SAPIENZA
UNIVERSITÀ EDITRICE

E-ISSN 2284-4880
ISSN 0429-288X

Fragmenta entomologica, 57 (2): 213–218 (2025)

Research article
Submitted: August 9th, 2025 – *Accepted*: October 10th, 2025 – *Published*: October 31st, 2025
Doi: 10.13133/2284-4880/1834

From rearing to spreading: ecological constraints and distribution patterns of *Carausius morosus* (Sinéty, 1901) (Phasmatodea: Lonchodidae)

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Abstract
Based on available data on the occurrence of *Carausius morosus* (Sinéty, 1901) and its subsequent graphical processing into map outputs, it was possible to identify basic ecological requirements responsible for its spread beyond its original Indian range. Despite considerable adaptability, certain factors significantly limit the spread of the stick insect in several regions and currently represent insurmountable barriers to its further advance. The species shows a clear link to warm, humid areas with subtropical and tropical climates, providing a framework for understanding its possible future dispersal.

Key words: stick insect, adaptability, species distribution, invasive potential, map outputs.

Introduction

Carausius morosus (Sinéty, 1901) is a species of stick insect native to southern India (commonly known as the Indian stick insect), with a long-standing history of captive breeding. It was introduced to British enthusiasts during the colonial period, when India was under British rule (Cooper 2023). Today, despite competition from other, often more attractively colored species in captivity, it is one of the most commonly kept phasmids.

An important factor contributing to this success in captivity is its polyphagous nature. *C. morosus* is capable of feeding on a wide variety of plant families and species. Cassidy (1978) confirms that the species feeds on rose (*Rosa canina*), privet (*Ligustrum vulgare*), bramble *(Rubus fruticosus*), ivy (*Hedera helix*) and lilac (*Syringa vulgaris*). Bragg (1992) lists hawthorn (*Crataegus* spp.) alongside these plants. This has been confirmed by the author's own breeding, and the feeding spectrum was shown to be even wider. Nymphs and adults also readily fed on firethorn (*Pyracantha coccinea*), oak (*Quercus spp.*), hazel (*Corylus avellana*), rhododendron (*Rhododendron ponticum*) and beech (*Fagus sylvatica*). *C. morosus* populations are parthenogenetic, which naturally increases the survival potential of the species both in captivity and in the wild. During breeding in laboratory conditions by Aguiar et al. (2014), a single female laid 339 eggs over a period of under five months. The experiment by Leclercq (1946) further showed that the eggs are able to survive in different environments, with relative humidity ranging from 7% to 100%. Combined with the high hatching rate, which exceeded 80% during breeding, it is clear that the species is very adaptable and demonstrates notable reproductive resilience.

These factors make them an ideal model organism for scientific research (Shelomi 2017, 2019; Liessem et al. 2018). However, it is these characteristics that allow the stick insect to expand beyond its native range and colonize diverse regions and habitats around the world (e.g., southern Europe, Madeira, Azores, South Africa, Madagascar, and California) which, in certain areas, may pose ecological risks.

Methodology

Experimental Rearing
To assess the species' reproductive potential and host plant flexibility relevant to its capacity for geographic spread, breeding of 2 *Carausius morosus* females was carried out. The stick insects were kept in an enclosure measuring 30 x 30 x 45 cm, maintained at a relative humidity of approximately 60% and a temperature range of 20–22°C. The food plant used was bramble (*Rubus fruticosus;* Rosace-

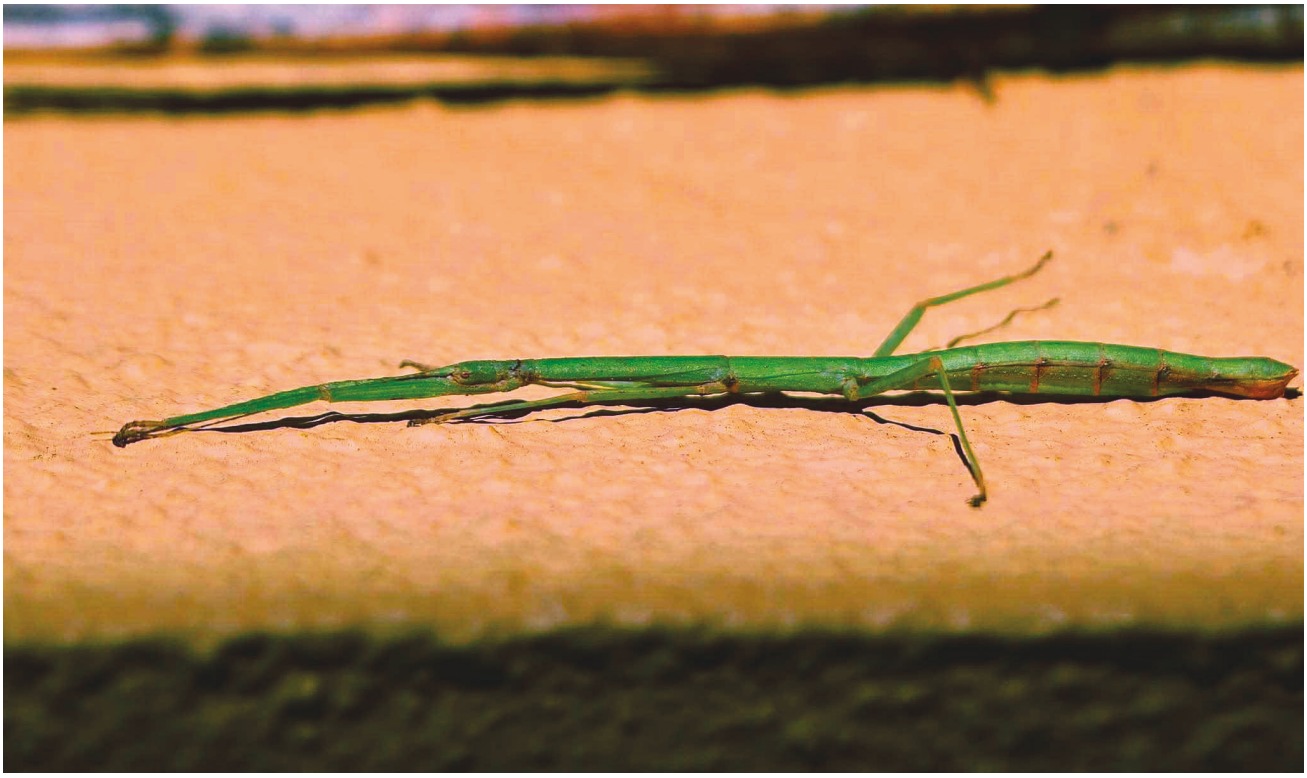

Fig. 1 – Wild specimen of *Carausius morosus*, city of Sintra, Portugal. By Alfonso Almeida.

ae). A total of 60 eggs were collected and incubated on a mesh platform positioned above a water container to maintain humidity. The eggs were misted every other day and the humidity in the room where incubation took place fluctuated between 50 and 60%. The host plants previously reported in the literature as accepted by this species were tested for their suitability on the F1 generation hatched from the collected eggs. The highest number of nymphs hatched between 90 and 120 days. Individuals hatching after 180 days were also observed; such prolonged incubation periods are common and were previously observed among several Phasmatodea species. The hatching rate reached 85% (51 specimens). Newly hatched nymphs were separated into groups, each successfully maintained on a different host plant species, confirming the polyphagous nature of *C. morosus.*

Data Acquisition & Visualization

Datasets for map processing were obtained from the biodiversity databases iNaturalist and GBIF. For iNaturalist, only verifiable observations were included. The following GBIF datasets were used:

Azorean Biodiversity Portal
Biodiversity4all Research-Grade Observations
Observation.org, Nature data from around the World
Observations.be - Non-native species occurrences in Wallonia, Belgium
Waarnemingen.be - Non-native animal occurrences in Flanders and the Brussels Capital Region, Belgium
Validated photographic identifications and observations from the Forum "Le Monde des Insectes" (LMDI).

The data provided verifiable records of specimens' locations, which were essential for the creation of distribution maps. Records from entomological collections or those lacking specific location information were therefore excluded. At the same time, the iNaturalist dataset, listed in GBIF as iNaturalist Research-grade Observations, was not used as it did not contain all verifiable records available on the iNaturalist platform. It was therefore filtered and used separately directly from the website. A total of 2,719 records were utilized. Data from both databases were merged and subsequently imported into the GIS mapping software ArcGIS Online, where all the map outputs used were created.

Results

The studied stick insect is fully meeting the conditions necessary for dispersal beyond its native range, southern India. The species has been repeatedly recorded as introduced in several regions, namely Madagascar, South Africa, Spain, Portugal (including the Azores and Madeira) and California, USA (Headrick & Wilen 2011; Cliquennois 2012; Aguiar et al. 2014; Picker & Griffiths 2017; Beucke 2020; Figs 2-4). The species has become established in

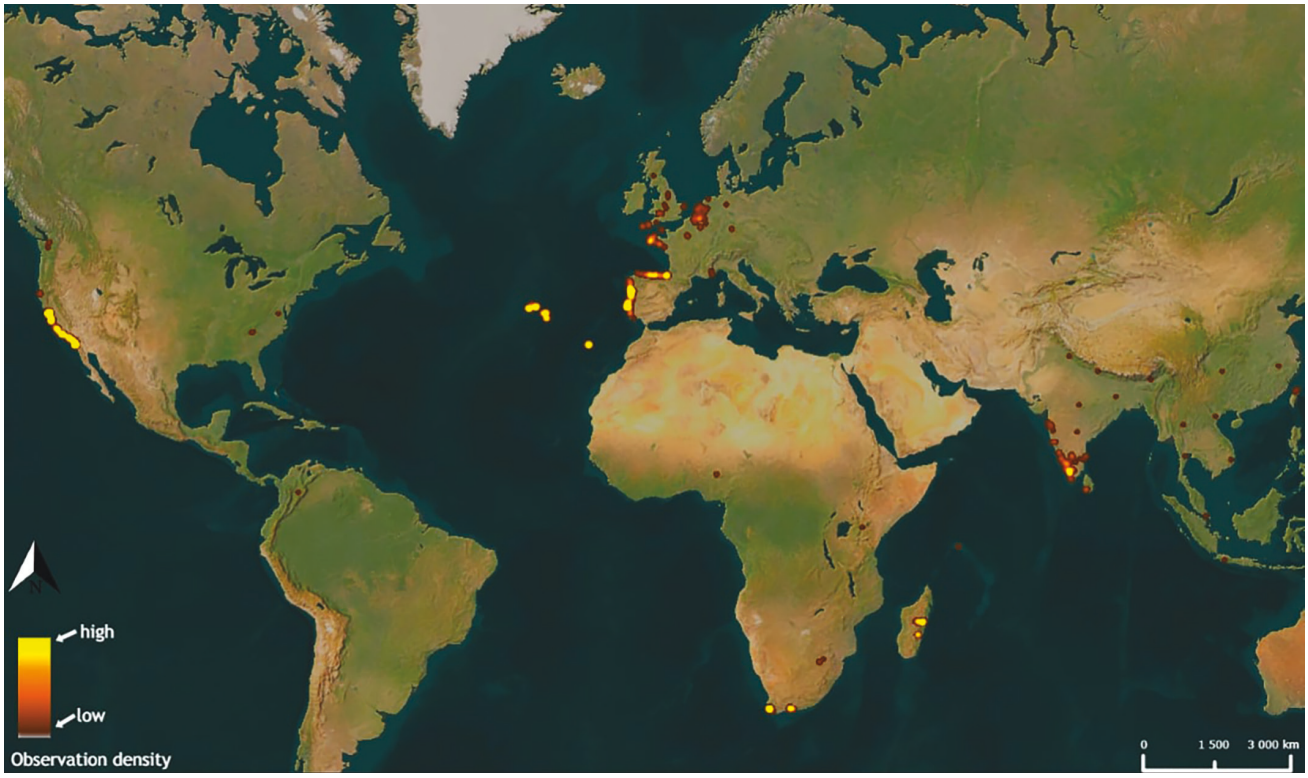

Fig. 2 – World distribution map of *Carausius morosus.* Data sources: GBIF and iNaturalist, visualized ArcGIS Online.

these areas and records indicate its spreading. The status of *C. morosus* is currently under active monitoring in California. According to Beucke (2020), the phasmid was first recorded in the region in 1991 and is now listed as a pest, although no significant damage has been associated with the species so far. Less numerous records (most of them in anthropogenic controlled habitats, and with no evidence of establishment in the wild) within Europe come from Belgium, France, the Netherlands and the United Kingdom (Brock et al. 2018; Lee & Brock 2018; Lee 2024).

The distribution of this stick insect in Europe is highly fragmented. While in the northern parts of its range records are mainly linked to urban regions, in southern mainland Europe the species occurs along the coast. High observation densities are also reported from the Azores and Madeira. On the other hand, it is absent in inland southern Europe, suggesting that the environmental conditions there are unsuitable for this phasmid. The key to understanding the distribution of *C. morosus* in Europe lies in comparing the climate of this region with that of India, its native habitat.

The climate map focusing on rainfall compares 2 areas of interest that are currently strongly associated with the distribution of *C. morosus*. In India, the species is found mainly on the west coast, where precipitation levels are substantial, exceeding 5,000 mm in certain areas. These extreme totals are associated with the regular southwest monsoon (Pattanaik & Rajeevan 2010). Looking at European conditions, it is clear that rainfall totals do not reach such values, and precipitation is distributed more evenly throughout the year. However, *C. morosus* has adapted to these less favorable conditions, and populations tend to cluster in warm subtropical areas where annual rainfall exceeds 1000 mm per year. The map thus shows that the species has a strong association with humid areas, which distinguishes it from native European species of phasmids, that usually inhabit drier environments.

Discussion

The preference of *Carausius morosus* for humid areas is also reflected throughout the areas colonized beyond its native range. In California and South Africa, it is found primarily in areas with higher precipitation. In Madagascar, the species also tends to occur in moist habitats (Cliquennois 2012). Leclercq (1946) reported that nymphs, when under conditions of low humidity, showed a higher mortality after hatching. In some cases, individuals failed to hatch and died with their body trapped in the egg. Humidity is therefore not only a matter of preference, but a critical factor influencing the survival and vitality of introduced populations. This may help explain the stabilization of the species on the Azores and Madeira, regions characterized by high annual precipitation, and at the same time its absence in the nearby Canary Islands, where total rainfall is on average lower. While Aguiar et al. (2014) reported the

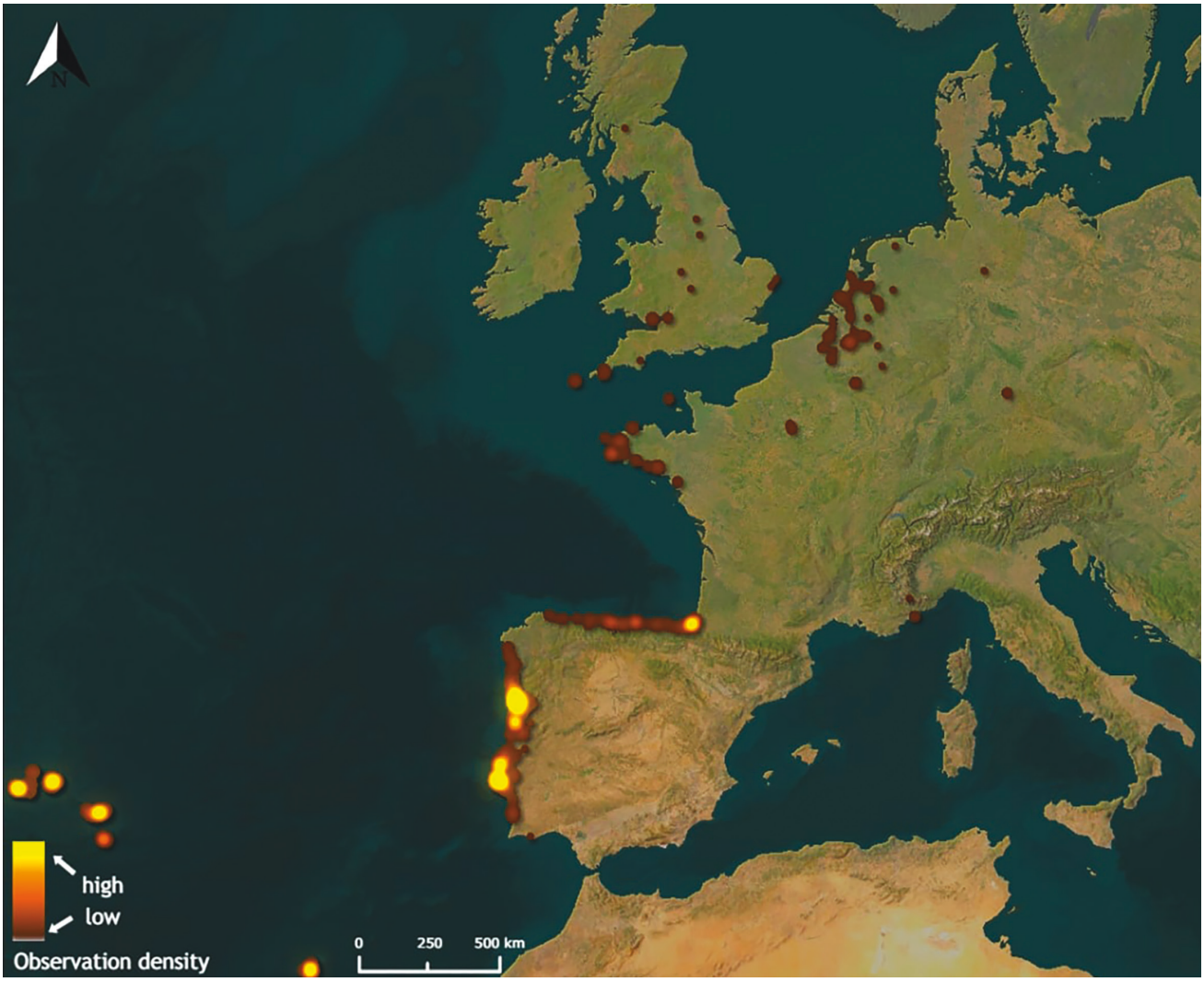

Fig. 3 – Distribution map of *Carausius morosus* in Europe. Data sources: GBIF and iNaturalist, visualized ArcGIS Online.

presence of the species in the southern part of Madeira, recent records indicate that *C. morosus* is already widely observed throughout the whole eastern half of the island, showing the species' invasive potential and capacity for further expansion.

Although the phasmid has been able to establish itself in different regions of the world, the distribution map together with the findings (Fig. 2) reveals three main environmental limitations to its spread:

Tropical arid regions
Subtropical arid regions
Temperate climate regions

While occurrences have been reported in temperate oceanic regions of Europe, these are mainly occasional observations, primarily in urban areas. In Belgium, France and the Netherlands, the winter conditions are too harsh for the species to establish itself, the records likely represent individuals that escaped from captivity and can survive temporarily but are unable to reproduce in there. The question of the species' establishment in the UK, particularly in the Isles of Scilly, has been subject to ongoing discussion. Lee & Brock (2018) argue that the frequency of sightings in the area is insufficient, and, given the semi-tropical nature of the species, naturalization is unlikely. Furthermore, a survey conducted on the Isles of Scilly in September 2021 did not confirm the presence of *Carausius morosus* (Lee 2024). A similar approach can be taken to findings in Brittany, France, where the species appears to be able to survive for several months, but there is no evidence of its reproduction in the wild and thus no indication of stable populations.

Climatic reasons also contribute to the broader distribution of *C. morosus* along the west coast of California. From a regional perspective, this area is relatively humid and maintains higher year-round temperatures than the European sites where the phasmid occurs. These conditions are thus very favorable for the species, resulting in its successful spread to the extent that it is now listed as a pest. Nevertheless, Headrick & Wilen (2011) suggest

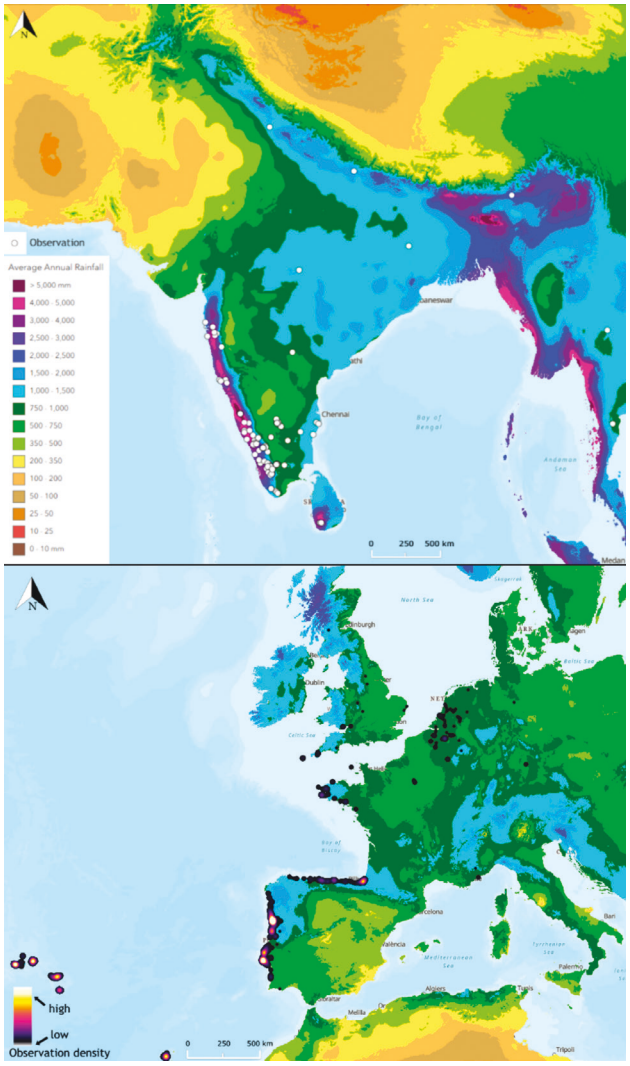

Fig. 4 – Distribution of *Carausius morosus* and average annual rainfall world map. Data sources: GBIF and iNaturalist, visualized in ArcGIS Online.

that it is mainly the eggs that survive the winter period, which may explain the increase in damage in spring when nymphs begin to hatch. Eggs are generally considered to be the most resilient developmental stage of stick insects. A comparison of live records in the iNaturalist and GBIF databases for January and June shows more than twice as many observations in the summer month. A similar pattern is also observed in European records from Portugal. Although the number of individuals seems to decrease in winter, documented records confirm that adults are present throughout the year, enabling continuous reproduction, which promotes the species' ongoing expansion.

With the knowledge gained on climate requirements and high level of adaptability, it is clear that *C. morosus* is well-suited for further spreading into other subtropical and tropical regions of the world. The case of California highlights the potential risks associated with its introduction. On the other hand, the phasmid is unlikely to become a species capable of causing widespread economic damage, partly due to its lack of wings and thus limited mobility, although in certain regions potential ecological risks due to competition with other native stick insect species cannot be excluded. Regular monitoring may contribute to a better understanding of its ability to adapt and naturalize, both in its present range and in regions susceptible to future colonization.

Conclusions

Carausius morosus has proven to be a species with excellent adaptive abilities within the order *Phasmatodea*, thanks to several factors. These include polyphagy, which has been proven also through experimental breeding, parthenogenesis, which greatly facilitates reproduction, and the ability to establish populations even in less favorable conditions, such as those present in subtropical regions. Breeders who either intentionally released individuals or allowed them to escape also contributed to the spread of the phasmid. Records of the species in the temperate zone of Europe demonstrate that it is capable of surviving for extended periods even under harsh climatic conditions. The map outputs provided a comprehensive overview of the ecological preferences and current distribution of this species (Figs 2-4). At the same time, they pointed to the fact that the density of records is increasing, and the case of Madeira illustrated its rapid spread.

On the other hand, several barriers have emerged that limit the expansion of the species. The main ones are areas with low rainfall. These regions are diametrically different from the phasmid's original range in South India, which is characterized by a monsoonal climate, and they negatively affect the viability of populations. Currently, the species is unable to maintain stable populations in regions such as Brittany, southwestern England including Scilly, Belgium, and the Netherlands.

Climate change is a factor that will influence its spread by breaking down existing ecological barriers. As a result, a shift in its distribution range and the establishment of populations can be expected in regions that currently do not allow year-round occurrence due to climatic constraints.

Acknowledgements – I would like to acknowledge Alfonso Almeida (Sintra, Portugal), for providing the photographic material of the *Carausius morosus* specimen observed in the wild.

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