

## A review of the status of the coconut mite, *Aceria guerreronis* (Acari: Eriophyidae), a major tropical mite pest

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**Abstract** The coconut mite (CM), *Aceria guerreronis* Keifer, has spread to most coconut production areas worldwide and it has been considered one of the most notorious and important pests of coconut fruits in many countries. Although CM has been reported to damage coconuts for over 40 years in the Americas and Africa it continues to cause considerable losses in countries of these continents, and in the last 15 years it has also reached countries from southeast Asia—India and Sri Lanka. Several other countries of southeast Asia are also major coconut producers and the impact by the mite in currently affected areas suggests that the dispersion of CM to these major producers could lead to very heavy losses. Great advances about our knowledge on CM and its control have been achieved, especially in the last decade, after its introduction into Asia. However, much remains to be known to allow the design of efficient strategies to it. This paper brings together information on CM invasive history, distribution, hosts, morphology, biology, dispersal, colonization process, population dynamics, symptoms and injury, estimated losses, sampling techniques, control strategies and new perspectives for its control.

**Keywords** Plant protection · Invasive mite · Eriophyoidea · Biological control ·  
*Cocos nucifera* · Pest management

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## Introduction

Several palm species have been developed into crops over the centuries, one of the most important being coconut (*Cocos nucifera* L.) (Howard et al. 2001). This palm probably originated between the extreme southeast Asia and the Pacific island of Papua New Guinea (Lebrun et al. 1998; Persley 1992). Since prehistoric times the fruits of this palm have been carried by ocean currents (Chan and Elevitch 2006) and then by human activity. Coconut palm has now a wide pantropical distribution (Chan and Elevitch 2006). Currently, hundreds of millions of people consume each day both coconut water and kernel derivatives (Foale 2003). Not only is coconut nowadays a staple food, but it is also of major commercial importance and some products derived from the fruit (copra, coconut cream and protein, whole mature nuts, coir, and activated carbon) are traded internationally. Coconut cultivation covered approximately 11.2 million ha in 2009 (9.4 million ha in Asia, 0.7 in the Americas and 0.7 in Africa), mainly in Indonesia, Philippines, India, Sri Lanka, Thailand, Vietnam, Papua New Guinea, Malaysia, Brazil and Mexico (FAOSTAT 2011).

Probably due to the wide dissemination of coconuts around the globe, many coconut pests also became widely distributed. However, new invasive pests associated with coconut have been of concern during the last decades, including the coconut leaf beetle, *Brontispa longissima* Gestro (Aquino 2008); the palm red mite, *Raoiella indica* Hirst (Peña et al. 2006; Welbourn 2009), and the coconut mite (CM), *Aceria guerreronis* Keifer. This phytophagous mite has spread to most coconut production areas worldwide and it has been considered one of the most notorious and important pests of coconut fruits in many countries.

Although CM has been reported to damage coconuts for over 40 years in the Americas and Africa (Cabral and Carmona 1969; Mariau 1969; Ortega et al. 1967; Robbs and Peracchi 1965; Zuluaga and Sánchez 1971), new information about its biology, ecology, taxonomy, control and economic importance of CM have been continuously published. CM not only continues to cause considerable losses in American and African countries, but in the last 15 years it has also reached countries from southeast Asia—India and Sri Lanka (Fernando et al. 2002; Sathiamma et al. 1998)—, where coconut is economically and socially much more important than in the countries from where CM was known before. Several other countries of southeast Asia are also major coconut producers (FAOSTAT 2011). The impact by the mite in India and Sri Lanka (Fernando et al. 2002; Haq 2011) suggests that the dispersion of CM to these countries could lead to very heavy losses.

This paper brings together information on CM invasive history, present distribution, hosts, morphology, biology, dispersal, colonization process, population dynamics, symptoms, injury, estimated losses, sampling techniques, control strategies and new perspectives for its control.

## Invasive history, present distribution and hosts

Coconut mite was described by Keifer in 1965 from specimens collected in the state of Guerrero, Mexico, although, as suggested by Mariau and Julia (1970), some records indicated that it was already found in several regions of the American continent by the time of its original description (Ortega et al. 1967; Robbs and Peracchi 1965; Zuluaga and Sánchez 1971); in Colombia, symptoms had been observed since 1948 (Bain 1948 cited in Zuluaga and Sánchez 1971); in Brazil, since 1953 (GP Arruda, Instituto Agronômico de Pernambuco, Recife, Brazil, pers. comm.); and in Mexico since 1960 (Ortega et al. 1967).

In addition, around the time of its description, CM was also found in 1963 in São Tomé e Príncipe, on the coast of Africa, and in 1967 in Benin, Cameroon, Nigeria and Togo (Cabral and Carmona 1969; Mariau 1969). It was then reported in Colombia in 1970 (Estrada and Gonzalez 1975), Ivory Coast in 1975 (Mariau 1977), Dominica in 1976 (Moore and Alexander 1985), Saint Lucia in 1980 (Moore et al. 1989), Costa Rica in 1985 (Schliesske 1988), Jamaica in 1986 (McDonald 1996 cited in Howard et al. 2001), Oman at the end of the 1980s (Al-shanfari et al. 2010), Puerto Rico in 1990 (Howard et al. 1990) and Tanzania in the late 1990s (Seguni 2000). In Asia, CM was first reported from Sri Lanka in 1997 (Fernando et al. 2002), and soon after, in central Kerala, southern India (Sathiamma et al. 1998). In 1999, it was reported from the entire states of Kerala and Tamil Nadu, in areas of Karnataka and on Lakshadweep islands (Minicoy, Kalpeni and Kavaratti) (Haq 1999). During the last decade, CM spread rapidly to all coconut growing states of India (Muthiah 2007). Surprisingly, the mite has never been reported in the presumed region of coconut origin, namely between the remaining of southeast Asia and Papua New Guinea (Chan and Elevitch 2006).

In addition to coconut, CM has been reported from only three other palm species. Two of these are of American origin: *Lytocaryum weddellianum* (H. Wendl.) (cited as *Cocos weddelliana* H. Wendl.) was found attacked by CM in Brazil (Flechtmann 1989) and *Syagrus romanzoffiana* (Cham.) Glassm. in southern California, USA (Ansaloni and Perring 2002). In both cases, CM was only found on plants in nurseries. It was not found on other wild and cultivated native or introduced palms in extensive surveys conducted in South America since the 1990s (Flechtmann 1998; Gondim et al. 2000; Navia and Flechtmann 2002; Santana and Flechtmann 1998). The third non-coconut host, the Asian palmyra, *Borassus flabellifer* L., was observed to be attacked by CM in India, shortly after the first report of this mite on coconut there (Ramaraju and Rabindra 2002).

Typically, eriophyoid mites have restricted host ranges (Lindquist and Oldfield 1996). Many mites of this group co-exist with their host plants in such a way that they do not cause serious damage, perhaps as a result of co-evolution. Thus, serious harm caused to a plant by an eriophyoid has been conceived to suggest a recent association between the plant and the mite. It has been hypothesized that coconut was recently adopted by CM as a new host (Moore and Howard 1996; de Moraes and Zacarias 2002). According to that hypothesis, CM moved from its original host to coconut after it became extensively cultivated in the Americas or Africa, continents where the mite was first found (Moore and Howard 1996). Several facts support the hypothesis that the original host of CM is not coconut: (1) it has never been reported from the suspected region of origin of coconut (Chan and Elevitch 2006; Lebrun et al. 1998; Persley 1992); (2) it seriously damages coconut, can cause extensive premature fruit drop and has been reported to kill coconut seedlings (Aquino and Arruda 1967; Doreste 1968; Moore and Howard 1996); and (3) it has been reported from other palm hosts. Studies carried out by Navia et al. (2005a) about the genetic variability of CM populations supported the hypothesis of an American origin of this mite, possibly on a non-coconut palm, given that in contrast to the diversity in the Americas, all samples from Africa and Asia were identical or very similar to each other.

## Morphology and biology

Coconut mite is an elongate wormlike, yellowish white eriophyid. Adult females are 205–255  $\mu\text{m}$  long and 36–52  $\mu\text{m}$  wide (Keifer 1965). Eggs are small, white, round to oval. Except for sizes and for the presence of genital openings in adults, all developmental stages

are quite similar. Information about the morphometric variation among populations from the Americas, Africa and Asia was presented by Navia et al. (2006, 2009).

On coconut, CM populations develop on the meristematic zone of the fruits covered by the perianth (bracts). Feeding in this zone causes physical damage that leads to necrosis (Moore and Howard 1996). Mites can be found on coconut inflorescences during the dispersion process (see details in the following section).

Earlier studies on CM biology were conducted by Mariau (1977) in Benin, Suarez (1991a) in Cuba, and Haq (2001) and Sobha and Haq (2011) in India. The authors determined that immature development on coconut can be completed in 8–10.5 days, and that each female may lay up to 66 eggs. Similar to other eriophyids, the immature phase of CM includes the egg, larval and one nymphal stage (Manson and Oldfield 1996).

A more detailed biological study was conducted by Ansaloni and Perring (2004) on pieces of meristematic tissue of young *S. romanzoffiana* leaves, at different temperatures. Development from egg to adult was observed to require 30.5, 16.0, 11.5, 8.1 and 6.8 days at 15, 20, 25, 30 and 35 °C, respectively, and the maximum temperature to allow development was estimated to be close to 40 °C. Lower threshold and optimal development temperatures were calculated to be 9.3 and 33.6 °C, respectively. Although CM is found mainly in tropical and subtropical climates, it can survive for at least 5 h of frost and for more than a week below 5 °C (Howard et al. 1990). Ansaloni and Perring (2004) determined that fertilized females were able to lay a maximum of 51 eggs over a maximum of 43 days. Eggs laid by non-fertilized females produced only male offspring, indicating this species to be arrhenotokous.

## Dispersal

Mite dispersal may occur actively and passively. Active dispersal involves voluntary migration by walking to new host tissues or to neighbor host plants to establish colonies or to a suitable spot where biotic (e.g. phoresy) or abiotic factors (mainly wind) can carry the mites to more distant places. Knowing the mechanisms of CM dispersal is essential for understanding the infestation process of new bunches within or between plants, important for the establishment of management strategies.

It has been determined that CM can walk at a rate of 22.5 cm in 30 min (Galvão et al. 2012). Being negatively geotactic, it tends to move from older to younger inflorescences or upwards (Galvão et al. 2012; Moore and Alexander 1987; Moore and Howard 1996). It has been observed that dispersal involves mostly movement of inseminated females (Moore and Howard 1996). Coconut trees provide a large target for aerially dispersing organisms, but the mortality associated with aerial dispersal is probably high (Moore and Alexander 1987; Moore and Howard 1996). The likelihood of arriving on a fruit is probably increased when air currents carry the mites to inflorescences or to the more vertical leaves in the crown, from which they may drop to bunches (Moore and Howard 1996). Mariau and Julia (1970) observed an increase in the proportion of infested nuts with the distance from the sea line, and related this with the action of the wind, dislodging (and thus, carrying) the mite from the fruits. In their study, the proportion of uninfested nuts decreased from about 45 % on plants growing about 20 m from the sea line to practically 0 on plants about 370 m inland. Similar results were reported by Mariau (1977) in a different study, who determined progressively higher CM damage on plants growing at increasing distance from the sea line, relating it to the action of wind blowing inland.

It has been conjectured that some CM dispersal may take place by phoresy, either on animals attracted to the inflorescences (e.g. pollinators) or fruits (rodents), or on those attracted to such animals (e.g. predatory lizards, birds, predaceous insects) (Moore and Howard 1996). However, these possibilities still remain unconfirmed. Griffith (1984) found adult CM on bees visiting female flowers. He considered that the source of the mites would have to be an infested flower. However the presence of CM on flowers has not been observed on coconut in the studies conducted by Mariau and Julia (1970), Moore and Alexander (1987) and Lawson-Balagbo et al. (2008a). It is possible that infested bees were attracted to fruit exudates allowing dispersing CMs to get on them. Galvão et al. (2012) evaluated the presence of CM on small insects—the bees *Apis mellifera* L. and *Trigona spinipes* (Fabr.) and the curculionid *Parisoschoenus obesulus* Casey—and large insects (e.g., the curculionid *Rhynchophorus palmarum* L.) visiting coconut trees in the field. She also conducted laboratory experiments, concluding that phoresy could occur occasionally. From a total of 1,500 insects collected in the field, only three CM were found, all of them on *P. obesulus* studied specimens. Under laboratory conditions, these authors rarely found CM on *A. mellifera* that had access to highly infested coconut fruits from which the bracts had been removed. Although those numbers are low, the results demonstrate the possibility that new infestations could be initiated by CM dispersing on insects. Given the limitation of CM for active dispersal and its specificity, not only in relation to the host plant but to the host organ attacked (meristematic tissue on coconut fruit), it seems logical to suppose that CM would disperse mostly by climbing onto other organisms that move more efficiently and live on or visit infested coconut fruits or the plant parts next to it, onto which CM may be found while dispersing.

### Colonization process

Varadarajan and David (2002) observed no significant difference between the number of mobile CM on the fruit surface covered by the bracts and on the bracts, but found more eggs on the bracts. Conversely, Thirumalai Thevan et al. (2004) observed more CM on the fruit surface than on the bracts. Recent surveys of the acarine fauna on different parts of coconut palms revealed that the area under the perianth is occupied mostly by CM, harboring a lower diversity of phytophagous and predatory mites than the leaves (Lawson-Balagbo et al. 2008a). Varadarajan and David (2002) evaluated the pattern of CM distribution among the bracts, observing more eggs and post-embryonic stages on the inner bracts. Similar results were obtained by Lawson-Balagbo et al. (2007a) in relation to CM post-embryonic stages.

Very young fruits are almost entirely covered by the perianth, which is tightly adherent to the fruit surface, giving maximal protection against CM. However, as the fruits grow, the space underneath the bracts increases, in many cases allowing CM to first have access to the protected tissues when fruits are about a month old (Howard and Abreu Rodríguez 1991; Mariau 1977; Mariau and Julia 1970; Moore and Alexander 1987; Moore and Howard 1996). The tightness of the bracts to the fruit surface depends on variety, fruit age, water stress and infestation by other phytophagous organisms (Aratchige 2007; Mariau 1977; Moore 1986).

Information on the process of CM colonization of coconut trees and phenological periods when fruits are susceptible to CM infestation is important for the development of management strategies. Mariau and Julia (1970) observed a high rate of abortion of young

coconut fruits, independent of mite attack. At the same time, they noticed that CM could be found on a small proportion of fruits that had been fecundated just a few days earlier and that the level of infestation increased progressively afterwards. Thus, it seems that infested young fruits could also be aborted, reducing the number of infested young fruits on the plants to low levels, possibly turning their detection difficult.

Considerable variation in population levels are observed between infested fruits of a bunch. A study conducted in Sri Lanka indicated that variations seem to be lower on 6-month old fruits, suggesting that the sample from this bunch would be more reliable in population assessments of CM (Fernando et al. 2003). In Brazil, Galvão et al. (2011a) observed no significant differences between CM densities on fruits of basal, median and apical thirds of a bunch, when all fruits of 2- to 6-month-old bunches were considered together. However, the authors observed that on younger bunches fruits of the apical third tended to have lower CM densities than those of the basal third. Fruit age at which lesser variability is observed is expected to vary according to variety and prevailing edapho-climatic conditions. In Brazil, smaller variations for Green Dwarf variety was also observed to occur on 6-month-old fruits, but that was associated with a reduced CM population level (Galvão et al. 2011a).

As with most mites, CM is not evenly distributed among the coconut bunches in a palm. Highest CM population densities have been reported on fruits ranging from 3 to 7 month after fertilization (Moore and Alexander 1987, Varadarajan and David 2002, Fernando et al. 2003, Mallik et al. 2003, Thirumalai Thevan et al. 2004, Galvão et al. 2011a, Negloh et al. 2011). Soon after reaching the maximum level, CM population usually declines quickly. Galvão et al. (2011a) suggested that CM population decline on bunches older than 4 months could be due to an effect of the predator, reduction of the proportion of undamaged tissue amenable to attack and/or less favorable characteristics of the fruits to attack, as indicated by their increasing lignin content as fruits get older. Variations between studies are probably in part due to the different coconut germplasms involved. In one of those studies (Moore and Alexander 1987), CM was observed on fruits up to 13 months after fertilization.

Distribution of CM within a coconut field has not been adequately evaluated. Irregular distribution in many small-grower fields is to be expected, given the common mixture of germplasms under those conditions and the difference in susceptibility observed between germplasms, as discussed further on.

## Population dynamics

High CM population densities have usually been correlated with low humidity levels, but different results have also been reported. Small reduction of CM population was observed by Moore et al. (1989) in Saint Lucia during the rainy season. Mariau (1986) considered that higher CM densities in months of low rainfall may be related to the slower growth of the fruits under those conditions, leaving the growing tissues under the bracts exposed longer to CM attack.

Higher CM levels were reported in the dry periods of the year in Ivory Coast (Julia and Mariau 1979; Mariau 1977), Trinidad & Tobago (Griffith 1984) and India (Mallik et al. 2003; Nair 2002; Varadarajan and David 2002), as well as in dry regions in Colombia (Zuluaga and Sánchez 1971). Results of a study conducted in 112 localities of a wide area in parts of northern and northeast Brazil in 2004–2005 suggested CM to be most abundant in areas with longer dry periods (Lawson-Balagbo et al. 2008a). From July 2008 to January

2010, CM population densities in the state of Bahia, Brazil, showed a positive correlation with temperature and a negative correlation with relative humidity and precipitation (Souza et al. 2012).

In Sri Lanka, CM has spread to all coconut growing areas in the dry- and intermediate-zones (<900 and 900–1,800 mm of rainfall, respectively) and some parts of the wet-zone (>1,800 mm). In that country, damage levels and rate of spread are higher in the dry- and intermediate-zones than in the wet zone (Fernando and Aratchige 2010). A survey carried out from 2000 to 2010 in Sri Lanka revealed that CM population densities are lower in the wet-zone compared to dry- and intermediate-zones of the country (Annual report of the Crop Protection Division, Coconut Research Institute of Sri Lanka 2010; Aratchige et al. 2012). Generally, peak CM densities in Sri Lanka are observed in February–March (onset of the dry season) and June–September (during dry season) and the densities are lower in November, the month with the highest volume and frequency of rainfall (Aratchige et al. 2012). Higher prevalence of CM in Oman was reported to occur in the months with higher temperatures, between February and May (Al-shanfari et al. 2010).

Very different results were obtained in other studies. In Benin, Julia and Mariau (1979) observed that CM levels on 3- to 4-month-old coconuts were 4–5 × higher in months with higher relative humidity (May–October) than in months with lower relative humidity (December–February).

Some studies failed to show significant correlations between CM densities and abiotic factors. In Brazil, Reis et al. (2008) evaluated the prevalence of CM and associated predators on the underside of bracts and on the surface of the fruits underneath the bracts, for 12 months, on coconut palms grown along the coast of northeastern Brazil. No significant correlations were observed between the levels of abiotic factors and the population levels of CM or of the associated phytoseiid predatory mites. Also in Sri Lanka, total rainfall, frequency of rainfall and length of the dry period were not significantly correlated with the variation in CM densities (Aratchige et al. 2012). A non-significant correlation observed between CM densities and levels of each isolate abiotic factor may be due to the simultaneous and conflicting effects of other factors on the mite in the field, or to significant differences between the climatic factors measured in the environment and those prevailing in the habitat occupied by its colonies (Reis et al. 2008). Perhaps the cryptic habitat of CM under the perianth may protect them from direct external abiotic stresses, such as rainfall. It is also possible that this correlation is obscured by other factors, e.g., biotic factors (Moore and Howard 1996).

### Symptoms, injury and estimated losses

Early damage caused by CM becomes progressively more visible as a triangular white patch next to the margin of the perianth; as infested fruits grow, the damaged tissue turns necrotic and corklike, sometimes with deep fissures and gummy exudates. Area damaged by CM may cover half or more of the fruit surface (Howard et al. 2001). Infested fruits later become distorted and stunted, due to uneven growth, leading to reductions in copra yield (Howard et al. 2001; Moore and Howard 1996). CM infestations can also cause extensive premature fruit drop (Doreste 1968; Nair 2002; Wickramananda et al. 2007), significant reduction in coconut fiber length and tensile strength (Naseema Beevi et al. 2003), as well as a reduction in husk availability for the coir industry (Wickramananda et al. 2007).

Coconut mite was reported in the late 1960s to kill coconut seedlings in Brazil, by feeding on coconut palm growing tips (Aquino and Arruda 1967). For unknown reasons, however, this type of damage has not been reported since then.

Symptoms of CM infestation on coconut fruits differ from those of other phytophagous mites also found on coconuts, namely the eriophyid mite *Amrineus cocofolius* Flechtmann and the tarsonemid mites *Steneotarsonemus concavuscutum* Lofego & Gondim Jr. and *Steneotarsonemus furcatus* De Leon. *Amrineus cocofolius* symptoms are characterized by a necrotic transverse strip whose proximal margin is not in contact with the perianth. The strip can encircle the whole fruit and is commonly referred to as ‘ring spot’. Necrosis caused by this mite is more superficial and losses are relatively minor, as the mite affects mostly fruit aesthetic. Damage caused by *S. concavuscutum* and *S. furcatus* is somewhat similar to that of CM; however, the damaged area is typically not triangular, the lateral margins tending to be subparallel to each other (Lofego and Gondim 2006; Navia et al. 2005b).

The impact of CM on coconut has been estimated in several countries, based on several parameters. Comparisons of estimated data between countries are quite difficult because of the use of diverse methodology. Information available for different countries is summarized in Table 1. According to Negloh et al. (2011), the damage reported by Mariau and Julia (1970) for Benin is probably an underestimation of the present situation in that country. Damage today seems to be widespread and high in that country.

Relatively detailed data on the effect of CM have been obtained in Sri Lanka, where the proportions of small and deformed fruits have been observed to be considerably higher when fruits are infested (0.7–25.5 and 0.3–6.9 %, respectively) than when they are not infested (<1 %) (KP Waidyarathne, Coconut Research Institute [CRI], Lunuwila, Sri Lanka, pers. comm.). In India, Rethinam et al. (2003) claimed that the economic value of de-husked fruits was reduced by 30–40 %. Significant reduction in coconut fiber length and tensile strength has also been reported in the same country (Naseema Beevi et al. 2003). Yields of 60.1 kg of white fiber and 59.2 kg of brown fiber were obtained from 1,000 fruits with severe infestation, as compared to yields of 100.5 and 99.4 kg of white and brown fibers, respectively, from the same number of uninfested fruits (Kumar and Ramaraju 2010). An extensive economic analysis of the impact of CM in Indian economy was published by Mathew et al. (2004). These authors concluded that the mite did not play a significant role in reducing the area planted with coconut, but they concluded that CM led to the production of fruits of inferior quality, which in turn led to reduced prices of coconut and coconut products.

Still another effect attributed to CM refers to higher incidence of other pests on CM-attacked fruits, as for example the coconut moth *Atheloca subrufella* (Hulst) (Lepidoptera: Phycitidae), a key pest of coconut in Brazilian coastal areas (Santana et al. 2009). Necrosis around the perianth resulting from CM attack was mentioned to provide access to larvae of this moth under the perianth, causing fruit abortion. Santana et al. (2009) observed that coconut moth larvae were unable to colonize fruits without necrosis.

Coconut mite has also been mentioned to cause significant damage to the queen palm, *S. romanzoffiana*. It has been reported to cause necrosis of meristematic tissues and death of young palms in nurseries of southern California (Ansaloni and Perring 2004), where the plant is valued as an ornamental.

**Table 1** Estimated impact of coconut mite, *Aceria guerreronis*, on coconut

Continent/Countries/Regions	Estimated parameters	References
<i>Africa</i>		
Benin (=Dahomey)	Copra yield loss: 6–18 % (ca. 10 %)	Mariau and Julia (1970)
Benin	Proportion of damaged fruits: 68–85 % (30–40 % of fruit surface damaged)	Negloh et al. (2011)
Ivory Coast	Copra yield loss: 7–15 %; total yield losses: 16–24 %	Julia and Mariau (1979)
Tanzania	Proportion of infested fruits: 70–100 %; premature fruit drop: 10–100 % (mean 21 %); yield loss: 34 %; dry and fresh weight of coconut meat loss: 20–30 %	Seguni (2000, 2002)
	Proportion of damaged fruits: 43–81 % (30–40 % of fruit surface damaged)	Negloh et al. (2011)
<i>The Americas</i>		
Brazil, northeast and northern	Proportion of infested fields: 87 %	Lawson-Balagbo et al. (2008a)
Costa Rica, southern Limon	Proportion of infested palms: 90 %	Schlieske (1988)
Colombia (Caribbean coast)	Fruit infestation: 60 %; reduction on commercial value of fruits: 38 %	Zuluaga and Sanchez (1971)
Cuba, Baracoa	Fresh weight of coconut loss: 15 %; copra yield loss: 12–60 %	Suarez (1990)
	Proportion of infested palms: 42–65 % (ca. 53 %); damage intensity on fruits: 29–41 % (ca. 32 %)	Suarez (1991b)
Jamaica	Copra yield loss: 1–9 %	McDonald (1996), cited in Howard et al. (2001)
Mexico	Copra yield loss: ca. 7–24 %	Mariau (1967)
Mexico, Guerrero	Copra yield loss: 40 %	Hernandez Roque (1977)
	Copra yield loss: 30–80 %	Olivera Fonseca (1986)
Puerto Rico	Proportion of infested palms: 22.4–71.6 %	Howard et al. (1990)
Saint Lucia	Proportion of fruit loss: 31 %	Moore et al. (1989)
USA, Florida	Proportion of infested palms: 66–98 %	Howard et al. 1990
Venezuela	Yield loss: 70 %	Doreste (1968)
	Proportion of damaged fruits: 43–81 % (30–40 % of fruit surface damaged)	Negloh et al. (2011)
<i>Asia</i>		
India	Husk yield: 41.7 %	Muralidharan et al. (2001)
	Husk fiber length: 53 %; time-dehusk: increase in 63 %	Paul and Mathew (2002)
	Proportion of infested palms: 9.2–100 %; button drop: 30 %; copra weight loss: 15–33 %	Rethinam et al. (2003)
	Total weight, husk weight, wet kernel, copra >50 %; water content: 66.9 %	Ramaraju et al. (2005)

**Table 1** continued

Continent/Countries/Regions	Estimated parameters	References
Sri Lanka	Premature fruit drop: 2.9 %; proportion of infested harvested fruits: 69.8–94.5 %; total crop loss: 15.8 %	Wickramananda et al. (2007)
	Proportion of infested palms: 2–100 %	Fernando and Aratchige (2010)
<i>Middle East</i>		
Oman	Proportion of infested palms: 100 %; proportion of infested fruits: 82 %	Al-Shanfari et al. (2010)

### Sampling techniques

One of the most difficult aspects in experimental work with CM refers to sampling, given the small size of the mite and the secluded habitat it occupies. A procedure to relate CM incidence with copra content was proposed by Mariau and Julia (1970). This consisted of the classification of fruits in four categories, according to the degree of damage caused by CM. A slight modification of this procedure, based on five categories, was proposed by Moore et al. (1989).

A procedure to evaluate CM population level was proposed by Galvão et al. (2008) for 2- to 6-month-old fruits of the Dwarf Green variety, based on the proportion of the area damaged by the mite in relation to the total fruit surface. With this scale, they determined that in northeast Brazil CM population peak occurred when the necrotic area due to mite attack corresponded to about 16 % of fruit surface. However, assessment of infestation levels by damage symptoms alone, for fruits of different ages, has been considered not reliable, for at least two reasons: (1) in the very early phase of CM colonization, a considerable percentage of infested fruits does not show damage symptoms (Fernando et al. 2003), and (2) the decline in CM population starts shortly before the maximum level of damage symptoms is expressed, progressing very quickly afterwards, without a proportional reduction in damage symptoms. Thus, quite often actual count of mites is necessary.

However, care should be taken when sampling, to account for the pattern of CM distribution between bunches of different ages in a coconut plant and between fruits in a bunch. Given the high variability of CM population densities, pre-treatment assessment of densities in different plots is often advisable in experimental procedures, to allow adequate statistical analysis (see Fernando et al. 2010). Density variation also affects decisions about sample size, number of samples and sampling frequency.

Counting CM in the field or in the laboratory is difficult because of the small size of the mite and their high population densities. Several techniques have been put into practice to assess population density. The technique used by David and Varadarajan (2001) consisted of placing drops of glycerine onto the attacked surface and counting the mites trapped in each drop, calculated to cover an area of 7 mm<sup>2</sup>, under a stereomicroscope. Another method includes washing the bracts and the surface of the fruit in 30 ml detergent solution, counting the mites in a 1 ml aliquot of this solution and estimating the total number of mites by extrapolation (Fernando et al. 2003, 2010; Siriwaradena et al. 2005). Another procedure involves transferring CM with a brush into 3 ml of 70 % alcohol and a drop of

Tween 80 % and taking a sample of 1 ml of the liquid to count the mites on a Peterson's slide (Reis et al. 2008). A third procedure also involves transferring the mites with a brush into 10 ml of 70 % alcohol and taking a sample of 1 ml of the liquid to count the mites in a counting chamber (Lawson-Balagbo et al. 2007a).

## Control strategies

Mariau and Julia (1970) were the first to point out that chemical control of CM could be difficult because of its secluded habitat, its high reproductive capacity and the possibility for permanent infestation. An additional factor is that many of the common coconut varieties are very tall, hampering pesticide applications. Thus, although efforts have been dedicated to the determination of effective chemical control agents, other means of pest control have also been evaluated.

### Chemical

Apparently, the first evaluation of chemical products for CM control was done by Mariau and Julia (1970) in Africa. They observed that most of the 23 tested products were not effective; only chinomethionate (Morestan) showed some efficiency. As a follow up, Mariau and Tchibozo (1973) also reported promising CM control with the use of chinomethionate and monocrotophos (Nuvacron), when applications were repeated every 3 weeks. Hernández Roque (1977) showed that CM control with dicrotophos, monocrotophos or chinomethionate sprayed onto bunches of developing fruits every 20 or 30 days significantly reduced damage. Julia and Mariau (1979) verified that periodic injection of monocrotophos could effectively control the mite on young plants, but concluded that this application was too traumatic for use in adult plants.

In the Caribbean region, Moore and Alexander (1987) and Moore et al. (1989) reported unsuccessful results with stem injection of vamidothion. However, in the same region Cabrera (1991) considered dicrotophos, chinomethionate and monocrotophos to be efficient in CM control.

Soon after the pest was first reported in Sri Lanka, trunk injection of monocrotophos was recommended. Although control seemed quite effective initially, it was soon abandoned, as the effectiveness lasted only for about 2 months (Fernando et al. 2002). Later, two botanical products were recommended, namely 2 % neem oil + garlic mixture, and Neem Azal T/S (1 % azadirachtin). Studies are still being conducted, to identify chemicals of low toxicity to be integrated with other control strategies.

In India, quite many chemicals have been tried successfully, such as 2 % neem oil and garlic mixture (Nair et al. 2002), root feeding with monocrotophos (Nair 2002; Sujatha et al. 2003), fenpyroximate (Sujatha et al. 2003), triazophos (Mohanasundaram et al. 1999; Ramaraju et al. 2002; Rethinam et al. 2003), methyl demeton 25EC (Ramaraju et al. 2002), azadirachtin, endosulfan and carbosulfan (Rethinam et al. 2003; Sujatha et al. 2003), and sprays of carbosulfan (Muthiah et al. 2001), dicofol and triazophos (Muthiah et al. 2001; Rethinam et al. 2003) and fenazaquin, azadirachtin, NSKE and neem oil (Pushpa and Nandihalli 2010). Several other trials with chemical pesticides were reported by Pushpa and Nandihalli (2010). However, the need for repeated applications showed those techniques to be mostly unsustainable.

In Brazil, good control of CM was reported by Moreira and Nascimento (2002) with the use of hexythiazox (Savey), either in isolation or when associated with other products.

Coconut growers were reported to obtain good control using botanical miticides (e.g. cotton, soybean, neem oil) mixed with a surfactant (detergent) each 3 or 4 weeks (Chagas et al. 2005).

Regardless of the results of efficiency tests of pesticides, chemical control is usually an expensive practice, especially when repeated applications are necessary, as seemingly the case for CM control. The high cost turns this practice economically prohibitive for small-scale farmers (Moore and Howard 1996; Muthiah and Bhaskaran 2000; Persley 1992; Ramaraju et al. 2002), who in most countries are the main coconut producers. In addition, the frequent use of chemicals can cause undesirable environmental impact. Under these circumstances, alternative control measures seem highly desirable.

### Biological control

Relatively little efforts had been dedicated to the evaluation of natural enemies of CM until the end of the last century (Moore and Howard 1996; de Moraes and Zacarias 2002), but efforts have become more intense in the last 10 years, after the first detections of CM in Asia. Predators and acaropathogenic fungi are the most common natural enemies collected.

### Predator diversity

Information about predatory mites on coconut palms was reviewed by de Moraes and Zacarias (2002). The predators reported were species of the orders Prostigmata and Mesostigmata. Among the Mesostigmata, they reported a few species of Blattisociidae and Melicharidae (both then included in the Ascidae) and many more Phytoseiidae, in various parts of the world. Few of those species had been reported in close association with CM, namely the blattisociid *Lasioseius* sp., the melicharids *Proctolaelaps* sp. and *Proctolaelaps bickleyi* (Bram), as well as the phytoseiids *Amblyseius largoensis* (Muma), *Neoseiulus baraki* Athias-Henriot, *Neoseiulus mumai* (Denmark), *Neoseiulus paspalivorus* De Leon and *Typhlodromips sabali* (De Leon).

Classical biological control has been considered an appropriate approach to provide a sustainable solution to the CM problem. This approach essentially corresponds to the determination of effective natural enemies in the area of origin of the pest, which should then be introduced and field released in the new region where the pest was introduced, seeking the permanent establishment of the natural enemies and the subsequent pest control. In this context, efficient natural enemies of CM should be prospected in the tropical areas in the Americas, considered to be its possible area of origin (Navia et al. 2005a).

As part of the first step to identify effective CM natural enemies, surveys have been conducted throughout northern and northeastern Brazil. The first work conducted in that country specifically to determine the common predatory mites on coconut palms was reported by Gondim and de Moraes (2001). In that study, 18 phytoseiid species were found, but emphasis was then placed on mites on leaves. Subsequently, Navia et al. (2005b) reported the following predatory mites in direct association with CM: the melicharids *Proctolaelaps longipilis* Chant and *Proctolaelaps bulbosus* de Moraes, Reis and Gondim Jr. (reported as *Proctolaelaps* sp.; see de Moraes et al. 2008) and the phytoseiids *Typhlodromus (Anthoseius) ornatus* (Denmark and Muma) and *Amblydromalus manihoti* (de Moraes). The first extensive work specifically to search for prospective natural enemies of CM in Brazil was conducted by Lawson-Balagbo et al. (2008a). About 81 % of all predatory mites found were phytoseiids, mainly represented by *A. largoensis*,

*N. paspalivorus* and *N. baraki*; 12 % were reported as melicharids and blattisociids, mainly *Proctolaelaps* sp., *P. bickleyi* and *Lasioseius subterraneus* Chant. *Neoseiulus paspalivorus* and *N. baraki* were the most abundant predators on fruits attached to the palms, melicharids and blattisociids were predominant on fallen coconuts, whereas *A. largoensis* was predominant on leaves. *Neoseiulus paspalivorus*, *N. baraki* and *P. bickleyi* were reported by those authors as the most promising CM predators in the surveyed areas.

A new study was initiated in 2008 to evaluate the natural enemies in other coconut-growing areas in the northern Brazilian states of Roraima and Rondonia, as well as in states of Colombia, Mexico and Venezuela (Silva et al. 2010). The most abundant predatory mite found on fruits was *N. paspalivorus*, followed by *P. bickleyi*. *Neoseiulus baraki* was rare in the visited areas. Phytoseiids and ascids were commonly found in association with CM in Colombia and Venezuela, but not in Roraima, Rondonia or Mexico. The authors concluded that the predators found apparently could not prevent damage by CM, but admitted that damage could be higher in the absence of predators. For unknown reasons, neither *N. baraki* nor *N. paspalivorus* were found in the state of São Paulo, southeastern Brazil, in three surveys conducted within a period of one year in six coconut plantations (Oliveira et al. 2012). In that study, the most common predators on coconut fruits were *P. bickleyi* and *P. bulbosus*.

Studies on diversity of CM natural enemies have also been conducted in other continents. Such studies are necessary, as a base line for subsequent determination of the role of native natural enemies in the control of the pest and to facilitate the analysis of eventual efforts for the establishment of introduced natural enemies. In Sri Lanka, de Moraes et al. (2004a) reported five phytoseiid species on coconut, three of which, *N. baraki*, *N. paspalivorus* and *A. largoensis*, on fruits, in association with CM. *Amblyseius largoensis* was determined to be mostly found on leaves. The authors stated that what was reported by Fernando et al. (2002, 2003) and Fernando and Aratchige (2003) as *N. aff. paspalivorus* most probably referred to *N. baraki*, determined to be much more abundant than *N. paspalivorus* in that country.

Several studies have also been conducted in India. Haq (2001) reported many predatory mites from that country, including *A. largoensis*, *N. paspalivorus* and *Bdella indicata* (could be a misspelling for *B. distincta* Baker and Balogh) (Bdellidae). Ramaraju et al. (2002) reported the predator *N. paspalivorus* in association with CM on the surface of infested coconuts in southern India. Shobha (2004) reported the predatory mites from Kerala, including species reported as *Typhlodromus pyri* Scheuten (Phytoseiidae), *Cheyletus cocos* (Cheyletidae), *Agistemus industani* Gonzalez (Stigmaeidae), *Amblyseius* sp. and *Bdella* sp. It is possible that *T. pyri* corresponds to a misidentification, given that this species seems to occur mainly in temperate areas (de Moraes et al. 2004b). In the Indian state of West Bengal, the following predatory mites were reported in association with CM: *A. largoensis*, *N. paspalivorus*, *Proctolaelaps* sp., *Lasioseius* sp. and the Cheyletidae *Cheyletus malaccensis* Oudemans (Banerjee and Gupta 2011).

In Oman, Middle East, the main natural enemies associated with CM were the phytoseiids *N. paspalivorus* and *Cydnoseius negevi* (Swirski and Amitai) (Hountondji et al. 2010; Perez et al. 2010).

In Africa, the occurrence of *N. baraki* (Negloh et al. 2008) and *N. paspalivorus* (Negloh et al. 2010) was reported in Benin, while Sourassou et al. (2011) reported the latter species also in Benin and Ghana. Negloh et al. (2011) reported *N. baraki*, *N. paspalivorus* and *Neoseiulus neobaraki* Zannou, de Moraes and Oliveira as the most common predators in Benin and Tanzania, indicating that *N. neobaraki* was the prevalent predator in Tanzania, whereas *N. paspalivorus* was prevalent in Benin.

Given the widespread distribution of populations identified as *N. baraki* and *N. paspalivorus*, recent studies have been conducted to determine whether these are really two widespread species, or whether either could actually comprise a complex of very similar species. Comparisons of geographic populations identified as *N. paspalivorus* and *N. baraki* have shown considerable variation between them, in terms of their morphology, biology and predation potential on CM. These differences have been observed for populations identified as *N. paspalivorus* from geographically largely separated populations, from Brazil, Benin and Ghana (Sourassou et al. 2011). Inter-population crosses showed complete reproductive isolation between them, despite the absence of interpopulation discontinuities in relation to evaluated morphological characters. The results suggested that the tested populations are distinct biological entities. Further molecular analysis to determine genetic distance between populations/taxons should be conducted to help understand whether these *N. paspalivorus* populations could represent cryptic species. However, it could be argued that gene flow between the tested African populations could still occur, through crossings between geographically intermediate populations. In addition, the determined reproductive isolation could be the result of differential occurrence of endosymbionts between mite populations.

Studies to compare populations of *N. baraki* from Brazil and Africa have also been conducted, and important differences have been found (Negloh et al. 2008), suggesting that those differences could be due to the occurrence of a complex of species identified as *N. baraki* in Brazil and Africa. Morphological, molecular and cross-breeding studies of those populations provided evidence for the existence of cryptic species. Subsequent morphological research showed that the Benin population can be distinguished from the others by the number of teeth on the fixed digit of the female chelicerae (Sourassou et al. 2012).

### *Predator biology*

Studying life history is one of the basic requirements for evaluating the potential of natural enemies as bio-control agents. The biology of the predatory mites most commonly found on coconut plants has been studied in the last few years. Lawson-Balagbo et al. (2007a,b) studied life history parameters of *N. paspalivorus* and *P. bickleyi* comparing survival, development and reproduction when feeding on CM, two other mite prey, a fungus and coconut pollen. The results showed that CM is a suitable food source for both predators. When fed with CM, the predators had relatively shorter developmental times, higher oviposition rates and higher intrinsic rates of increase. This work indicated *N. paspalivorus* and *P. bickleyi* as promising candidates for classical or augmentative biological control of CM. Their characteristics suggest that they may complement each other in relation to CM control.

To evaluate the type of interaction of *N. paspalivorus* and *P. bickleyi*, Lawson-Balagbo et al. (2008b) conducted a laboratory study in units mimicking the area under the perianth of coconut fruits. They determined that both predators preyed upon the other, but their interaction was considered to be relatively moderate, concluding that it should not compromise their compatibility and that it should not preclude their combined use for CM control. If the perianth remains tight to the fruit surface and the entrance points are small, only *N. paspalivorus* would gain access, leaving *P. bickleyi* outside. This would reduce the encounter rate of the two predators. However, if the access points to the area under the perianth are wide enough, *P. bickleyi* is expected to invade, building up its populations and then being able to affect *N. paspalivorus* (Aratchige 2007; Aratchige et al. 2007; Finke and Denno 2006). Such a situation may influence residence of *N. paspalivorus* under the

perianth and possibly trigger earlier dispersal out of this area. However, the voracity of *P. bickleyi* when preying on CM should more than compensate premature dispersal of *N. paspalivorus*. In a recent study, however, Lima et al. (2012) obtained evidences that *P. bickleyi* might not have a strong dependence on CM as food source, given its high feeding requirement in relation to the average number of CM on each infested fruit.

The life history of a Brazilian and a Beninese population of *N. baraki* on prey and non-prey diets were studied under laboratory conditions by Negloh et al. (2008). Both populations were able to complete juvenile development and to reproduce when feeding on CM, *Tetranychus urticae* Koch eggs and maize pollen, but they developed faster on CM than on any other diet. The intrinsic rate of natural increase and net reproductive rate were significantly higher for the Brazilian than for the Beninese population: 0.19 vs. 0.16 and 24.9 vs. 18.0, respectively. These results suggest that the Brazilian population is a more specialized and efficient predator of CM, suggesting the former to deserve detailed experimental field evaluations in Africa.

A detailed biological study of a Brazilian population of *N. baraki* was conducted by Domingos et al. (2010). In choice tests, *N. baraki* showed a marked preference for CM in relation to two other mite species and coconut pollen. The predator completed immature development when fed on CM and these other mite species, but not on coconut pollen. Fecundity was highest on the acarid mite *Tyrophagus putrescentiae* (Shrank) followed by CM. However, attempts to establish a colony of *N. baraki* on a mixture of the stages of *T. putrescentiae* was unsuccessful. This latter information contrasts with the results of Fernando et al. (2004), who were able to mass rear this predator on a diet composed of all stages of *T. putrescentiae*. Results also suggest that *N. baraki* may use the tarsonemid *S. concavuscutum* and coconut pollen as alternative food items. These are not very favorable, as demonstrated by the low values of biotic parameters, but they may be used during temporary absence of more favorable food items, as they are both commonly found on coconut fruits. The work suggested that the Brazilian population of CM is a favorable prey for the Brazilian population of *N. baraki*, and that this predator can also consume other items commonly found on coconuts as alternative food.

In Sri Lanka, efforts have been directed to the augmentative biological control of CM with *N. baraki*. Researchers have considered that among the predators found in association with CM, this species and *N. paspalivorus* are apparently the most fitted as control agents of the pest, for the flattened idiosoma and short legs (de Moraes et al. 2004a), which allow them to more easily reach the microhabitat occupied by CM. In Sri Lanka, emphasis has been given to turn viable the use of *N. baraki* for CM control. A successful method to mass rear this predator is a pre-requisite to evaluate the viability and effectiveness of its inundative releases. Two successful methods, namely tray-type arena (Aratchige et al. 2010) and sachet-type method (Kumara et al. 2012) have been developed to mass produce *N. baraki*.

*Proctolaelaps bulbosus* was described from northeastern Brazil in association with CM. The biology of this species was studied under laboratory conditions (Galvão et al. 2011b). Results indicated that this is another prospective species for use as biocontrol agent of CM in other parts of the world, given that it is more commonly found on standing fruits than the somewhat larger *P. bickleyi* (Lawson-Balagbo et al. 2008b, reported as *Proctolaelaps* n. sp.; Galvão et al. 2011b). It was able to develop to adulthood when fed on CM, *Rhizoglyphus* aff. *stolonifer* (Ehrenb) and *T. putrescentiae*, but not on *S. concavuscutus*, *T. urticae* or coconut pollen. CM was shown as the most suitable food for *P. bulbosus* (Galvão et al. 2011b).

Biological aspects of the phytoseiid mites *A. largoensis* and *Euseius alatus* De Leon, phytoseiid mites commonly found on coconut plants in northeast Brazil, were also studied by Galvão et al. (2007) and da Melo et al. (2009), respectively. The morphology of these predatory mites does not favor the exploitation of the meristematic area of the fruit inhabited by CM; they are mostly found on leaves and on the exposed fruit surface. The results suggested that *A. largoensis* and *E. alatus* can prey upon CM under natural condition and that they may help in the control of this pest when it leaves its refuge to disperse.

### Predator ecology

Understanding plant-pest-predator interactions is needed for the development of a biological control strategy. Hence, the ecology and biology of both pest and natural enemies should be known.

In Brazil, *N. paspalivorus* and *N. baraki* were reported to have different climatic requirements, the first being most abundant in warmer and dry areas and the second prevailing in moderately tempered and humid areas (Lawson-Balagbo et al. 2008a). Fernando and Aratchige (2010) also observed the different climatic requirements of those species in Sri Lanka, the former being most common in the dry and intermediate zones and the latter, in wet zones and wet areas within dry zones.

Foraging directly interferes with the efficiency of a particular biological control agent. To understand how *N. baraki* and *P. bickleyi* respond to olfactory cues from CM and its host plant, the foraging behavior of the predatory mites was investigated in a Y-tube olfactometer and on T-shaped arenas by da Melo et al. (2011a). They concluded that *N. baraki* and *P. bickleyi* are attracted to chemical cues emitted by coconut plants infested by CM, facilitating the encounter of predator and prey and increasing their efficiency by reducing the time required for prey localization, a desired foraging behavioral trait for biological control agents.

Field and laboratory observations suggest that many potential predators have difficulties to invade the refuge used by CM. Lawson-Balagbo et al. (2007a) investigated the fine-scale spatial distribution of CM and associated competitors and predators on 360 CM infested coconut fruits (Hybrid PB121 and Dwarf Green) in fields in the Brazilian states of Pernambuco and Alagoas. Coconut fruits were sectioned and discrete chambers were identified under the perianth. *Neoseiulus baraki* was by far the most abundant and predominant predator under the bracts. It was found on 35 % of fruits. *Proctolaelaps bickleyi* was present on 7 % of fruits with a maximum density of 13 mites per fruit. *Neoseiulus paspalivorus*, *A. largoensis*, *P. bulbosus* (mentioned as *Proctolaelaps* sp. nov. according to de Moraes et al. 2008), *L. subterraneus* as well as *B. distincta* were only scarcely found. The voracious *P. bickleyi* was more abundant in chambers away from the fruit surface, suggesting that it has difficulties to invade the tightest chambers of the perianth.

Given the preferred microhabitat inhabited by CM, the distance between the surface of the coconut fruit and the edge of the lower bracts is determinant in allowing the initiation of the interaction between CM and its predators. Adult phytoseiid and ascid mites may reach the CM colony when the tight adherence of the bracts to the fruits is relaxed, which may happen due to the natural dehydration and collapse of surface tissue, which works as a defensive mechanism of coconut palms against CM. It has been suggested that fruit-perianth gap could be mediated by the production of herbivore-induced plant volatiles (Aratchige 2007; Lesna et al. 2004). Lawson-Balagbo et al. (2008b) speculated that in the initial development of the fruit, the distance is large enough for CM to move under the bracts, but too small to allow the entrance of predators. Lima et al. (2012) concluded that

the body sizes of *N. baraki* and *P. bickleyi* may limit their performance as control agents of CM. A study conducted in Benin by Negloh et al. (2010) indicated that *N. paspalivorus* usually enters the fruit about a month after CM does, leading to highly diverging population curves of both species.

In a study conducted in India, Thirumalai Thevan et al. (2004) determined that the peak population of predatory phytoseiids identified as *Amblyseius* spp. occurred on 5-month-old fruits, that is, 1–2 months after CM reached its highest population level. Galvão et al. (2011a) observed the occurrence of CM and *N. baraki* on 2- to 6-month-old fruits in three coconut plantations in northeastern Brazil. The population density of the predator peaked about a month after the pest (5- vs. 4-month-old fruits), both reducing drastically 1–2 months after the respective peaks were reached. They concluded that similar to CM, *N. baraki* was about evenly distributed along the 2- to 6-month-old bunches, but that on younger bunches, there was a tendency for fruits of the apical region to have lower predator densities than fruits of the basal region of the bunch. Together with a similar pattern for the proportion of fruits hosting *N. baraki*, this pattern suggested that this predator initially reaches the basal bunch region, from where it moves to the apical region. The results suggest that the reduction of CM population in bunches of more than 4 months old could be due to the effect of the predator, the reduction of the proportion of undamaged tissues amenable to attack and/or the increasing reduced favorable suitability of the substrate to CM, as fruits get older.

In Sri Lanka, a single inundative release of this predator significantly increased its population and decreased CM population on released palms (Fernando et al. 2010). However, coconuts of suitable stage for the continuous infestation by CM are available throughout the year and CM can damage a given fruit for 2–6 months. Thus, multiple releases may be necessary (Aratchige et al. 2012). Pilot scale trials are in progress in farmers' fields to determine suitable rates and frequencies of release of *N. baraki* to control coconut mite (Aratchige et al. 2012).

### *Acaropathogenic fungi*

The possibilities of producing and using acaropathogenic fungi for CM control have been explored (Cabrera 1982; Hall et al. 1980; Lampedro and Luis Rosas 1989). Work conducted until the end of the 1990s was summarized by Cabrera (2002). This author reported two fungi, *Hirsutella thompsonii* Fisher and *Hirsutella nodulosa* Petch, infecting CM. At about the same time, Beevi et al. (1999) also reported *Hirsutella thompsonii* var. *synnematososa* Samson, McCoy and O'Donnell infecting CM in India.

Promising results have been reported with the use of a commercial formulation of *H. thompsonii* in India (Sreerama Kumar and Singh 2000; Gopal and Gupta 2001). Mycohit, a commercial formulation of *H. thompsonii*, has been reported as effective under laboratory and field conditions in India (Rabindra and Sreerama Kumar 2003; Sreerama Kumar 2010). Sreerama Kumar and Singh (2008) conducted laboratory and field studies to examine the prospect of applications of mycelia of an Indian CM isolate of *H. thompsonii*—MF(Ag)66 in association with nine adjuvants. The result was positive, especially when glycerol was used as adjuvant. Multilocation trials are in progress in six Indian states.

Experiments with *H. thompsonii* have also been conducted in Sri Lanka. Here, the fungus seems suitable to be used in combination with other dominant control agents, as it appears to have no detrimental effects on *N. baraki* (Edgington et al. 2008; Fernando et al. 2007). A survey carried out in CM-infested areas revealed a naturally low incidence of *H. thompsonii* on CM (Edgington et al. 2008). Out of the isolates of *H. thompsonii*

collected from different geographical regions of Sri Lanka, four isolates, namely IMI 390486, 391722, 391942 and 390486, were more promising in relation to growth and sporulation in culture. These were used in biological laboratory (Edgington et al. 2008) and field (Fernando et al. 2007) evaluations. Despite the positive results, the effect of a single application of *H. thompsonii* is of relatively short duration, producing inconsistent results and suggesting the need of frequent applications for long-term effect (Fernando et al. 2007). Therefore, experiments with those promising isolates were recently discontinued in Sri Lanka.

Why *H. thompsonii* did not persist long enough on treated fruits to cause significant epizootics in Sri Lanka is not clear. As suggested by Fernando et al. (2007), the movement of CM underneath the coconut perianth is mostly confined to individual colonies and therefore the chances of a slow-growing fungus such as *H. thompsonii* spreading between colonies are low, especially in a situation where the number of mites on a fruit is lowered after fungus application.

### Agricultural practices

After unsuccessfully trying the use of different chemical pesticides as well as applications of *H. thompsonii*, Moore et al. (1989) concluded that in order to increase coconut yield in a region where CM is present, emphasis should be placed not on controlling the mite with these products, but rather on using improved agronomic practices and replanting with improved and mite-resistant varieties.

In Sri Lanka, when the pest was first reported in 1998, it was declared as a quarantine pest and transportation of infested fruits out of the infested area was banned, but this was discontinued because of the fast spread of the mite in the country. Present recommendation in Sri Lanka when infestation is first found on low numbers of palms in new areas, is for infested bunches to be pruned and burnt in situ. In India, a 'holistic' approach to CM control is recommended, by incorporating cultural practices that improve palm vigour (CPR Nair, Central Plantation Crops Research Institute, Kayangulam, India, pers. comm.). Destruction of fallen buttons and restriction on transportation of mite-infested fruits from place to place have also been recommended in India (Rethinam et al. 2003).

In Brazil, cultural practices have been recommended to small farmers, including the pruning of infested bunches and the cleaning of palms (Alencar et al. 1999; Aragão et al. 2002). However, the effectiveness of these practices has never been evaluated. Studies conducted by da Melo et al. (2012) could not demonstrate the efficiency of these practices, probably because of the ability of the mite to disperse by wind from infested palms from the same area or from infested neighbor areas (Moore and Alexander 1987; Galvão 2009).

Efforts have been dedicated to the determination of the effect of agronomic practices on the population level of CM. Some authors have observed a reduction of CM damage when coconut was planted in association with other crops (Moore et al. 1989; Muthiah et al. 2001; Varadarajan and David 2003).

Damage by CM generally increased with increasing levels of nitrogen in coconut leaves and it was suggested that higher levels of potassium could result in less damage by the mite (Moore et al. 1991). The use of organic fertilizers and potassium was reported to result in reduced mite damage in India (Muthiah et al. 2001). Sujatha and Rao (2004) reported less severe damage by CM in well managed, fertilized and irrigated plantations, as well as in intercropped plantations in Andhra Pradesh, India. In the state of Tamil Nadu, also in India, Muthiah and Natarajan (2004; 2005) reported reduced damage by this pest with the application of borax, calcium and manure in addition to adequate fertilization with NPK.

They also reported reduced damage when palms were treated with any of four types of bio-fertilizers. Yet, the response of the plants to the application of fertilizers is expected to vary according to prevailing soil conditions. Michereff Filho et al. (2008) did not find significant differences in proportion of fruits attacked by CM or degree of damage caused by CM among plants receiving various levels of application of nitrogen or potassium. This result might have been influenced by the fact that the plantation where the experiment was conducted had been fertilized for at least 2 years before the study was initiated.

### Host plant resistance

Varietal differences in susceptibility to CM have been observed in Costa Rica (Schliesske 1988), Cuba (Suarez 1991b), India (Muthiah and Natarajan 2004; Nair 2002; Ramaraju et al. 2002; Thirumalai Thevan et al. 2004; Varadarajan and David 2003), Ivory Coast (Julia and Mariau 1979; Mariau 1977, 1986), Saint Lucia (Moore and Alexander 1990) and Sri Lanka (IR Wickramananda and C Perera, CRI, Lunuwila, Sri Lanka, pers. comm.). Tightness of the perianth to the fruit, most probably related to the shape of the fruits, has been suggested as mechanism for resistance (Hall and Espinosa Becerril 1981; Julia and Mariau 1979; Moore 1986; Moore and Alexander 1990). Usually, rounded fruits have been reported to be less damaged by CM than angular fruits (Moore 1986; Moore and Alexander 1990; Varadarajan and David 2003). Tightness of the perianth could also be related to its radius or to the angle between the inner overlapping bracts. Varadarajan and David (2003) reported less CM damage on fruits having perianth with less than 2 cm in radius and on fruits onto which the angle between the inner bracts was greater than 136°. Resistance has also been related to fruit color. In Saint Lucia, Moore and Alexander (1990) observed that dark green fruits of Jamaica Tall cultivar were consistently less attacked by CM than lighter fruits. In India, Muthiah and Bhaskaran (2000) and Varadarajan and David (2003) reported orange colored fruits to be less injured by CM than green and yellow fruits.

Relatively little effort has been dedicated to the use of varietal resistance against CM in Sri Lanka and in-depth studies are necessary in this direction. In addition to morphological features, anatomical and biochemical characters of different varieties deserve consideration for varietal resistance/tolerance to CM. Moore and Alexander (1990) considered that the lower CM attack on the dark green fruits of the Jamaica Tall cultivar may not be directly linked to its color, but to the biochemical characteristics of those fruits.

### Perspectives for coconut mite control

Great advances about our knowledge on CM and its control have been achieved, especially in the last decade, after its introduction into Asia, where coconut is most important. However, much remains to be known about the biology and ecology of CM and its natural enemies, to allow the design of efficient strategies to it.

Why CM has become a pest of coconut is an important question to be answered. Despite the suspicion that coconut is not its original host plant (de Moraes and Zacarias 2002; Navia et al. 2005a), CM's true original host has still not been determined. Perhaps it is one of the two other host plants on which it has been found in the Americas, but in an extensive study in which more than 190 native and introduced palm species were examined, including *L. weddellianum* and *S. romanzoffiana*, CM was never found (Navia 2004).

If CM has become a pest after it moved from its original host onto coconut, then it is conceivable that effective natural enemies could be found on the former, although they

might not be as effective on coconut. Another hypothesis is that coconut could have been the host of CM for many years, and that the latter became a pest in response to changes in the genetics of CM or in the coconut cropping system (e.g. adoption of new cultivars that are [more] susceptible to the CM) or due to climatic changes in the area (de Moraes and Zacarias 2002).

Uses of low toxic chemicals which are essentially less harmful to the natural enemies seem to be the most feasible short term approach to control the pest. However, cost and practical difficulties in the application, because of the height of the plants, certainly limit its feasibility, making it suitable mainly for crops grown under intensive cultivation. For most small growers around the tropics, the application of chemicals might not be suitable, and other more sustainable techniques should continue to be developed or searched.

Biological control may be the most feasible long term solution for the control of CM, and all biocontrol strategies must be considered (i.e., classical biological control, augmentation and conservation). Although efforts have been dedicated to the study of approaches to the first two strategies, as discussed previously in this paper, less has been done in relation to conservation. As far as this strategy is concerned, changing the cropping system (e.g., from monocrop to intercropping systems with suitable crop combinations) could be appropriate. Generalist predatory mites are expected to do better in fields with a diversity of crops. In coconut plantations, coconut can be intercropped with, for instance, green legumes, tuber crops, fruit crops and vegetables. In addition, some plant species such as *Phaseoloides* sp. are used as cover crops to conserve moisture in coconut plantations. Intercrops, cover crops and weeds may all serve as alternative food sources and refugia for predatory mites of the pest. In principle, this could supply alternate prey or host for CM natural enemies, while probably supplementing growers' income with the production of the additional crop. Yet, in practice it still remains to be determined which other crops could serve the purpose, given that the most common predators of CM have only occasionally been reported from plants other than coconut in areas where coconut is grown (de Moraes et al. 2004a). An integrated approach with proper use of agronomic practices and intercropping coconut palms with suitable cash crops has been recommended in India (CPR Nair, pers. comm.). Generalist phytoseiids could play a major role in the control of CM, given the fact that coconut is a perennial crop, onto which many alternative foods (pollen, fungi, extra floral nectar, other mites) can be found (McMurtry and Croft 1997).

The nature of coconut pollination is such that heterogeneity among individual palms is high and fruits of different palms may differ. This aspect is important to be considered in selection of predatory mites for coconut varieties and perhaps in different agroecological regions within a country, because one variety may behave differently in different climatic regimes.

Many predatory mites have been found in studies conducted so far on coconut leaves. Although most of these probably cannot reach the colonies of the pest, given their relatively large size, they could conceivably help in the control of dispersing CM. Many gaps exist in our knowledge on CM migration behavior in relation to the age of the fruits, stage of the pest, time of the day, what proportion of the CM population inside the perianth migrates and how biotic or abiotic factors interfere with migration. In addition, how they migrate—whether wind-aided or by phoresy or by walking from plant to plant, or any other mode—, needs to be deeply investigated in developing control methods against CM. The information so far available cannot be considered conclusive.

Mass production of the biological control agents involves high costs, skilled personnel and strict quality control measures. Frequent applications of those organisms also incur

high labour costs. Therefore the cost of application of biological control to maintain low population levels of CM should be evaluated critically before its use can be proposed.

Access to the perianth remains the key issue for CM biological control. Search for natural enemies with dimensions that allow them to penetrate the fruit perianth simultaneously or shortly after penetration of CM should be intensified. Despite the efforts to find prospective natural enemies to control CM in the Americas, until now the only species that seem to have relatively early access to CM colonies are *N. baraki* and *N. paspalivorus*. Interestingly, the most common predatory mites found in Brazil and other American countries are the same as those found in association with CM in Africa and southeast Asia. One wonders whether effective predators could not be found in other parts of the world, where the counterparts of CM are found. It has long been reported that when searching for hosts or prey, a natural enemy is often first attracted to their habitat. The eriophyid *Colomerus novaehybridensis* Keifer has been reported from several countries in Asia, where it is not a serious pest, possibly, among other things, because of its natural enemies. The predators of *C. novaehybridensis* have not been studied adequately. The preferred habitat of this species is very similar to that of CM. On the other hand, even the more specialized phytoseiid predators usually feed on various prey species. Thus, it seems that given the difficulty in finding effective natural enemies of CM in the Americas, some effort should be dedicated to the study of the natural enemies of *C. novaehybridensis* in Asia and to the evaluation of their possible impact on CM populations.

A variable effect of *H. thompsonii* on CM populations has been experienced by scientists (Cabrera 2002; Espinosa Becerril and Carrillo-Sanchez 1986; Suarez et al. 1989). Variability of micro-climatic conditions, particularly in relative humidity among sites, and of virulence of isolates may be likely explanations, which need to be looked into carefully before considering the application of *H. thompsonii*.

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