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OVERVIEW AND PRELIMINARY RISK ASSESSMENT OF THE PROCESSIONARY CATERPILLAR *OCHROGASTER LUNIFER* (LEPIDOPTERA: NOTODONTIDAE), A *EUCALYPTUS* PEST FROM AUSTRALIA

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Overview and preliminary risk assessment of the processionary caterpillar Ochrogaster lunifer *(Lepidoptera: Notodontidae), a* Eucalyptus *pest from Australia*

As human population increases, so does the demand for resources from domestic and international suppliers for their quality and/or quantity. Increase in international trade, has exacerbated the introduction of non-native invasive pests causing ecological, societal and economic damage. In order to reduce this outcome, it is crucial to consider all possibilities of potential pests from foreign countries that could establish in Europe. *Eucalyptus* and *Acacia* spp. are used as ornamental plants in Europe, commonly planted in parks, suburban and recreational areas frequented by humans and pets/animals in the Mediterranean region. Here, we explore the potentials of a *Eucalyptus* and *Acacia* pest, *Ochrogaster lunifer* Herrich-Schäffer (Lepidoptera, Notodontidae), a medically important species from Australia, entering and establishing in Europe. In outbreak years, *O. lunifer* larvae completely defoliate host plants but more importantly, it can increase the number of cases of urticaria and allergic reactions in humans and domestic animals because each larva possess millions of urticating setae. The species may enter Europe as eggs, larva, pre-pupa and pupa found on the host plant, in the soil or in packaging material. Establishment and spread of *O. lunifer* will depend on the host plant availability, efforts by inspectors during quarantine checks and phytosanitary measures. *Ochrogaster lunifer* is only found in Australia, but with the severity of various health implications that they cause to humans and animals, and with the frequent introduction of eucalypt pests from that continent, it is necessary to assess risks for the introduction of this species into Europe.

KEY WORDS: Defoliator, medical importance, setae, social Lepidoptera

INTRODUCTION

As human population increases, so does the demand for resources from domestic and international suppliers for their quality and/or quantity. Increase in international trade, has introduced invasive pests causing ecological, societal and economic damage. Plant-insect pest management is economically demanding; however, it becomes more problematic when serious health implications are involved with humans and animals. A species of recent interest is the processionary caterpillar, *Ochrogaster lunifer* Herrich-Schäffer (Lepidoptera, Notodontidae), an urticating species found throughout Australia. The name 'processionary caterpillar' arises from their dispersal behaviour when larvae travel in a single file head-to-tail from the nest to search for a new host plant or a pupation site (FITZGERALD, 2003). Populations of *O. lunifer* are concentrated in coastal and inland habitats where *Acacia* and *Eucalyptus* spp. host plants occur (FLOATER, 1996; Fig. 1). There are other plants which *O. lunifer* feed on but are less recognised as primary host plants, therefore, more confirmation is needed. In outbreak years, *O. lunifer* are known to cause severe damage to plants through complete defoliation (FROGGATT, 1911; VAN SCHAGEN *et al.*, 1992a; Fig. 2). Outbreak years can also increase the number of cases of urticaria and allergic reactions in humans and various medical problems in animals (see *Damage and health impacts of* Ochrogaster lunifer *on humans, animals and plants*).

Medical risks associated with *O. lunifer* is derived from their urticating microscopic hairs called setae, which are found on the abdominal segments of mid to late instars (BATTISTI *et al.*, 2011). From third instar, each larva produces approximately 4000 setae and progressively increases until they reach final instar (VIII) where the number of setae increases up to approximately 2.0-2.5 million (PERKINS *et al.*, 2016). Setae can be easily detached during inadvertent contact with the larva but can also be released and spread throughout the environment by wind (PERKINS *et al.*, 2019). *Ochrogaster lunifer*

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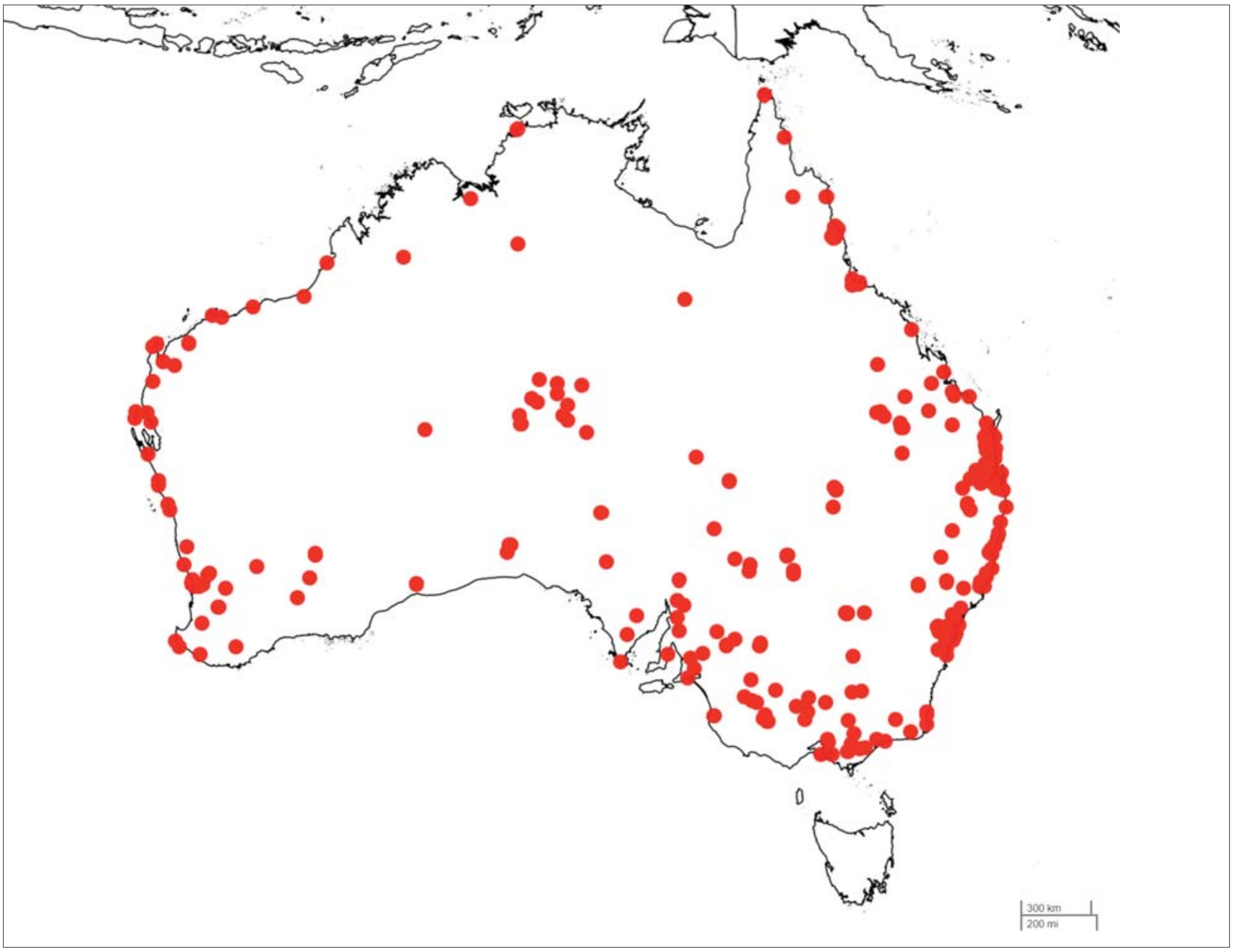

Fig 1 – Occurrence records of *Ochrogaster lunifer* in Australia represented as red dots (Atlas of Living Australia, 2020).

larvae live in a communal nest throughout all instar stages, with some nests easily exceeding a few hundred individuals. Within a nest, at each larval moult, there is an accumulation of exuviae containing millions of setae from each individual (PERKINS *et al*., 2016). When the colony of final instar larvae abandon the nest in search for a pupation site, the structure of the nest deteriorates. As the nest breaks down over time, millions of setae that can remain active for at least a year (BATTISTI *et al*., 2011) are now exposed and dispersed in the environment (PERKINS *et al*., 2016; Fig. 3).

LIFE HISTORY OF *OCHROGASTER LUNIFER*

Ochrogaster lunifer are a univoltine species and remains gregarious from egg to pupa (FLOATER and ZALUCKI, 1999; Fig. 4). Adult moths emerge in Austral spring (October - November), and mated females deposit an egg mass consisting of 150-550 eggs on the host tree (FLOATER and ZALUCKI, 1999). The eggs are covered with material from the female moth's anal tuft, composed of filamentous scales and long urticating setae which are thought to provide protection from natural enemies (FLOATER and ZALUCKI, 1999). Eggs hatch after a month and the neonates remain within the egg mass and do not feed until second instar (FLOATER, 1996). The neonates moult to second instar after approximately 14 days, and leave the egg mass and ascend to the canopy to feed on the foliage during the day (FLOATER, 1996). Later instars feed almost exclusively at night, leaving the nest at approximately sunset every day (FLOATER, 1996). The gregarious larvae continuously spin silk throughout all larval stages to build a communal nest within the tree (FLOATER, 1996). Within the species *O. lunifer*, there are five distinct nesting forms and they differ by phenotypic, genotypic and ecological characteristics (more information in *Nesting forms of* Ochrogaster lunifer). *Ochrogaster lunifer* has eight larval instars, with later instars showing sexual dimorphism with females being larger than males (FLOATER, 1996). As the larvae get older, the nest expands around the original egg batch (FLOATER, 1996). In *O. lunifer* that feeds exclusively on *Corymbia tessellaris* (syn. *Eucalyptus tessellaris*), at third instar, the larvae

Fig. 2 – Completely defoliated *Corymbia tessellaris* by *Ochrogaster lunifer* larvae in Gatton, Australia. Image taken by Mizuki Uemura.

Fig. 3 – Deteriorating abandoned *Ochrogaster lunifer* nest tangled on a branch of *Corymbia tessellaris* and blown by the wind, in Gatton, Australia. Image taken by Andrea Battisti.

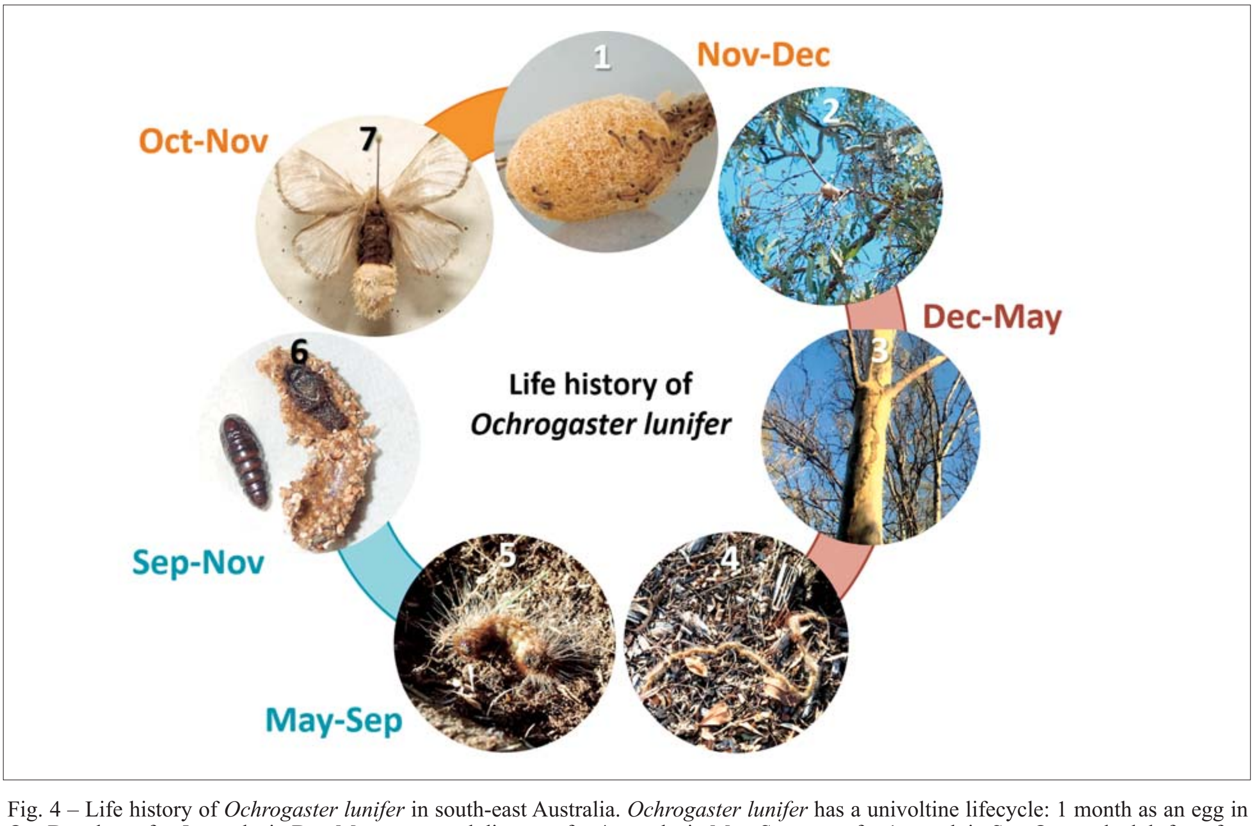

Fig. 4 – Life history of *Ochrogaster lunifer* in south-east Australia. *Ochrogaster lunifer* has a univoltine lifecycle: 1 month as an egg in Oct-Dec, larva for 5 months in Dec-May, pre-pupal diapause for 4 months in May-Sep, pupa for 1 month in Sep-Oct, and adult for a few days in Oct-Nov. Going clockwise from the image in the top middle: **1)** a golden above ground nest *O. lunifer* egg mass with L2 larvae, **2)** above ground nest egg mass in the canopy of a eucalypt, **3)** procession of late instar larvae on a eucalypt, **4)** pre-pupation procession of last instar (VIII) larvae leaving the host tree to search for a pupation site, **5)** uncovered pre-pupa in diapause, **6)** cocoon, pupa and larval exuvia of a male *O. lunifer*, **7)** *O. lunifer* female. Images 1 and 6 taken by Lynda Perkins, and images 2-5 and 7 taken by Mizuki Uemura.

move to the trunk and build a nest on the surface of the tree at approximately mid height (M. Uemura, pers. obs. 2017). If there is more than one egg mass on a host tree, different colonies may gather in one nest consisting of a few hundred individuals (Floater, 1996). In May, when final instar *O. lunifer* larvae are fully fed, the colony leaves the nest in a procession to find a pupation site underground (Floater, 1996). Processions may spend several days to find a suitable site, creating temporary 'bivouacs' during their journey (Uemura *et al.*, 2020). When the colony finds a suitable pupation site, the larvae burrow together to a depth approximately 10-20 cm from the surface (M. Uemura, pers. obs. 2017) and goes into diapause for approximately three months as a pre-pupa (Floater and Zalucki, 1999). In September, pre-pupa spins a cocoon that is embedded with larval setae and emerges as an adult in October-November (Floater, 1996). Moths have reduced mouthparts and do not feed during the few days they are alive (Floater, 1996). Mated females find a suitable host tree by 'sampling' the leaves and branches of a tree, which may take a few attempts to find the right one (Floater, 1996).

Larval numbers decreased as *O. lunifer* development progressed, due to natural enemies such as predators and parasitoids and from other natural causes (van Schagen *et al.*, 1992b). There are various invertebrate predators and parasitoids that prey on *O. lunifer* at different life stages. Highest mortality occurred during the egg and first instar stages by dermestid larvae (Coleoptera: Dermestidae) predation (Floater, 1996). Two species of dermestid larvae present in *O. lunifer* egg masses were *Dermestes ater* De Geer and *Trogoderma apicipenne* Reitter however, the prevalence of dermestid predation was variable (Floater, 1996). Other predators recorded feeding on *O. lunifer* are predatory pyrrhocorid bug, *Dindymus circumcinctus* Stål (Hemiptera: Pyrrhocoridae) (Floater, 1996), predatory moth, *Titanoceros* sp. (Lepidoptera: Pyralidae) and spiders (van Schagen *et al.*, 1992b). Egg parasitism by chalcid wasps *Anastatus fuligispina* Girault (Hymenoptera: Chalcidoidea) was a common occurrence with 95% of egg masses parasitised in Gatton, Australia (Uemura *et al.*, 2019). However, this is possibly due to a concentration effect of the local *A. fuligispina* population in Gatton, since Floater (1996) found low prevalence of *A. fuligispina* in 1.2 - 3.6 % of egg masses surveyed (Uemura *et al.*, 2019). An important mortality in *O. lunifer*, is larval parasitism by *Carcelimyia dispar* Macquart (Diptera: Tachinidae) and less commonly by sarcophagid flies (Diptera: Sarcophagidae) (Floater, 1996). In the case of *C. dispar*, mated female flies deposit one or several eggs on the head capsule of *O. lunifer* larvae (Floater, 1996). As for vertebrate predators, adult moths were recorded to be predated by pied butcher bird *Craticus nigrogularis* Gould (Passeriformes: Artamidae) (van Schagen *et al.*, 1992b) and noisy miner bird *Manorina melanocephala* Latham (Passeriformes: Meliphagidae) (M. Uemura, pers. obs. 2018). Vertebrate predators of larval *O. lunifer* are likely to be less abundant because of the inflammatory reaction to the short urticating setae, which are considered a defence mechanism against mammalian and avian predators (Battisti *et al.*, 2011). However, in addition to setae, the volatile chemicals present on the body of *O. lunifer* larva deterred predatory ants from attacking (Uemura *et al.*, 2017). Therefore, the combination of setae and volatile chemicals produced by *O. lunifer* larvae may deem unpalatable to vertebrate predators (Perkins *et al.*, 2019).

Nesting forms of *Ochrogaster lunifer*

Ochrogaster lunifer have five different nesting forms: canopy, trunk, tree-hugger, hanging and ground nests (Perkins *et al.*, 2016; Fig. 5). The variation of nesting forms found within *O. lunifer* depend on the location of oviposition site, morphology and ecology of the species (Mather *et al.*, 2019). Female moths from all nesting forms except for the ground nest, oviposits in the canopy of the host tree. Females from ground nests oviposit on the base of the host tree trunk (Floater, 1996), whereas the canopy nest females oviposit on the branches and twigs of the host tree. Additionally, the white colouration of the egg mass is found only in ground nests, which differs from other nesting forms which are golden (Floater, 1996; Fig. 6). The egg mass colouration is derived from the colour of the anal tuft scales present on the female moth. Correspondingly, the morphology of adult moths of both sexes differ between the nesting forms (Fig. 7). Size and colour of larvae appear to differ between above ground and ground nest forms (Mills, 1951). Colouration of the silk produced by the larvae to build the nest is white in ground nests and yellow to golden in above ground nests (M. Uemura, pers. obs. 2017). Nesting forms found both on the ground and above ground feed on various *Acacia* spp., however, *O. lunifer* nests above ground feed on eucalypts (*Eucalyptus* and *Corymbia*) (Floater, 1996). Numerous scientists have raised the question if *O. lunifer* is a cryptic species. Mather *et al.* (2019) have identified at

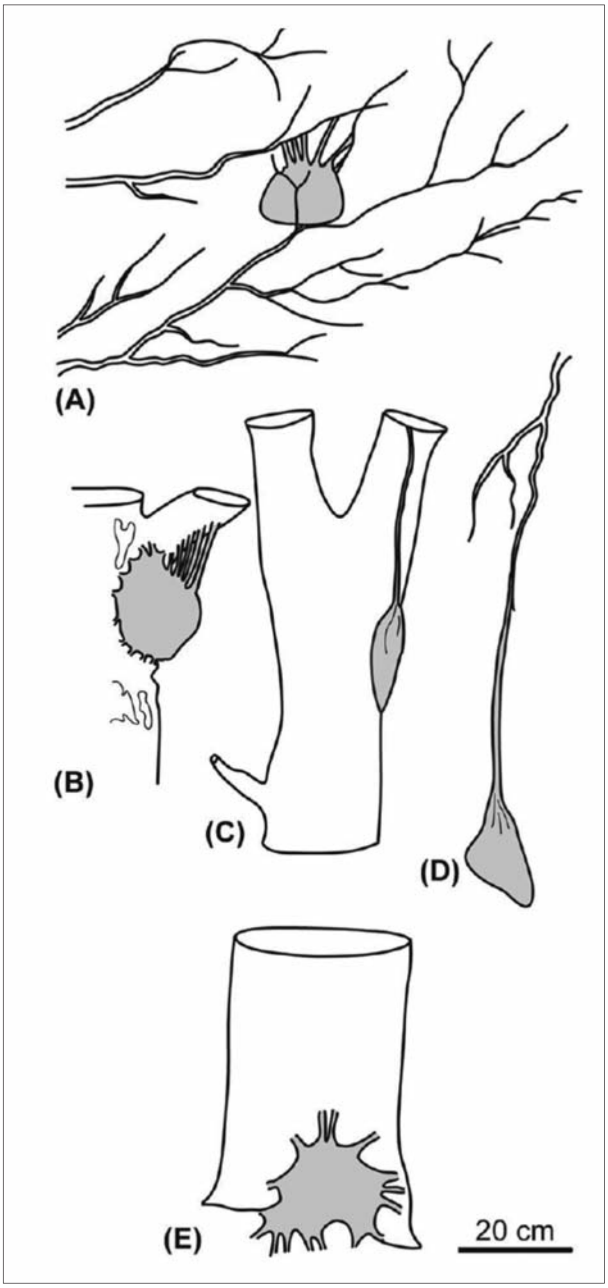

Fig. 5 – Schematic diagrams of the five nest types built by *Ochrogaster lunifer* larvae in Australia. (A) Canopy nest. (B) Trunk nest. (C) Tree-hugger nest. (D) Hanging nest. (E) Ground nest. (PERKINS *et al*., 2016).

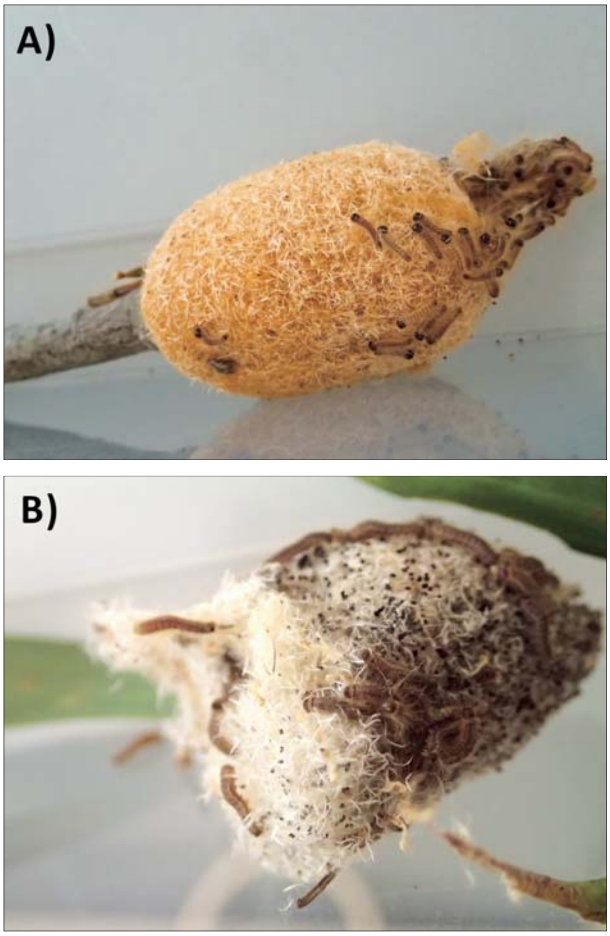

Fig. 6 – **A)** Golden above-ground nest and **B)** white ground nest *Ochrogaster lunifer* egg mass with second instar larvae crawling on the surface. Images taken by Lynda Perkins.

least two reproductively isolated species within the current concept of *O. lunifer* and is under further taxonomic review.

DAMAGE AND HEALTH IMPACTS OF *OCHROGASTER LUNIFER* ON HUMANS, ANIMALS AND PLANTS

Recently, more research efforts on *O. lunifer* arose after their role in equine amnionitis foetal loss (EAFL), a medical condition in pregnant mares which can result in miscarriage after accidental setae ingestion (CAWDELL-SMITH *et al*., 2012). What follows is based on the setae of the larvae, whereas those produced by the female moth to protect the eggs are still to be studied in detail. Urticating setae are used as a defence against natural enemies, and this defence is enhanced by living gregariously as seen in this species. Setae contain proteins which the mammalian immune system recognizes as foreign, which then results in inflammatory or immunological defence reactions of varying severities (BATTISTI *et al*., 2011). In Australia, urticaria cases in humans from *O. lunifer* have been reported in literature as early as 1911 (FROGGATT, 1911) (as *Teara contraria*). Humans and animals can be exposed to urticating setae by direct contact with larvae, by wind carrying the setae, and by ingestion of contaminated feed and water (MULLEN, 2009). Direct contact with larvae may occur when humans and animals are near infested host trees but most commonly when the larvae leave the nest permanently to search for a pupation site (PERKINS *et al*., 2016). During a study at the university campus in Australia, there were 22 cases out of 82 *O. lunifer* pre-pupation processions which came into contact

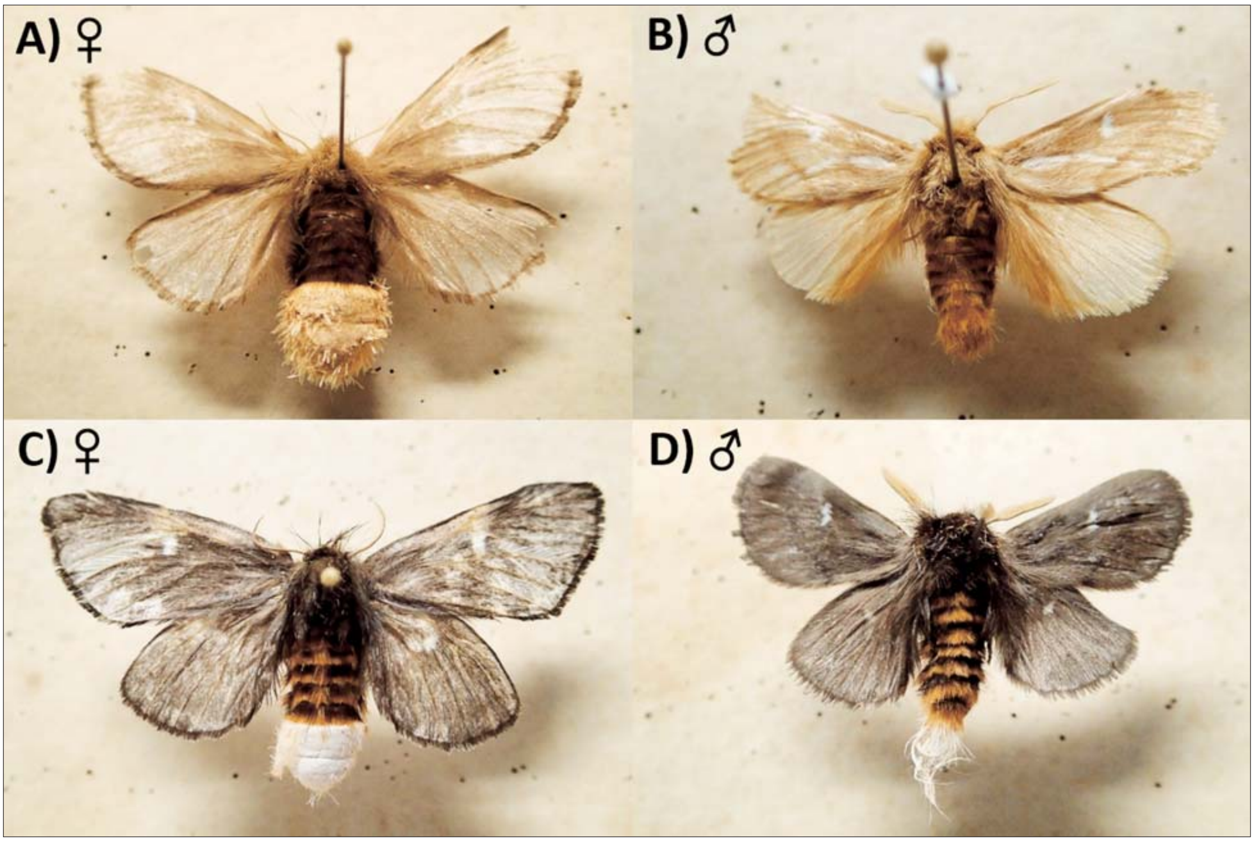

Fig. 7 – *Ochrogaster lunifer* female and male from above ground (A & B) and ground nests (C, D). There are variations of wing pattern and colouration within and between nest types and sex. Images taken by Mizuki Uemura.

with pedestrians or by vehicles (Uemura *et al*., 2020). After contact, the shoes, clothing and/or wheels may be contaminated with setae and brought back to the car, home, classroom, etc. (Uemura *et al*., 2020). Irritation and other reactions may occur even after some time, since the materials in the setae remain active and the microscopic scale of the setae can be undetected (Uemura *et al*., 2020). The health impacts and contamination are exacerbated because of the gregarious behaviour throughout all life stages, especially as larvae. Devastating impacts are not limited to humans and animals, it can also affect the host trees of *O. lunifer*, as larvae defoliate large stands of trees (Floater, 1996) which can then have an ecological and economic impact. Defoliation of trees may impact cattle and other animals which used the trees as shade to protect them from the harsh Australian sun. Complete defoliation of the host occurs most frequently at later instar stages when larvae need to feed more and when the cohort is large from merging of multiple egg masses (M. Uemura, pers. obs. 2017). The cohort of larvae move during the day to find another host and subsequently, people may encounter these processioning larvae.

Preliminary risk assessment of *Ochrogaster lunifer* introduction to Europe

Pest distribution and occurrence

Ochrogaster lunifer occur throughout Australia, with higher density around the coastlines of the country (see Fig. 1). Within the occurrence areas, populations of *O. lunifer* are found in disturbed and non-disturbed environments. These environments include university campus, home and backyard, public parks, national parks, bushlands and roadsides. *Ochrogaster lunifer* are edge species therefore, female moths restrict their oviposition on isolated trees on the outer edges of forests, road verges, etc. (van Schagen *et al*., 1992a; Floater and Zalucki, 2000). The species is only found in Australia where it is not regulated.

Entry, establishment and spread in Europe

Ochrogaster lunifer may enter Europe through cargo ships and flight vessels for international trade and tourism. The species may enter as eggs, larva, pupa or pre-pupal larva found on the host plant, in the soil or in packaging. Adults are unlikely to survive because of the short life span of a few days (Floater, 1996). Eggs of *O. lunifer* may be undetected in the canopy or the trunk of the host plant being shipped for planting. Eggs and neonates can survive without feeding/care for one and a half months, until the larvae moult to second instar which they can feed on the host foliage. Tree-hugger nest for example, are well camouflaged on the trunk of the tree therefore, the larvae living inside the nest may go unnoticed. Pupa and pre-pupal larva may be found within bare root host trees and/or contained in the soil of host plant liners. *Ochrogaster lunifer* processions searching for pupation sites were commonly found entering in human settlement (Uemura *et al*., 2020), including buildings which contained storage for dairy products (M. Uemura, pers. obs. 2019). Larvae are also capable of crawling up vertical surfaces such as walls (M. Uemura, pers. obs., 2018). Therefore, pre-pupal larvae may end up in packaging and commodities during this pre-pupation procession period. From the life stage of pre-pupal larva onwards, *O. lunifer* do not feed and remain in diapause as a pre-pupa for three months, pupa for a month and adult for a few days (Floater, 1996).

After successful entry of *O. lunifer* into Europe, the species may establish where host plants *Acacia*, *Eucalyptus*, *Corymbia* spp. and others occur (see Floater [1996]). There may be a higher possibility of establishment if *O. lunifer* are exposed to host plants that are readily available at harbors and airports. The Mediterranean basin has a similar climate to Australia, which can be favourable for *O. lunifer* development. This species occurs throughout all Australian landscapes therefore, climate may not be a limiting factor except for cold stress. However, normal development of *O. lunifer* may be complicated by day length and opposite seasonality (in northern and southern hemispheres).

Spread of *O. lunifer* will depend on the density and location of where host trees are present. *Eucalyptus* and *Acacia* spp. are used as ornamental plants in Mediterranean Europe, commonly planted in parks, suburban and recreational areas frequented by humans and pets/animals. Therefore, once established, *O. lunifer* could spread in areas with high human population density. This will create a higher risk for humans and animals affected by various medical problems associated with the setae (see *Damage and health impacts of* Ochrogaster lunifer *on humans, animals and plants*).

Availability and limits of mitigation measures

Currently in Australia, there are no mitigation measures for *O. lunifer* populations. Australian farmers and landowners with cattle, horses and other animals have used various methods to reduce/eliminate *O. lunifer* colonies from their own property (land) by: removing host trees, cutting bag nests from trees, burning nests, removing nests and burying it underground, and pouring gasoline and/or burning egg masses (L. Perkins, pers. comm. 2017).

Many eucalypt pests have been introduced to Europe from international trading and *O. lunifer* could also be added to the list. Therefore, strict phytosanitary measures and quarantine checks should be done to mitigate the introduction of *O. lunifer* into Europe. However, with thousands of cargo ships and flights coming into Europe every day, it is unfeasible to check everything with the limited number of staff.

Ochrogaster lunifer is highly social throughout all life stages and the chance of survival decreases with fewer number of larvae. Additionally, *O. lunifer* is not an 'hitch-hiker' and will not be attracted to commodities of food or wood, nor can they disperse far in the environment. Therefore, the possibilities of *O. lunifer* introduction to Europe are limited to host plants shipped from infested places and possibly inside packaging of commodities from where *O. lunifer* nests occur nearby.

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RIASSUNTO

L'aumento degli scambi commerciali va di pari passo con la popolazione umana e comporta una continua esposizione al rischio di introduzione di specie esotiche di parassiti delle piante, che possono talvolta presentare un rischio per la salute dell'uomo e degli animali. La coltivazione di specie esotiche di piante per uso forestale e ornamentale, come gli eucalitti e le acacie nella regione mediterranea, rappresenta un caso tipico di esposizione al rischio di introduzione di specie esotiche. In questo lavoro viene presentato il caso del rischio di introduzione di una specie di lepidottero notodontide, *Ochrogaster lunifer* Herrich-Schäffer, più noto come processionaria dell'eucalitto e dell'acacia, noto per causare danni ingenti agli alberi e alla salute pubblica in Australia. Negli anni di pullulazione le larve defogliano completamente le piante ospiti e inoltre producono, analogamente alle processionarie europee, ingenti numeri di setole urticanti che vengono disperse nell'ambiente e sono causa di rilevanti disturbi a uomini e animali allevati. La specie può essere introdotta in Europa come uovo, larva, prepupa e pupa associati a piante ospiti e relativo substrato di sviluppo, oppure come prepupa e pupa casualmente incluse in spedizioni di vario materiale. L'insediamento dipende dalla presenza di piante ospiti e dall'accuratezza dei controlli eseguiti dalle autorità specifiche. Al momento *Ochrogaster lunifer* è presente solo in Australia dove è causa di ingenti danni e disturbi. L'insediamento in Europa di molte specie di insetti legati all'eucalitto consiglia un'attenta valutazione dei rischi associati a una possibile introduzione.

Parole chiave: defogliatore, importanza medica, setole urticanti, socialità.

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