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EDITORIAL

Integrating ecology and genetics to address Acari invasions

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Abstract Because of their small size and tolerance to many of the control procedures used for a wide variety of commodities, Acari species have become one of the fastest, unwanted pest travelers since the beginning of this century. This special issue includes eleven studies on adventive and invasive Acari species affecting major crops and livestock around the world. The nucleus for this special issue is formed by the presentations in the symposium on invasive mites and ticks organized at the International Congress of Acarology in Recife, Brazil (ICA-13), in the summer of 2010. This special issue illustrates the increased concerns about domestic and international invasive mites and ticks worldwide.

Keywords Acari · Plant feeding mites · Ticks · Invasive · Adventive · World trade · Systematics

An introduction to adventive and invasive Acari and their importance in our shifting technological culture

Adventive (non-native) species as defined by Frank and McCoy (1990) is a neutral term used to designate both immigrant and introduced species. By contrast, invasive species is a rather value-based term used to designate species that cause socio-economic or environmental damage (Wheeler and Hoebeke 2009). As in many other groups of organisms, concerns regarding domestic and international invasive and adventive Acari around the world have come to the forefront of many studies. During the summer of 2010, we organized and participated in a two-session symposium on Invasive Acari at the XIII International Congress of Acarology (ICA-13) held in Recife, Brazil (de Moraes et al.

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2010). This was a unique opportunity to address some of the most relevant, recent invasion events which have involved Acari species. Special focus was placed on the relevance of genetic and ecological studies to understand the biology of these invasive species. The symposium addressed a wide diversity of topics, ranging from plant feeding mites in the Americas, via tropical cattle ticks on the island of New Caledonia, to the effect of environmental modifications driven by global change, their impact on the expansion of adventive and invasive Acari and their potential collateral effect on bio-control agents. A clear outcome of the symposium was the need for more in-depth studies in taxonomy, biology, ecology and genetics of adventive and invasive Acari on this planet of fast changing demographics and climate. This special issue covers several of the most aggressive, dynamic and rapidly spreading domestic and international mite travelers of the early twentyfirst century.

The voyage of adventive and invasive Acari

Surprisingly, it was only recently discovered that many mite species have been moving around the world for centuries. At least two, non-exclusive facts can explain this: (a) the small size of most mites, which makes them difficult to detect, and (b) the great acceleration in the global movement of commodities with which many mites are often associated, some being prominent agricultural pests. The detection of some species of acarines has been facilitated by a better understanding of their unusual feeding behavior, such as those feeding on or under the bark of trees (Beard et al. 2012a, b; EA Ueckermann pers. comm.). Others have been transported quickly across the globe as hitch-hikers on other invasive or commercially sold insects, reptiles and birds (Léger et al. 2012; Goka et al. 2012; R Ochoa and WC Welbourn unpubl. data), on human travelers, or by taking advantage of past and present military conflicts, using the movement of the war logistical resources to extend their range to other countries and continents (Lockwood 2009; Canyon et al. 2011; Pimentel 2011; Chevillon et al. 2012). The economic or medical importance of the Acari increases with their ability to vector viruses, rickettsiae, spirochaetes, phytoplasmas, mycoplasmas and protozoas, or to harbor and transport nematodes, bacteria and fungi pathogens that affect plants, domestic and wild animals and humans (Jongejan and Uilenberg 2004; Mullen and OConnor 2009; Nicholson et al. 2009; Bastianel et al. 2010; Navajas et al. 2010; Navia et al. 2010, 2012a; Rodrigues and Childers 2012).

The exact number of species of Acari remains a mystery; estimates vary from 500,000 to one million (Krantz 2009). Due to the dramatic increase in international movement of human and animal food products, baggage, ornamental plants, seeds, exotic pets, cattle and humans, mites from a wide range of hosts, habitats and countries are quickly transported across the globe. The detection of these species at the ports of entry has significantly increased our knowledge of the number and diversity of acarine species worldwide. The total number of mite species may be grossly underestimated; it is possible that the number may be between 3 and 5 million species. Faunal studies in small, targeted habitats such as patches of rain forests, 'cerrado' forests, savanna, deserts, and tundras have greatly augmented the number of species of certain groups of mites. These studies have challenged our concept of the degree of Acari biodiversity. Furthermore, the finding of mites associated with the international trade of tiles, construction tools and material, toys, machinery, cloth material, packing material, tourist souvenirs and arthropod specimens used by teachers in their classrooms (e.g., Oregon State University 2012), not only are new pathways for mites to travel, but have also shown how little we know about the adaptability and diversity of these organisms in our globally changing ecosystems. As Rodrigues and Peña (2010) stated at the opening of the symposium on *Raoiella* mites at the ICA-13 meeting in Brazil, like people, mites can board a non-stop flight and arrive in any country in the world in less than 18 h, and travel between countries in less than an hour. The dispersal of mites by land, air and sea as a result of natural causes or by human intervention is exacerbated by the limitations of many countries in lacking personnel with the necessary expertise, equipment and other resources to detect and accurately identify mites.

Global environmental and economic costs

The direct and indirect monetary cost of damage caused by invasive invertebrates to the global economy has been calculated at hundreds of billions of dollars annually (Pimentel 2005, 2011; Pimentel et al. 2005; Hong et al. 2006; Wheeler and Hoebeke 2009; Ananthakrishnan 2011; Canyon et al. 2011; Roques 2011). Adventive and invasive Acari share this impact with other small arthropods such as scale insects, aphids, whiteflies, thrips and psyllids. All of these organisms are closely associated with plants and have in common their tiny size (most specimens are less than 3 mm long), cryptic coloration, tolerance for extreme low or high temperatures, ability to survive in dry or wet conditions, and some with the ability to go without food for months and perhaps years, making the mites and these small insects one of the most successful adventive and often invasive groups of arthropods. Miller et al. (2005) and Foottit et al. (2006) indicated that there are around 255 adventive Coccoidea species and 262 adventive Aphididae species in North America, respectively. Efforts to control these species have led to an increase in the number of pesticide applications, crop production costs, and environmental contamination. Estimates of damage caused by eriophyid, tarsonemid, tenuipalpid, and tetranychid mites due to their direct feeding, vectoring of fungi or viruses, and control costs range to millions of dollars (Jeppson et al. 1975; Ochoa and von Lindeman 1988; Childers et al. 2003; Hong et al. 2006). In addition, many poorly known mite species could have a great impact on the diversity of crops and cattle industries that are valued in billions of dollars (Childers et al. 2003; Hummel et al. 2009; Léger et al. 2012).

Adventive species: friend or foe?

Species of several of the plant-feeding mite families—as well as species of animal-parasitic mite and tick families—are moving daily from country to country, mostly due to international trade (Fig. 1). As a consequence, native species are continuously expanding their range from their native geographical areas (Vila et al. 2010). The growing number of alien species of Tetranychidae recorded in Europe has increased 10-fold in the last 50 years (Navajas et al. 2010). Most of these spider mites are prominent crop pests, illustrating the threat that species moving beyond their geographic area represent for agriculture. Predatory mites associated with plant mites are also moving and have the potential to displace or interfere with native predator mite species (Palevsky et al. 2012, Montserrat et al. 2012). Phytoseiid mites are among the most important biological agents of spider mites and other organisms. Denmark and Evans (2011) recently reported on 428 species of phytoseiids from North America and Hawaii, of which 75 were new species.

The Tenuipalpidae are among the mite families that are most rapidly moving and spreading throughout the world (Gerson 2008; Mesa et al. 2009; Peña et al. 2012;

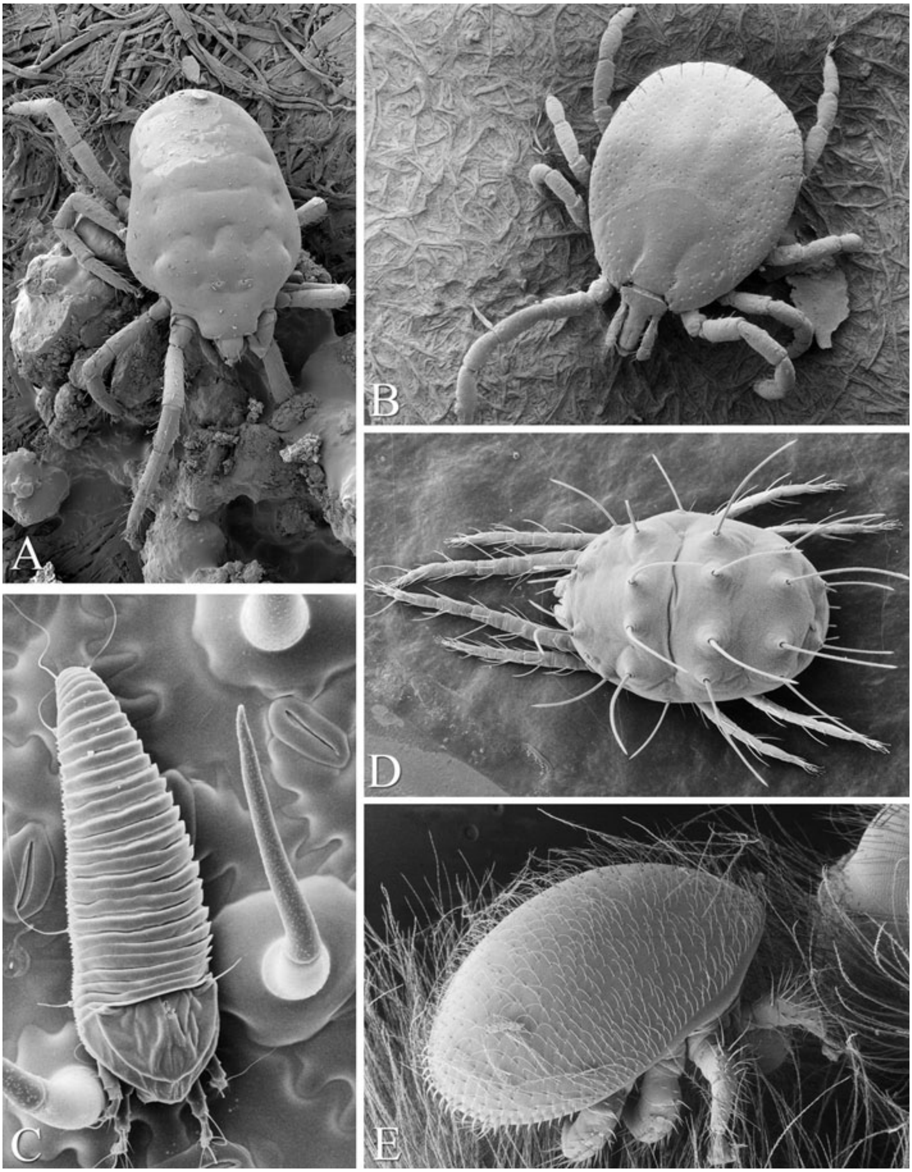

Fig. 1 Mites and ticks of economic importance: **a** Winter red legged mite *Penthaleus* sp., **b** long star tick *Amblyomma americanum* (L.) nymph, **c** tomato rust mite *Aculops lycopercisi* (Tryon), **d** Citrus red spider mite *Panonychus citri* (McGregor), and **e** the bee mite *Varroa destructor* Anderson & Trueman. LT-SEM photo and digitation: G. Bauchan and C. Pooley, LT-SEM mounting: R. Ochoa

Rodrigues and Childers 2012). With 891 species, this family of mites was once considered as being secondary in economical importance (Mesa et al. 2009), but the list of tenuipalpid species is continually being added to and currently there are close to 1,100 species described (JJ Beard, R Ochoa & EA Uekermann, unpubl. data).

Another group of fast-moving, adventive mites are species in the superfamily Eriophyoidea (Navia et al. 2010, 2012a, b). The number of described species of eriophyoid mites is also quickly growing, which will certainly lead to an increase in the number of invasive species. Amrine et al. (2003) listed over 3,442 species; today there are close to 5,000 species (JW Amrine, pers. comm.). Just in the first months of 2012, seven adventive eriophyid species were recorded in the USA. Of these, some are associated with crops and fruit groves, whereas others have the potential to be used as biological control agents of specific weed species (WC Welbourn & R Ochoa, unpubl. data).

In the plant-feeding family Tetranychidae, several species in the genus *Tetranychus* are known for being intercepted between continents. Some prominent examples are *Tetranychus evansi* Baker & Pritchard, *T. fijiensis* Hirst, *T. kansawai* Kishida, *T. mexicanus* (McGregor), *T. pacificus* McGregor, and *T. piercei* McGregor. The increasing number of Acari interceptions clearly illustrates that inter-continental movements of fruits, flowers and ornamentals have provided adventive species with the opportunity to expand their range into new areas. The need for accurate species identification studies of *Tetranychus* native and exotic pests is illustrated in the study done in Australia by Seeman and Beard (2011). The relevance of the Tetranychidae as crop pests has also motivated studies on host-plant mite associations which sometimes called for the re-examination of the current quarantine regulations (Ferragut et al. 2012; Goka et al. 2012; Navajas et al. 2012).

The number of species in minor families, such as the Tuckerellidae, has continued to rise, leading also to an increase in the number of invasive species (Beard et al. 2012c). Members of the family Penthaleidae are considered important mite winter pests and we have been observing an increase of their presence and damage in Australia, North America and some parts of Europe (Qin and Halliday 1996; Halliday 2005; WC Welbourn, R Ochoa & RB Halliday, unpubl. data). For other groups, such as the family Acaridae (Astigmata), data on the number of species and their impact on plants are scarce (Gerson and Weintraub 2012). Adventive ticks have also been spreading (Chevillon et al. 2012), with some of them carrying very detrimental diseases to domestic and wild animals and posing a threat to human health (CDFC 2000; George et al. 2004; Léger et al. 2012).

Integration of molecular, morphological and ecological data

Nowadays, the input of DNA-based approaches for systematics to distinguish and describe new species and also to detect and identify invasive species is fully accepted. The approach is, however, applicable to live specimens, and analysis of dead ones should relay on integrative taxonomy (Schlick-Steiner et al. 2010). As in other fields, acarology has benefited from molecular methods which have contributed to progress in the discovery and recognition of a large number of mites and ticks. In the case of closely related species, especially difficult to distinguish, the integration of morphological and molecular data is particularly valuable (e.g., de Mendonca et al. 2011). Recently, the entire genome of the two-spotted spider mite, *Tetranychus urticae* Koch, was sequenced (Grbic et al. 2011). This has provided acarologists with a powerful resource for novel studies on *T. urticae*, which can serve as a model for the study of other arthropod species (Grbic et al. 2007). For invasion studies, molecular methods have proven to be a powerful tool to trace movements (Estoup and Guillemaud 2010). Where does an invasive mite species come from? How many invasion events occurred? What are the historical colonization pathways behind the present distribution of an invasive mite species? These are some questions that molecular data and the associated data analyses can help to answer. The review by Navajas et al.

(2012) in this issue, illustrates this approach based on the recent invasion of the red tomato spider mite *T. evansi* (see also Boubou et al. 2011, 2012).

Recent advances and improvements in optical technology have provided some very promising tools to study morphology, microstructures and feeding habits of mites in much greater detail. In particular, differential interphase contrast (DIC) and confocal microscopes, variable pressure and low-temperature scanning electron microscopes (LT-SEM) (Dowling et al. 2010; Beard et al. 2012a) are giving a fresh and more detailed view of new characters that are more clearly observed and help to discriminate species. Dowling et al. (2010) were able to freeze mite samples, take high-resolution digital images of the specimens with the LT-SEM and afterwards extract their DNA without significantly damaging the specimens. The specimens could then be processed, mounted on microscope slides and deposited in a voucher collection. This represents a major breakthrough in our ability to explore mite behavior and ecology observed *in natura* or in the laboratory. Since the specimens are immediately 'frozen in action' in their habitat, we are able to gather information on their feeding habits (ecology), observe them in greater detail (morphology) and analyze their DNA (molecular criteria). This three-pronged approach may be what is needed to solve several of the problematic issues of species that previously could only be separated using molecular techniques, e.g., cryptic species, which is of much value in the case of invasion events (Gotoh et al. 2009; Dowling et al. 2010).

Final considerations

Nowadays, we have in hands an array of techniques and approaches to characterize samples as help to distinguish and identify species, a key first step to detect, and then manage alien species. As for most invasive pests, a major concern of invasive Acari is two-fold. First, it is crucial to prevent the entry of alien species into new geographical areas. Second, once a non-native species has gained entry and has established in a new environment, there is urgent need to prevent its dissemination into new areas and to mitigate its economical, medical and/or environmental impact. Scientists and public bodies are conducting research and building strategies to help face the challenges posed by bioinvasions (e.g., Hengeveld 1989; Simberloff et al. 2012). Biosecurity measures are growing steadily (Heikkila 2011), and are being used as a means of surveying the mite fauna associated with imported and exported products and goods; this is an important step in detecting pest species and preventing them from entering and establishing in the country.

The threat posed by invasive alien species is far from being well-defined; for example, urban areas are regarded as a gateway for exotic pests (Colunga-Garcia et al. 2010), yet their significance for invasions is barely explored. Moreover, the tremendous economic and environmental impact of invasive species is expected to continue with the effect of global change which might favor expanded geographical distribution areas of the species (Migeon et al. 2009; Walther et al. 2009; Kriticos 2012; Montserrat et al. 2012). Addressing these threats should involve a combination of genetic and ecological studies plus operational measures devoted to biosecurity. From a practical point of view, many countries may save time and resources by upgrading existing equipment in their agriculture–veterinarian-protection laboratories, which could be used to detect and study ticks and mites intercepted at their ports of entry. The use of web digital tools, such as interactive keys, fact sheets on the most invasive species, and good descriptions associated with high-quality images to aid in the identification of mites are necessary (Beard et al. 2012a).

The invasion of the Americas by the red palm mite *R. indica*, the invasion of Asia by the coconut mite *Aceria guerreronis* (Keifer), the invasion of Africa by *Mononychellus tanajoa* (Bondar), the invasion of Europe by *T. evansi*, and the invasion of the Americas, Eurasia and Oceania by the wheat curl mite, *Aceria tosichella* Keifer are clear examples of the ability of mites to colonize and establish outside their native range (Yaninek and Herren 1988; Peña et al. 2012; Navajas et al. 2012; Navia et al. 2012a, b). The negative impact of alien invasive Acari species, as for many other groups, is unfortunately expected to increase. In the coming years, an essential challenge for acarologists is to make use of the variety of available techniques, while also creating novel ones. The diversity and integration of approaches being used to address Acari invasions are reflected in the contributions of this special issue. Although this shows that much has been accomplished, it also opens new avenues in the study of invasive and adventive Acari.

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