The invasive mealybug Maconellicoccus hirsutus: *lessons for its current range expansion in South America and invasive pest management in general*

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REVIEW

The invasive mealybug *Maconellicoccus hirsutus*: lessons for its current range expansion in South America and invasive pest management in general

Mark P. Culik · Maurício José Fornazier · David dos Santos Martins · José Salazar Zanuncio Jr. · José Aires Ventura · Ana Lúcia B. G. Peronti · José Cola Zanuncio

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Abstract The invasive mealybug *Maconellicoccus hirsutus* (Green) (Hemiptera: Pseudococcidae) is a plant feeding insect believed to be native to Southern Asia or Australia. This mealybug has become established in many regions throughout the world (including the Caribbean and North America) in the past 100 years and is currently expanding its range in South America. Because this insect is of concern as a potential pest of many plant species, this review is provided to summarize knowledge of *M. hirsutus* based on past research that may be most useful for addressing the current invasion of South America by the species, and to identify gaps in information that may need to be addressed to inhibit the spread of the insect and improve management methods for this and similar organisms. In most areas into which *M. hirsutus* has expanded its range it is commonly suppressed by native or introduced natural enemies. Therefore, besides preventing introduction, establishment and spread of this potential pest, efforts should be made to determine if natural enemies of *M. hirsutus* are present in areas of concern (i.e., where the mealybug may be introduced and become established). Such information will enable determination of the need for introduction or augmentation of biological control agents in response to possible entry and establishment of the mealybug in new areas. Methods developed in response to the recent invasion of the Caribbean and North America by *M. hirsutus* may serve as models for addressing the threat of this and similar invasive pests in South America and elsewhere.

Keywords Neotropical · Biodiversity · Biological control · Natural enemies · Geographic distribution · Integrated pest management (IPM)

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Introduction

The invasive pink hibiscus mealybug (PHM), *Maconellicoccus hirsutus* (Green) (Hemiptera: Pseudococcidae), is currently expanding its range from Caribbean South America to other parts of the continent where it is of concern as a potential pest of many plant species. Therefore, the purpose of this review is to summarize knowledge of *M. hirsutus* that may be most useful for addressing the current invasion of South America by this species, as well as identify gaps in information that may need to be addressed to inhibit the spread of *M. hirsutus* and improve management methods for this insect in South America and other areas where it is currently established or expanding its range. This is not meant to be a complete review of the scientific literature on *M. hirsutus*, but to serve as a guide to information and options to consider (or in need of further research) for managing the species if it becomes established more widely in South America and elsewhere. The review is based principally on recent scientific research on

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M. hirsutus, with emphasis on information most applicable for management of the mealybug obtained during its recent invasions of the Caribbean and North America. We also note some observations from experiences with *M. hirsutus* that may be relevant to management of other invasive species as well.

Origin, past range expansion, and current geographic distribution

Maconellicoccus hirsutus is believed to be native to Southern Asia or Australia (Williams 1996; Goolsby et al. 2002) and was originally described from an unidentified plant in India in 1908. Subsequently, this mealybug was noted initially in the Middle East (Egypt) in 1912 and in Africa (Kenya) in 1954, and the species is now present in several countries in the Middle East and is widespread on Africa (DeLotto 1954; OEPP/EPPO 2005; Roltsch et al. 2006). In 1993 *M. hirsutus* was first detected in the Caribbean on the island of Grenada and in several years this insect spread throughout the region (Michaud and Evans 2000). *M. hirsutus* was initially found in North America in 1999, in the area of the Imperial and Mexicali Valleys of the United States and Mexico, and it has subsequently been found in many other widely distributed locations in these countries (Roltsch et al. 2006; Chong 2009; SINAVEF 2010). The mealybug was also initially detected in Central America in 1999, in Belize, and was reported in Guatemala in 2002; however, in this region the species currently occurs only in Belize (OEPP/EPPO 2005; OIRSA 2012). In South America *M. hirsutus* was first noted in Guyana, in 1997 (Tambasco et al. 2000), and until recently it has been restricted to Caribbean South America (Guyana, French Guiana, Venezuela, Suriname, Colombia) (OEPP/EPPO 2005). However, in 2010 this insect was detected in Brazil, in the State of Roraima, which borders Guyana, (Marsaro Jr. et al. 2013), and in 2012 we found this species in the State of Espírito Santo, Brazil, which is located approximately 3,400 km southeast of Roraima

Fig. 1 Distribution of *M. hirsutus* in South America as of 2012 and year of first record in Country/Region (State) if known (Matile-Ferrero et al. 2000; Tambasco et al. 2000; Cermeli et al. 2002; Gajadin 2004; Kondo et al. 2008; Marsaro Jr. et al. 2013)

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Table 1 Stages in the invasion process, relevant ecological processes, and examples of factors that influence invasion by *M. hirsutus* and similar organisms

Phase of invasion	Ecological process	Influential factors	Reference
Arrival	Immigration	Quarantine measures	Schrader and Unger (2003)
Establishment	Reproduction	Suitable host plants	Serrano and Lapointe (2002)
Integration	Population growth	Favorable climatic conditions	Chong et al. (2008)
	Dispersal (short-distance)	Wind	OEPP/EEPO (2006)
	Mortality	Natural enemies	Roltsch et al. (2006)
Spread	Dispersal (long-distance)	Travel, commerce (seedlings, produce)	Chong (2009)

(Fig. 1). The past range expansion of *M. hirsutus* from its presumed center of origin in Asia or Australia has been limited to locations between approximately 30° N and 30° S latitude (CABI/EPPO 2004) and the geographic distribution of the species may be restricted by its relatively high lower developmental threshold and optimal developmental temperatures (Chong et al. 2008; Jara et al. 2012). However, *M. hirsutus* is now established in all major biogeographic regions except the Antarctic and recent detections of the species in Brazil indicate that this potential pest is continuing to expand its range in South America.

Important aspects of the invasion process (Venette and Carey 1998; Radosevich 2007) as related to the ecology of invasive pests are summarized in Table 1 and discussed further below with respect to the biology and management of *M. hirsutus*.

Biology and pest status

Maconellicoccus hirsutus is a plant feeding insect with a wide host plant range. This insect has been recorded from a very large number and diverse variety of plant species (298) from approximately 75 families including many economically important fruit, fiber, and grain crops, as well as ornamental and timber species such as: Anacardiaceae (mango, *Mangifera indica* L.), Euphorbiaceae: (cassava, *Manihot esculenta* Crantz), Fabaceae (legumes), Musaceae (banana, *Musa* spp.), Myrtaceae (guava, *Psidium guajava* L.), Poaceae (corn, *Zea* mays L.; sugarcane, *Saccharum officinarum* L.), Rubiaceae (coffee, *Coffea arabica* L.), Rutaceae (*Citrus* spp.), Sterculiaceae (cocoa, *Theobroma cacao* L.), and Vitaceae (grape, *Vitis vinifera* L.) (Meyerdirk et al. 2001). However, most of these records are from sources that apparently were not published publicly and may include many records of incidental hosts (unsuitable hosts infested by *M. hirsutus* from nearby heavily infested, preferred hosts) (Kairo et al. 2000; Michaud and Evans 2000). Preferred hosts of *M. hirsutus* include Malvaceae especially *Hibiscus rosa-sinensis* L. (Goolsby et al. 2002; Vitullo et al. 2009).

As a scale insect, *M. hirsutus* feeds on plant sap and such feeding may damage plants directly and indirectly (Ben-Dov et al. 2012). Feeding by *M. hirsutus* on some plants such as *H. rosa-sinensis* may cause noticeable symptoms of leaf distortion or deformation of fruit (Fig. 2) and death of plants has been attributed to dense infestations of the pest (Sagarra and Peterkin 1999). However, despite the apparently broad and extensive host plant range of *M. hirsutus*, documented reports of yield losses caused by this insect to economically important crops are relatively rare (Ben-Dov et al. 2012). Kairo et al. (2000) also noted that despite the wide distribution of *M. hirsutus* it had only been noted as a serious pest in Egypt and India prior to its establishment in the Caribbean. As discussed in Williams (1996) damage by this insect in other regions before its arrival in the Caribbean in 1993 may be summarized as follows: in Egypt *M. hirsutus* was reported to cause damage to *Albizia lebbek* (L.) Bentham, a preferred host, mulberry (*Morus* L.), *Hibiscus* spp., and other plants including cotton, *Gossypium* L. (however, as an annual crop, time was not sufficient for the mealybug to cause severe damage to cotton, and an introduced parasitoid was

Fig. 2 Symptoms of *Maconellicoccus hirsutus* infestation of okra, *Abelmoschus esculentus* (L.) Moench (Photograph JS Zanuncio Junior)

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effective in reducing populations of the pest); in Africa *M. hirsutus* was implicated as a possible pest of cocoa; and in India and Bangladesh, *M. hirsutus* was considered to be a pest of cotton, mulberry, and several fiber crop species (*Hibiscus* spp. and *Boehemeria nivea* (L.) Gaudichaud-Beaupré); and it has also been considered to be a severe pest of grapes in India, stunting growth and destroying grape clusters, but management practices possibly inhibited natural enemies of the pest. Outbreaks of *M. hirsutus* caused damage to a wide variety of plant species in the Caribbean after its initial arrival in the region but the subsequent introduction of natural enemies has been effective in controlling this mealybug and reducing damage to plants in the Caribbean as well as North America (Sagarra and Peterkin 1999; Michaud and Evans 2000; Michaud 2003; Roltsch et al. 2006; Reddy et al. 2009). Thus, although *M. hirsutus* may occur on many different species of plants, it is likely that relatively few plants species are suitable hosts for development of *M. hirsutus* and even fewer are favorable hosts (Sagarra and Peterkin 1999; Michaud and Evans 2000; Michaud 2003). And, in areas where natural enemies of *M. hirsutus* are present they also commonly inhibit development of damaging populations of the insect (Sagarra and Peterkin 1999; Michaud and Evans 2000; Michaud 2003; Roltsch et al. 2006; Reddy et al. 2009). Besides the fact that this mealybug is invasive and has been noticed on many species of plants, the status of *M. hirsutus* as a pest appears to be based in most part on extremely noticeable (but short-lived) outbreaks of the insect in newly invaded areas prior to the establishment of its natural enemies (Sagarra and Peterkin 1999; Kairo et al. 2000), possible disruption of natural enemies by misuse of pesticides or other factors in regions where biological control agents commonly maintain the mealybug below damaging levels (Williams 1996; Singh 2004; Daane et al. 2012), and damage caused by the insect to ornamental plants (Vitullo et al. 2009; Castle and Prabhaker 2011; Aristizábal et al. 2012).

Regarding potential effects of *M. hirsutus* on important agricultural crops that may be hosts of the insect in South America including cotton, grapes, and coffee, geospatial information studies such as those of Jara et al. (2012) are warranted to identify areas of greatest risk for establishment of the insect, and to identify areas with suitable environmental conditions for the pest in which specific crops of concern are located. With such information, those in areas of most concern could be better prepared to prevent, delay, and respond to entry or establishment of *M. hirsutus*. Although *M. hirsutus* has been found on *Coffea arabica* (Ben-Dov et al. 2012) it apparently has not been noted on *Coffea canephora* Pierre ex A.Froehner and is not known as a common pest of coffee. However, because of the economic importance of coffee production in South America additional research to determine the suitability of *C. arabica* and *C. canephora* as hosts and the potential impact of *M. hirsutus* on coffee in this region, especially *C. canephora*, is also warranted.

Maconellicoccus hirsutus reproduces parthenogenetically or sexually (Williams 1996). Females produce large numbers of eggs (approximately 150–600) that are laid in masses of sticky wax (ovisac), Fig. 3, over a period of about 1 week on plants in which they feed (Sagarra and Peterkin 1999). Nymphs hatch from eggs after approximately 6–9 days and the first instar nymphs (crawlers) are active and disperse by crawling or wind, and also likely carried to new areas on animals and objects (Sagarra and Peterkin 1999; Chong et al. 2008; Chong 2009). After locating a suitable host plant, nymphs settle on the host to feed and develop through 3 or 4 instars (female and male, respectively). Chong et al. (2008) determined life history parameters of *M. hirsutus* on *H. rosa-sinensis* at temperatures between 15 and 35 °C. Development was the fastest

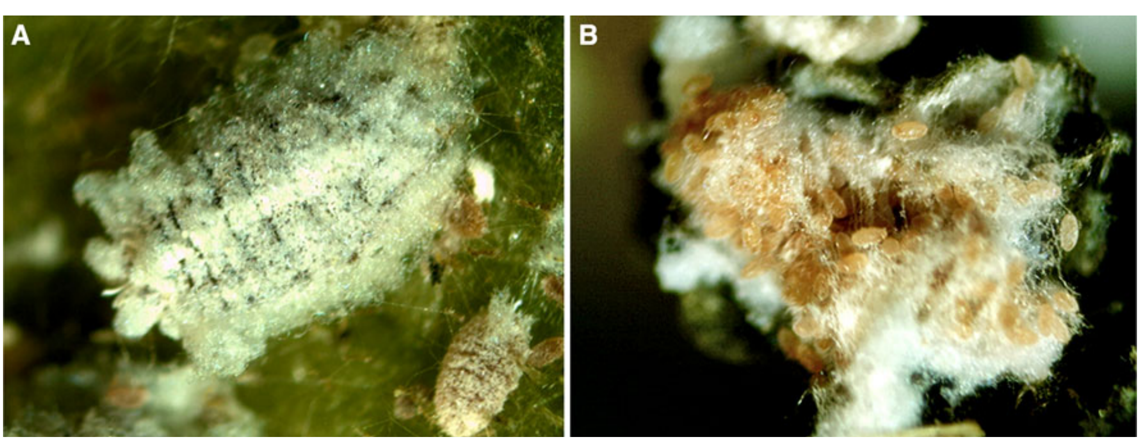

Fig. 3 Live appearance of *Maconellicoccus hirsutus*: adult female and nymph, A; egg mass, B (Photographs MP Culik)

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at 27 °C, at which *M. hirsutus* completed development in approximately 29 days. Lower and upper developmental thresholds, and optimal developmental temperature for females were estimated to be 14.5, 35, and 29 °C, respectively (Chong et al. 2008).

Characteristics of the biology of *M. hirsutus* that contribute to its potential as an invasive pest include its broad host plant range, high reproductive potential, rapid development rate, and the great dispersal ability of life stages such as crawlers (Sagarra and Peterkin 1999; Chong et al. 2008; Chong 2009). Such factors greatly influence management of *M. hirsutus* as discussed below.

Management

Quarantine measures, education, and exclusion

Maconellicoccus hirsutus commonly infests fruit and ornamental plants (Kairo et al. 2000; OEPP/EEPO 2006). Thus, common pathways for introduction of this pest to new areas include movement of infested plants (e.g., fruit tree and ornamental nursery seedlings), and commercialization of infested fruit or other plant products (Meyerdirk et al. 2001). In addition, because immature forms of the insect include masses of eggs covered with sticky wax and a small, active, and mobile crawler stage, the insect may also be carried to new areas by humans and other animals that come in contact with the eggs and crawlers (Sagarra and Peterkin 1999; Chong et al. 2008; Chong 2009). Wind also contributes to dispersal of the crawlers (OEPP/EEPO 2006).

Because of the importance of humans in dispersal of *M. hirsutus* on plants, plant products, clothing, and other articles, management of *M. hirsutus* and similar invasive species begins with quarantine measures to prevent entry of the pest to uninfested regions (Schrader and Unger 2003) as well as education of the public to prevent spread of the insect to new areas (Sagarra and Peterkin 1999). For invasive species considered to be of particular importance and concern for an uninfested region, a formal monitoring system may be warranted to enable rapid response to eradicate, if possible, initial populations of the potential pest that may be introduced while their numbers are limited and before they are able to multiply and disperse (Simberloff 2009).

Accurate estimates of damage caused by invasive pests are needed to assess the threat of these organisms and develop appropriate quarantine regulations, and a more complete knowledge of host plants and economic damage caused by specific invasive pests such as *M. hirsutus* would better enable resources to be directed toward prevention of entry and establishment of the species of greatest threat to uninfested areas (Schrader and Unger 2003; FAO 2011). Discussion of specific quarantine measures appropriate for *M. hirsutus* (which depend on climate, presence of economically important host plants, and other characteristics of each location of concern) is beyond the scope of this review. However, the importance of quarantine measures and education to exclude such invasive pests is emphasized because it is likely that prevention of entry of potential pests may be much less costly than eradication or management of a pest species if it becomes widely established (Simberloff 2009).

Because *M. hirsutus* has a relatively high reproductive potential, crawler stage with great dispersal ability, rapid development rate, and many potential hosts (Sagarra and Peterkin 1999; OEPP/EEPO 2006; Chong et al. 2008; Chong 2009), the feasibility of eradication of *M. hirsutus* from areas with favorable environmental conditions is likely to depend on the amount of time between arrival of the insect and its detection. Although eradication of *M. hirsutus* from areas in which it has begun reproduction and has become widely established is likely to be extremely difficult, it is possible that infestations may be eradicated from limited areas if they are detected soon after entry and before reproduction has resulted in widespread dispersal of crawlers or other life stages (Chong 2009).

As for other regions, quarantine management of mealybugs in South America falls within the jurisdiction of national governments which maintain active programs to prevent entry of invasive pests (IPPC 2013). For example, Brazil adheres to the international plant protection convention (IPPC) and is an active participant in its governing body, the commission on phytosanitary measures (CPM), which develops international phytosanitary norms (Ministério da Agricultura 2013). *M. hirsutus* was recognized as a quarantine pest in Brazil prior to its establishment in neighboring countries (Sanches and Carvalho 2010) and quarantine measures to prevent entry of pests into Brazil were likely helpful in delaying entry of *M. hirsutus* into this country for at least 10 years after its establishment in the region (Fig. 1). Soon after detection of the pest in the northern part of Brazil quarantine measures were also taken to prevent spread of the insect to other areas including prohibition of transport of plant seedlings from the State where the pest was first detected (Ministério da Agricultura 2011).

Surveying for and monitoring *M. hirsutus*

Surveying for and monitoring of *M. hirsutus* is required to determine if the insect has entered previously uninfested areas, and to time and evaluate effects of management practices on *M. hirsutus* populations in infested areas. Monitoring to detect entry of *M. hirsutus* into uninfested areas and surveys to determine if the species has spread within regions may be most efficiently achieved by use of pheromone traps. A pheromone for *M. hirsutus* was recently

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identified and studies of Francis et al. (2007) indicate that pheromone traps enabled detection of *M. hirsutus* in areas where infestations were not otherwise apparent. More recently González-Gaona et al. (2010) demonstrated the usefulness of pheromone traps for determining the regional distribution of *M. hirsutus* in Mexico. Monitoring of *M. hirsutus* with pheromone traps may also be useful for timing management strategies based on the phenology of the pest (Hall et al. 2008). Periodic examination of sentinel plants (plant species that are favored hosts of *M. hirsutus*) such as *H. rosa-sinensis* may also be useful for detection of the mealybug in newly invaded areas, and for monitoring its possible spread from a focus of limited infestation to nearby areas (OEPP/EEPO 2006).

If established and examined on a regular, ongoing basis, pheromone traps may enable early detection of the entry of *M. hirsutus* in uninfested areas of concern, and thus enable rapid elimination (eradication) of populations before they become widely established in the region. Ramos and Hernández (2010) provide detailed contingency plans for surveying for, monitoring, and managing *M. hirsutus* including guidelines for evaluating the feasibility of eradication if the insect is found in uninfested countries in Central America that would also likely be useful for planning in other uninfested regions as well.

The difficulty of preventing and detecting entry of invasive pests is indicated by the recent invasion of North America by *M. hirsutus* as discussed by Castle and Prabhaker (2011) who concluded that this insect was only detected in California several years after its entry, and was also relatively well-established in Florida prior to its discovery there even though the potential entry into the region of the pest was anticipated due to its presence in the Caribbean. Pheromone traps for *M. hirsutus* were not available at the time of the establishment of this insect in North America and it is likely that these traps would have been helpful in detecting entry of the mealybug in the region earlier (Francis et al. 2007). Thus, development of pheromone traps for invasive insects of significant concern may be warranted to enable early detection of the organisms if they enter areas considered to be at risk for establishment of the pest.

Field characteristics and live appearance of *M. hirsutus*

To monitor population levels and verify effects of management practices on *M. hirsutus* populations in infested areas, visual examination and sampling of plants for *M. hirsutus* may be necessary. Specific details of sampling methods will vary depending on the purpose but in general sampling may be focused on examination of plants considered to be preferred hosts of *M. hirsutus* such as *H. rosa-sinensis*, examination of plants with visual symptoms of *M. hirsutus* damage (deformed foliage, sooty mold etc.), or random examination of plants (for example, monitoring plants of specific concern such as high value crops) for the presence of mealybugs. In either case, knowledge of field characteristics of the species is needed to enable recognition of probable *M. hirsutus* and to enable collection of specimens for confirmation of identification of the species. Field characteristics useful for monitoring of *M. hirsutus* include symptoms of infestation as well as live appearance of the insects.

Symptoms of *M. hirsutus* infestation of plants include deformed foliage and fruits (Fig. 2), sooty mold, and the presence of associated ants (Williams 1996; OEPP/EEPO 2006). However, it is important to note that symptoms of *M. hirsutus* infestation of plants vary depending on the plant species and cultivar as well as other environmental factors and may not always be present on infested plants (Vitullo et al. 2009; Aristizábal et al. 2012). Also, other mealybug species may cause similar symptoms so collection of specimens is necessary to confirm the identification of mealybugs if present.

For survey and monitoring purposes *M. hirsutus* specimens may be tentatively identified based on the live appearance of the species and collected for verification of the identification. Live appearance depends on life stage and other factors but the typical live appearance of *M. hirsutus* is summarized as follows: adult female body oval-oblong, orange-pink to reddish-brown, covered with white powdery wax (Fig. 3), often covered with white waxy ovisac dorsally; eggs pink, in masses, in waxy ovisac (Fig. 3); nymphs oval, pinkish, lightly covered with white powdery wax; pinkish adult males with a single pair of wings (Williams 1996; Miller 1999; Rung et al. 2007). More complete descriptions of symptoms and live appearance of *M. hirsutus* are found in Meyerdirk et al. (2001). To enable definitive identification of suspected *M. hirsutus* specimens, adult females should be collected and preserved in 70 % alcohol with a label containing complete collection data (location, date, collector, host).

Identification of *M. hirsutus*

Identification of suspected *M. hirsutus* specimens requires microscopic examination of slide-mounted adult females and verification of the presence of key morphological characters as discussed in Williams (1996), Miller (1999), and Rung et al. (2007). *Maconellicoccus* species are distinguished from all other mealybugs by the following combination of characters: antennae normal, with nine segments (one species with 7–9 segments), shorter than length of body (not usually long and slender); legs present, normal; trilocular pores present; oral rim tubular ducts present; dorsal oral collar tubular ducts without orifice

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surrounded by a round adjacent, sclerotized area containing one or more setae within its borders, or with the setae adjacent to the rim; cerarii numbering 1–7 pairs (on abdomen only), each with a pair of conical setae, at least on anal lobes (sometimes replaced with slender setae on anterior segments); cerarii not situated on prominences; anal lobes not projecting, at most only moderately produced, rounded, each with a long flagellate apical seta (Williams 1996; OEPP/EEPO 2006).

Maconellicoccus hirsutus identification can be confirmed by verifying the presence of key morphological characters of slide-mounted adult females examined microscopically. However, all other *Maconellicoccus* species have limited geographic distributions, and *M. hirsutus* may be distinguished from most other *Maconellicoccus* species by relatively easily observed characters (Table 2). As with any of such work, competent recognition and identification of invasive species depends on proper training and experience which depends on investment in qualified personnel, suitable facilities, and adequate support.

Because of the difficultly of identifying mealybug species based on morphology, research has recently been directed toward developing molecular techniques for species identification (Malausa et al. 2011; Abd-Rabou et al. 2012). Although molecular tools for identifying *M. hirsutus* are not routinely available at present it is likely that further research will soon lead to more widely applicable molecular methods to facilitate identification of this species and other invasive pests.

Biological control of *M. hirsutus*: natural enemies (parasitoids and predators)

In most areas where *M. hirsutus* has become established, native or introduced natural enemies of the species have been effective in maintaining *M. hirsutus* populations below unacceptable levels (Sagarra and Peterkin 1999; Michaud and Evans 2000; Michaud 2003; Roltsch et al. 2006; Reddy et al. 2009). Worldwide, 81 natural enemies of *M. hirsutus* have been identified including 43 parasitoids and 34 predators (Krishnamoorthy and Mani 1989; Michaud and Evans 2000; Meyerdirk et al. 2001; Goolsby et al. 2002; Roltsch et al. 2006; Abd-Rabou 2008; Nalini and Manickavasagam 2011; Ben-Dov et al. 2012; Noyes 2012). Thus, *M. hirsutus* is subject to biological control by a large complex of natural enemies. Many of the natural enemies of *M. hirsutus* are widely distributed and 27 are known to occur in the Neotropical region (Table 3). In various areas where *M. hirsutus* was introduced and became established (Egypt, India, Caribbean, Puerto Rico, California, Florida, Mariana Islands) effective control of *M. hirsutus* has been attributed to several natural enemy species including the encyrtid parasitoids *Anagyrus kamali* and *Gyranusoidea indica*, and the ladybeetle *Cryptolaemus montrouzieri* and/or other coccinellid predators (Sagarra and Peterkin 1999; Michaud and Evans 2000; Singh 2004; Roltsch et al. 2006; Reddy et al. 2009). In Central America, the current restriction of *M. hirsutus* to Belize is attributed to a biological control program that has been established which includes surveillance, monitoring, and production of the natural enemy *A. kamali* (OIRSA 2012).

Since effective natural enemies of *M. hirsutus* including *A. kamali, G. indica*, and *C. montrouzieri* are now present in South America it is possible that they will minimize future impacts of the pest as it spreads in this region. However, in areas where such natural enemies are not present their introduction and release may be warranted. These parasitoids and predators can be relatively easily cultured and multiplied on mealybugs reared on pumpkins, and released as mature adults (or larvae in the case of *C. montrouzieri*). Detailed information on rearing natural enemies of *M. hirsutus* is provided by Meyerdirk et al.

Table 2 Geographic distribution and some key morphological characters that distinguish *M. hirsutus* from other *Maconellicoccus* species

Species	Geographic distribution	Number of cerarii (pair)	Circulus
Maconellicoccus hirsutus (Green)	Afrotropical, Australasian, Nearctic, Neotropical, Oriental, Palaearctic	4-7 (usually 4-6, 4-5 recognizable)	Present (usually undivided)
M. lanigerus (Fuller)	Australasian: Australia	1	Present
M. tasmaniae Williams	Australasian: Australia	1	Present
M. australiensis (Green and Lidgett)	Australasian: Australia	1	Absent
M. leptospermi Williams	Australasian: Australia	4	Absent
M. multipori (Takahashi)	Oriental: India, Indonesia, Malaysia, Nepal, Philippines, Singapore, Thailand	4	Absent
M. ramchensis Williams	Oriental: Nepal	4	Present (divided)
M. ugandae (Laing)	Afrotropical: Cameroon, Ghana, Kenya, Sudan, Tanzania, Uganda	4	Present (variable)

Table modified from Miller (1999) based on Williams (1996) and Ben Dov et al. (2012); *M. hirsutus* differs from *M. ugandae* by having oral rim tubular ducts of one size compared to those of *M. ugandae* which are of two sizes (Williams 1996)

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Table 3 Natural enemies (parasitoids and predators) of *M. hirsutus* known in the Neotropics as of 2012

Taxa	Geographic distribution[a]	Reference
Aphelinidae		
Aphelinus sp.	Aus, Nea, Neo, Ori, Pal	Meyerdirk et al. (2001)
Marietta leopardina Motschulsky	Afr, Aus, Nea, Neo, Ori, Pal	Abd-Rabou (2008)
Marietta picta André	Nea, Neo, Ori, Pal	Abd-Rabou (2008)
Encyrtidae		
Acerophagus nubilipennis Dozier	Neo	Michaud and Evans (2000)
Anagyrus dactylopii (Howard)	Aus, Neo, Ori, Pal	Noyes (2012)
Anagyrus fusciventris (Girault)	Aus, Nea, Neo, Ori, Pal	Noyes (2012)
Anagyrus greeni Howard	Afr, Neo, Ori, Pal	Ben-Dov et al. (2012)
Anagyrus kamali Moursi	Neo, Ori, Pal	Marsaro Jr. et al. (2013)
Anagyrus pseudococci Girault	Afr, Nea, Neo, Ori, Pal	Noyes (2012)
Blepyrus insularis Cameron	Afr, Aus, Nea, Neo, Ori, Pal	Noyes (2012)
Cheiloneurus inimicus Compere	Nea, Neo	Michaud and Evans (2000)
Coccidoctonus sp.	Afr, Aus, Neo	Noyes (2012)
Coccidoxenoides perminutus Girault	Afr, Aus, Nea, Neo, Ori, Pal	Noyes (2012)
Gyranusoidea indica Shafee, Alam and Agarwal	Aus, Neo, Ori, Pal	Noyes (2012)
Leptomastidea abnormis (Girault)	Afr, Aus, Nea, Neo, Ori, Pal	Noyes (2012)
Leptomastix dactylopii Howard	Afr, Aus, Nea, Neo, Ori, Pal	Abd-Rabou (2008); Culik et al. (2011)
Rhopus nigroclavatus Ashmead	Aus, Nea, Neo, Ori, Pal	Noyes (2012)
Eulophidae		
Aprostocetus minutus (Howard)	Nea, Neo, Ori	Michaud and Evans (2000)
Pteromalidae		
Pachyneuron muscarum L.	Neo, Pal	Ben-Dov et al. (2012)
Coccinellidae		
Coelophora inaequalis (Fabricius)	Aus, Nea, Neo, Ori	Michaud and Evans (2000)
Cryptolaemus montrouzieri Mulsant	Afi, Aus, Nea, Neo, Ori, Pal	Michaud and Evans (2000)
Cycloneda sanguinea limbifer Casey	Nea, Neo	Michaud and Evans (2000)
Diomus sp.	Neo	Michaud and Evans (2000)
Hippodamia convergens Guérin-Méneville	Nea, Neo	Meyerdirk et al. (2001)
Scymus coccivora Ayyar	Aus, Neo, Ori	Meyerdirk et al. (2001)
Zilus eleutherae (Casey)	Nea, Neo	Michaud and Evans (2000)
Chrysopidae		
Chrysoperla carnea (Stephens)	Afr, Aus, Nea, Neo, Ori, Pal	Krishnamoorthy and Mani (1989)

[a] Biogeographic regions: *Afr* Afrotropical, *Aus* Australasian, *Nea* Nearctic, *Neo* Neotropical, *Ori* Oriental, *Pal* Palearctic

(2001) and Sanches and Carvalho (2010), and useful methods for monitoring and evaluating the impact of management methods on *M. hirsutus* and its natural enemies are described in Roltsch et al. (2006).

Although natural enemies are usually effective in controlling *M. hirsutus*, it has been observed that significant populations of the insect may develop on some species of plants including *Citrus* spp. and cocoa even in areas where natural enemies are effective in controlling the mealybug on other host plant species (Kairo et al. 2000). Williams (1996) noted the apparent relationship between problems with *M. hirsutus* on grapes in India and destruction of natural enemies in "fields sprayed regularly with insecticides." Therefore, additional research may be needed to identify factors that favor development of *M. hirsutus* (or inhibit natural enemies) in such cases, and to develop and institute integrated pest management methods in such crops.

Because large populations of invasive pests may build up in newly invaded regions before their natural enemies are established or develop sufficient population levels for effective control of the pest, there is a danger that pesticides or other management methods may be inappropriately applied that may inhibit the establishment or buildup of the natural enemies (Sagarra and Peterkin 1999). Therefore, verification of the presence of natural enemies of the invasive species in areas of concern and newly invaded areas, and education of the public to prevent the

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destruction of effective natural enemies if they are known to be present is especially important for invasive pests such as *M. hirsutus* which are commonly controlled by natural enemies in invaded regions (Sagarra and Peterkin 1999; Michaud and Evans 2000; Michaud 2003; Roltsch et al. 2006; Reddy et al. 2009).

Although the immense biodiversity of South America, like that of much of the world, remains largely unknown, it is apparent that this biodiversity contributes to control of invasive and other pests in this region (Parra et al. 2003; Millennium Ecosystem Assessment 2005; Culik et al. 2011). Clearly this is one of many reasons why care must be taken to prevent destruction of biodiversity as well as obtain a more complete knowledge of it. Although native natural enemies are likely to help control many invasive pests in South America in some cases classical biological control has also been utilized for control of such organisms in the region. These efforts have included successful introduction of the Asian parasitoid *Neodusmetia sangwani* for control of the mealybug *Antonina graminis* (Machado da Costa et al. 1970) and the parasitoids *Apoanagyrus diversicornis, Aenasius vexans,* and *Acerophagus coccois* for control of mealybug *Phenacoccus herreni* (Bento et al. 2000).

Anagyrus kamali and *G. indica* are known to be present in Brazil and Guyana (Noyes 2012; Marsaro Jr. et al. 2013) and *C. montrouzieri* is established in several South American countries including Brazil where it was introduced in 1998 as a proactive strategy for control of *M. hirsutus* in case it entered the country (Sanches et al. 2002; González 2012). Thus, populations of these natural enemies adapted to areas in South America may be available for use in other areas in the region for control of *M. hirsutus* where these beneficial insects are not currently present. Past experience indicates that it is feasible to introduce these insects to new areas for control of *M. hirsutus*, and that ecological risks from introduction of *A. kamali* and *G. indica* may be considered to be minimal since they are relatively host specific (Roltsch et al. 2006; Noyes 2012). As a predator with a broader host range, risks from introduction of *C. montrouzieri* to new areas may be considered to be of greater concern but should be evaluated with respect to alternatives for *M. hirsutus* management which may be of greater ecological risk.

Other management methods

It is apparent that biological control agents are generally effective in controlling *M. hirsutus* and maintaining populations of the mealybug below economically damaging levels (Sagarra and Peterkin 1999; Michaud and Evans 2000; Michaud 2003; Roltsch et al. 2006; Reddy et al. 2009). However, eradication of limited infestations to prevent spread of the insect to uninfested regions may be justified in some locations, and in regions where *M. hirsutus* is established there may be a low tolerance for infestation, damage, or symptoms of the pest on some plants such as ornamentals (Vitullo et al. 2009; Castle and Prabhaker 2011). Therefore integration of other pest management methods may be necessary for management of this mealybug in some cases and several other management methods for *M. hirsutus* have been investigated recently including pesticide application, post-harvest treatment, and plant breeding.

Because of the importance of natural enemies for control of *M. hirsutus* in most areas where it is established, other management methods such as pesticide application can only be recommended if used in an integrated manner to avoid negative impacts on the biological control agents that commonly maintain pest populations at low levels (Sagarra and Peterkin 1999; Michaud and Evans 2000; Michaud 2003; Roltsch et al. 2006; Reddy et al. 2009). In general, pesticide application for management of *M. hirsutus* has been considered to be impractical for various reasons including cost and ineffectiveness (Sagarra and Peterkin 1999). In addition, if not used properly there is a danger that insecticides applied for control of *M. hirsutus* will negatively impact natural enemies and inhibit natural biological control of the pest (Williams 1996; Daane et al. 2012). However, as part of efforts to evaluate methods to contain and reduce *M. hirsutus* infestations in the Imperial Valley, Castle and Prabhaker (2011) tested several systemic insecticides to eliminate *M. hirsutus* from infested trees. Insecticide treatment eliminated *M. hirsutus* infestation in about 50 % of the trees treated indicating that the method might be of use for elimination of high risk *M. hirsutus* infestations such as those on plants located in high traffic areas (representing a high risk as a source for spread of the pest), and for eradication of initial (limited) infestations in new areas to prevent establishment of the pest (Castle and Prabhaker 2011). An insecticidal soap was among the most effective pesticides evaluated for control of *M. hirsutus* on grapes and safest for natural enemies (Katke 2008; Daane et al. 2012).

Ants often form a symbiotic relationship with mealybugs such as *M. hirsutus* by feeding on honeydew secreted by the insect and inhibiting its natural enemies (García-Valente et al. 2009). Various studies in cultivated crops indicate that management of ants associated with mealybugs may reduce damage caused by these insects and methods including use of baits to control ant colonies may also be useful for management of *M. hirsutus* (Daane et al. 2012).

There are also concerns regarding the potential spread of *M. hirsutus* on infested fruit, therefore Hara and Jacobsen (2005) studied hot water treatments for disinfestation of fresh fruits infested with the mealybug. Effective temperature time combinations for control of *M. hirsutus* on fruits

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were considered to be 55 min 47 °C, 23 min 48 °C, and 13 min 49 °C and it was concluded that the hot water immersion treatment used to control fruit flies on longan, *Dimocarpus longan* Loureiro, and lychee, *Litchi chinensis* Sonnerat, (20 min 49 °C) is also effective for this insect (Hara and Jacobsen 2005).

Cosmetic damage to ornamental plants such as *Hibiscus* species is one of the major problems caused by this pest in infested regions because there is commonly a low tolerance for signs or symptoms of the pest on these plants (Vitullo et al. 2009; Aristizábal et al. 2012). Because symptoms of *M. hirsutus* infestation on plants vary depending on the plant species and cultivar (OEPP/EPPO 2005; Vitullo et al. 2009), Aristizábal et al. (2012) conducted studies of *H. rosa-sinensis* cultivars to determine if the cultivars differed in susceptibility or resistance to the mealybug. Although resistance to *M. hirsutus* by *H. rosa-sinensis* was not detected in several cultivars evaluated, some differences in damage symptoms and development of the pest were observed and it was concluded that selection or breeding of tolerant cultivars could be useful for low management input landscapes (Aristizábal et al. 2012).

As for any pest, regardless of what pest management methods are used for control of *M. hirsutus* they should be used in an integrated manner as part of an established integrated pest management program to ensure environmental safety and sustainability (Daane et al. 2012).

Conclusions

Maconellicoccus hirsutus is an invasive pest in part because it is easily transported to new areas on infested plant products (produce, ornamentals etc.) and other objects (for example, sticky eggs and mobile crawlers on clothing) (Kairo et al. 2000). Therefore, besides quarantine measures, public education is necessary to reduce the spread of this insect to new areas. Because *M. hirsutus* is difficult to eradicate after it becomes established, in addition to public education to minimize spread of the insect, education, and extension in infested areas should be directed toward preventing improper use of pesticides which may inhibit effective control of *M. hirsutus* by natural enemies (Sagarra and Peterkin 1999).

Maconellicoccus hirsutus occasionally causes damage to plants especially in areas where it has been newly introduced, where suitable and susceptible host plant are present, and where its natural enemies are not present, but where natural enemies of this insect are present it usually causes little damage (Sagarra and Peterkin 1999; Michaud and Evans 2000; Michaud 2003; Roltsch et al. 2006; Reddy et al. 2009). Therefore, management of *M. hirsutus* depends on preservation of its natural enemies (and introduction of natural enemies if they are not present). A better understanding of the actual, specific factors that favor *M. hirsutus* development and damage, as well as the factors that inhibit the species (such as biological control agents), will also contribute to appropriate, sustainable methods for integrated management of the species in those areas where it may be introduced or established and inhibit its spread to new areas (Kairo et al. 2000). Because native or established biological control agents may be sufficient to control invasive pests that become established in new areas (Michaud 2003), increased knowledge of, and preservation of indigenous biological control agents of pests is likely to reduce problems from invasive species such as *M. hirsutus* where they may be introduced. In addition, knowledge of the presence of indigenous natural enemies is also necessary because when considering the introduction of biological control agents (classical biological control) for control of invasive pests in areas where they may be newly established, it is necessary to evaluate potential impacts of introduction of non-native biological control agents on native fauna and ecosystems (Roltsch et al. 2006; Simberloff 2009).

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