Chapter 24

Integrated pest management of mites

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1 Introduction

Many plant feeding mites injure and cause economic damage to agricultural crops and ornamentals. Worldwide there are more than 6000 species of mites that feed on plants but only about 100 species cause economic damage to crops and ornamentals (Hoy, 2011). The majority of phytophagous (plant feeding) mites belong to two major super families: (1) Eriophyoidea and (2) Tetranychoidea. Eriophyoid mites are very small (<300 μm long) and cannot be seen easily with the naked eye. These mites are common agricultural pests including bud mites, rust mites, gall mites, and erinose mites. Tetranychids include some of the most important agricultural pests. Approximately 1200 species are known worldwide. They are larger than eriophyoid mites (~1 mm long). They are polyphagous with a wide host range. Well-known members of the group include the two-spotted spider mite (TSSM), *Tetranychus urticae* Koch, and the southern red mite, *Oligonychus ilicis* McGregor. Other significant plant feeding mites include those in the family Tenuipalpidae, Tarsonemidae, and oribatid mites (Hoy, 2011).

The family Tenuipalpidae has over 1100 species from 38 genera and are known as false spider mites or flat mites (Akyazi et al., 2017; Vacante, 2016).

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Brevipalpus is a dominant genus among the tenuipalpids and is considered as one of the most important groups of the species among the flat mites (Vacante, 2016). These mites feed on plant tissues by sucking sap and inject toxins into the plants causing changes in the physical appearance of the leaves. In addition, some species transmit viruses to host plants (Mesa et al., 2009). *Brevipalpus yothersi* Baker is suspected to transmit cytoplasmic leprosy viruses in plants in the Rutaceae and Malvaceae families (Roy et al., 2015).

Only a relatively small number of mites in the family Tarsonemidae actually feed on plants. Two species in the family, *Polyphagotarsonemus latus* (Banks) (broad mite) and *Phytonemus pallidus* (Banks) (cyclamen mite), cause extensive damage to crop plants and ornamentals. Broad mites, also known as tea mites in Southeast Asia, are very small (0.2 mm long) and widely distributed in semitropical areas. Broad mites feed on terminal leaves and flower buds causing flower abortion. Heavy feeding results in deformed leaves that are semi-folded and stunted growth. Similarly, cyclamen mites are very small (230–270 µm long). They feed on the midvein of young unopened leaves and on tightly packed young leaves and floral buds. This feeding results in wrinkled upper surfaces, irregular folding and browning of the leaf margins (Ajila et al., 2018; Zhang, 2003). If damage is severe, leaves become brittle, turn brown or silvery, and the plants may eventually die causing a reduction of fruit and lower yield (Ajila et al., 2018).

Phytoseiidae is an important family of predatory mites that have been used extensively in biological control programs to regulate phytophagous mite populations in agricultural crops, especially those belonging to the tetranychid group (McMurtry and Croft, 1997). Phytoseiids are also used in vegetable systems to control key pests such as thrips and whiteflies. Their success is dependent on when these predators are released in relation to crop phenology and the conditions under which they are released since they respond dramatically to temperature and humidity, and the formulation used.

2 Mite taxonomy and morphology

2.1 Systematic position of the Acari

All mites (phytophagous, parasitic, predatory, saprophytic etc.) belong to the subphylum Chelicerata, class Arachnida, and subclass Acari or Acarina. They are the most abundant and diverse group of all living arachnids (Walter and Behan-Pelletier, 1999). While some earlier studies consider the Acari to be an order of the class Arachnida (Zhang, 2003; Lindquist et al., 2009), the latest studies accepted the Acari to be a subclass (Vacante, 2016). Here, the classification proposed by Krantz and Walter (2009) is adopted (Table 1). They accepted the Acari to be a subclass including two superorders, the Parasitiformes and the Acariformes.

Table 1 Classification of the Acari (Acarina)

- *Phylum: Arthropoda*
  - *Subphylum: Chelicerata*
    - *Class: Arachnida*
      - *Subclass: Acari (Acarina) (Mites)*
        - *Superorder: Parasitiformes (Anactinochaeta)*
          - Order Opilioacarida (Notostigmata)
          - Order Holothyrida (Tetrastigmata)
          - Order Ixodida (Metastigmata)
          - Order Mesostigmata (Gamasida)
            - Suborder Sejida
            - Suborder Trigynaspida
            - Suborder Monogynaspida
        - *Superorder Acariformes (Actinochaeta)*
          - Order Trombidiformes
            - Suborder Sphaerolichida
            - Suborder Prostigmata (Actinedida)
          - Order Sarcoptiformes
            - Suborder Endeostigmata
            - Suborder Oribatida (Cryptostigmata)

Source: adapted from Krantz and Walter (2009).

2.2 General mite morphology

The mite body is covered by a chitinous exoskeleton. The exoskeleton of a typical mite consists of epicuticle, exocuticle, endocuticle, Schmidt layer, epidermis, and a basal lamina set below the epidermis. There are three major layers in the epicuticle, namely cuticulin, tectostracum, and cement. Exocuticle and endocuticle together are called procuticle. Pore canals appear to arise from the epidermal cells underlying the Schmidt layer and move in a helical fashion toward the surface through the exocuticle. The possible function of pore canals may be transporting secretions from the epidermal cells to the cuticulin surface layer, whereas the tectostracum and cement layers offer protection against excessive water loss from the body surface (Dhooria, 2016; Krantz and Walter, 2009).

A mite's body is divided into two main sections: the anterior part of the body called gnathosoma or capitulum, followed by a large portion known as the idiosoma. The gnathosoma is separated from the idiosoma by a circumcapitular furrow (Capinera, 2008). The idiosoma is formed by the anterior podosoma and posterior opisthosoma (Vacante, 2016). The podosoma is sometimes subdivided into the propodosoma that bears the first two pair of legs, while the metapodosoma carries the posterior two pair of legs. The combined gnathosoma and podosoma is designated as prosoma. Sejugal furrow may be found at a level between legs II and III. Postpedal furrow may also be found just behind legs IV. The part posteriorly of the sejugal furrow is named hysterosoma (Dhooria, 2016).

The gnathosoma performs feeding and sensory functions. It resembles the head of insects but is not exactly comparable because it does not contain eyes or brain. It comprises only the mouthparts consisting of the chelicera, the pedipalps, the oral cavity, and the hypostome in ticks (Singh, 2007; Ruppert et al., 2004).

The chelicerae are the primarily organs of food acquisition. They are usually modified for chewing, piercing, tearing, or sucking. Most mites (most of Gamasida, Astigmatina, and Oribatida) have a primitive chelate-dentate chelicera. However, some modifications occur in the shape of the chelicerae according to the different feeding habits. In tetranychids, the movable digit has been modified into a stylettiform for piercing plant tissues. In Mesostigmata, the chelicerae are relatively slender, chelate-dentate which has teeth usually on both digits (Walter and Proctor, 2013). The pyroglyphid mites also have chelate-dentate chelicerae (Colloff, 2010). The movable digit of the male chelicera is also modified as a fingerlike structure for sperm transfer. It is called spermotodactyl in Dermanyssina and spermatotreme in Parasitina (Mesostigmata) (Zhang, 2003).

In some mites, cheliceral teeth are absent. This type of chelicera is called edentate and occurs in parasitic mites (Rhinoyssidae). A different form of edentate chelicera occurs in the *Euseius* genera, where chelicera digits look like a pair of sharp tongs. The condition is accepted as an edentate or nearly edentate chelicerae. Some mite groups have chelate-serrate chelicerae. In this chelicera type, an array of small, even teeth are fixed to the digit like the teeth of a saw. If serrations are flexible and soft, this kind of chelicera is named as serrate-membranous (Walter, 2006).

The palps are lateral to the chelicerae. They are often used as sensory organs, for capturing or holding the prey, and sometimes used for cleaning the chelicerae (Dhooria, 2016; Walter and Proctor, 2013; Krantz and Walter, 2009). The palps typically look like a smaller pair of legs and several modifications can be found among mite species. In the family Bdellidae, the palps are simple and modified as antenniform structures (Dhooria, 2016; Walter and Proctor, 2013). The palpi may be modified as raptorial structures in some predatory families such as Halacaridae, Cheyletidae, Cunaxidae (Krantz and Walter, 2009). The palps may bear a distinctive claw-like structure such as the case of many tetranychid, caeculid, and trombidifom (Trombidiodea) mites (Dhooria, 2016).

The idiosoma comprises the posterior part of the gnathosoma (Krantz and Walter, 2009). The brain and the eyes (if present) are found in the anterior part of the idiosoma (propodosoma) (Jeppson, 1975). In the idiosoma are found external structures with locomotory, respiratory, copulatory, and sensorial functions (Hartini and Saim, 2005). There are sclerotized shields or plates in the dorsal part of the idiosoma that vary among different systematic groups of mites. Their shape, size, and their degree of sclerotization have been used in mite classification. The dorsal chaetotaxy (number and disposition of setae) of the idiosoma is important in taxonomy and used in classification in many mite groups. The structure of setae, distance between setal base, and the relative length of setae are also of great taxonomical importance (Vacante, 2016; Zang, 2003). Ventrally, the idiosoma may be soft and unsclerotized, but a variety of shields such as the presternal, ventral, sternal, metasternal, epigynial, metapodal, and ventrianal shields may be present (Hartini and Saim, 2005).

Legs are primarily used for locomotion. They may be modified to serve specific functions such as jumping, grasping, swimming, and anchoring (Dhooria, 2016). With some exceptions, mites typically possess four pair of legs in the adult and nymph stages and three pair of legs in the larval stage. For example, eriophyoids have only two pair of legs in all life stages (Capinera, 2008). Interestingly, adult members of *Larvacarus* (Tenuipalpidae) possess only three pairs of legs (Dhooria, 2016) and adult males of *Phytoptipalpus* (Tenuipalpidae) may sometimes have three pairs of legs (Ueckermann et al., 2018). Adult males of *Raoillana* (Tenuipalpidae) have four pairs of legs, whereas the females have three (Baker and Tuttle, 1972).

Typically, the legs consist of the seven basic segments, from the base to the tip: the coxa, trochanter, femur, genu, tibia, tarsus, and pretarsus (apotele). In various groups, there has been significant fusion of leg-bearing segments or loss of appendages. For example, in parasitiformes, the coxae are usually free and movable, whereas in Acariformes, they are fused with the idiosomal venter (Vacante, 2016). Commonly, the apotele is present as a pair of claws and is pad-like to a highly modified empodium or a single median claw. But primitively, three claw-like structures are present (Walter, 2006).

2.3 Life cycle

Most mites pass through six developmental stages after egg hatching: the prelarva, larva, protonymph, deutonymph, tritonymph, and adult (Krantz and Walter, 2009). Each development stage typically bears after a pharate quiescent stage. The prelarva which is also called the ‘prolarva’ or ‘deutovum,’ is typically a non-feeding stage. Most species are inactive and closed within the egg chorion during this stage (Cowles, 2018). The prelarva molts to the larval stage. Acarine larvae typically exhibit the hexapod form, have little to no sclerotization, and no sign of external genitalia. If there is any sclerotization, it is confined to the podosoma region. Larvae may be non-feeding forms (many Mesostigmata), voracious predators (Chelatidae), or aggressive parasites (Trombiculidae) (Southcott, 1999).

The larvae molt into an eight-legged protonymph, the first nymphal stage. Protonymphs are generally free, active, feeding, or non-feeding instars (Capinera, 2008). Protonymph develops the deutonymph, the second nymphal stage. Deutonymphs differ from the adults in size, the pattern of sclerotization, and setation. The tritonymph (if occurs) is typically an active and eight-legged stage. It is uncommon in Mesostigmata and absent in many Prostigmata. In astigmatid mites, the third post larval instar is considered to be the tritonymph.

Prostigmatid mites typically have egg, prelarva, larva, protonymph, deutonymph, tritonymph, and adults (Fig. 1a). However, various kinds of modifications are common in different mite groups (Zang, 2003). For example, tarsonemid mites go through egg, larva, and adult stages only. The nymphal stages are probably passed within the larval skin. In tetranychoid mites, there are two nymphal stages, protonymph and deutonymph, besides larva and adult (van de Vrie et al., 1972; Laing, 1969). The families Bdellidae and Tydeidae pass through egg, larva, protonymph, deutonymph, and tritonymph stages before becoming adults. The life cycle of Erythraeidae (Muñoz-Cardenas et al., 2015; Belozerov, 2008) and Trombididae also includes egg, larva, protonymph, deutonymph, tritonymph, and adult stages. However, larva, deutonymph, and adult are active stages while protonymph and tritonymph are inactive within the cuticle of the previous stage.

The life cycle of free-living Mesostigmata typically includes egg, prelarva, larva, protonymph, deutonymph, and adults (Fig. 1b). Each development stage is preceded by a pharate quiescent stage (Jeppson et al., 1975).

Astigmatid mites go through six stages in their life cycles: egg, larva, protonymph, deutonymph, tritonymph, and adult (Fig. 2a). But their deutonymphs are highly modified for phoresy or surviving adverse environmental conditions (Farfan and Klompen, 2012; O'Connor, 2009). Such

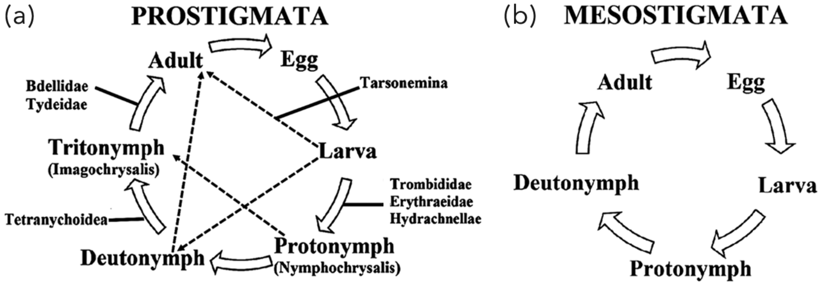

Figure 1 Life cycle of prostigmatid (a) and mesostigmatid (b) mites. Source: adapted from Ecevit (1981).

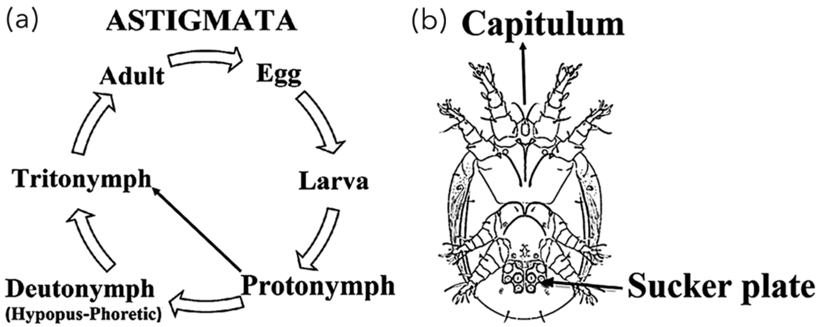

Figure 2 Life cycle of astigmatid mites (a) and heteromorphic deutonymphal stage or hypopus (b) of the Astigmatina (Walter, 2006). Source: (a) adapted from Ecevit (1981).

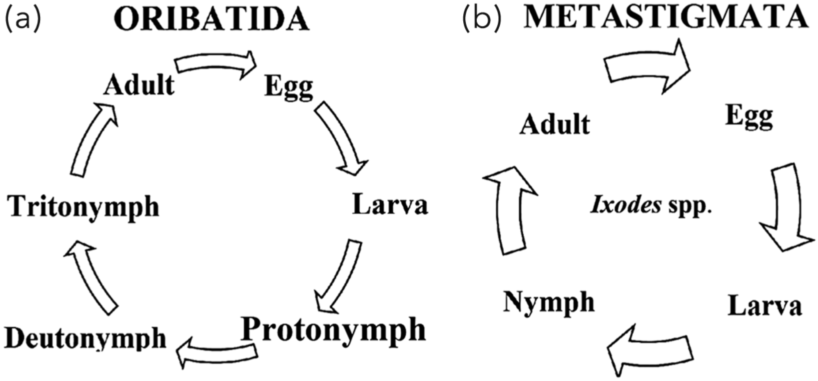

Figure 3 Life cycle of oribatid mites (a) and an ixodid tick (b). Source: adapted from Ecevit (1981).

deutonymphs are called hypopodes (or hypopi, singular hypopus) (Fig. 2b) (Reynolds et al., 2014; Mullen and Durden, 2009).

The soil mites (Oribatida or Cryptostigmata) also pass through the following stages; egg, larva, protonymph, deutonymph, tritonymph, and adult (Fig. 3a) (Ermilov and Lochynska, 2008).

The life cycle of ticks (Metastigmata) includes egg, larva, several nymphal stage (depend on the species), and adult (Fig. 3b) (Eremeeva and Dasch, 2015).

2.4 Feeding behavior

Mites feed on a variety of food and have developed different feeding habits (Dhooria, 2016). While many mites in agricultural systems feed on plants, others feed on plants, fungi, detritus, pollen, nectar, humus, and some are predators (Krantz and Walter, 2009).

Some investigations were made to understand the details of how mites feed. For example, Lee (1974) observed the feeding behavior of several Mesostigmata species including species from the predatory family Phytoseiidae. The feeding process is divided into the following four phases: contacting (approaching and locating the prey), grasping (holding of the prey), chewing, and discarding. The chewing phase includes the break of solids by the chelicera. Proteolytic enzymes are injected into the body of the prey, then the liquefied body contents of the prey are sucked up and the remaining parts of the body are discarded (Vantornhout, 2006; Flechtmann and Mucmurty, 1992). After the discarding phase, the grooming behavior starts between the chelicerae, palps, and legs (Vantornhout, 2006).

The feeding behavior of *Iphiseius degenerans* (Berlese) (Phytoseiidae) was also investigated. It first touches the prey with tarsi 1, and then grasps it with leg 2, cuts the cuticle with the chelicerae, the corciculi are then partially introduced in the prey body. With chelicerae and part of the hypostome inserted in the prey, after a short time of struggling, the prey is lifted from the substrate. It then stands on its third and fourth pairs of legs. The predator turns the prey around several times. Proteolytic enzymes are injected into the body of the prey. And then the liquefied body contents of the prey are sucked up (Vantornhout, 2006; Flechtmann and Mucmurty, 1992).

The body of the *Tetranychus macfarlanei* Baker and Pritchard (Tetranychidae) is pierced by other mesostigmatid mite species *Euseius ovalis* (Evans) (Phytoseiidae) using its chelicera and then it sucks out the internal content (Liyaudheen et al., 2014).

However, the plant feeding spider mites have stylet-like chelicerae in which the stylets are probably formed by the elongation of movable digits. They can penetrate plant tissues up to 100 micron deep. *Tetranychus urticae* can inject the stylets 18–22 times/min and is capable of exhausting the contents of 100 cells every 5 min (Beard et al., 2012; Liesering, 1960).

2.5 Reproduction

Mites have different reproductive strategies, including both sexual and asexual reproduction (Cabrera et al., 2009). Sexual reproduction is the most common mode of reproduction of the Acari. It has been identified in the Mesostigmata (Norton et al., 1993), Prostigmata (Shirai et al., 1984), Oribatida (Norton et al., 1993), and Astigmata (Heinemann and Hughes, 1970).

In sexual reproduction, offspring are biparental (Cabrera et al., 2009) and may have indirect or direct sperm transfer strategies (Walter and Proctor, 2013). Indirect sperm transfer involves deposition of a sperm packet (spermatophore) on the substrate by males (Proctor, 1992). In some cases, the spermatophores are deposited in groups. Females then pick up the spermatophore and place them in their sperm receptacle (Hoy, 2011; Michalska, 2014).

Direct transfer involves males placing their sperm directly into the sperm receptacle of females. These males have special structures used to grasp the females during mating. These structures may be enlarged legs with spurs or suckers on the posterior pair of legs or in the anal region. Direct transfer by copulation has been observed in the families Tetranychidae, Tenuipalpidae, Stigmaeidae, and Acaridae and at least one Tydeid (Hoy, 2011). In some mite families such as Penthaleidae, Anystidae, and Erythraeidae (Zhang, 2003), males may produce spermatophore and transfer it to the female genital opening.

Mites may also reproduce asexually via arrhenotoky, parahaploidy (pseudoarrhenotokous), or thelytokous parthenogenesis (Norton et al., 1993). In arrhenotoky, unfertilized eggs develop as males, while females usually arise from fertilized eggs (Cabrera et al., 2009). In phytoseiid mites, males are haploid and females are diploid. So, first, it was thought they were arrhenotokous species. However, it was observed that phytoseiids require mating in order to lay eggs. Further studies showed that male phytoseiids arise from fertilized eggs but become haploid after losing the paternal set of chromosomes by inactivation and/or chromosome elimination (Atalay and Schausberger, 2018; Cabrera et al., 2009; Sabelis and Nagelkerke, 1988; Nelson-Rees et al., 1980; Hoy, 1979). This type of reproduction is called parahaploidy and is found in several phytoseiid species (Mesostigmata).

Thelytoky refers to the production of females from unfertilized eggs. Males are not known or only a few are produced (Cabrera et al., 2009; Norton et al., 1993). Thelytoky is found in many groups of mites and especially common in soil-inhabiting Mesostigmata (Uropodidae), Endeostigmata, Oribatida, and Astigmata (Norton et al., 1993). It is also known or suspected in many groups of Prostigmata (Vacante, 2016) including *Penthaleus* spp. (Penthaleidae) (Robinson et al., 2002; Halliday, 2005), species in Bryobiinae (Tetranychidae) (Perotti and Braig, 2004), and *Brevipalpus phoenicis* Geijskes (Tenuipalpidae) (Berry and Fan, 2012).

2.6 Sex determination

In mites, genetic mechanisms of sex determination are diverse (Hoy, 2011). Diplodiploidy, haplodiploidy, and thelytoky are the main genetic systems. Diplodiploidy has been assumed to be the ancestral genetic system where populations consist of two sexes and both sexes have the diploid set of chromosomes (Vacante, 2016). Mites with diplodiploidy are biparental and only sexual reproduction is present (Capinera, 2008). Arrhenotoky is the most widely distributed haplodiploid genetic system followed by Thelytoky.

Thelytoky involves obligate parthenogenesis and haploid eggs develop into females (Vacante, 2016).

The sex ratio is the proportion of females to males. The apparent sex ratio is the observed sex ratio in the field. This ratio may be distorted by factors such as differential mortality of sexes in the egg or subsequent stages, and sex dispersion (Vacante, 2016; Krantz and Walter, 2009; Wrensch and Young, 1983). The acarine sex ratio is commonly more female-biased (e.g. 60–95%) among the studied mite species, although the progeny sex ratios of approximately 1:1 would be expected to occur in diplodiploid mites (Krantz and Walter, 2009). For example, the sex ratio varies in Tetranychidae, but 3:1 ratio (female: male) is the most common (Vacante, 2016; Krainacker and Carey, 1990). Similarly, the percentage of females in eriophyoids ranges between 51% and 95% (Lindquist et al., 1996).

A wide variety of intrinsic and extrinsic factors influence the sex ratio in mites. The temperature, host quality, and the population density are among the most important extrinsic factors. Important intrinsic factors affecting sex ratios include the amount of sperm transferred to the female and the age of female. Moreover, the first egg laid by a mated female is unfertilized and male determined. This may be due to these eggs being too mature for sperm penetration at the time of copulation (Hales, 1994; Feiertag-Koppen and Pijnacker, 1985).

2.7 Identification

Mite systematics is based on morphological characters. Mites are usually stored in 70–80% alcohol and due to their small size, they often need to be cleared and mounted on microscope slides for identification. The most popular clearing agent for mites is lactophenol. Other options include aqueous solutions of 50–95% lactic acid for soft-bodied mites, pure lactic acid colored with lignin pink for tetranychid mites, Nesbitt's fluids, Andre's fluids, or 5–10% solution of KOH for hardened specimens, and Keifer's booster or lactic acid for eriophyoid mites. While lactic acid can be used for temporary mounts of specimens, a permanent mount is commonly made using Hoyer's medium (Vacante, 2016). Two labels should be included in the slides, one including the host plant, collection date, and collector name, and other including the scientific name, sex, and name of the scientist who identified the specimen (Gutierrez, 1985). The specimens mounted with these methods usually are well preserved.

Mite identification to species-level using taxonomic keys is difficult and needs special training. Tarsi, mouthparts, dorsal-ventral plates, and setal patterns are considered the main taxonomic characters for most mite groups. The development of faster and more accurate methods is underway because of the difficulties in the morphological identification of mites in some cases.

Especially, the use of molecular identification techniques has increasingly been advocated for mites recently and could complement the morphological methods (Zele et al., 2018; Skoracka et al., 2015; Matsuda et al., 2013; Li et al., 2012).

3 Plant feeding mites

3.1 Tetranychidae

The most significant plant feeding mite pests that have impacted agriculture and the ornamental industry include species from the family Tetranychidae (Prostigmata). Approximately 1250 species are known to feed on almost 4000 plant species, although only about 100 species are considered economically important (Wu and Hoy, 2016). They are generally less than 0.8 mm in size and with varied colors. One of the most common species of the group is the TSSM, *Tetranychus urticae* Koch (Fig. 4), a major pest of many fruit, vegetable, field crops, and ornamental plants (Nyoike and Liburd, 2013).

The developmental period for tetranychids is dependent on plant phenology (Chaaban et al., 2012), cultivar (Vasquez et al., 2008), temperature (White and Liburd, 2005), and changes in the chemical composition of plants (Palevsky et al., 2005). This period varies among species; for instance, *T. urticae* can complete its development in as little as 6 days at an optimum temperature of 26.6°C, whereas *Oligonychus punicae* takes an average of 17.5 days on certain grape cultivars (*Vitis vinifera*). The lower temperature limits for development in certain species including *T. urticae* is about 12°C, while the upper threshold averages ~ 40°C (Jeppson et al., 1975). Generally, the life cycle of tetranychids involves an egg, larva, protonymph, deutonymph, and an adult stage. The larva, protonymph, and deutonymph are the immature stages but most species have active feeding and quiescent (resting) stages (Huffaker

Figure 4 *Tetranychus urticae* females on a bean leaf.

et al., 1969). The larva has three pairs of legs while the other active stages protonymph and deutonymph have four pairs similar to the adult stage. The shape of eggs may vary slightly according to species and are usually spherical or oval (approximately 0.2 mm in diameter). The color also varies from clear, tan, to white. Eggs are usually laid on the underside of leaves by the females, away from chemical sprays and potential predators. Usually, the eggs are attached to the leaves with fine silk webbing. Egg hatch in 2–3 days (Fasulo and Denmark, 2000); fertilized eggs hatch into females while males develop from unfertilized eggs. Generally, a mated female can produce both male and female progeny but unmated females only develop into males.

Tetranychids disperse to new hosts once the current host plant quality declines. Factors that facilitate the dispersal process include overcrowding, aging plants, or elimination of their feeding source. Short distance dispersal such as within plant movement is achieved through crawling, whereas long-distance dispersal is facilitated by wind currents or movement of materials and animals including humans from infested mite areas. When wind-assisted dispersal takes place, female mites will move to the top of the plant canopy and position themselves where they can be easily blown away by prevailing winds (Kennedy and Smitley, 1985). Males are not known to participate in active dispersal.

Tetranychids injure plants by piercing and removing chlorophyll from leaves interfering with the plant's ability to carry out photosynthesis causing reduction in yield (Nyoike and Liburd, 2013; Wyman et al., 1979; Sances et al., 1982). The lack of chlorophyll on leaves that are heavily infested with *T. urticae* often displays white or yellow spots or 'stippling' on the leaf surfaces (Sances et al., 1979; DeAngelis et al., 1982) (Fig. 5). Other observations include a reduction in key nutrients including nitrogen, potassium, and magnesium were

Figure 5 Feeding injury of *Tetranychus urticae* with webbing on bean plant leaves.

recorded in chrysanthemum after *T. urticae* feeding (Tomczyk and Kropczyńska, 1985).

Tetranychids are usually managed with broad-spectrum pesticides (mostly miticides). They have high reproductive rates and short generational times that cause selection pressure to be increased quickly (from high pesticide usage). For this reason, growers scout (monitor) their fields weekly to check mite population densities. Growers also use pesticides with different modes of action to reduce the potential for resistance development. Phytoseiids are frequently released early in the season to delay the onset of bi-weekly pesticide applications. *Phytoseiulus persimilis* and *N. californicus* are two common mite predators frequently released in field crops preventatively to prevent the build-up of tetranychid population.

3.2 Tarsonemidae

The family Tarsonemidae (Prostigmata) is very diverse in feeding styles, with some species feeding on algae, fungi, and plants as well as some parasitic species. Tarsonemids are primarily tropical and subtropical, and only a few species are found in the Nearctic and the Palearctic regions. Tarsonemid mites are very small, ranging from 0.1 to 0.3 mm in length with semitranslucent, white, or yellow appearance. Their life cycle requires approximately 1 week to develop from egg to adult but in some regions, they can develop as quickly as in 5 days. They develop best under warm temperatures, high humidity, and low light intensity (Hoy, 2011).

Economically important tarsonemid species are in the Tarsoneminae subfamily including *Steneotarsonemus ananas* Tyron or the pineapple tarsonemid, *S. spinki* Smiley or the panicle rice mite, and *S. laticeps* Halbert or the bulb scale mite, which are important pest mites around the world. However, *Polyphagotarsonemus latus* Banks and *Phytonemus pallidus* Banks can be considered the most important pests in the family (Hoy, 2011).

Polyphagotarsonemus latus (Fig. 6), commonly known as broad mites or tea mites, feed on plants from over 60 families and cause economic damage on a wide range of food crops, including apple, avocado, beans, cantaloupe, citrus, coffee, cotton, cucumber, eggplant, grapes, guava, mango, papaya, pear, potato, tea, tomato, and watermelon, as well as many ornamental plants. In temperate and subtropical areas, broad mites are a pest of greenhouse crops and infest field-grown plants in tropical regions (Renkema et al., 2017). Nonetheless, *P. latus* can withstand temperatures below its lowest reported developmental threshold (10°C) without affecting its potential to produce high infestations levels (Luypaert et al., 2015).

Broad mite feeds on the youngest growth tips, causing malformation of the flower buds and the terminal leaves. The latter become severely stunted

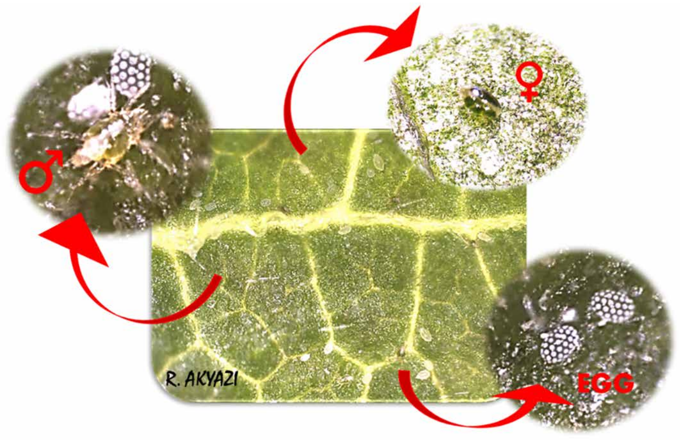

Figure 6 *Polyphagotarsonemus latus* female, male, and eggs on a bean leaf.

and hardened, curl down at the edges, and show brownish or reddish lower surfaces. This feeding behavior results in severe economic damage. In azalea production (*Rhododendron simsii* Planch, Ericaceae), such as in many other ornamental crops, yield losses are significant due to *P. latus*. Flowers are produced almost year-round and require a specific number of chilling hours to release the flowers from their dormant state. Even at temperatures as cold as 7°C or 2°C, broad mite females can survive for long exposure periods (28–49 days) and continue to lay eggs soon after exposure. Eggs and larvae, on the other hand, can only survive to short exposure times without damaging effects on hatchability and offspring performance but cannot survive under such low temperatures for more than 24 h (Luypaert et al., 2015).

The cyclamen mite *P. pallidus* ssp. *fragariae* (Zimmerman), also known as the strawberry tarsonemid mite, is an important pest of strawberry worldwide. Similarly to *P. latus*, there has been pressure to reduce the use of pesticides for *P. pallidus* control due to their ability to develop resistance rapidly. Moreover, the number of pesticides available for these key tarsonemid mites is limited and used as an ultimate option (Lopez et al., 2015; Hellqvist, 2002).

Because of *P. latus* and *P. pallidus* endurance, the use of predatory mites is increasing in the last few years to prevent rapid mite population build-up since the predators can reach tight areas between leaves and flowers that spray applications cannot (Renkema et al., 2017). Predatory mites such as *A. swirskii*, *N. cucumeris*, and *N. californicus* have been evaluated for broad mite and cyclamen mite control (Lopez et al., 2017; Renkema et al., 2017; Jovicich et al., 2008). Alternatively to curative methods, the main strategy for control of the tarsonemid mites is the use of clean plant material at the beginning of the season. In the case of strawberry crops, hot water treatment is one method to produce mite-free strawberry runners before rooting and can be done by the farmers with relatively simple equipment. Hellqvist (2002) showed that 6 min at 46°C is enough to kill all cyclamen mite stages without causing any harm to the runners.

3.3 Eriophyoidea

The Eriophyoidea is a superfamily consisting of three families: Eriophyidae, Phytoptidae, and Diptilomiopidae. Most economically important mites are included in the Eriophyidae family.

These mites found on the leaf or bud surfaces are called rust mites whereas mites within buds, blisters, or in galls are known as gall mites. Eriophyoids are the smallest arthropods known to feed on plants between 0.1 and 0.5 mm in length. They feed on young, soft tissues and meristems of their host plants. Although some eriophyoid mites can be crop pests, the relationship between many of these species and their host plants is more benign. They have evolved to allow both plant and mite to coexist without significant harm (Hoy, 2011).

Eriophyiod species are known to cause substantial damage in various crops of economic importance including fruit, vegetable, ornamental, and perennial crops (Navia et al., 2010). Among the plant feeding mites, the Eriophyidae are the second most economically important family of pests after the Tetranychidae (Van Leeuwen et al., 2010). Most mite species that are known to vector plant pathogens are within this family, with at least 26 plant diseases associated with eriophyid mites. As a result of their tiny size and very short stylets feed on only the epidermal cells of their plant hosts where they may acquire and transmit disease agents to these plant cells (Hoy, 2011; Navia et al., 2010).

The major problem with eriophyoid control is their hidden lifestyle within galls, blisters, and buds that are not easily accessible. In these cases, accurate timing for miticide applications is important, in order to reach the life stages that temporarily leave the hiding places. Thus, much of the research is aiming to manage strategies including conservation and augmentative biological control (Van Leeuwen et al., 2010).

Vegetables can be damaged by various eriophyoid mites of which the tomato russet mite *Aculops lycopersici* (Tryon) is the most important on tomato, capsicum, eggplant, and several other plant species (Van Leeuwen et al., 2010).

4 Integrated mite management

4.1 Planting schedule

Timely planting may be an effective way to avoid periods of high mite population growth and mite migrations between consecutive crops. If a mite has a predictable seasonal appearance, early or late planting can be used to mitigate mite infestations. For instance, the wheat curl mite, *Aceria tosichella*

Keifer (Eriophyidae) transmits the wheat streak mosaic virus (WSMV) to wheat and corn. Wheat curl mite migration from wheat to corn or from spring to fall wheat crops are associated with an increased incidence of WSMV. Fritts et al. (1999) suggested that the incidence of WSMV can be reduced by planting corn before or after the seasonal peak migration from wheat in early summer. Elimination of sources of *A. tosichella* before planting limits the risk of early WSMV infection (Thomas et al., 2004).

In areas where spring and winter wheat season overlap, early planting of spring wheat reduces the risk of mite infestation in the fall planted winter wheat. However, McMechan and Hein (2016) suggested that late planting can reduce *A. tosichella* numbers and the length of time that they have to transmit WSMV. Similarly, the Banks grass mite, *Oligonychus pratensis* Banks (Tetranychidae), occurs on corn and sorghum early during the crop-growing season. Archer et al. (1990) reported larger infestations of the Banks grass mite occur on early-planted than on late-planted sorghum in Texas.

Early planting can be used to mitigate damage by *Aceria tulipae* Keifer (Eriophyidae). A combination of early planting dates and low storage temperatures after harvest can be used to reduce infestations by this mite on tulips (Conjin et al., 1996). Early planting during the rainy season is also a cultural practice against cassava green mites, *Mononychellus tanajoa* Bonda (Tetranychidae). Hot and dry periods promote *M. tanajoa* population growth, whereas prolonged rainy periods are likely to lessen breeding in mite populations. Cassava can be planted early during the rainy period so that the plants are more mature when *Mononychellus* mites attack during the dry season (Bellotti, 1985). Because of the potential variety of responses of mite pests to early or late planting, a detailed knowledge of the pest's biology is of extreme importance.

4.2 Host tolerance and resistance

Host plants show different reactions or intensity of reaction to mite feeding. Host plant resistance, or the characteristics of a host that suppress mite reproduction, or tolerance, and the ability of a host to cope with mite damage have been widely documented. Krips et al. (1999) found that differences on host susceptibility of different gerbera cultivars to *T. urticae* were associated with variability in the intrinsic rate of population increase of the mite on the different cultivars. Similarly, different strawberry varieties show different susceptibilities to infestation with *T. urticae*. The susceptibility of strawberry cultivars to spider mite infestations is associated with the density and shape of leaf trichomes of the different cultivars. For instance, the denser, longer, and sharply pointed trichomes on the 'Sweet Charlie' cultivar are not conducive to spider mite infestations in comparison with other cultivars (Afifi et al., 2010).

Shanks and Barritt (1975) screened 85 strawberry cultivars and clones for resistance to *T. urticae*. The cultivars Siletz, 'WSU 1019,' and 'BC 25' showed tolerance to damage. Shuster et al. (1980) also reported tolerance of the Siletz cultivar to spider mite damage. In addition, Gong et al. (2018) found substantial differences in preference and performance of *T. urticae* across Chinese strawberry cultivars.

Tomato is another host that illustrates how different cultivars can affect the survival, development, and oviposition rates of mite species. Onyambus et al. (2011) studied the effect of trichomes in eight tomato strains on the spider mite *Tetranychus evansi* Baker & Pritchard (Tetranychidae). Resistance to *T. evansi* in some of the tested tomato strains was associated with some trichomes types and their density. Similarly, Maluf et al. (2007) indicated that selection of tomato cultivars with higher densities of glandular trichomes can be an efficient parameter to select for tomatoes resistant to spider mites. However, high glandular trichome densities on tomato cultivars can also interfere with biological control using acarine predators (Nihoul, 1993).

Variability in the susceptibility of perennial fruit crops to mite feeding has also been documented. Some lychee varieties are more susceptible to lychee mite (*Aceria litchi* Keifer, Eriophyidae) infestations than others (Arantes et al., 2017). According to Alam and Wadud (1963), the Mongalbaria variety is less susceptible than other varieties. Varieties that derive from Bombay and China are highly susceptible, being most vulnerable during the flowering and fruiting seasons.

Kerguelen and Hoddle (2000) compared the susceptibility of different avocado cultivars to the persea mite, *Oligonychus perseae* Tuttle, Baker, and Abbatiello (Tetranychidae). Based on the leaf area damaged by *O. perseae*, Hass and Gwen were susceptible, Fuerte, Lamb, Hass, and Reed were resistant, and Esther and Pinkerton were of intermediate susceptibility. Another example of variability on the susceptibility of mite hosts was provided by Vazquez et al. (2016) who reported longer life spans and lower oviposition rates of the Red palm mite, *Raoiella indica* Hirst (Tenuipalpidae), on Jamaican tall compared with dwarf coconut cultivars.

4.3 Host nutrition influence on mite species

Plant nutrients can have a direct effect on mite populations. *Tetranychus urticae* females respond to leaves with high nitrogen availability and low carbon to nitrogen ratio (Hoffland et al., 2000). Large amounts of nitrogen or a deficiency of potassium increase the soluble nitrogen in the plant which induces an increase in the population growth of spider mites. In addition, high fertilizer rates and excess soluble elements such as silicon, magnesium, and calcium, also tend to favor spider mite populations (Jeppson et al., 1975).

The susceptibility of strawberry cultivars to spider mites is associated with different levels of phenols and total sugars on leaves (Afifi et al., 2010). Higher phenol contents resulting from calcium and potassium sulfate fertilization were associated with increased resistance to spider mite populations on two strawberry cultivars (Afifi et al., 2010). In contrast, high levels of total sugars resulted in increased mite populations.

Different irrigation regimes can also have a direct effect on mite infestations. Chandler et al. (1979) found that controlled overhead irrigations that wet plant foliage can limit the growth and severity of spider mite populations on corn. Opit et al. (2006) found that overhead watering reduced the number of leaves sustaining *T. urticae* injury by fourfold compared with drip irrigation on Impatiens. However, caution should be exercised in systems that use biological control because overhead irrigation can also have a negative effect on predatory mites (Opit et al., 2006).

White and Liburd (2005) studied the effects of soil moisture on the reproduction of *T. urticae* in strawberries and concluded that low soil moisture promotes spider mite reproduction during the early season. In contrast, the red palm mite *R. indica* is more abundant on well-watered coconut palms compared to water-stressed palms (Villasmil et al., 2014). However, populations of *R. indica* decline naturally during the rainy season because of the physical effect of rain dislodging the mites from the palm fronds (Otero-Colina et al., 2016). Overhead irrigation directed to the underside of coconut leaves has been used as a management tactic to control *R. indica* on coconut.

4.4 Host structure and mite dispersal

Plant density and plant architecture influence the distribution of mites on a plant species. Spacing may affect the searching behavior and dispersal of phytophagous mites, as well as on the ability of predators to locate them. Ambulatory dispersal of mites between plants is favored if the plants are spaced so closely that they touch. On the other hand, relative humidity can be higher in high-density crops which could negatively affect mites that prefer dry conditions. In addition, close spacing may result in greater control of a pest population by natural enemies (Lopez et al., 2017). However, responses to different crop densities can vary among mite species and some mite pests can increase on high-density crops. Because of the potential variety of responses of mite pests to crop spacing, a detailed knowledge of the pest’s biology is of extreme importance.

Planting an area repeatedly with a single crop provides constant food supply for a mite pest and predisposes rapid development of pest populations. Crop rotations with non-mite hosts can be an effective cultural control strategy to disrupt mite populations. However, in order to be effective, the use of crop rotation in mite management must consider a whole-farm and sometimes even an area-wide approach.

4.5 Insect predators of plant feeding mites

Several insects belonging to the orders Coleoptera, Diptera, Hemiptera, Thysanoptera, and Neuroptera prey naturally on acarine pests but few insect species are used in augmentative biological control. Key predatory insect species include spider mite specialist beetles from the genus *Stethorus* (Coccinellidae). Larvae and adults of *Stethorus* prey on spider mite species found in many agricultural systems, such as stone fruits, tree nuts, citrus, avocados, banana, papaya, palms, tea, cassava, maize, strawberries, vegetables, and cotton (Biddinger et al., 2009). Among more than 60 described *Stethorus* species, *S. punctillum* Weise, also known as the spider mite destroyer, is mass-reared and sold commercially to control spider mites in various crops.

Oligota (Staphylinidae) is a cosmopolitan genus with more than 170 species of beetles predacious on mites. Larvae and adults of *O. flavicornis* Boisduval and Lacordaire and *O. oviformis* Casey prey naturally on tetranychid mites but have not been produced commercially for use in augmentative biological control (Chazeau, 1985). Thrips are generally phytophagous but a few species prey on tetranychid and eriophyid mites (Perring and McMurtry, 1996). The six-spotted thrips (*Scolothrips sexmaculatus* Pergande, Thripidae) is a common predator of mites in North America that can cause rapid reduction of tertranychid mites. However, *S. sexmaculatus* has not been used effectively in augmentative biological control (Jeppson et al., 1975). The predatory gall midge, *Feltiella acarisuga* Vallot (Cecidomyidae), is used commercially for control of spider mites in various crops including tomato, cucumber, sweet pepper, and roses (Osborne et al., 2016).

Nymphs of the mirid, *Macrolophus pygmaeus* Rambur, prey on whiteflies, thrips, and aphids, but can also prey on spider mites and are naturally found on solanaceous crops such as tomato and tobacco. This species is commercially available for use in augmentative control. However, this species is also phytophagous and can feed on other mite predators such as phytoseiid mites (Zhang, 2018). Chrysopidae are mainly aphid predators, but some species have general feeding habits including predation on spider mites. *Chrysoperla carnea* Stephens (Chrisopidae), the common green lacewing, can achieve development on a spider mite diet in the laboratory, but in the field, they attack mites only after the decline of their preferred prey (Chazeau, 1985).

4.6 Mite predators of plant feeding mites

Mites of the family Phytoseiidae (Fig. 7) are probably the most important predators of plant feeding mites and have been extensively used in biological

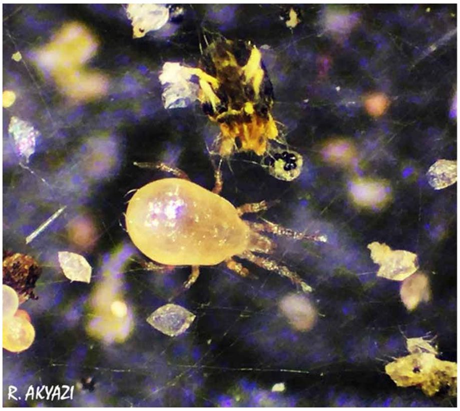

Figure 7 Adult female *Neoseiulus californicus* on a waxed black paper disc.

control. Phytoseiids have special attributes that make them effective biological control agents, including short developmental times (sometimes shorter than their prey), high reproductive potential, effective searching capacity at low prey densities, and microhabitat preferences similar to their prey, among others. Some species specialize on tetranychids, some are generalists and feed on a combination of tetranychids, other mites, and insects, and some other feed on mites and pollen (McMurtry and Croft, 1997; McMurtry et al., 2013).

Several species are commercially available to control acarine and insect pests. Table 2 lists the most widely used acarine predators in augmentative biological control that are produced by several biocontrol companies around the world. Other phytoseiids from the genus *Amblyseius* (i.e. *A. largoensis* (Muma), *A. tamatavensis* Blommers etc.), *Euseius* (i.e. *E. stipulates* (Athias-Henriot), *E. scutalis* (Athias-Henriot), *E. tularensis* Congdon, *E. hibisci* (Chant)), and *Neoseiulus* (i.e. *N. longispinosus* (Evans), *N. californicus* (McGregor)) naturally occur on fruit orchards or vegetable crops, and play an important role regulating phytophagous mites in these systems. In addition, other predators of phytophagous mites are found in the families Laelapidae, Stigmaidae, Bdellidae, Anystidae, Erythraeidae, and Cheyletidae (Carrillo et al., 2015).

4.7 Predatory mite conservation

Conservation strategies for beneficial predatory mites include minimizing use of pesticides that are harmful to them and use of compatible pesticides at doses that cause low predator mortalities. Timing of pesticide application and release of predators depend on prey densities. In general, pesticides are used to suppress pest outbreaks and predatory mites are subsequently released to maintain the pest mites at tolerable levels.

Vegetation surrounding crop fields can serve as a source of pollen, which is a critical food source for some predatory mite species. Some predators of

Table 2 List of acarine predators that are commercially available and used in augmentative biological control of plant feeding mites

Predator	Family	Target
Amblydromalus limonicus (=Amblyseius lailae)	Phytoseiidae	Thrips, whiteflies, spider mites
Amblyseius andersoni	Phytoseiidae	Spider mites, rust mites, broad mites, cyclamen mites
Amblyseius swirskii	Phytoseiidae	Thrips, whiteflies, spider mites, cyclamen mites, broad mites
Euseius gallicus	Phytoseiidae	Thrips, whiteflies, spider mites, broad mites
Iphiseius degenerans	Phytoseiidae	Thrips, spider mites
Mesoseiulus (=Phytoseiulus) longipes	Phytoseiidae	Spider mites
Neoseiulus (=Amblyseius) cucumeris	Phytoseiidae	Thrips, spider mites, broad mites
Neoseiulus (=Amblyseius) fallacis	Phytoseiidae	Spider mites, broad mites, cyclamen mites
Neoseiulus barkeri	Phytoseiidae	Thrips, spider mites
Neoseiulus californicus	Phytoseiidae	Spider mites
Phytoseiulus persimilis	Phytoseiidae	Spider mites
Transeius montdorensis	Phytoseiidae	Thrips, whiteflies, spider mites
Typhlodromus pyri	Phytoseiidae	Rust mites, spider mites
Galendromus (=Typhlodromus) occidentalis	Phytoseiidae	Rust mites, blister mites, spider mites
Hypoaspis (=Gaeolaelaps) aculeifer	Laelapidae	Bulb mites, thrips pupae
Stratiolaelaps scimitus (=Hypoaspis miles)	Laelapidae	Sciarids, thrips, spider mites

Source: modified after Knapp et al. (2017).

the genus *Euseius* play a significant role as control agents of spider mites and can reproduce solely on pollen in the absence of prey (McMurtry and Croft, 1997). In addition, the combination of prey and pollen may result in increased fitness of the predator and overall improved pest control. Pollen can also be artificially applied to the crop to enhance predatory mite performance (van Rijn and Tanigoshi, 1999). In special cases, plants can be deliberately infested with prey in a controlled manner prior to releasing predators to favor establishment in a technique known as pest in-first (Parrella et al., 1999).

5 Biological control

5.1 Mite culture

Large numbers of predatory mites can be obtained through rearing systems using their primary prey, pollen, and/or a factitious host (alternative prey). A factitious prey consists of a food source that the predator would not normally encounter in its natural environment but on which the predator can be reared for mass production (Midthasset et al., 2014a). Based on the predatory mite, various factitious prey has been used in commercially available breeding sachets including astigmatid mites such as *Carpoglyphus lactis* L. (Acari: Carpoglyphidae) (Bolckmans and van Houten, 2006), *Suidasia medanensis* Oudemans (Acari: Suidasidae), and mold mites *Tyrophagus putrescentiae* Schrank (Acari: Acaridae) (Pochubay et al., 2015).

Mite culturing techniques vary depending on the feeding habits of the predators (McMurtry and Croft, 1997). Spider mite specialist predators (i.e. *Phytoseiulus* and *Neoseiulus* species) are generally reared only on their primary prey, generalist predators (i.e. *Amblyseius*, *Typhlodromus* species) can be reared on different prey items and pollen, and other species (i.e. *Euseius* species) can be reared solely on pollen. Small laboratory cultures for research purposes usually use leaves of the host plant or plastic rearing arenas placed on water-soaked cotton or a sponge to prevent escape of the mites. The food is provided in the arena and replenished on a regular basis. Mass rearing systems involve the use of an alternative prey, usually astigmatid mites, that results in high fecundity and survival rates of the predatory mites (Barbosa and Moraes, 2015).

The use of *Phytoseiulus persimilis* Evans (Phytoseiidae) for control of TSSM (*T. urticae*) made it the first predatory mite massively reared in the United States back in the 1960s (Fournier et al., 1985). The rearing and storage systems developed to facilitate the release of *P. persimilis* included the use of carrying materials such as wheat bran or vermiculite. Nowadays, most commercially available predatory mites are distributed in different types of formulations with the most common being the use of cups or shaker bottles using one of these carriers.

5.2 Formulations and release methods

The loose product (bran or vermiculite) is sprinkled directly on the plants (Fig. 8), so prey or pollen needs to be present for the predatory mites to survive. For generalist predators, an additional non-phytophagous prey mite can be added to the predator-carrier mixture to serve as food and maintain the predatory mite population. The main advantage of using this type of formulations is the direct introduction of large predatory mite numbers into the plants. It was used for several years despite some limitations. For example, sprinkling loose product on the crop can be easily blown away by the wind in unprotected crops. If the bran gets wet due to rain or overhead irrigation, proliferation of fungal pathogens may become an issue. Lastly, increases in labor and therefore in pest management costs is another disadvantage of manual releases using loose product (Pickett et al., 1987).

Figure 8 Predatory mite release methods. (a) loose product sprinkled onto the leaves of a squash plant, (b) shaker bottle for manual releases, (c) mechanical hand blower, (d) sachets used for early establishment of predatory mites in zucchini squash, (e) banker plants with predatory mite inoculations using loose product.

Broadcasting devices integrating shaker bottles are being released into the market to minimize the time and labor required for predatory mite applications. The development of delivery systems to broadcast predatory mites goes back to the 1980s when *P. persimilis* was first released by aircraft into corn fields in the Texas high plains for biological control of Banks grass mites (*O. pratensis*) and *T. urticae* (Pickett et al., 1987). Since then, several broadcast devices have been designed for the release of various commercially available predatory mites. From release systems mounted on standard tractors (Colfer et al., 2004; Giles et al., 1995) to manually operated blowers, mechanical releases have become common for the release of predatory mites such as *P. persimilis*, *N. californicus*, *Metaseiulus occidentalis* Nesbitt, and *Amblyseius swirskii* Athias-Henriot, among others (Pezzi et al., 2015; Ade et al., 2010; Opit et al., 2005; Colfer et al., 2004).

Leaf blowers and other similar devices are adapted with controlled extraction systems that allow the loose product from bottles into the radial fan and diffuser of the blower where it is transported by an air flow (Fig. 8). Gentle extraction and mixing are vital for survival of the predatory mites during application.

The main advantage of mechanical releases is the reduction in time required for application of the predatory mites in a specific area. In other words, predatory mite release using mechanical blowers can be achieved in substantially shorter periods of time compared to using slow-release sachets or manual releases (Opit et al., 2005).

The main limitation to mechanical releases is that beneficial organisms may be damaged by the machine parts during their handling and distribution due to possible contact with mechanical elements and abrasion against carrier materials (Pezzi et al., 2015). Nevertheless, the advantages of mechanical applications usually overcome its limitations. For example, the use of a mechanical blower for release of *P. persimilis* and *A. swiskii* in greenhouse-grown eggplants dramatically reduced mite application time to six times shorter than manual releases and to two times shorter compared to the use of sachets for *A. swirskii* (Lanzoni et al., 2017). Larger areas inoculated in shorter time result in labor cost returns and increase in homogeneity of the predator throughout the cropping area.

Augmentative releases of predatory mites from shaker bottles with or without mechanical blowers can be a preventive strategy but are more often used as a curative tactic during pest outbreaks. Slow-release sachets or breeding systems are used as an augmentative release method as well as a preventative strategy and are the most popular release system. Slow-release sachets consist of paper envelopes that contain a mixture of bran, factitious prey, and predatory mites that can be hung in the plant canopy (Fig. 8) (Pochubay et al., 2015). A small hole in the sachet allows random and sustained dispersal of predators from the system into the crop as the breeding population of the factitious host or prey mite will continuously supply prey stages for the predator (Midthasset et al., 2014a).

The use of sachets can be cheaper than a repeated introduction of predatory mites directly on the crop as loose product because at least threefold the initial number of predators is released in a period of 3–5 weeks (Groot et al., 2017). Breeding sachets are considered especially suitable in crops with little pollen where a sustained release improves preventive protection from pests (Midthasset et al., 2014a). A final advantage of slow-release sachets is the ease of application (Groot et al., 2017). A variety of different types have been developed for predatory mites such as *A. swirskii*, *Neoseiulus cucumeris* Oudemans, and *Amblydromalus limonicus* (Groot et al., 2017); however, no sachets have been developed for specialist predators such as *P. persimilis* because they do not prey on factitious mites.

Sachets generally perform well under moderate climatic conditions but are sensitive to adverse conditions. RH and temperature have a significant effect on predator release from breeding sachets. Relative humidity has a marked effect on sachet performance as productivity and release increased with increasing RH. High RH retains the moisture content of the sachet medium allowing good productivity and therefore higher release rates, whereas low RH can desiccate the sachet medium resulting in unfavorable conditions for the predatory mite population (Buitenhius et al., 2014; Midthasset et al., 2014b).

Similarly, when the sachet is exposed to direct rain, the humidity of its contents may increase to levels that favor the growth of molds, or even drowning of the mites (Groot et al., 2017). Proper placement of release sachets according to microclimate conditions is an important factor for sachet performance. Companies recommend placing the sachets in the shade where moderate temperature and appropriate RH levels are encountered, otherwise pest control might be compromised (Buitenhius et al., 2014).

5.3 Predatory mites in the field

Crops grown under the protection of a cropping structure, such as greenhouses or tunnels, are particularly suitable for release of predatory mites (Midthasset et al., 2014a). Controlled environmental conditions under protected structures may positively impact the development time and longevity of phytoseiid mites (Lee and Gillespie, 2011). Relatively high RH levels can influence egg viability and successful egg to adult development. Predatory mites are also protected from the rain, migration is minimized, and mite carriers such as loose product or sachets are protected from desiccation. Therefore, most companies recommend predatory mites for use under protected structures where they usually show better performance.

The use of predatory mites in open fields is rather limited compared to the use in protected crops. The most common limitations involve adverse environmental conditions such as extreme hot or cold temperatures and low RH. For example, most predatory mites show reduced egg hatchability under low RH. Similarly, low or high extreme temperatures impairs adult stages, reduces oviposition, and stops immature development (Midthasset et al., 2014a).

Wind is another factor that may compromise the survival of the predators. Loose product can be easily dispersed out of the targeted crop and in the case of release sachets, it increases the probability of bran dissection. Shimoda et al. (2017) developed plant-based shelters to protect predatory mites in release sachets from environmental stress and enhance their prevalence in the crop. Similarly, Koppert Biological Systems recently developed a new type of slow-release sachet that is more resistant to adverse climatic conditions. The development of this sachet is intended to open new possibilities for the use of predatory mites in open field. As an additional feature, the new sachet is designed to be fully biodegradable and can be ploughed into the soil together with the crop residues at the end of the season (Groot et al., 2017).

To reduce costs in biological control programs and enhance the establishment of predatory mites under both protected and unprotected structures, cost-effective methods such as the establishment of predatory mites on banker plants were developed. Banker plants, also known as open rearing systems, are mobile habitats that provide alternative food sources (i.e. secondary prey, pollen, or nectar) and shelter for commercially available biocontrol agents (Lopez et al., 2017).

Banker-plant systems consist of three basic components that are dependent and influence each other in complex ways: the predatory mite, the banker plant, and the prey or alternative food (Kumar et al., 2015; Frank, 2010; Pratt and Croft, 2000). The alternative host plants are usually non-crop plants with special characteristics (e.g. domatia, early, or extended blooming periods) that aid in the development and dispersal of predatory mites used for control of herbivorous pests.

Generalist phytoseiids are commonly used as part of banker-plant systems due to their ability to survive on alternative food items (Fig. 8). The main goals of using banker plants include: (1) production of a growing population of predatory mites on alternative host plants that will provide long-term pest suppression (Frank, 2010) and (2) target the pests at their incipient stage of infestation by enhancing the early establishment of predatory mite populations. However, complexity in the screening of non-host banker plants and their integration into multiple cropping systems as well as slow dispersal of biocontrol agents from the banker plants are major limitations (Kumar et al., 2015).

5.4 Intraguild predation

Several studies have reported the effectiveness of introducing multiple phytoseiid species to suppress tetranychid mites or major insect pests such as thrips and whiteflies (Rahman et al., 2012). Yet, releases in unaccustomed habitats or lack of food resources may result in opportunities for unexpected interactions among predators (Maleknia et al., 2016; Pochubay et al., 2015). The killing and eating of potential competitors is known as intraguild predation. In another words, it refers to a predatory species (at any developmental stage) feeding on another predatory species. This phenomenon has been observed between generalist predators and it is becoming a major consideration for biological control programs including predatory mites as biocontrol agents.

Intraguild predation is common among natural enemies released in greenhouse biological control programs where multiple predator species are often released to target the spectrum of greenhouse pests inhabiting plant foliage and soil. For example, encounters between phytoseiids and rove beetles are one example of intraguild predation that can affect suppression of spider mites if not implemented correctly (Pochubay et al., 2015). In this case, it has been shown that sachets protect *N. cucumeris* from intraguild predation by *Dalotia coriaria* Kraatz (Coleoptera: Staphylinidae) resulting in higher populations of mites, whereas loose product is vulnerable to predation in greenhouse-grown gerbera plants (Pochubay et al., 2015). Conversely, early releases of *A. swirskii* (4-week-old plants) using sachets in zucchini squash may be vulnerable to fire ant predation in open fields.

Similar negative interactions have been observed between phytoseiid species. The generalist predator *N. cucumeris* can feed on immature stages of the specialist phytoseiid *P. persimilis* in periods of prey scarcity. These interactions can reduce considerably the offspring of *P. persimilis*, thus, having a negative effect on spider mite suppression (Schausberger and Walzer, 2001). Some release methods can limit negative predator interactions by providing physical barriers that minimize intraguild interactions. Additionally, the vulnerability to intraguild predation is related to the release method, the characteristics of the growing system (e.g. shelter and food availability), and native or secondary introduced predators.

Major negative connotations associated with intraguild predation include failure of biological control, higher costs for pest control due to the need of more frequent releases, and secondary pest outbreaks. Integration of multiple predator species is still limited in some biological control programs because of these concerns. However, effects of intraguild predation are most of the time minimal. Many authors argue that the scale of intraguild predation is low enough not to interfere with the predator's ability to suppress the target pest and that multiple-species releases of these predatory mites are more effective than single-species releases (Rahman et al., 2011).

5.5 Chemical control side effects on predatory mites

Due to the recognition of several adverse effects associated with solely chemical applications to manage agricultural pests (e.g. emergence of resistant populations, pest resurgence, outbreaks of secondary pests, decreased beneficial arthropods), a growing body of literature is aimed at addressing this issue (Assis et al., 2018; Desneux et al., 2007). For the past 30 years, the effects of pesticides on beneficial arthropods including predatory mites have been the subject of an increasing number of studies, and the potential effects have been reviewed numerous times (Desneux et al., 2007). Predatory mites have received substantial attention in this regard because of their value as biological control agents in integrated pest management (IPM) programs.

Biological control has some advantages compared to chemical control: can be more effective and reduces chemical use, minimizing worker exposure, residues, and environmental pollution (Gradish et al., 2011). Nonetheless, chemical control methods (e.g. insecticides, acaricides, fungicides, herbicides) are often part of pest management programs and exposure to pesticides in agroecosystems may result in mortality of the predatory mite populations and/or sublethal effects (Cheng et al., 2018; Gradish et al., 2011). Sublethal effects are defined as effects (either physiological or behavioral) on individuals that survive exposure to a pesticide (Desneux et al., 2007). A variety of methods has been used to evaluate the lethal and sublethal effects of chemicals to predators. However, there are no fixed assessment criteria to evaluate the risk of insecticides to all predatory species. Standard guidelines can be found only for a few of the predatory mite species commercially available such as *P. persimilis* and *N. cucumeris*.

The primary method is to assess the lethal rates or application rates in laboratory bioassays and use International Organization for Biological and Integrated Control of Noxious Animals and Plants classifications to categorize insecticides as harmless, slightly or moderately harmful, or harmful. This approach can identify the risk of insecticides tested at a defined rate, but do not consider the field-recommended application rates, or the drift of compounds in the environment (Cheng et al., 2018).

Thiamethoxam, imidacloprid, azadirachtin, spinosad, pyriproxyfen, fenpyroximate, biphentrine, abamectine, and avermectine are just a few of the several insecticides and acaricides that have been used in risk evaluations on biological control agents such as *P. persimilis*, *N. cucumeris*, and *N. barkeri*, among others. Chemical compounds such as fenpyroximate and spinosad have been reported as harmless or slightly toxic to *A. swirskii*, *N. Cucumeris*, and *H. miles* respectively. On the other hand, bifenthrin was reported to be extremely toxic to *A. swirskii* and *P. persimilis* (Fernandez et al., 2017; Lopez et al., 2015). Various of these studies included evaluations of predatory mite direct and residue exposure to the pesticides, estimation of lethal rates, lethal dose/concentrations, and risk assessments for different developmental stages (Assis et al., 2018; Cheng et al., 2018; Kungu et al., 2019).

Total abandonment of chemical inputs is often not feasible because the sole use of biological control may not maintain crop pests below the economic injury level but creating better conditions for predatory mite establishment may enhance the performance of predatory mites (Lopez et al., 2015). Development of reduced-risk pesticides, which are more toxic to their intended target pest than to beneficial species, can improve the incorporation of biological control agents into IPM programs; however, even these products can be harmful. Most pesticides are sprayed directly onto infested plants, threatening the predators that are usually near the pests. Predatory mite released after reduced-risk pesticide can result in successful pest suppression and/or predator establishment (Cheng et al., 2018).

Although challenging, the combination of insecticides acaricides with phytoseiid predators must be encouraged. The integration of reduced-risk chemicals and biological control for arthropod pest management may provide more comprehensive management than either approach alone. Such practice may be impaired because of the similar physiology of both predatory and phytophagous mites, which may also be killed by the action of acaricides (Hoy, 1985). Therefore, before recommending the integration of chemicals and biological control agents for commercial use, the effectiveness of the strategy needs to be evaluated both in the greenhouse and the field (Assis et al., 2018; Rahman et al., 2011; Gradish et al., 2011).

5.6 Genetic improvement

By 1994, at least 12 phytoseiid species have developed resistance either in the field or through laboratory selection (Kostiainen and Hoy, 1994). To date, at least 25 phytoseiid species have been reported to show different levels of pesticide resistance. *P. persimilis, N. cucumeris, Typhlodromus pyri* Scheuten*, A. fallacis, E. filandicus*, and *M. occidentalis* are a few of the predatory mite species with resistant strains reported. These species show resistance to a variety of chemical compounds including organophosphates such as parathion and dimethoate, carbamates such as carbaryl and propoxur, permethrin, and sulfur (Hoy, 1985).

Naturally occurring populations of predatory mites showing different levels of resistance to pesticides increased since the 1950s due to the high amount of chemical inputs used in agricultural systems. Variability in responses to pesticides among populations of phytoseiids suggests that phytoseiids can develop resistance in locally adapted populations as a response to past selection pressures (Hoy, 1985). For example, different levels of organophosphate resistance were found in native *M. occidentalis* populations in California since 1975 in pear, apple, and almond orchards (Hoy, 1985).

In Brazil, native populations of *N. californicus* have shown resistance to insecticides including organophosphates, fenpyroximate, fenpropathrin, propargite, and deltamethrin (Assis et al., 2018). This predatory mite is vital for suppression of *T. urticae* in several cropping systems in Brazil and resistance to acaricides in populations of *N. californicus* may allow growers to use the predatory mites in conjunction with chemical products in the field (Assis et al., 2018). In this study, authors showed that chlorfenapyr, fenpyroximate, and spiromesifen were safe for eggs and adults of the predator. Thus, their use in management programs associated with release of *N. californicus* is encouraged, provided high frequency of resistance in the prey population does not exist in the area (Assis et al., 2018; El Adouzi et al., 2017).

Genetic improvement implies that man can alter the genetic characteristics of a species to suit his needs. The underlying assumption made is that man can define what those desirable attributes are and, through hybridization or artificial selection, can improve the usefulness of the candidate species (Hoy, 1985). Since the 1970s, carbaryl, organophosphate, and sulfur resistant strains of *M. occidentalis* have been developed through laboratory selection and have been used in biological control programs since the early 1980s (Wu and Hoy, 2016). *Metaseiulus occidentalis* was successfully released and established for control of *T. urticae* in apple and almond orchards in California (Field and Hoy, 1986). However, this predator showed a rapid loss of resistance when released in an orchard where native susceptible mites were abundant while when the same resistant population was released in an orchard after a pyrethroid application had eliminated the susceptible natives, the resulting population maintained its pyrethroid resistance for several generations (Hoy, 1985).

Additionally, the proteins and molecular pathways involved in pesticide resistance in *M. occidentalis* remain unclear. To confer resistance phenotypes, arthropods can achieve resistance through elevated expression of pesticide-metabolizing enzymes such as members of the glutathione-S-transferases (GST), cytochrome P450 (CYP), or carboxyl/cholinesterases (CCE) superfamilies that result in increased metabolism, decreased penetration, sequestration, or increased secretion. A recent study showed that *M. occidentalis* has few members of GST, CYP, and CCE superfamilies and further studies are needed to clarify resistance pathways. Resistance mechanisms and possible fitness costs in *M. occidentalis*, or in any other mite in the Phytoseiidae, continue to be undetermined (Wu and Hoy, 2016).

Studies of resistance mechanisms at the molecular level were made possible thanks to genomic sequencing. Nevertheless, genetic improvement projects with biological control agents continue to face limitations due to the concern that artificial selection would necessarily result in laboratory-adapted strains that would perform poorly in the field (Wu and Hoy, 2016; Hoy, 1985).

Thanks to the commercialization of new technologies and its implementation in insect ecology, spatial and temporal relationships of mite populations can be studied in much greater depth. Geospatial tools including Global Positioning System, imagery systems, and Geographic Information Systems have now become more available to pest management practitioners and can be used together to analyze spatial distribution of insects and mites to be integrated into management decisions (Fleischer et al., 1999). Spatial interpolation, site-specific management, remote sensing, and machine learning (ML) are common tools used to analyze pest and predatory mite spatial and temporal dynamics nowadays.

5.7 Site-specific pest management

Site-specific pest management, a precision management technique, uses spatial information on the pests' distribution in the field to apply management tactics to a much smaller area than that of the whole field (Liu et al., 2016; Plant, 2001). Management tactics are applied to areas where pest densities are above the economic threshold level. This strategy can benefit the grower by substantially reducing the cost of inputs, including pesticides, consequently decreasing the selection pressure for resistance (Dunley and Croft, 1992).

Site-specific management decisions rely heavily on the results from sampling programs. In strawberries grown in north central Florida, economic analysis demonstrated that the application of site-specific management tactics can reduce the cost of *T. urticae* management by as much as 75% without any decrease in marketable yields. Likewise, precision IPM reduced insecticides targeted against the Colorado potato beetle by 30–40% across a range of colonization pressures and also reduced pesticide used against the green peach aphid (Weisz et al., 1996). Site-specific management also changes the spatial distribution of the pesticide, resulting in unsprayed areas within the field, resulting in temporally dynamic refuges. The combination of reduced pesticide load and the creation of temporally dynamic refuges can slow the development of pesticide resistance and conserve natural enemies (Fleischer et al., 1999).

There are various studies investigating insect spatial patterns using interpolation and site-specific management (Liu et al., 2016; Rhodes et al., 2011); however, there are only a few focusing on mite species and even fewer including phytoseiids (Lara et al., 2016).

5.8 Case study: novel technology for the detection and monitoring of TSSM

Due to the prolific reproduction and subsequent foliar damage caused by TSSM, it is critical to employ efficient and effective detection and monitoring methods to allow for adequate control. As TSSM feeding increases on plant foliage, the appearance of white and yellow spots appears and worsen on the upper leaf surface. This is a result of chlorophyll being evacuated from the mesophyll cells, specifically the palisade parenchyma cells (Sances et al., 1979). It is this form of damage that novel detection and monitoring technologies, specifically the use of remote sensing and imagery, seek to characterize in order to improve traditional scouting methods.

Digital imagery of vegetation can use any number of imaging technologies to observe a wide array of biological and environmental phenomena relevant to plants. While these techniques make use of indirect observation of physical parameters of plants, such as size and the way plant canopies absorb, transmit, or reflect particular wavelengths of light, these indirect observations are inextricably linked to the physiological and physical condition of the plants being observed. These imaging technologies can range from simple red-green-blue cameras, much like the ones we use to take family photos, to multispectral cameras capable of seeing a handful of wavelengths with fine detail, to hyperspectral cameras capable of capturing data for 30 or more individual wavelengths. Due to the visually apparent damage caused by TSSM at moderate-to-high infestation levels, it is possible to use captured images in order to create predictive image-based analyses to estimate levels of TSSM infestation directly in the field.

Traditional approaches to detection and monitoring of TSSM populations focus heavily on in-field scouting techniques that look for foliar damage to the upper leaf surface, as well as sampling leaves and quantifying mite populations on the underside of leaves using a hand lens. Novel remote sensing techniques, predominately the use of multispectral and hyperspectral imaging, have begun to surface as means to detect and quantify the patterns of damage and foliar stress caused by TSSM. Remote sensing techniques have already been heavily utilized in plant stress detection (e.g. water stress, nutritional stress, disease/pest stress etc.) and the monitoring of physiological status (e.g. phenological stage, nutritional condition etc.) of individual plants (Peñeulas and Filella, 1998).

The detection of TSSM using these techniques has already been demonstrated in a number of crops including strawberries, cotton, peppers, and peaches (Herrmann et al., 2012; Fraulo et al., 2009; Luedeling et al., 2009; Reisig and Godfrey, 2007). Much of this previous work has focused on the ability to estimate TSSM population levels from plant-specific reflectance data derived from aerial images of plant canopies. While published models have been able to predict qualitative measures of mite populations (low, medium, and high levels of infestation) and damage (low, medium, and high damage) as well as quantitative estimates of resident mite populations, accurate estimation of TSSM populations below economic thresholds has not been achieved. For these methods to become practical on commercial farming operations, emphasis is placed on achieving detection thresholds below these economic thresholds.

6 Future trends

Spatial interpolation describes spatial relationships by estimating variables such as pest density at unsampled points using data obtained from sampled points (Shabaninejad et al., 2017). Interpolation assumes that nearby samples provide information about unsampled locations. It is a method capable of generating interpolated distribution maps of species at specific time intervals and comparing these maps to detect changes in the spatial patterns over time. Maps are created by displaying the estimates in a grid of fine resolution (Fleischer et al., 1999).

Mapping pests influences both our understanding and management of organisms. One objective is to understand the spatial variability of relevant variables and the processes that drive this variability at the field scale. Because pests exhibit spatial variation, it makes sense to consider spatially varying management, but this will not occur until we are able to produce pest management maps. Mapping can improve our understanding of the spatial interactions between biological control agents, prey within the target crop, and crop phenology, which may lead to targeted approaches for inundative release of biological control agents (Lara et al., 2016; Fleischer et al., 1999).

Accounting for spatial correlation has practical implications for developing effective sampling guidelines that reduce bias toward sampling only within 'hot spot' areas with unusually high organism densities. Sampling only within 'hot spot' areas may not be representative of mite activity over the whole spatial area of interest because significantly lower densities exist outside of these 'hot' areas. Consequently, ignoring spatial correlation could result in unreliable sampling estimates of organism densities and lead to incorrect management decisions (Lara et al., 2016).

Twospotted spider mite distribution patterns have been identified as typically clumped in 'hot spots' thanks to interpolation analysis. If management tactics for *T. urticae* are directed toward these hot spots in strawberry fields, it may be possible to reduce mite populations to levels achieved with whole-field application (Liu et al., 2016). This, in turn, could significantly reduce the cost of mite management and miticide residues on the fruit.

Remote sensing represents one method for mapping the spatial distribution and severity of anomalies, including damage caused by pest mites. It detects the physical characteristics of an area by measuring its emitted radiation at a specific distance. Multispectral remote sensing has been shown to be effective at relating reflectance to the incidence of agronomic pests and its use to monitor and manage spider mite infestations is increasing in cotton and strawberry cropping systems (Fitzgerald et al., 2004).

Analysis of the shapes of the spectra allows discrimination of the scene components. The large amount of data in hyperspectral imagery permits the application of advanced image analysis techniques designed to extract unique data features from high-dimensional data sets and reduce complexity to make the data more interpretable. The resulting images show features and explainable changes in the crop including differentiation between a mite-infested and -uninfested field and map the distribution and relative severity of mite damage (Fitzgerald et al., 2004). A map like this could be used as diagnostic tools for a farmer or scout to locate mite damage. Moreover, if loaded into a computer or downloaded into a tractor, this could guide personnel and machinery to the affected locations for appropriate treatment.

Machine learning (ML) is a data analytics technique that consists of giving computers access to data and let them learn information for themselves without relying on predetermined equations (Marr, 2016). The overall goal of ML is to develop methods based on algorithms that can automatically detect patterns in data (e.g. spectral imagery from remote sensing), and then use the uncovered patterns to predict future data, explain phenomena underlying the data, or perform other kinds of decision-making under uncertainty (Murphy, 2012).

Machine learning has immense potential for analysis of pest and predatory mite species. Using ML would allow to generate mite distribution models, forecasting systems for mite infestations in sampled and unsampled areas, identification of conservation areas for native predatory mites, identification of localized variations of abiotic (e.g. temperature, RH, precipitation, human movement) and biotic (e.g. vegetation coverage, presence of natural enemies) conditions that help understand the species' distribution pattern and outbreaks, and their contribution to pest colonization, establishment, and predator interactions. Various forecasting systems have been developed for insect pests using remote sensing and different ML methods (Tripathy et al., 2011), but ML has been used to a lesser extent for mite species.

7 Conclusion

Increased globalization and climate change have facilitated the spread of invasive species that has caused major disruption in IPM programs. As a result, broad-spectrum pesticides are being used extensively to combat key invasive species. These pesticides are mostly nonselective and kill endemic mite predators, as well as other beneficial arthropods, thereby preventing the natural regulation of plant pest mites. We hypothesized that these factors may have contributed to the recent increase in plant mite pest problems in many parts of the United States.

Recently, more emphasis is being directed toward the use of biological control programs to reduce reliance on pesticides for plant mite pest management. This will require a better understanding of the systems in which these biotic factors exist and how they interact with other abiotic factors so that the biological agents that are released do not interfere with the naturally occurring or endemic predators or beneficial arthropods.

Recent developments in technology involving the use of remote sensing (Fitzgerald et al. 2004), site-specific management (Liu et al., 2016), and spectral imaging (Crockett et al., unpublished data) hold promise to help manage field and greenhouse mite population in agricultural and ornamental systems. One of the issues that is becoming problematic in the United States is the lack of trained personnel in mite taxonomy and the inability to find competent acarologists. Hopefully, this will be resolved in the near future as more resources are being directed to train scientists in these areas.

8 Where to look for further information

For more information on pest management of mites, the book *Agricultural Acarology: Introduction to Integrated Mite Management* (Hoy, 2011) gives a thorough overview of mite identification, biology, and ecology of predatory mites and the most damaging plant feeding groups in agriculture, as well as classical and emerging approaches against pest mite species. Families such as Tetranychidae, Tarsonemidae, Tenuipalpidae, Penthaleidae, and superfamily Eriophyoidea infesting vegetables and perennial cropping systems (e.g. orchards) are illustrated in the book. Additionally, mite pests of bee colonies such as the varroa mite, tick management in animal production, and mite problems on stored products are discussed in the book.

McMurtry and Croft (1997) categorization of the lifestyles in the family Phytoseiidae is an excellent source to understand the ethological diversity among its predatory species. Because of high levels of overlapping characteristics between phytoseiid lifestyles, McMurtry et al. revised the categories in 2013 to include more detailed groups based on recent discoveries on mite biology and ecology. Both articles discuss naturally occurring mites as well as the species most commonly used in pest management programs. Several predatory mite species are commercially available for biological control and knowledge about the feeding preferences of these species is crucial when choosing the appropriate biocontrol agent for each pest problem.

The journals *Systematic and Applied Acarology* and *Experimental and Applied Acarology* are excellent sources to the most recent studies in agricultural acarology. Their platforms are easy to navigate and allow you to get notifications on the recently published open access articles. Both encompass peer-reviewed original papers including subjects in a variety of disciplines including biology, ecology, epidemiology, biochemistry, toxicology, and pest management.

The Acarological Society of America (ASA) is an international organization dedicated to promoting all aspects of the knowledge related to mites and ticks. The ASA board and members include experts working in the field for over 20 years as well as students advancing their career in acarology. The society holds symposiums annually as part of the Entomological Society of America. These symposiums represent an important opportunity to get updates on the most recent investigations in the field of agricultural acarology.

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