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The invasive moth *Paysandisia archon* in Europe: Biology and control options

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Abstract

The palm borer moth (*Paysandisia archon*, Burmeister) is a member of the Castniidae family originally from South America, and is currently included on the A2 list of the OEPP/EPPO. This moth was introduced to Europe in 2000 through ornamental palms. Since its accidental introduction, it has become a major threat for natural stands of native palms, as well as for nurseries and gardens in the Mediterranean Basin. To date, neither preventive nor control methods have been implemented for managing this pest under field conditions. In this review, we highlight the most relevant information on the biology of *P. archon* and summarize the available control strategies with a special focus on biocontrol-based treatments.

Keywords: Biocontrol, Castniidae, *Chamaerops humilis*, Integrated pest management (IPM), Invasive species.

1-Introduction

Globalization embodies one of the most important threats for plant protection today. The international movement of plant material, from seeds to soil carrying ornamental mature trees, favor the propagation of organisms that sometimes remain undetected and eventually become problematic for native ecosystems. Forest pests and diseases are not an exception of this global tendency (Liebhold, Brockerhoff, Garrett, Parke, & Britton, 2012). Every year, new pathogens and herbivorous pest species increase the list of invasive taxa, challenging the human capacity to control their associated economic and ecological impacts (Eriksson et al., 2019; Hulme, 2009).

The Mediterranean Basin is particularly susceptible to biological invasions. The climate is characterized by hot, dry summers and cool winters, which together with the diversity of environmental conditions present in Mediterranean ecosystems (e.g., agroforest systems, fruit orchards, mixed forest stands, and the urban interface), provides many options for the invasion of non-native species. Some notable examples include outbreaks of *Xylella fastidiosa* Wells et al. (causal agent of a quick decline syndrome in *Olea europaea* L., among a wide range of plant hosts) vectorized by some xylem-sap feeder insects (Hemipera: Aphrophoridae, Cercopidae, Clastopteridae and Cicadellinae) (Janse & Obradovic, 2010; Morente et al., 2018; Sicard et al., 2018); *Cryphonectria parasitica* (Murrill) M.E. Barr, an ascomycete fungus that causes chestnut blight (Robin & Heiniger, 2001); the pine wood nematode (*Bursaphelenchus xylophilus* [Steiner & Buhrer] Nickle), the causal agent of the devastating pine wilt disease (Vicente, Espada, Vieira, & Mota, 2012); and the Asian gall wasp (*Dryocosmus kuriphilus* Yasumatsu), which strongly reduces the yield of chestnut orchards (EFSA Panel on Plant Health, 2010).

The palm borer moth (PBM) *Paysandisia archon* Burmeister (Lepidoptera; Castniidae), is an example of the accidental introduction of a forest pest caused by international trading of plant material. This species was first detected in Europe in 2000, and is currently included in the A2 list of taxa recommended for regulation as quarantine pests of the European and Mediterranean Plant Protection Organization (OEPP/EPPO, 2019). To date, it has been recorded in more than 10 European countries, and causes severe damage to both ornamental palm species and *Chamaerops humilis* L. The latter is the only palm species native to continental Europe, and its populations are legally protected in several regions of Spain and Italy (EFSA Panel on Plant Health, 2014). Although this invasive moth poses an important threat to palm nurseries and native shrub communities, several aspects of its ecology remain unknown. Consequently, the goals of this review are: (i) to summarize knowledge of this invasive species (i.e. biology, distribution, and host range) that should be considered in the development of management measures, and (ii) to evaluate the control strategies that have been tested to date to manage this invasive pest.

2-An overview of P. archon's biology

2.1. Lifecycle

Paysandisia archon is a Neotropical phytophagous lepidopteran species, whose lifecycle is strongly linked to its plant hosts, which belong to the Arecaceae family. In fact, this insect spends most of its larval states inside the stem (stipe) of the host plant, feeding on fresh tissues. Usually, it completes an annual cycle, although larvae that hatch from eggs deposited at the end of the laying period (autumn) may exhibit a biannual cycle. Sarto i Monteys & Aguilar (2005) summarized both cycles as follows:

the annual cycle starts with adult flight and corresponding oviposition from the middle of May to September, although Closa et al. (2017) observed imagines up to November in the Balearic Islands (Spain). Larvae with an annual cycle are active from June onwards, and begin the pupation period in mid-March. In the biannual cycle, larvae hatched in autumn (September onwards) spend at least 18 months inside the host, with cocoon formation beginning in March.

2.2. Larval development and host infestation

PBM passes through nine larval instars, reaching 90 mm in length during the final instar. Larvae are the only stage that causes plant damage, since no feeding activity has been reported in adults. The first larval instar has an extremely short exophagous state following hatching (up to 3 min). Then, larvae penetrate into the crown of the palm where they start feeding on young leaves. This stage induces the characteristic double hole-shaped damage, which is visible when the leaves unfold; however, larvae can also feed on fruits and rachises (Montagud, 2004). Larvae consume the apical meristem and excavate galleries that usually go through the complete stem of the host (average length around 80 cm in *Trachycarpus fortunei* [Hook.] H. Wendl. as reported by Sarto i Monteys & Aguilar, 2005). This feeding habit severely damages the host, leading to growth reduction, browning and death of the leaves and offshoots, deformation and twisting of stipes, detritus accumulation, and oozing of liquid in the stipe, galleries in the stem, and, if the level of infestation is high, palm death (EFSA Panel on Plant Health, 2014; Kontodimas et al., 2017). In addition, galleries dug by larvae promote host weakness and also facilitate the access of secondary pathogens (Frigimelica, Pozzebon, Duso, & Pellizzari, 2012), which will eventually kill the palm.

Complete larval development lasts 10.5–18.5 months (annual/biannual cycle, respectively). Individuals of the 9th instar (sometimes 7th or 8th) stop feeding and spend a variable period (from a few days to several weeks) preparing a cocoon using palm fibers. Pupation takes 35–68 days depending on the larvae growth history. After metamorphosis, the remaining exuviates are usually visible in the bases of leaves (Sarto i Monteys, 2013; Sarto i Monteys & Aguilar, 2005).

2.3. Reproductive flights and oviposition

The adults are diurnal and fly during maximal insolation hours (from 11.00 to 17.00 h). The moth avoids temperatures below 22 °C (flying temperatures are 22–40 °C for males and 25–30 °C for females) and relative humidity must be below 32% (Liégeois, Tixier, & Beaudoin-Ollivier, 2016). Most of the adults reach sexual maturity 3 h after emergence, with the females being mostly monogamous (Delle-Vedove, Beaudoin-Ollivier, Hossaert-Mckey, & Frérot, 2012). Liégeois et al. (2016) used telemetry to analyse the dispersal patterns of adults in France. They analysed flight patterns between 10.00 and 18.00 h in virgin imagines and found that females fly longer distances than males (16.8–>500 and 11.6–224 m, respectively). These results supported the idea of "territorial" behaviour by males, also noted by Quero, Monteys, Rosell, Puigmartí, & Guerrero (2017) (see below).

Gravid females usually select a palm crown for oviposition (1–10 eggs per oviposition event) (Hamidi & Frérot, 2016). The oviposition period extends from the day of mating to 4 days after mating (Delle-Vedove et al., 2012) and egg laying usually occurs between 11:00–17:00 h in Mediterranean environments (Hamidi & Frérot, 2016). The eggs are rice-shaped, white-pink and around 4 mm in length. They lack any substance that allows them to remain fixed to the surface of crown tissues or to the basal lignified layer of petioles (covered by plant fibers, in some host species) and are usually deposited close to each other. The incubation period extends for 12–21 days until larvae emerge and start feeding (Sarto i Monteys & Aguilar, 2005).

2.4. Sexual communication

To date, sexual pheromones have not been described in this species. Consequently, mate selection is thought to be mediated by visual and short-distance chemical cues. Females fly to attract the attention of males, which usually perch on shrubs (Delle-Vedove, Frérot, Hossaert-McKey, & Beaudoin-Ollivier, 2014; Liégeois et al., 2016). Visual recognition is followed by landing and sometimes by direct copulation. Otherwise, when females exhibit evasive behavior, males perform rubbing movements using brush-like structures in the distal tips of their mid-legs (Quero et al., 2017) to segregate short-range attractants (i.e., E2,Z13-18:OH) (Delle-Vedove et al., 2014; Frérot et al., 2013). Quero et al. (2017) reported the presence of three acetate compounds in male terminalia, which may have a role in mate acceptance by females. Those authors also suggested that E2,Z13-18:OH could be related to territorial signaling or social communication. Thus, chemical communication has not been clarified; however, an aggregative sexual pheromone is not thought to be involved.

3-Distribution and host range

3.1. Native range and recent introductions

Palm borer moth is a Neotropical species considered native to northeastern Argentina, Uruguayan Chaco, western Paraguay, and Rio Grande do Sul state in Brazil (Sarto i Monteys & Aguilar, 2005). The ecology of PBM in its native range is not well-known; however, this insect does not induce relevant damage in its local hosts (e.g., *Butia yatay*

[Mart.] Becc. or *Trithrinax campestris* [Burmeist.] Drude & Griseb.; see below) which seem to be less susceptible than other palms throughout its exotic range. Bourquin (1993) noted intense infestations of this moth in Paysandú department (Uruguay) in 1927–1928, which decreased the following year. According to that author, the species remained as an infrequent taxon after the epidemic.

Paysandisia archon was accidentally introduced to Spain through infested ornamental palms in 2000. In its most recent review, the OEPP/EPPO (OEPP/EPPO, 2019) considered that PBM is, or has been present in many European countries, including on the mainland and on islands (Table 1). The moth was first detected in Catalonia (Spain) in November 2000 (Sarto i Monteys & Aguilar, 2005); however, Montagud (2004) suggested an undetected earlier introduction in the 1980–90s. One year later, the pest was reported in the neighboring region of Comunidad Valenciana, from where it could have reached the Balearic Islands via intense maritime trading from the mainland. In the latter location, PBM has had severe impacts on gardens and natural ecosystems since 2002 (Núñez, 2013). Other Spanish regions, including Andalusia, Madrid, and Murcia, have reported the presence of the moth (Agoiz-Bustamante, 2015; Perez & Guillem, 2019), supporting the progressive colonization of new areas in the country. This exotic insect was detected in France in 2001 (Provence-Alpes-Côte-d'Azur region), and to date, has been recorded in the regions of Aquitaine and Languedoc-Roussillon (Leraut & Martin, 2016; OEPP/EPPO, 2008). The moth severely reduced the number of ornamental palms in France; for example, 80%–90% of *T. fortunei* in Languedoc-Roussillon disappeared as a result of PBM invasion between 2002 and 2012 (EFSA Panel on Plant Health, 2014). Palm nurseries have been particularly affected by PBM in Italy, where 12 regions have reported damage (i.e. Apulia, Basilicata, Campania, Friuli-

Venezia Giulia, Lazio, Liguria, Lombardy, Marche, Tuscany, Sicily, and Veneto) (OEPP/EPPO, 2019). In this country, PBM caused extensive damage in palm nurseries, with reported losses of up to 90% in the Marche region (EFSA Panel on Plant Health, 2014). In Greece, native and exotic palms have been affected both in the mainland and in Crete (Vassarmidaki, Thymakis, & Kontodimas, 2006), as well as in Cyprus (Vassiliou, Michael, Kazantzis, & Melifronidou-Pantelidou, 2009). In Croatia, PBM was detected in 2012 in five different palm species in a nursery where infested material was subsequently eliminated (Milek & Šimala, 2012). According to the most recent report of the OEPP/EPPO (2019), the moth has also been recorded in ornamental palms in Slovenia and in transient plant material in Switzerland. The moth was reported in Denmark in 2013; however, no data regarding established populations have been recorded by the OEPP/EPPO (2019). Additionally, *P. archon* was found in Germany in a palm greenhouse and subsequently eradicated. The pest was also identified in Czech Republic, Northern Ireland, and England, where the infested material was destroyed to avoid expansion of the insect within the UK.

3.2. Host species and habitat selection

PBM is a specialist of the plant family Arecaceae, among which it can induce damage in more than 20 species. In its native range, this insect attacks *Butia capitata* (Mart.) Becc., *B. yatay*, *Syagrus romanzoffiana* (Cham.) Glassman, and *T. campestris* among other taxa used as ornamental plants (Isidoro, Riolo, Verdolini, Peri, & Beaudoin-Ollivier, 2017; OEPP/EPPO, 2008). All of those native palm species provide relevant environmental services (i.e. forest protection) and products (e.g., nuts, leaves, or biodiesel) (Falasca, Miranda Del Fresno, & Ulberich, 2012; Hoffmann, Barbieri, Rombaldi, & Chaves, 2014; Lewis, Noetinger, Prado, & Barberis, 2009). The scarce records of PBM outbreaks in South America (Bourquin, 1993) suggest a high level of tolerance in its native hosts, causing only sporadic damage in gardens and parks.

Several palm species, either endemic or exotic, exist in territories where *P. archon* has been introduced and have been reported as susceptible. Among American species, *Brahea armata* S. Watson, *Brahea edulis* H. Wendl., *Jubea chilensis* (Molina) Baillon, *Sabal mexicana* Mart., *Sabal minor* (Jacq.) Pers., *Sabal palmetto* (Walt.) Lodd., *Syagrus romanzoffiana* (Chamisso) Glassman, *Washingtonia filifera* (Lindl.) H. Wendl., and *Washingtonia robusta* H. Wendl have been cited as hosts (Isidoro et al., 2017; Sarto i Monteys & Aguilar, 2005). Most of these species have ornamental use in Europe even though some of these species, such as *B. edulis,* have restricted or threatened populations in their native range (León de la Luz, Rebman, & Oberbauer, 2003). Regarding Asian hosts, *Latania* spp., *Livistona* spp., date palm (*Phoenix dactylifera* L.), *Phoenix reclinata* O'Brien, *Phoenix roebelenii* O'Brien, *Phoenix sylvestris* (L.) Roxb., and *T. fortunei* have been reported to be infested by *P. archon* in European countries, in addition to the Australian species *Howea forsteriana* Beccari (Isidoro et al., 2017; OEPP/EPPO, 2008). Specifically, *T. fortunei* is considered one of the most suitable hosts for the moth (Sarto i Monteys *pers. com.*), and is used broadly as an ornamental species in Europe.

Particular attention should be paid to date palms, because of the significant economic revenues provided by fruits harvested in the southern Mediterranean rim and Middle East (Chao & Krueger, 2007). In 2010, South-Mediterranean countries (i.e. Morocco, Algeria, Libya and Egypt) cultivated more than 22,0000 hectares of date palm plantations (Zaid, 2010). To our knowledge, there are no records of PBM in African countries. However, its climatic range (see section 3.3) and host abundance indicate the availability of suitable habitats and the associated high risk of invasion in such areas.

Three European palm species are particularly threatened by PBM. The dwarf fan palm (*C. humilis*) is distributed along the western Mediterranean Basin, including some populations in Atlantic areas of Portugal and Spain. This species frequently occurs in the understory of Mediterranean pine (*Pinus* spp.) and oak (*Quercus* spp.) forests, as well as forming thermophilic shrub communities. This palm is associated with nutrient-stable soils in southern Spain (Aranda & Oyonarte, 2005), and its ability to survive after forest fires (Ladd, Crosti, & Pignatti, 2005) makes it a relevant component of habitat restoration projects. Dembilio, Jacas, & Llácer (2009) studied the defense mechanisms of *C. humilis* against the red palm weevil (*Rhynchophorus ferrugineus* Olivier), another stem borer insect that induces substantial damage in palms worldwide. Their study revealed that dwarf fan palm was negatively selected by the weevil (antixenosis) in natural infestation trials, whereas almost 67% of plants were fed when larvae were artificially introduced in the crown. The latter result differs from those previously reported by Barranco, De la Peña, Martín-Molina, & Cabello (2000), who recorded the exudation of gummy compounds that covered the galleries and larvae resulting in a protective response. The high incidence of *P. archon* in *C. humilis* suggests an inefficient defense mechanism (constitutive and/or induced) in the palm against moth infestation. Nevertheless, the signals that induce the exudate in *C. humilis* have not been studied; therefore, more research is required to understand the basis of palm defense against stem borers.

The Canary Island date palm (*Phoenix canariensis* Hort. ex Chabaud) requires special attention, since it is endemic to the Canary Islands (Spain). *Paysandisia archon* has not been reported in this area, although its introduction may cause an ecological disaster in the subtropical laurel forest or in the thermophilic forests where *P. canariensis* is common (Morici, 1998). This species is also used extensively in agriculture (it is considered the third most economically important palm worldwide), and is a valued ornamental species in parks and avenues (Gómez-Vidal, Salinas, Tena, & Lopez-Llorca, 2009). Another endemic taxon potentially threatened by PBM is the Cretan date palm (*Phoenix theophrasti* Greuter). This palm shows high ecological singularity and ornamental value, and it is plausible that it lacks any resistance against *P. archon* (Isidoro et al., 2017; Kontodimas, Milonas, Vassiliou, Thymakis, & Economou, 2006).

Habitat selection by PBM remains poorly understood. Ruiz, Traveset, Lázaro, Alomar, & Fedriani (2017) studied habitat selection in Mallorca (Balearic Islands, Spain) where *P. archon* spread from gardens to the natural landscape. Those authors found lower infestation intensity with higher dwarf fan palm density in the source area (so-called infestation core). This contrasts with areas of early expansion, where a higher density of dwarf fan palms was associated with more infestation. No density-dependence was found regarding the advancing front areas. Interestingly, host selection seems to be driven by a clear preference for larger palms, irrespective of the vigor of surrounding vegetation (Ruiz et al., 2017).

3.3. Future perspectives of expansion

It is difficult to predict the future range of *P. archon* since it is mainly propagated by human negligence. Despite this, the distribution of native palms, such as *C. humilis,* is a key factor in future expansion pathways that deserves consideration, since it will allow expansion of the moth without human intervention. PBM can colonize many exotic palms; therefore, the existence of suitable climate regimes for insect development may be sufficient for expansion, since the use of ornamental palms is common in Europe. Thus, climate predictions could be used to indicate future risk areas. According to the database of the World Bank Group, most African and Asian countries along the Mediterranean shore have demonstrated historic temperature regimes matching the lifecycle of the pest (Figure 1). In contrast, European countries along the northern rim of the Mediterranean Basin do not present suitable temperature regimes despite the presence of the moth in Spain, France, Italy, and Greece. Latitudinal climatic variability in these countries may explain this misprediction, since *P. archon* is mainly stablished in the warmer areas.

The predictive models MIROC5 and CCSM4 have previously been used to estimate the future distribution of plant diseases (Ramos, Kumar, Shabani, & Picanço, 2019). In the case of *P. archon*, predictions under a middle-to-high carbon emission scenario (i.e. RCP 6.0) revealed that in the coming decades (2020–2039) Turkey and some European countries (i.e. Albania, Greece, Italy, Republic of North Macedonia, Montenegro, Portugal, Spain, and Ukraine) may exhibit a suitable temperature range for adult flight. Some of these countries, such as Greece and Italy, have already been colonized, at least in part, by the moth. Thus, under this scenario, the number of areas potentially occupied by PBM is expected to increase substantially. In addition, the selected models predict that countries such as Portugal, in which the presence of the insect is not confirmed despite the abundance of *C. humilis* (García-Castaño, Terrab, Ortiz, Stuessy, & Talavera, 2014), would become highly suitable for the pest to spread in the near future.

In the longer term (2040–2059; Figure 1), Belarus, Croatia, and Serbia are expected to reach temperatures sufficient for *P. archon* breeding (>22°C average between May and September). The moth has been occasionally detected in Croatia (Milek & Šimala, 2012); however, predictions suggest that its presence in natural landscapes will become more likely in the coming decades. Therefore, current spring-summer climatic regimes identify North Africa as a suitable region for this invasive pest, while future predictions suggest that central and Mediterranean Europe may represent the range of probable spread by the middle of this century.

4-Pest management: monitoring, eradication, and control

4.1. Early detection and monitoring

The moth is mainly spread through the commercial movements of ornamental plants. Hence, strict legislative measures are required on local, national, and international levels for the surveillance of potentially infested palms. The development of an intensive survey protocol for plant material might be the most effective method to limit future expansion of the insect (Table 2), together with effective penalties for non-compliant behaviors.

Paysandisia archon lacks sexual pheromones, which makes it difficult to monitor populations in the field and restricts the ability of large captures for monitoring and as a control strategy (Table 2). Closa et al. (2017) assayed two different trap models (i.e. adhesive delta trap and interception trap) baited with three potential attractants in the Balearic Islands and reported negative results. Host selection seems to be performed by females, since Hamidi & Frérot (2016) reported their probing behavior of the substrate with the antennae and ovipositor. Ruschioni et al. (2015) reported that females were more sensitive than males to six plant volatiles (including five esters associated with damaged palm tissues). These findings suggest that olfactory cues from stressed palms could play an important role in host selection by gravid moths. Consequently, a comprehensive study of its chemical ecology is needed to determine the cues used by the insect to select hosts and mates. This knowledge would be of value to determine whether disruption of mating would be a useful preventive tool in the future.

4.2. Eradication measures

The results reported by Ruiz et al. (2017) supported the idea that early eradication is the optimal, and perhaps only, method to prevent outbreaks of PBM in recently colonized areas. Thus, the removal and mechanical chipping of infested palms is a reliable method of larvae elimination. Nevertheless, this procedure requires heavy machinery and specialized staff; therefore, the results are mainly applicable in public gardens or urban areas with easy access and high economic value, as summarized in Table 2. Alternatively, infested plants could be burnt; however, due to the high risk of wild fires in Mediterranean landscapes, this is only advisable under very controlled conditions or in nurseries (Montagud, 2004).

4.3. Chemical control

Chemical treatments have high potential in urban areas and nurseries. Several compounds and treatments (foliar spray and stipe injection) have been assayed on palms, focusing on red palm weevil (reviewed by Jaques et al., 2017). To date, there is no effective commercial product for eradicating or controlling *P. archon*. In an earlier study, Sarto i Monteys & Aguilar (2005) reported the effective use of Chlorpyrifos 48% w/v sprayed on the crown (dose: 200 ml/hl), as well as the application of Acephate 75%

w/v (dose: 150 g/hl). The use of these insecticides is not allowed in natural stands since they affect several non-target insect orders (e.g. Chlorpyrifos affects Coleoptera, Lepidoptera and Orthoptera, among others). PBM is protected inside the host for a long period. Consequently, endotherapy would be the most adequate method to control the pest in gardens, if an effective compound was identified. The high economic costs of these kinds of treatments make them unaffordable in the forest, encouraging the use of other extensive methods, such as biocontrol.

4.4. Biological control

The use of organisms to fight a pest or disease (biological control or biocontrol) is an alternative for managing PBM infestations (Table 2). The preventive use of fungi as biocontrol agents has gained relevance in recent years, since many phytosanitary developers market products based on fungal propagules for crop protection (such as those involving *Trichoderma* spp. [Woo et al., 2014]). Furthermore, the categorization of a single fungal species as entomopathogen (mycoinsecticide) or antagonist (bio-fungicide) has recently been challenged, since several taxa exhibit dual-control roles, and can remain as endophytes in treated plants (Jaber & Ownley, 2018), increasing interest in this control alternative.

The ascomycete fungus *Beauveria bassiana* (Bals.-Criv.) Vuill., has proven to be an effective tool for controlling some insect populations (Zhang et al. 2011; Zhang et al. 2019). A commercial strain of this fungus was tested under laboratory conditions against the eggs and larvae of *P. archon* by Besse-Millet, Bonhomme, & Panchaud (2008). The results showed that only 42% of eggs hatched and that only 24% of the emerging larvae survived the treatment. When larvae of different ages were treated, 100% mortality was observed 14 days after treatment. The effectiveness of *B. bassiana* against PBM has also been assessed *in planta*. Besse-Millet et al. (2008) treated *P. canariensis* plants with three concentrations of sporal suspensions (1.4×10^9, 4.1×10^9, and 1.4×10^{10} spores/plant), after which they were artificially infested with 21–37-day-old larvae. Treatment with the highest concentration killed almost 80% of the larvae, and decreased the growth of surviving individuals by 50% compared with the healthy larvae. These results suggested that effective colonization by *B. bassiana* requires, at least in part, the ability of the fungus to remain in healthy tissues of the plant (increased prevalence) in order to infect the newly laid eggs or hatched larvae before they enter the stem of the palm. This was supported by Gómez-Vidal et al. (2006), who confirmed the endophytic behavior of *B. bassiana* and two further taxa, *Lecanicillium dimorphum* (J.D. Chen) Zare & W. Gams and *Lecanicillium psalliotae* (Treschew) Zare & W. Gams, in the petioles and leaves of *P. dactylifera*. The use of these taxa against palm borers may be feasible since they are considered entomopathogens and can spread through plant tissues (especially *B. bassiana* and *L. dimorphum*) (Gómez-Vidal et al., 2006). In addition, inoculation with these taxa promoted a physiological response in the host by up-regulating one resistance-like protein homologous to RPP13 protein from *Arabidopsis thaliana* (L.) Heynh, which is involved in pathogen recognition (Gómez-Vidal et al., 2009). Additionally, another protein highly homologous to a stress-responsive protein of *Pinus taeda* L. (LP3-1) was up-regulated in treated plants. Moreover, a small heat shock-like protein belonging to a complex protein family associated with resistance in *Pinus nigra* Arnold (highly homologous to smHSP) was accumulated at low levels in inoculated palms (Gómez-Vidal et al., 2009). These findings suggest that endophytic fungi may contribute to plant protection through their entomopathogenic role and by triggering molecular defensive responses in the host plant before insect infestation.

Other endophytic fungi of interest include members of the genus *Cladosporium*, which have been isolated from palm tissues (Ben Chobba et al., 2013; Gómez-Vidal et al., 2006). This genus includes species with reported virulence against arthropods (insects and mites) (Eken & Hayat, 2009). Consequently, fungal endophytic communities of palms may include other taxa of entomopathogenic interest. Hence, the study of mycobiota techniques such as metagenomics, could help to identify candidate biocontrol agents to reduce the damage caused by *P. archon*.

Nematodes are well-known biocontrol agents, and the broadly-distributed *Steinernema carpocapsae* Weiser has been successfully tested as a biocontrol agent of several insect species, including red palm weevil (mortality rate >70%) (Llácer, Martínez de Altube, & Jacas, 2009). Immature nematodes penetrate insect larvae and release symbiotic bacteria *Xenorhabdus nematophila* (Poinar & Thomas) Thomas & Poinar, which eventually induce the host's death. Two commercial formulations of this nematode have been assayed to control *P. archon* both in curative (dose range: 8–10 × 10^6 nematodes/plant) and preventive (dose range: 6.3–7.4 × 10^6 nematodes/plant) assays (Nardi et al., 2009). No significant effects were observed with preventive treatment, probably due to a low rate of new infestations in control plants. However, both formulations yielded high larvae mortality in the curative trial (>94%). Soto & Duart (2008) performed a greenhouse infestation assay with *S. carpocapsae*, which resulted in 87% larvae mortality (Abbot´s efficacy index) 16 days after treatment (assayed doses: 0.3 × 10^6 and 1 × 10^6 nematodes/plant). In parallel, those researchers reported larvae mortality rates of 50% (50 nematodes/larva) and >80% (100 and 500 nematodes/larva) 6 days after treatment under laboratory conditions. Additionally, Nardi et al. (2009) reported that this parasite actively searches larvae within the palm's stipe. The available evidence suggests that *S. carpocapsae* has high potential as a biocontrol agent against PBM.

The integrated management of a single phytopathogen or plant pest usually requires the coordination of multiple approaches (Lacey et al., 2015). The combined use of biocontrol agents may be highly desirable. Wakil, Yasin, & Shapiro-Ilan (2017) reported additive and synergistic effects of *B. bassiana* and the nematode *Heterorhabditis bacteriophora* Poinar when larvae of *R. ferrugineus* were treated with both organisms (doses: 1×10^6 spores/ml and 100 juveniles/ml, respectively). The synergistic effect was most pronounced when nematode treatment was delayed for 2 weeks after fungal inoculation (highest mortality rate: 88.65%). In addition, the combined application of *H. bacteriophora* and the fungus *Metarhizium anisopliae sensu lato* (Metschn.) Sorokin also provided synergistic effects on host mortality (Wakil et al., 2017). Those biocontrol results, using a combination of *B. bassiana* and *S. carpocapsae,* indicate that further preventive and curative trials are needed to evaluate the existence of synergy or antagonistic (Shapiro-Ilan, Jackson, Reilly, & Hotchkiss, 2004) effects of these or other organisms against *P. archon*.

Parasitoids are also promising biocontrol agents since they are highly specific and relatively easy to breed in captivity. The minute wasp genus, *Trichogramma,* was proposed as a candidate to control PBM because of its ability to parasitize eggs of large lepidopteran species. Tiradón et al. (2013) selected 19 strains belonging to nine species of the genus, and evaluated their effectiveness at parasitizing eggs of *P. archon*. The results showed that females of *Trichogramma* spp. were not attracted by eggs of the moth. Conversely, a more recent study suggested a positive control effect of three unidentified strains of this genus under controlled conditions (Ortega-García et al., 2016). According to those authors, the studied strains increased the abortion rate and were able to detect *P. archon* eggs in any point of the host´s stipe. Further research on the use of parasitoids as biocontrol agents is needed to clarify some key factors, such as host specificity or technical requirements for massive production.

Predation is another phenomenon that has been considered for biocontrol during early states of infestation in other pathosystems. Reptiles, birds, or small mammals are expected to capture imagines of PBM, since moths are large and active during the day. Thus, Liégeois et al. (2016) recorded adults of *P. archon* with damages attributable to birds. Nevertheless, the identification of predator taxa and their possible effects on the population dynamics of *P. archon* require further study.

5-Concluding remarks

This review aimed to summarize available information about the ecology and management of *P. archon* in Europe. This insect, which was carelessly introduced in Europe in 2000, embodies a major threat for ornamental and native populations of palms in the Mediterranean Basin. To date, France, Greece, Italy, Slovenia, and Spain harbor incipient populations of the moth. In addition, habitat suitability suggests high risk of expansion to other European and North African countries (including islands) if the relevant governments do not react quickly by developing preventive strategies. International plant movements are the main pathway for the propagation of this insect.

Consequently, an exhaustive and coordinated survey program aiming to guarantee the sanitation of plant material is highly needed. Several control and eradication methods have been assayed with various degrees of success. Chemical treatment and tree management practices are suitable tools in gardens, but are difficult to apply in the field. Conversely, integrated biocontrol strategies involving both entomopathogenic fungi and nematodes are the most promising control methods. The potential use of parasitoids has yet to be further evaluated, and methods of applying mass-propagated specimens need to be adjusted to the specific habitats harboring PBM eggs or larvae. Projected propagation scenarios encourage strict controls of plant movement and indicate that efforts should be invested in optimizing field-applied biocontrol tools to prevent the loss of palms in our natural shrub communities, as well as in parks and gardens.

Authors contribution

E.J.M.-A. and C.C. conceived the review, E.J.M.-A. and C.C. wrote and reviewed the article. Both authors read and approved the final manuscript.

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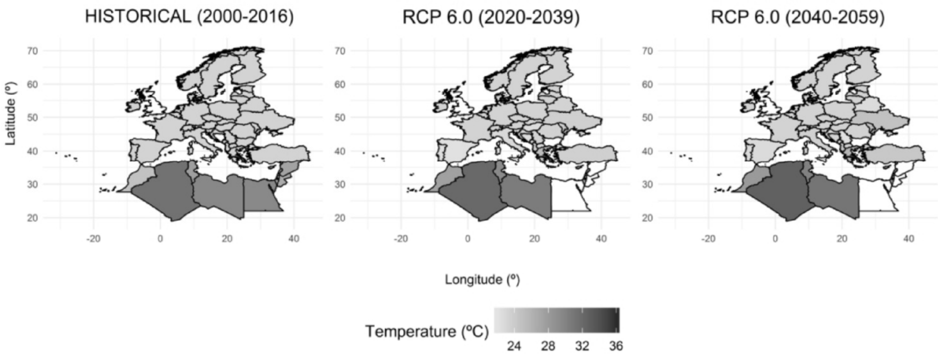
Figure legends

Figure 1. Current and future suitable ranges of *Paysandisia archon* in Europe and the Mediterranean Basin considering mean temperatures during the flight period (May to September). Predictions were based on average data from the models MIROC5 and CCSM4 (Climate Change scenario: RCP 6.0. medium-high emissions) from the database of the World Bank Group (https://climateknowledgeportal.worldbank.org/download-data). White countries: data not available.

Table legends

Table 1. European countries with documented presence of *Paysandisia archon* according to OEPP/EPPO. [ ]: eradication date; †: record supported by the literature.

Table 2. Efficacy of the proposed measures in the management of *Paysandisia archon* infestation. Environment: forest areas (F); gardens and palm nurseries (G&N). ‡: Regional category only applicable under a large-scale infestation scenario.



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372x146mm (96 x 96 DPI)

Table 1. European countries with documented presence of *Paysandisia archon* according to OEPP/EPPO. [ ]: eradication date; †: record supported by the literature.

Country	Year of first citation	Pest status according to OEPP/EPPO criteria
Spain	2000	Present, restricted distribution
France	2001	Present, restricted distribution
Italy	2002	Present, restricted distribution
United Kingdom	2002 [2002/2009]	Absent, pest eradicated
Greece	2006	Present, restricted distribution
Slovenia	2008	Present, restricted distribution
Cyprus	2009	Present, few occurrences
Switzerland	2010	Present, few occurrences
Belgium	2011	Absent, pest no longer present
Czech Republic	2011 [2018]	Absent, pest eradicated
Portugal	2011	Absent, unreliable record
Croatia	2012 [2012]	n.a. †
Denmark	2013	Absent, intercepted only
Germany	2016 [2018]	Absent, pest eradicated
Austria	n.a.	Absent, no pest record
Netherlands	n.a.	Absent, confirmed by survey

Table 2. Efficacy of the proposed measures in the management of *Paysandisia archon* infestation. Environment: forest areas (F); gardens and palm nurseries (G&N). ‡: Regional category only applicable under a large-scale infestation scenario.

Category	Measure	Expected efficiency	Environ ment	Scale	Expected cost	Observations
Prevention / Early detection	Intensive commercial surveys	High	G&N	International	Moderate	International coordination recommended
	Pheromone trapping / Host attractants	Low-Moderate	F; G&N	Local-Regional	Moderate	Research required
	Risk map elaboration	High	F; G&N	Local-International	Low-Moderate	
	Visual prospection of susceptible stands	Moderate-High	F; G&N	Local	Moderate	Staff training required
Control	Chemical treatments	Moderate-High	G&N	Local	Low-Moderate	High risk of environmental negative impact. Not allowed in forest areas
	Fungal-based biocontrol	Moderate	F; G&N	Local-Regional	Moderate	Research required
	Nematode-based biocontrol	Moderate-High	F; G&N	Local-Regional	Moderate	Research required
	Parasitoid release	Moderate	F; G&N	Local-Regional	Moderate	Research required
	Predators promotion	Low-Moderate	F	Local-Regional	Low	Research required
Eradication	Infested palm burning	High	G&N	Local	Moderate-High	High risk of environmental negative impact. Not allowed in forest areas
	Mechanical chipping	High	F; G&N	Local-Regional ‡	Moderate-High	