucens* and raised a hypothesis of an earlier introduction to Europe four centuries before its first published record from the continent (Benelli *et al.*, 2014).

In this article, specimens deposited in private and institutional collections along with citizen-science observations present the first records of *H. illucens* for Austria, Belgium, Cyprus, Israel, Lebanon and the United Kingdom, supplementing our knowledge regarding the distribution of the species in the Western Palearctic (figure 1).

Materials and methods

Material examined

The presented material derives from the Steinhardt Museum of Natural History, Tel Aviv University, Israel (SMNHTAU), the Museum of Zoology of the National and Kapodistrian University of Athens, Greece (ZMUA) as well as the private entomological collections of Christodoulos Makris (CM) and Jakovos Demetriou (JD) from Cyprus as well as David Ignace (DI) from Belgium. Specimens deposited in institutional or private collections were identified by M. Mostovski (SMNHTAU), J. Demetriou and E. Koutsoukos (JD, ZMUA), Ch. Makris (CM) and D. Ignace (DI), according to the following distinct morphological features. Head, thorax and abdomen black. Eyes predominantly dark brown with white stripes medially and near eye margins. Antennae dark brown/black, two times the size of the head with 8-segmented antennal flagellums. Legs mostly black except from white basal half of hind tibia and tarsus. Abdominal segments 1 and 2 dorsally with a pair of translucent white spots while ventrally only abdominal tergite 1 translucent. Abdominal segment 5 sometimes reddish-brown. Length: 10-17 mm (Rozkošný, 1983; Oliveira *et al.*, 2016; Roy *et al.*, 2018; Duzell, 2019; Lessard *et al.*, 2019).

Observational records of *H. illucens* derived from the online citizen-science platform of iNaturalist (iNaturalist, 2021) were promptly assessed and identified as *H. illucens* due to the species' distinct morphology. In addition, the notion that the species constitutes the sole representative of the Hermetiinae in the Western Palearctic (Rozkošný, 1983; Rozkošný and Nartshuk, 1988) has been molecularly assessed and confirmed (Ståhls *et al.*, 2020). Nevertheless, photographic material of insufficient quality was excluded to retain high taxonomic accuracy.

Results and discussion

Specimens and citizen-science observations from Austria, Belgium, Cyprus, Israel, Lebanon and the United Kingdom constitute the first evidence for the presence of *H. illucens* in these countries (supplemental material table S1). The presented material suggests that the species has formed established populations in most of the aforementioned countries, as individuals have been collected during a period of at least two consecutive years. Although, merely a single observation is presented from Lebanon, evidence of further spread of *H. illucens* was identified through the examination of poor quality photographic records on iNaturalist, which were excluded in the present study. This does not come as a surprise since the species has already been recorded from neighbouring countries with similar climatological conditions e.g. Cyprus and Israel. Benelli *et al*. (2014) speculated that European populations of *H. illucens* may either be native to the Palearctic region or belong to a cryptic species closely related to *H. illucens*. In addition, the head structures of the specimen from the sarcophagus of Duchess Isabella d'Aragona (Benelli *et al*., 2014) differ noticeably from confirmed *H. illucens* (Bruno *et al*., 2020). Nevertheless, according to Ståhls *et al*. (2020) all presumed *H. illucens* records belong to a single species with strong evidence of its introduction in the Western Palearctic and the Afrotropics. This validation allows the swift identification of photographic records as *H. illucens*, allowing efficient and accurate monitoring of the species even from citizen-science observations.

In Europe, *H. illucens* has been released in nature as a biological agent against the house fly in stables and farms and compost movement has been suggested as its main introduction and movement pathway (Skuhravá *et al.*, 2010). Records of the species from South-eastern Europe and the Middle East (i.e. Cyprus, Lebanon and Israel) may reflect on recent introduction events. This notion is

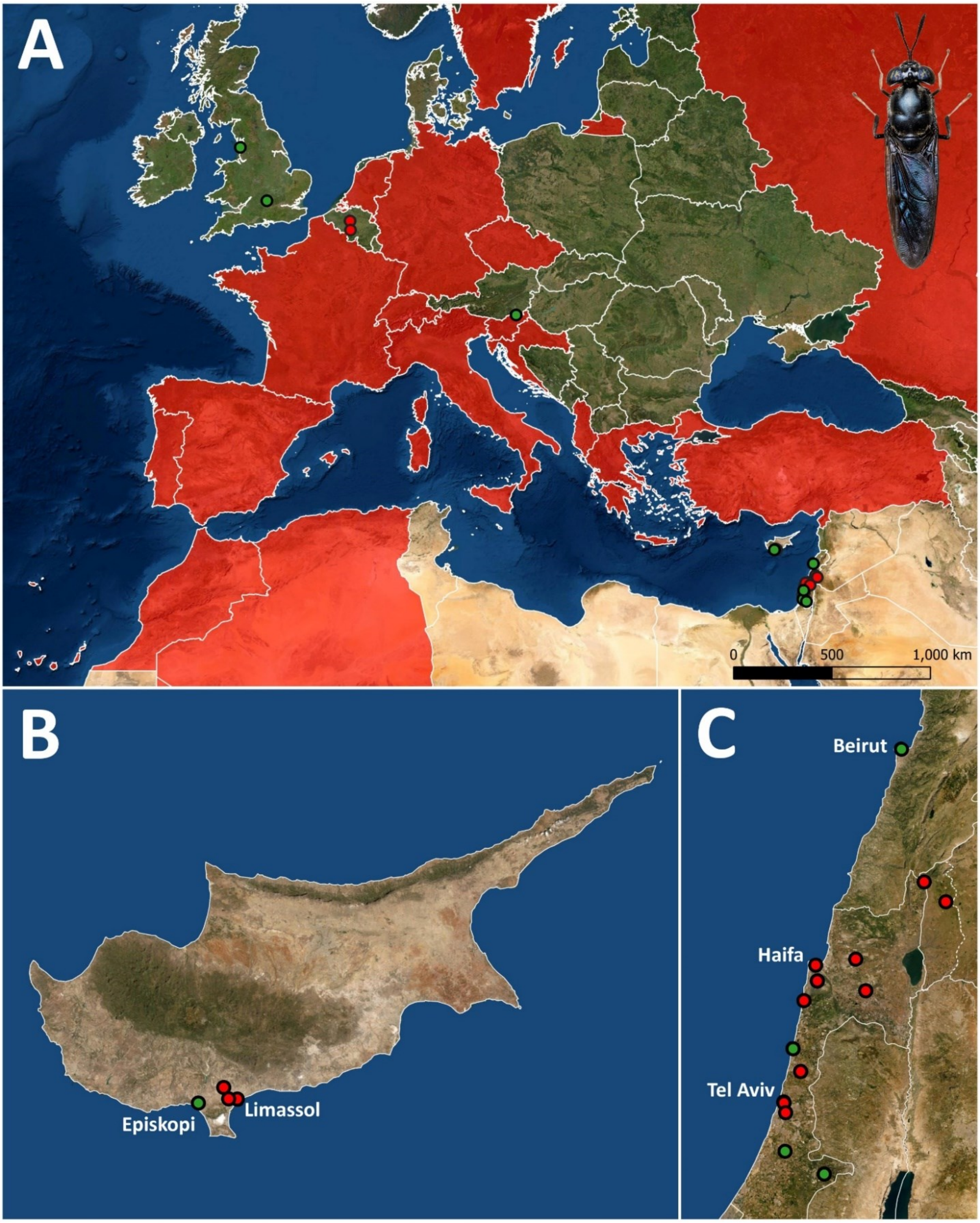

Figure 1. Distribution of *H. illucens* in the Western Palearctic (**A**). Shaded in red are countries where *H. illucens* has already been reported from. Red and green dots indicate new records of the species by collected specimens and citizen-science data, respectively. Inset: Adult of *H. illucens* from Mt. Pelion, Greece. Enlarged view of the new records in Cyprus (**B**), Israel and Lebanon (**C**), where major urban areas are indicated.

supported by previous extensive work on the Stratiomyidae of Israel failing to detect the species in the country (Lindner and Friedberg, 1978; Üstüner *et al.*, 2003) but also the fact that the species' distribution in Cyprus seems to be restricted in Limassol, where the county's largest commercial port is situated. The black soldier fly may have reached Austria, Belgium and United Kingdom from already invaded neighbouring countries (figure 1). Insect farming in sustainable protein and waste management industries may also have contributed to the black soldier fly's spread, especially in Northern Africa (Algeria; Mr Allal Andaloussi personal communication), Central Europe and the United Kingdom where companies producing animal feed based on protein extracted from the black soldier fly are operating (EIP-AGRI, 2020).

According to our results, the black soldier fly has the potential to spread into all countries bordering the Mediterranean basin, as well as Central European countries and the Balkans. It is also likely that *H. illucens* has already invaded these areas but is yet to be noticed or identified. Any potential negative impacts of *H. illucens* on native biodiversity should be investigated and taken into consideration during future practices of intentional release for biological control or organic matter bioconversion. Our results highlight the contribution of citizen scientists in detecting new records of alien species, as well as the value of their observations in mapping the current and projected distribution of alien species, especially when the species in question can be accurately and easily identified from photographic material. In addition, the potential of citizen science in identifying species-interactions between *H. illucens* and native species could be incorporated in future citizen-science initiatives (Groom *et al.*, 2021). The riddle of the peculiar phylogeography of the black soldier fly in the Western Palearctic is undoubtedly in need of a thorough phylogenetic analysis (Ståhls *et al.*, 2020). At the same time, towards a better understanding of the presence of the species in both invaded and yet to be recorded countries of the Western Palearctic, extensive field monitoring with the assistance of citizen scientists could shed a light on the species' true extent of distribution.

Conclusions

For the past century, the black soldier fly has been spreading through the Western Palearctic, currently present in 25 countries of Europe and neighbouring regions. The species is expected to be found throughout the Western Palearctic, with its spread being mediated by human activities, such as international commerce and insect farming industries. Future studies should focus on molecular and genetic analyses of *H. illucens* populations as well as their genetic similarity to industrially used strains, thus shedding light to its invasion history as well as pathways of introduction and spread.

Despite its well-known beneficial role in waste management and agriculture, no studies have been conducted to study the adverse impacts of *H. illucens* on native biodiversity and detritivorous soil communities. In order to address these possible effects both laboratory experiments as well as field studies are required.

Lastly, citizen science can be efficiently used as an early warning system towards detecting the introduction and spread of *H. illucens*, a large, morphologically distinct and synanthropic species. In future studies, schemes of public participation in the scientific research of *H. illucens* could possibly incorporate citizen-science data identifying species interactions (e.g. predators or parasitoids) or preferred food sources and microhabitats of larvae and adults in natural habitats.

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