Chapter 12
Biology and Management of Mealybugs in Vineyards

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12.1 Introduction

Economic losses resulting from vineyard mealybug infestations have increased dramatically during the past decade. In response, there has been a cosmopolitan effort to improve control strategies and better understand mealybug biology and ecology, as well as their role as vectors of plant pathogens. Mealybugs are named for the powdery secretions covering their bodies. The most important vineyard mealybugs belong to the subfamily Pseudococcinae (Hardy et al. 2008). Although numerous mealybug species are found in vineyards, this chapter will cover only those that have risen to the level of primary pest. These are the grape mealybug, *Pseudococcus maritimus* (Ehrhorn),

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obscure mealybug, *Pseudococcus viburni* (Signoret), longtailed mealybug, *Pseudococcus longispinus* (Targioni-Tozzetti), citrophilus mealybug, *Pseudococcus calceolariae* (Maskell), vine mealybug, *Planococcus ficus* (Signoret), citrus mealybug, *Planococcus citri* (Risso), pink hibiscus mealybug, *Maconellicoccus hirsutus* (Green), and the newly identified Gill's mealybug, *Ferrisia gilli* Gullan. Meanwhile in Brazil and India, *Dysmicoccus brevipes* (Cockerell) and *Xenococcus annandalei* Silvestri respectively, feed on vine roots. Collectively, these species will be referred to as the vineyard mealybugs, although their host range is diverse and many are pests of other agricultural crops and ornamental plants (McKenzie 1967; Ben-Dov 1995).

Outwardly, the vineyard mealybugs look similar. Mealybug females are wingless with an elongate-oval body (3–5 mm) that can be covered with wax secretions forming distinctive spine-like filaments. However, each species has distinct biological characteristics that result in different geographic ranges, host plant preferences, economic injury, and management strategies. This chapter presents a generalized description of their biology, damage, and life history, and summarizes the current information on cultural, biological, and chemical control practices. It provides brief descriptions of their regional significance and future control needs. For further reference, McKenzie (1967), Williams and Granara de Willink (1992), Ben-Dov (1995), and Hardy et al. (2008) provide reviews of Pseudococcidae taxonomy, geographic and/or host range and biology. Noyes and Hayat (1994) provide a review of some of the Anagyrini parasitoids attacking Pseudococcidae, and the ScaleNet (2011) website is an excellent reference tool.

12.2 Mealybug Biology and Development

12.2.1 Nomenclature and Geography

In order to provide even a brief description of the world's vineyard mealybugs some background on their nomenclature and geographic distribution is needed (Table 12.1).

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Table 12.1 The common vineyard mealybug species showing the pests geographic origin (by terrestrial ecozone) and present regional distribution, as well as common synonyms

Species (author and year)	Geographic origin	Current distribution	Common synonyms
Pseudococcus maritimus (Ehrhorn)	Nearctic	<u>North America</u>	*Dactylopius maritimus* Ehrhorn, *Pseudococcus bakeri* Essig, *P. omniverae* Hollinger
Pseudococcus viburni (Signoret)	Neotropic	Australia, Europe, New Zealand, North America (<u>California</u>), <u>South Africa</u>, <u>South America</u>	*Dactylopius indicus* Signoret, *D. viburni* Signoret, *D. affinis* Maskell, *Pseudococcus viburni* (Signoret), *Ps. affinis* (Maskell), *Ps. obscurus* Essig, *Ps. capensis* Brain, *Ps. nicotianae* Leonardi, *Ps. longispinus latipes* Green, *Ps. fathyi* Bodenheimer, *Ps. malacearum* Ferris, *Ps. affinis* (Maskell)
Pseudococcus longispinus (Targioni-Tozzetti)	Australasia	Australia, Europe, <u>New Zealand</u>, North America (<u>California</u>), South Africa, South America	*Coccus adonidum* L., *C. laurinus* Boisduval, *Dactylopius longispinus* Targioni Tozzetti, *D. adonidum* (L.), *D. adonidum* Auctorum, *D. hoyae* Signoret, *D. pteridis* Signoret, *D. longifilis* Comstock, *Oudablis lauri* Cockerell, *Pediculus coffeae* L., *Pseudococcus hoyae* (Signoret), *Ps. adonidum* (L.) *Ps. laurinus* (Boisduval), *Ps. adonidum* (Auctorum)
Pseudococcus calceolariae (Maskell)	Australasia	Australia, Europe, <u>New Zealand</u>, South America, South Africa, North America	*Pseudococcus citrophilus* Clausen, *Ps. fragilis* Brain, *Ps. gahani* Green
Planococcus citri (Risso)	Palearctic	Australia, <u>Europe</u>, New Zealand, North America, <u>South Africa</u>, <u>South America</u>	*Coccus tuliparum* Bouché, *C. citri* Boisduval, *Dactylopius alaterni* Signoret, *D. ceratoniae* Signoret, *D. citri* Signoret, *D. cyperi* Signoret, *D. robiniae* Signoret, *D. brevispinus* Targioni-Tozzetti, *D. destructor* Comstock, *D. secretus* Hempel, *Dorthesia citri* Risso, *Lecanium phyllococcus* Ashmead, *Phenacoccus spiriferus*, *Planococcoides cubanensis* Ezzat & McConnell, *Pl. citricus*, *Pl. cucurbitae* Ezzat & McConnell, *Pseudococcus citri*, Cockerell, *Ps. (citri) phenacocciformis* Brain
Planococcus ficus (Signoret)	Palearctic	North America (<u>California and Mexico</u>), <u>South Africa</u>, South America (<u>Argentina</u>), Europe (<u>Italy</u>), <u>Middle East</u>	*Coccus vitis* Lindinger, *Dactylopius ficus* Signoret, *D. vitis* Signoret, *D. subterraneus* Hempel, *Planococcus vitis* Ezzat & McConnell, *Pseudococcus citrioides* Ferris, *Ps. vitis* Bodenheimer

(continued)

Table 12.1 (continued)

Species (author and year)	Geographic origin	Current distribution	Common synonyms
Dysmicoccus brevipes (Cockerell)	Indo-Malaya	Australia, Africa, Asia, Middle East, South America (<u>Brazil</u>)	*Dactylopius brevipes* Cockerell, *D.* (*Pseudococcus*) *ananassae* Kuwana, *Dysmicoccus brevipes* (Cockerell), *Pseudococcus brevipes* (Cockerell), *Ps. missionum* Cockerell, *Ps. palauensis* Kanda, *Ps. cannae* Green, *Ps. longirostralis* James, *Ps. defluiteri* Betrem, *Ps. pseudobrevipes* Mamet
Ferrisia gilli (Gullan)	Nearctic	North America (<u>California</u>)	none
Maconellicoccus hirsutus (Green)	Indo-Malaya	Australia, Africa, Asia (<u>India</u>), Middle East, South America, Mexico, California	*Maconellicoccus perforatus* (De Lotto), *M. pasaniae* (Borchsenius), *Paracoccus pasaniae* Borchsenius, *Phenacoccus hirsutus* Green, *Ph. quarternus* Ramakrishna Ayyar, *Ph. quarternus* Shafee et al., *Pseudococcus hibisci* Hall, *Ps. glomeratus* Green, *Ps. crotolariae* Miller, *Ps. crotolariae* Yunus & Ho, *Spilococcus perforatus* De Lotto

Regions underlined indicate that the mealybug species is considered to be a primary pest

Historically, vineyard mealybug species were often misidentified, leading to confusion on their geographic distribution and economic importance. For example, many of the early North American specimens of mealybugs on grapes and pome fruit were described as *Ps. maritimus*, and yet, from the slides labeled as *Ps. maritimus* at the United States Museum of Natural History, there were at least 10 different species (Miller et al. 1984). It was particularly difficult to separate *Ps. maritimus* and *Ps. viburni* (Fig. 12.1) until the needed taxonomic descriptions of these closely related species were provided (Miller et al. 1984). Separation of *Pl. ficus* (Fig. 12.2) and *Pl. citri* is similarly difficult and can be made only through careful slide preparation to discern slight differences in multilocular pores and tubular ducts on adult females (Williams and Granara de Willink 1992). Demontis et al. (2007) and Cavalieri et al. (2008) provide a molecular separation of these species. Adult *Ps. calceolariae*, *M. hirsutus*, *F. gilli* are more easily distinguished. For example, *Ps. calceolariae* has distinctive dark stripes and short caudal filaments, *M. hirsutus* lacks lateral filaments, and *F. gilli* has glass-like rods (Fig. 12.3).

Complicating their proper identification is the fact that these pests have been often moved from their geographic origin such that many are now found in multiple regions (Table 12.1). The mealybug with the most limited range in vineyards is *F. gilli*, a Nearctic species that has been reported as vineyard pest only in California's Sierra foothills. This mealybug was only recently described, initially found infesting California pistachios (Gullan et al. 2003). It is included here as it could be misidentified
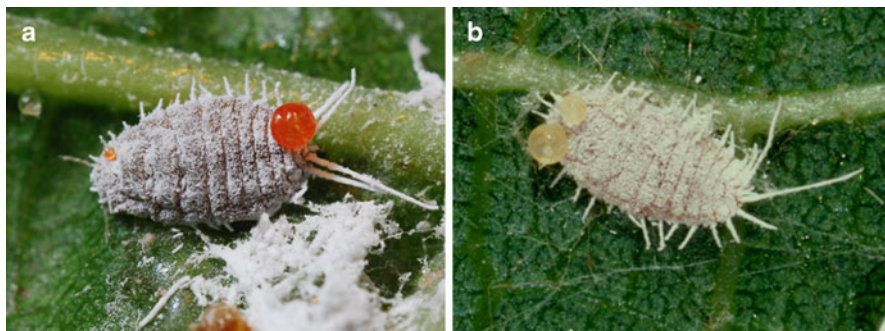
Fig. 12.1 Adult females of *Pseudococcus maritimus* (**a**) and *Ps. viburni* (**b**). These closely related species can only be discerned through slide preparation to view differences in multilocular pores and tubular ducts, or through the use of molecular techniques. A relatively reliable field tool is the color of the ostiolar fluid, extruded when the insect is prodded with a sharp object, which is *red* for *Ps. maritimus* and *clear* to *opaque* for *Ps. viburni*
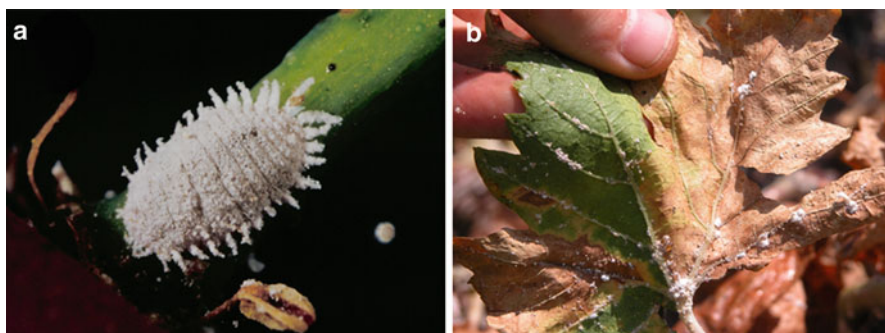

Fig. 12.2 *Planococcus ficus* on the petiole of a grape berry (**a**) provides the classic view of the large (3–5 mm) adult female mealybug. However, a better portrayal of mealybug size and appearance in the field is provided by the infested grape leaf (**b**) that has more than 1,000 *Pl. ficus* of all developmental stages, but primarily second and third instars

as *Ferrisia malvastra* (McDaniel), found in other grape-growing regions of the world. *Dysmicoccus brevipes* and *X. annandalei* are reported only as important vineyard pests of Brazil and India, respectively. Although *Ps. maritimus* is well known, it was reported only from California vineyards until the 1950s. It is now known to occur in all North American vineyard regions from Canada to Mexico and from California to New York (Ben-Dov 1995; ScaleNet 2011). *Maconellicoccus hirsutus* is an Indo-Malaya native, and although it is now found in numerous regions, it is a primary vineyard pest only in India (Table 12.1). The other vineyard mealybug species are commonly found in more than one of the world's vineyards regions, although their pest status varies. For example, *Pl. ficus* and *Pl. citri* are found across a wide geographic range, but only in a few countries (primarily Spain, Italy and

Fig. 12.3 Adult female *Ferrisia gilli* with glass-like rods that accompany the production of live crawlers (small *yellow-orange* insects in the photo)

Brazil) *Pl. citri* is consistently cited as a vineyard pest (Cabaleiro and Segura 1997), whereas *Pl. ficus* is cited as a pest in Europe, the Middle East, northern Africa, South Africa, South America, California, and Mexico (Ben-Dov 1995; ScaleNet 2011). The transport of vine wood (both legal and illegal) and fruit is often suspected in the movement of mealybugs. However the wide host range of many of these species, which includes commonly used ornamental plant species (Ben-Dov 1995; ScaleNet 2011), makes border screening for the more ubiquitous mealybug species a daunting task.

12.2.2   Life History

There are slight variations among the species, but vineyard mealybugs generally have three larval instars for the female and four instars for the male (McKenzie 1967; Ben-Dov 1995; Wakgari and Giliomee 2005). The unsettled first instar, or crawler, moves quickly to find a feeding spot and is considered to be the dispersal stage. The first instar is about 0.6 mm long. Viewed from above, it is elongate-oval in shape, but from the side it is extremely flat. There are three molts, resulting consecutively in the second instar, third instar, and the 'immature' adult. Each of these stages resembles the previous except for an increasing size and amount of wax secretion. Females are unwinged and as they mature, become more sessile. Immature males are slightly longer and more slender than females. At the fifth instar, the male goes through a cocoon or prepupal stage and the emerged adult male is winged.

Fig. 12.4 Adult mealybug males are winged, as shown here for *Planococcus ficus*, next to an adult female producing an ovisac

12.2.3   Reproduction

The mature or gravid adult female begins to grow in size as the ovaries develop, ending at about 4–5 mm in length and far less dorso-ventrally flattened. The adult male is about 1.5 mm in length, with long wings, a brown colored body and two multi-segmented antennae that are about half the body length (Fig. 12.4). Sex determination of the vineyard mealybugs is unusual and worth noting as it impacts pest management programs. These mealybugs have the lecanoid type of the paternal genome elimination system, where both sexes develop from fertilized eggs (i.e., diploidy), but during early development of the male the paternal half is deactivated through heterochroma-tinization (Ross et al. 2010a). This system suggests females would produce a male-biased sex ratio when alone, and a more female-biased sex ratio when crowded with other females. However, in one study with *Pl. citri*, the opposite effect of crowding was observed, with a more male-biased sex ratio, suggesting that some mealybug species may selectively adjust their sex ratio (Ross et al. 2010b).

As suggested, mealybug reproduction can be quite variable. For vineyard mealy-bugs, mating is probably necessary (e.g. Zaviezo et al. 2010; Waterworth et al. 2011), although facultative parthenogenesis has been reported for *Pl. citri* (da Silva et al. 2010). To attract adult males, females emit a sex pheromone. For those species tested, females mate multiple times, and the number of matings affects egg production (Waterworth et al. 2011). Most vineyard mealybugs place their eggs in cotton-like ovisacs. *Pseudococcus longispinus*, *F. gilli*, *D. brevipes* and *Heliococcus bohemicus* Sulc (Bohemian mealybug), are the exceptions being ovoviviparous (depositing live first instars). The number of offspring produced per female varies depending on the species, environmental conditions, and food supply (Zaviezo et al. 2010). It has been reported ranging from about 50 to over 800.

12.2.4   Seasonal Development

Temperature is the driving force for mealybug development, although development times and temperature thresholds differ among species. For example, *Ps. maritimus* will have two generations in California's interior valleys (Geiger and Daane 2001), whereas *Pl. ficus* can have seven generations in the same region (Gutierrez et al. 2008) but is reported to have only three generations per year in Italy (Ben-Dov 1995). Similarly, *Pl. citri* in Brazil has six generations per year in the south, but up to 11 per year in the northeast where grapes are produced year round (two harvests per season). Other than *Ps. maritimus* and *H. bohemicus*, there does not appear to be winter dormancy for vineyard mealybugs.

There is also variation in seasonal feeding location and movement on the vine among and within species, depending on factors such as regional temperatures and vineyard management practices, as described for *Ps. maritimus* (Geiger and Daane 2001; Grasswitz and James 2008), *Pl. citri* (Cid et al. 2010), and *Pl. ficus* (Becerra et al. 2006). Here, a *Pl. ficus* infestation in an untreated table grape vineyard in California's Central Valley is used to exemplify the seasonal population dynamics (Daane et al. 2011). The mealybug population overwinters primarily under the bark of the trunk and cordon, with some of the population found underground on the roots, especially when tended by ants. There is no diapause. On warm days, development may occur during the winter months, with completion of the first generation almost entirely under the bark. From spring to summer, the *Pl. ficus* population follows the movement of plant resources from roots to shoots to leaves. Four to five generations are completed and population density can increase rapidly, although high summer temperatures, in excess of 40°C, may slow the growth of the population and increase mortality. As berries ripen and sugars develop, mealybugs move into the berry clusters, first attacking those near the vine cordon. The rapid population increase in summer is followed by an equally rapid decline after harvest, resulting from biological controls and abiotic mortality associated with high temperatures and vine senescence.

12.3   Mealybug Damage

12.3.1   Mealybug Feeding and Contamination

Mealybugs are phloem feeders that use long, slender mouthparts to suck out plant fluids (McKenzie 1967). Most of the vineyard mealybugs can feed on the vine's root, trunk, canes, leaves, or berry clusters. There are, however, differences in the amount of damage caused by each species. This is often related to those factors that determine population size (e.g., number of annual generations and female fecundity), preferred feeding locations, and temperature tolerances.
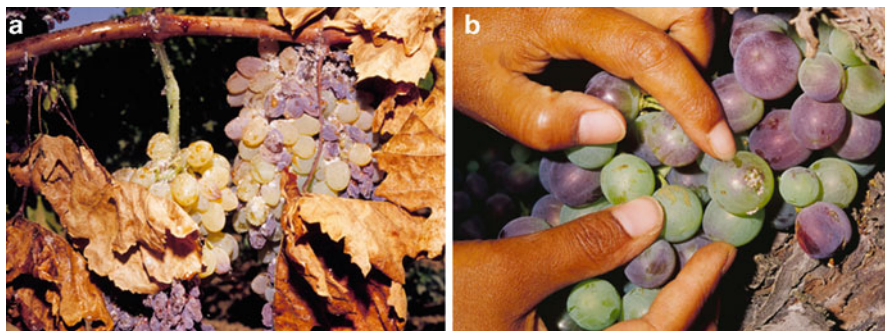
Fig. 12.5 Most mealybug species can feed on the vine roots, trunk, cane, leaves and fruit clusters. Severe infestations can result in defoliation, cluster infestation and rot, as shown for a *Planococcus ficus* infestation (**a**). Most mealybug populations remain at low levels with only a few berries in a cluster infested, as shown in (**b**) for *Pseudococcus maritimus*

As the mealybugs feed, they eliminate carbohydrate-rich honeydew, which can accumulate on the leaves and in the grape clusters, especially in late summer and early fall (Charles 1982). The mealybug 'flicks' honeydew away from its location, but it still accumulates on the vine. It has long been noted that honeydew serves as a substrate for the development of sooty mold fungi that can result in further vine damage. For table grape growers, any live or dead mealybugs and the honeydew or sooty molds will cause cosmetic damage to the grape cluster and reduce its marketability (Daane et al. 2011). In most raisin, juice, and wine grapes, the contamination from a small mealybug population, and the resultant honeydew droplets, will not cause economic damage. Although honeydew can be dissolved by light rain and will dry in warm temperatures, when mealybug populations are severe, honeydew can accumulate to form a hard, wax-like layer that covers the infested plant (Fig. 12.5). Feeding damage can result in defoliation and, after repeated annual infestations, cause vine death (Walton and Pringle 2004b).

12.3.2 Grapevine Leafroll Disease

In most of the world's wine grape regions, the transmission of viruses, rather than mealybug feeding or contamination, is the primary concern (Walton and Pringle 2004b; Charles et al. 2009; Bertin et al. 2010; Tsai et al. 2010). Grapevine leafroll disease (GLD) is caused by a complex of several viruses, collectively known as grapevine leafroll-associated viruses (GLRaVs). In cool-climate regions, the pathogen can be damaging to vines, crop, and wine quality. The most obvious GLD symptoms become apparent in the fall, when red cultivars display leaf reddening with green venation (Fig. 12.6). Symptoms are not as apparent in white cultivars where

Fig. 12.6 For many wine grape growers, grape leafroll disease is a greater concern than mealybug contamination. Many mealybug species have been shown to transmit the viruses that cause grape leafroll disease. The most apparent field symptoms are the *reddening* of leaves on *red* cultivars and the rolling of the leaf margin (**a**). The survival of mealybug on vine roots – even after the vine above has been pulled – is a major concern in the control of grape leafroll disease (**b**)

there is a slight leaf chlorosis. Both red and white cultivars develop the classic downward rolling of leaf margins and phloem disruption. GLRaV infections impact berry development and growth by delaying budbreak, flowering, and berry maturation, including changes in color, reduced sugar content, and increased acidity in fruit juice (Martelli et al. 2002; Charles et al. 2006).

Grapevine leafroll disease is associated with many distinct closteroviruses sequentially named GLRaV-1, -2 and so on; so far 10 species have been proposed (Martelli et al. 2002). Within this family of large single stranded RNA viruses, the majority causing GLD are ampeloviruses. GLRaV-2 belongs to the genus *Closterovirus*, and GLRaV-7 remains unassigned. GLRaV-3 is the predominant species in most vineyards with evidence of vector-driven disease spread (Cabaleiro and Segura 2006; Charles et al. 2009; Sharma et al. 2011) and reported yield losses of as much as 40% (Golino et al. 2002; Charles et al. 2006). All GLRaVs are graft-transmissible (Bertazzon et al. 2010) and this was initially assumed to be the main form of spread. However, researchers began to notice disease spread within vineyards that appeared to have a pattern of movement from a point source (Rosciglione and Castellano 1985; Habili et al. 1995). These spatial patterns implicated insect transmission, and have since been verified by monitoring the spread of infected vines over time (Cabaleiro et al. 2008; Charles et al. 2009).

In the 1980s, plant to plant transmission of GLRaV-3 by *Pl. ficus* was demonstrated (Engelbrecht and Kasdorf 1990). Since then, several species of mealybugs and soft scales have been shown to be GLRaV vectors, including *Ps. maritimus*, *Ps. viburni*, *Ps. longispinus*, *Ps. calceolariae*, *Pl. ficus*, *Pl. citri*, *H. bohemicus*, *Phenacoccus aceris* (Signoret) (apple mealybug), and *Pseudococcus comstocki* (Kuwana) (Comstock mealybug) (Rosciglione and Castellano 1985; Golino et al. 2002; Sforza et al. 2003; Cid et al. 2010). Additionally, GLRaVs can be transmitted by the soft scales *Pulvinaria vitis* (L.) (cottony vine scale) and *Parthenolecanium corni* (Bouché) (European fruit lecanium scale).

Most vector transmission studies focused on the identification of insect species capable of transmitting various GLRaV species, although recent studies have addressed transmission biology in more detail (Tsai et al. 2008, 2010). Importantly, transmission research has focused on GLRaV-3, which is the predominant species encountered in regions with disease spread. Although all mealybug and scale life stages may be capable of transmitting GLRaV-3, the smaller stages (e.g. crawlers or first instars) appear to be more efficient (Petersen and Charles 1997; Tsai et al. 2008). This is also the dispersal stage, with crawlers often being carried by the wind (Barrass et al. 1994) and other stages being moved on personnel, equipment, and infested nursery stock (e.g. Haviland et al. 2005). GLRaV-3 transmission by *Pl. ficus* occurs in a semi-persistent manner (Tsai et al. 2008), as would be expected for this genus and family of viruses. Acquisition and inoculation occur within 1 h of plant access period, although transmission efficiency increases proportionally with plant access time up to 24 h. The absence of an observable latent period required for transmission, together with the loss of vector infectivity over a period of days after acquisition, are hallmarks of semi-persistent transmission of plant viruses. Under laboratory conditions transmission efficiency of GLRaV-3 by *Pl. ficus* was ca. 10% per individual per day (Tsai et al. 2008). Although this value appears to be low when compared to other systems, the high fecundity of mealybugs places many potential vectors on each vine during each generation. Furthermore, the dispersal capability of minute first instar mealybugs is large, as previously shown in field studies in New Zealand.

Control of GLD is further hampered as both mealybug and virus can survive on the vine roots many years after the vine above ground has been pulled (Walton and Pringle 2004b; Bell et al. 2009). Generally, when removing diseased vines (roguing), all above-ground plant material is removed off-site and destroyed but the same is not always true of the roots. It is estimated that following vine removal, 70–80% of the roots may persist *in situ*, potentially for many years, although the quantity will vary according to factors like vine age, rootstock, and soil type (Bell et al. 2009). The retention of root debris following roguing is problematic as infected vine roots may sustain subterranean mealybug colonies (Bell et al. 2009), thereby leaving an unbroken link between virus and vector. Under these circumstances, South Africa and New Zealand managers argued that renewed disease pressure observed in some re-plant situations could be attributed to subterranean mealybug populations, feeding on and acquiring leafroll virus from residual vine roots, followed by dispersal to the roots of newly planted vines.

Although transmission of the various GLRaV species may follow the general trends observed with GLRaV-3 transmission by *Pl. ficus*, it should be noted that more research on the characterization of GLRaV transmission by various vector species is needed. Transmission studies aimed at identifying new vector species are essential to develop GLD management strategies, but yield little information on various aspects of transmission biology. Surprisingly, there is no evidence of virus-vector specificity in this system (Tsai et al. 2010). For example, different mealybug species transmit GLRaV-3, while *Pl. ficus* transmits at least five different GLRaV species. This finding has important epidemiological consequences: mealybug control may be necessary to limit disease spread, regardless of GLRaV (*Ampelovirus*) species.

12.3.3 Export Markets

Quarantine issues are a major concern for all vineyard mealybugs. As an example, molecular studies have shown that *Pl. ficus* in California probably originated from plant material in Israel and is thought to have been smuggled into the US on grape wood for commercial use. This pest eventually entered nursery material and was then spread within the state. Hot water dip and other procedures have been developed to clean nursery stock (Haviland et al. 2005; Liu et al. 2010). Still, the authors agree that movement of mealybug infested material across regional, provincial and state, and especially country borders is a serious concern.

12.4 Control Methods

12.4.1 Monitoring

There are no simple and effective methods to visually monitor vineyard mealybugs, and the process itself can be time-consuming and laborious. As exemplified for *Ps. maritimus*, the accuracy of monitoring plant material will depend on the mealybug population density, and the number of samples needed for an accurate count is often high because most mealybugs have a clumped distribution pattern, often being found on only a small percentage of the vines (Geiger and Daane 2001). The appropriate sampling programs will also vary throughout the season, depending largely on mealybug location as there are periods when much of the population is hidden (e.g. under bark) rather than exposed (e.g. on leaves). Also, as species have different numbers of annual generations and preferred feeding locations throughout the season, there is not a single sampling procedure appropriate for all vineyard mealybugs.

In most vineyards, signals of an infested vine can be used to aid the sampling program. First, ants are closely associated with mealybugs (Ripa and Rojas 1990; Addison and Samways 2000, Chap. 18) and their presence can help select vines for further sampling. Second, honeydew on the leaves can also be a good signal; a large population hidden under the bark will excrete enough honeydew that the infested trunk region will have a darker, wet appearance (Daane et al. 2011). Third, when some mealybug species numbers build, their feeding damage may cause leaves to turn yellow or brown and drop from the vine (Daane et al. 2011). Finally, at harvest time, berry clusters in direct contact with the spurs or trunk are more likely to be infested and by selecting these clusters a higher mealybug count can be made (Geiger and Daane 2001).

A faster sampling method is the use of sticky traps baited with sex pheromone to lure in and trap adult winged males. It has long been known that sexually mature female *Pl. citri* emit a sex pheromone to attract the winged adult males (Rotundo and Tremblay 1972). These pheromones can be synthesized and used in the field (Bierl-Leonhardt et al. 1981). Numerous sex pheromones have recently been identified,

including for *Pl. ficus* (Hinkens et al. 2001), *M. hirsutus* (Zhang et al. 2004), *Ps. viburni* (Millar et al. 2005), *Ps. maritimus* (Figadère et al. 2007), *Ps. longispinus* (Zou and Millar 2009), and *Ps. calceolariae* (El-Sayed et al. 2010). They are being tested as management tools to detect mealybug populations. Researchers have shown that trap counts can even be used to predict berry damage (Walton et al. 2004). Some of these synthetic sex pheromones are commercially available. However, both conventional sampling and pheromone trapping have advantages and disadvantages and, for that reason, both methods should be used in combination.

12.4.2   Pesticides

Historically, pesticides have been a large part of vineyard mealybug control. Early programs included potassium cyanide, sodium cyanide, and sulfur fumigation (e.g., Essig 1914), which gave way to the chlorinated hydrocarbons (e.g., DDT) and organophosphates (e.g. parathion) from the 1940s to the 1990s (e.g., Frick 1952; Grimes and Cone 1985b). These materials were effective. For example, rates as low as 48 g a.i./ha of ethyl parathion provided *Ps. maritimus* control (Frick 1952). Eventually, however, most of these materials became less effective (Flaherty et al. 1982) or were ultimately banned from use because of concerns on non-target organisms.

   Many organophosphates are still effectively used (Gonzalez et al. 2001; Walton and Pringle 2001; Sazo et al. 2008). Newer materials, with more novel modes of action, have also gained in popularity, including neonicotinoids, insect growth regulators, botanicals, and biosynthesis inhibitors (Daane et al. 2006b; Sunitha et al. 2009; Lo and Walker 2010). A major difference between the older and newer materials is the importance of coverage. As mentioned, a portion of the mealybug population is often under the bark, and for some species, on the vine roots. Many of the older foliar sprays did not effectively contact and kill mealybugs in these more protected locations. Some of the more novel materials have systemic properties, either applied through the irrigation system or as a foliar spray. For organic or sustainable farming programs, neem, light mineral oils, lime-sulfur, citrus products, and fatty acid soaps have been used. The few studies of these products have provided mixed results (Srinivas et al. 2007).

   Another historical difference is that the earlier materials were often broad spectrum and killed more than just the targeted mealybugs. Flaherty et al. (1982) stated that 'extensive use of DDT and other synthetic insecticides used to control leafhoppers apparently disrupted natural control of grape mealybug [*Ps. maritimus*].' Other researchers have since discussed the impact of broad spectrum insecticides on mealybug natural enemies (e.g. Mani and Thontadarya 1988; Satyanarayana et al. 1991; Walton and Pringle 2001; Mgocheki and Addison 2009a). The cosmopolitan goal of managing vineyards with fewer broad spectrum pesticides, along with the development of resistance to common pesticides has fueled use and further research with the more novel insecticide materials.

Application timing is critical to control mealybugs with most insecticides. Exposed mealybugs are more easily killed than those under the bark, and the smaller stages are more susceptible than the larger mealybugs. This is especially true for insecticides with a short residual period. Much research, therefore, has been aimed at proper application timing and developing materials with better penetration into the protected habitats of mealybugs. For example, dormant season or early spring application takes advantage of the leafless vine, but mealybugs are in more protected locations. Applications with systemic insecticides near bloom are often used as the insecticide moves quickly in the vines to the leaves. After bloom, foliar materials are applied beneath the leaf canopy and aimed towards the grape clusters and interior canes. Late season applications can have issues with insecticide residues for both domestic and export market, because of complicated residue regulations. In addition, fresh market table grapes possess a dull haze or dust on the skin, termed 'bloom', and the use of some insecticides can remove the bloom and lower the crop value.

12.4.3 Cultural Control

A number of cultural controls are practiced and these vary greatly among regions. Few have been sufficiently evaluated. Many practices are specific to the table grape market. For example, the crop load on each vine is commonly thinned to increase berry size, and by thinning out grape clusters that come in direct contact with the trunk or cordon, the more susceptible clusters are also removed (Geiger and Daane 2001). Berry cluster manipulations are not always feasible for either raisin or wine grape production because of the trellising system used, the cost of thinning, and the need for optimal yield. Similarly, trellising systems for cane-pruned cultivars result in grape clusters that hang away from the trunk and cordons, and this reduces cluster infestation. Harvest date also impacts mealybug infestation levels, which can be higher in cultivars harvested later in the season because of greater exposure time to the later mealybug broods (Daane et al. 2011).

Mealybugs are found underneath the bark of the trunk, cordon, spurs, and canes. These locations provide some protection from insecticides, natural enemies, and environmental conditions. Stripping the bark exposes the mealybugs to these mortality factors. The infested bark should be destroyed rather than left in the row middles as the mealybugs can move back onto the vine. Common treatments after bark stripping include pesticides, as well as flaming to kill the mealybugs or banding the trunk with Stickum® to reduce movement of both mealybugs and ants from the trunk upwards to the clusters. While this effectively lowers mealybug density, it is labor intensive and too costly in many grape markets worldwide.

Cover crops have been used to improve soil health and lower pest densities by increasing natural enemy numbers or diversity. In vineyards, parasitoids that attack mealybugs could utilize floral nectaries found on some cover crop species as a food source to increase adult longevity. Generalist predators, such as the lacewings and

some ladybeetle species, might also utilize these floral food resources as well as herbivores in the cover crop as alternate prey. However, many mealybug species can feed on ground vegetation. For example, *Pl. ficus* and *Ps. viburni* have been found on a number of common weeds such as *Malva parviflora* L. Therefore, the addition of a ground cover might also provide an alternate habitat for the mealybug. More work on the effect of ground covers on mealybugs and their natural enemies is warranted.

Overly vigorous vines can increase mealybug populations in two ways. First, excess nitrogen has been shown to increase the size of mealybug females and the number of eggs in each ovisac. Second, the increased foliage associated with overly vigorous vines provides better shelter for the mealybugs by reducing temperatures inside the vine leaf canopy, and may reduce the amount of applied foliar insecticide that reaches the mealybug. Controlling vine vigor is therefore a practice that can help improve mealybug control, in addition to being important for achieving viticultural goals.

12.4.4 Biological Control

Hundreds of natural enemies can attack mealybugs, making this brief review incomplete. A worldwide review of some of the earlier importation efforts is provided by Bartlett (1978) and Noyes and Hayat (1994). ScaleNet (2011) is also a good reference source. Here, the more common natural enemy groups are described, with specific mention of several key natural enemy species and programs (Figs. 12.7 and 12.8).

A number of predators contribute to mealybug control. Few specialize on mealybugs, whereas most are generalists that prey on any small, soft-bodied arthropods. For many of these natural enemies, there are no studies of their impact on mealybug populations. The most well known predator is the mealybug destroyer, *Cryptolaemus montrouzieri* Mulsant, which is native to Australia, but has been exported throughout the world. Both adults and larvae kill mealybugs. The larvae, to some extent, are mealybug mimics, possessing wax-like filaments similar to those of mealybugs. This 'camouflage' allows beetle larvae to forage without too much disturbance from mealybug-tending ants (Daane et al. 2007). One drawback is the poor tolerance of the predator to winter temperatures common in some vineyard regions (Smith and Armitage 1920). Surprisingly, there have been few studies that document the impact of *C. montrouzieri* on mealybug densities (but see Mani and Thontadarya 1989).

Other lady beetle species also attack mealybugs. Many beetle larvae in the subfamily Scymninae are covered with wax, similar to the mealybug, and are often mistakenly identified as *C. montrouzieri*. For example, these include species of *Hyperaspis*, *Nephus* (= *Scymnobius*), and *Scymnus*, which may be the most abundant mealybug predators in vineyards. However, because the taxonomic keys for these Scymninae beetles poorly differentiate among species, many of the observed beetles are seldom properly identified.
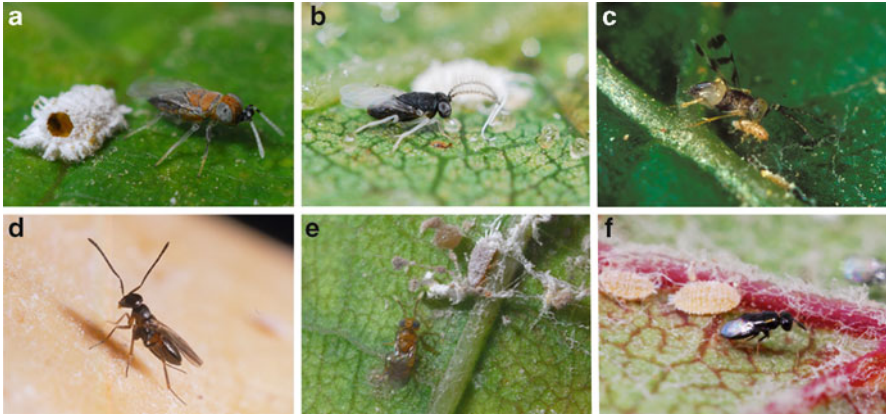
Fig. 12.7 Many parasitoid species attack mealybugs. The examples here are (**a**) a female *Anagyrus pseudococci* (ca. 2 mm) next to a vine mealybug 'mummy' showing the round parasitoid exit hole, (**b**) the smaller (ca. 1.3 mm) male *A. pseudococci*, which has a different color pattern and 'hairy' antennae, feeding on a drop of honeydew, (**c**) a female *Leptomastidea abnormis* 'host feeding' on a vine mealybug crawler, (**d**) *Leptomastix epona*, which was imported for obscure mealybug biological control in California but did not establish because of Argentine ant interference, (**e**) the small (ca. 1 mm) and fast-moving *Acerophagus flavidulus* closing in on a *Pseudococcus viburni*, and (**f**) *Coccidoxenoides perminutus* (ca. 1 mm) next to *Planococcus ficus* first instar

Migratory lady beetles, notably those in the subfamily Coccinellinae, are often attracted to large mealybug infestations and their honeydew. These include some of the large and recognizable species such as the convergent ladybeetle (*Hippodamia convergens* Guérin-Méneville) and the transverse lady beetle (*Coccinella transversoguttata* Falderman). More work is needed to document the effectiveness of the native lady beetles, found throughout the world's grape regions, as mealybug predators.

Lacewings have long been associated with mealybugs. For example, *Chrysoperla carnea* (Stephens) was first shown to suppress mealybugs (*Ps. maritimus*) in pears (Doutt and Hagen 1950). Lacewing larvae are effective predators of smaller mealybugs. They may have a difficult time feeding on eggs in the mealybug ovisac where waxy secretions provide some protection from the predator. Larger mealybugs excrete an ostiolar fluid that can act as a defensive mechanism. Native brown and green lacewing species are often overlooked while *C. carnea* has received more attention.

Cecidomyiid flies (i.e., predaceous midges) are another common mealybug predatory group (Abbas 1999). In most regions, little is known about their impact on mealybug population densities. However, Charles (1985) reported that *Diadiplosis koebelei* (Koebele) reduced *Ps. longispinus* in New Zealand vineyards by about 30%. Midges associated with mealybugs include *Dicrodiplosis californica* Felt in California (Geiger and Daane 2001), *D. koebelei* in New Zealand (Charles 1985), and a *Triommata coccidivora* Felt in India (Mani et al. 1987). The adult fly, which

Fig. 12.8 Common mealybug predators include lady beetles. Examples here are (**a**) an adult *Scymnus* sp. feeding on a grape mealybug, and (**b**) a large *Cryptolaemus montrouzieri* larva near the smaller obscure mealybug. The larvae of many of these lady beetle species have waxy filaments to mimic the mealybugs and reduce interference from mealybug-tending ants, (**c**) a cecidomyiid larva about to feed on *Pseudococcus maritimus*, and (**d**) a third instar green lacewing (*Chrysoperla carnea*) larva attacking a *Ps. maritimus* and prompting the mealybug to secrete a ball of red ostiolar fluid in defense

is not predatory, deposits its eggs in or near the mealybug ovisac and the maggot-like larvae feed, primarily, on mealybug eggs and small larvae. The fly larvae typically pupate in the ground.

Most successful biological control programs rely primarily on encyrtid parasitoids that are mealybug specialists, some attacking only a few specific mealybug species (Noyes and Hayat 1994). These parasitoids are typically internal koinobionts, but can be either solitary or gregarious and preferentially attack varying host stages. Parasitoids have been credited with some level of control for vineyard mealybugs throughout the world. For example, *Anagyrus pseudococci* (Girault), as a parasitoid of *Pl. citri* and *Pl. ficus*, is one of the most well-studied (Blumberg et al. 1995; Islam and Copland 2000; Daane et al. 2004) and widely distributed natural enemies (e.g., Israel (Berlinger 1977), Europe (Duso 1989), South Africa (Walton and Pringle 2004b), and elsewhere).

In some cases, parasitoid performance can be linked to geographic strains of the targeted mealybug. In New Zealand, for example, *Ps. viburni* was brought under

exceptional control by release of the parasitoid *Acerophagus maculipennis* Mercet (Charles et al. 2010), whereas in Chile *Ps. viburni* is controlled by *Acerophagus flavidulus* (Brèthes) (Ripa and Rojas 1990). The biology of *A. maculipennis* (Sandanayaka et al. 2009) and *A. flavidulus* (Karamaouna and Copland 2000, 2009) have been studied. Nevertheless, it is still unclear how these species exhibit a level of host discrimination that may differentiate between geographic strains of *Ps. viburni*. This intriguing level of discrimination, combined with the geographic location of these parasitoid species, has been used to assess the origin of *Ps. viburni* (Charles 2011).

Some parasitoid species are attracted to the mealybug's sex pheromone (Walton et al. 2006), which may act as a kairomone (Franco et al. 2008). For example, the parasitoid *A. pseudococci* was caught in *Pl. ficus* pheromone-baited traps (Millar et al. 2002). It was later observed that parasitism levels of *Pl. ficus* were higher in vineyards with mating disruption (Walton et al. 2006). Ongoing studies are screening the attractiveness of different parasitoid species to mealybug sex pheromones, to test the hypothesis that some parasitoid species spend more time searching for mealybugs in vineyards where a mating disruption program is implemented, thereby increasing parasitism rates.

Ants have long been associated with outbreaks of honeydew-producing homopterans. The mutualistic association has clear benefits for the ants, which are provided with a carbohydrate food source, and in return, ant-tending has been credited with protecting homopterans from natural enemies. Not surprisingly, ants have been shown to disrupt mealybug biological control in vineyards from South Africa (Mgocheki and Addison 2009b) to North America (Daane et al. 2007). Ant species vary in dominance in different vineyard regions (Addison and Samways 2000; Cooper et al. 2008). The Argentine ant, *Linepithema humile* (Mayr), is one of the world's most damaging invasive insects and it is now common in many vineyards in association with mealybugs and soft scale pests (Addison and Samways, Chap. 18).

12.4.5   Mating Disruption

Mating disruption was first attempted against *Pl. ficus* in North America (Walton et al. 2006), and is currently gaining in popularity. However, prior to this work, researchers in Europe and Israel investigated attract and kill for adult male *Pl. citri* in citrus. But that initial work found that the extent of male reduction was not enough to decrease fruit infestation (Franco et al. 2009). It is likely that future mealybug control programs will rely more heavily on novel control strategies using semiochemicals, especially if the price of synthetic sex pheromones for mealybugs can be reduced.

12.5   Mealybugs in Some Major Grape-Producing Areas

12.5.1   North America

Pseudococcus maritimus is the primary North American mealybug pest in vineyards. It is found from California to Canada, and from Washington to New York. Insecticides are generally not needed to control *Ps. maritimus*. Parasitoids have long been credited with *Ps. maritimus* control in North America, while early records indicate that *Zarhopalus corvinus* (Girault) was the dominant parasitoid and, in combination with *Anagyrus yuccae* (Coquillet), *Acerophagus notativentris* (Girault), *Anagyrus clauseni* Timberlake, and *Pseudleptomastix squammulata* Girault, provided up to 80% parasitism (Clausen 1924). Later surveys have reported *A. notativentris* and *Acerophagus angelicus* (Howard) to be the dominant parasitoids (Grimes and Cone 1985a; Grasswitz and Burts 1995; Geiger and Daane 2001).

For most of North America, *Ps. maritimus* is the only mealybug of concern. The occasional outbreak of *Ps. maritimus* generally results from pesticide usage removing the natural enemies, or outbreaks associated with ant populations. California, however, presents a more unique situation as most of the other vineyard mealybug species, discussed herein, can be found in the state. A review from the least to the most important vineyard mealybugs – other than *Ps. maritimus* – would begin with *Ps. calceolariae*, which was first recorded in California in 1913 as a citrus pest in southern California. A classic biological control program was initiated with natural enemies imported from Australia, including the first introduction of *C. montrouzieri* in 1916 (Smith and Armitage 1920). In the 1920s the importation of the encyrtids *Coccophagus gurneyi* Compere and *Tetracnemoidea brevicornis* (Girault) (formerly *Tetracnemus pretiosus* Timberlake) was credited with reducing *Ps. calceolariae* densities to 'almost negligible numbers' (Compere and Smith 1932).

Maconellicoccus hirsutus, the primary mealybug pest in India, is found in southern California, near the desert table grape region in the Coachella Valley. However, this mealybug is not a pest in California vineyards because of a successful biological control program, which was initiated for the Caribbean in 1994 and later extended to Mexico and southern California. The parasitoids *Anagyrus kamali* Moursi, *Gyranusoidea indica* Shafee, Alam & Agarwal, and *Allotropa* sp. nr. *mecrida* (Walker) are credited with reducing *M. hirsutus* densities to non-economic levels throughout the state (Roltsch et al. 2006) and it is not currently found in vineyards.

Pseudococcus longispinus was first reported as a citrus pest in California and, to help control this invasive pest, parasitoids were imported in the 1920s, including *Tetracnemoidea sydneyensis* (Timberlake) (from Australia), *Anagyrus fusciventris* (Girault) (from Hawaii), and *Tetracnemoidea peregrina* (Compere) (from Argentina) (Bartlett 1978). DeBach (1949) suggested that parasitoids helped suppress *Ps. longispinus* in citrus, but that predators, especially *C. montrouzieri*, were more important. Currently, *Ps. longispinus* infests a small number of vineyards in California's

coastal region. Recent surveys found *T. sydneyensis*, *T. peregrina*, *A. angelicus*, *A. pseudococci*, *Leptomastidea abnormis* (Girault), *Leptomastix dactylopii* Howard, and *Coccidoxenoides perminutus* Girault attacking this mealybug (Daane et al. 2008a).

Little is known about *F. gilli* as this species was only described in 2003, initially found infesting pistachios in the San Joaquin Valley (Gullan et al. 2003). Nevertheless, it became the primary vineyard pest in some of California's Sierra Foothill appellations. Similar to *Ps. maritimus*, *F. gilli* has two generations per year, overwintering under the bark, and moving onto the leaves and berry clusters during the summer. Some parasitoid species have been recorded, with a key parasitoid being *Acerophagus* sp. nr. *meritorius* Gahan that was most likely present in California as a parasitoid of the closely related *F. virgata*.

Pseudococcus viburni has long been in California, but only became a key vineyard pest when the wine grape industry expanded into the Central Coast region. Nevertheless, the range of this pest seems to be increasing. Prior to 1993, there were no effective parasitoids of *Ps. viburni* in California and for this reason, *Acerophagus flavidulus* (Brèthes) and *Leptomastix epona* (Walker) were imported from Chile (Daane et al. 2008a). Both *A. flavidulus* and *L. epona* were initially recovered. However, foraging ants diminished their impact (Daane et al. 2007). Insecticides are currently used for most *Ps. viburni* populations, especially when *Pl. ficus* is also found.

Planococcus ficus is currently the most damaging vineyard mealybug in California as well as in Mexico. *Planococcus ficus* appears capable of surviving across a wide geographic range, from desert table grapes to cool coastal wine grapes (Daane et al. 2007), with from 3 to 10 generations per year, depending on the temperature. To control this pest, parasitoids have been imported from Spain, Israel, and South Africa, and they include *A. pseudococci*, *L. abnormis*, *C. perminutus* and *L. dactylopii* (Daane et al. 2008b). Although these natural enemies provide some suppression, biological traits of *Pl. ficus* limit their effectiveness (Daane et al. 2004; Gutierrez et al. 2008). Mating disruption has shown some promise (Walton et al. 2006) and is being used on a larger scale each year. Nevertheless, insecticides are the primary control tool for *Pl. ficus*. Currently, most North American insecticide programs are based on the use of one or more of the following insecticides: imidacloprid (systemic – near bloom time), buprofezin (foliar – late spring or early summer), acetamiprid (late spring to harvest), clothianidin (foliar or systemic – from late spring to harvest), spirotetramat (late spring to early summer, or post-harvest), and chlorpyrifos (delayed dormant or post-harvest).

For North America, much of the future mealybug research concerns GLDs, such as determining the required treatment thresholds for mealybugs in order to reduce GLRaV spread. Connected to this is the development of better monitoring programs, using synthetic sex pheromones to determine the abundance and species of mealybugs. Better ant controls are also needed (Daane et al. 2007; Tollerup et al. 2007). Researchers have investigated the use of ant baits to deliver small but lethal amounts of toxicant to the ant colony by exploiting their social behavior to distribute food via trophallaxis, thereby delivering the toxicant to the nest population to provide season-long control (Tollerup et al. 2004; Daane et al. 2006a; Nelson and Daane 2007;

Cooper et al. 2008). In contrast, broad spectrum insecticide sprays targeted at ants may kill foraging ants, but unlike baits they have little effect on nests, allowing population resurgence.

12.5.2 South America

Grape production has distinct management practices and mealybug pest problems through South America. Here, mealybugs in Chile, Argentina and Brazil will be discussed as examples of the dynamics of South American mealybug problems and controls.

In Chile, grape is one of the oldest and most economically important crops, with ca. 180,000 ha, of which about one-third are destined for table grape production (42% of the total fruit exports). Mealybugs are the main phytosanitary problem for Chilean table grapes because of their quarantine importance for many markets. They have been responsible for up to 70% of table grape rejections by inspectors prior to export. In contrast, the economic impact of mealybugs in wine grapes is not well understood, although populations have increased over the years and recent work has demonstrated the potential negative impact of mealybugs. The questionable issue is the presence of GLD in Chilean vineyards (Herrera and Madariaga 2001). To some extent, GLDs are not considered as important in Chilean grape production as in other vineyard regions because the vines are not grafted (own-rooted vines), which are thought to be more tolerant to GLD than modern rootstocks.

Several mealybug species have been associated with grapes in Chile (Artigas 1994), but by far the most common is *Ps. viburni*, with *Ps. longispinus*, *Ps. calceolariae* and *Pl. citri* being rare (Gonzalez 2003; Ripa and Luppichini 2010), despite being common on other subtropical fruit crops such as citrus and avocados (Ripa and Larral 2008). Two other species have also been mentioned, *Ps. maritimus* and *Pl. ficus*, but the literature is contradictory in this regard (Artigas 1994; Gonzalez 2003; Gonzalez and Volosky 2005), and presently they are believed to be misidentifications. Earlier records of *Ps. maritimus* might correspond to a new species, which is in the process of being formally described.

Vineyard mealybug control in Chile has been mostly accomplished through applications of organophosphate insecticides, and more recently neonicotinoids and insect growth regulators (Gonzalez et al. 2001; Sazo et al. 2008; Salazar et al. 2010). Additionally, as organic wine grape production has increased, the use of augmentative biological control has increased accordingly, including the release of the endemic parasitoid *A. flavidulus*, predators like *C. montrouzieri* and *Sympherobius maculipennis* Kimmins, and entomopathogens such as the soil-inhabiting fungus *Metarhizium anisopliae* (Metschnikoff) Sorokin (Ripa and Larral 2008; Ripa and Luppichini 2010; Salazar et al. 2010).

In Argentina, viticulture began with the initial Spanish colonization in the sixteenth century. Currently, there are about 228,575 ha in grape production, with about 93% in wine grapes. Mendoza is the most important grape-growing province,

containing approximately 70% of Argentina's grape production which is mostly dedicated to wine grapes, followed by San Juan province with about 22% with 11,800 ha of table and raisin varieties.

Historically, Argentina had relatively few grape pests because of its hot and dry climate. Mealybug pest problems began in 2001 when *Pl. ficus* was first found. This invasive pest soon developed to damaging populations, initially in the table grape, and later in wine grape regions. Currently, *Pl. ficus* is distributed throughout most of Argentina's grape production valleys. Practices such as mechanical harvesting have hastened its movement among vineyards and regions. *Planococcus ficus* is not the only mealybug found in Argentina vineyards (Cordo et al. 2004), but it is the only one reported to cause significant economic damage. *Planococcus ficus* has six generations annually, with the first generation beginning in early spring (September to October). The mealybug directly infests the grape clusters, beginning with the third generation in midsummer (December) and building throughout the season, especially when tended by ants. Ants are associated with *Pl. ficus* spread, and in the Mendoza region, the ant species in the genera *Dorymyrmex*, *Linepithema*, *Pheidole*, *Solenopsis*, *Camponotus*, and *Brachymyrmex* have been observed tending this pest (Cucchi and Becerra 2009). The widespread distribution of *Pl. ficus* also presents the danger of further spread of GLRaVs in Argentina (de Borbon et al. 2004).

To develop improved control programs, research is now clarifying the extent of GLRaVs present in Argentina and their natural dispersion by mealybugs, including the use of epidemiological models. Initially, control programs relied on insecticide applications of neonicotinoid (e.g., imidacloprid) and organophosphate products (e.g., dimethoate and methyl pirimiphos). Although these pesticides are still used, current research has investigated semiochemical (mating disruption) and tetramic acid based pesticides (e.g., spirotetramat) as alternate control tools. Natural enemies, such as the lady beetle *Hyperaspis lanatii* González & Gordon, the lacewing *Chrysoperla asoralis* Banks, and the parasitoids *Anagyrus* sp., *Leptomastix* sp., *Leucopis* sp., have been found associated with *Pl. ficus* (Cucchi and Becerra 2009).

In Brazil, viticulture is a relatively new industry, with about 82,000 ha, primarily in the southern states (Paraná, Santa Catarina, São Paulo and Rio Grande do Sul) near Argentina and Uruguay, and in the eastern states of Bahia and Pernambuco. The vines are grown for table and wine grapes, with Rio Grande do Sul producing about 60% of the juice and wine grapes, whereas in São Paulo grapes are grown primarily for the table grape market, including the export market.

Mealybugs are a recent concern for Brazilian growers mainly due to direct infestation of table grape clusters. Although there is growing awareness of mealybugs as vectors of GLRaVs, their role in Brazil is still not well understood (Fajardo et al. 2003). *Planococcus citri* is the most abundant vineyard mealybug species (Morandi Filho et al. 2009), whereas *Pl. ficus* is rarely reported (Foldi and Kozar 2006). Surprisingly, the root-infesting mealybug *D. brevipes* is second most in importance, and unlike other root-infesting mealybug species, it is also found above ground and will infest the berry clusters in Brazil. Other species of mealybugs associated with

Brazilian grapes are *Ps. viburni*, *Ps. maritimus*, and *Planococcus minor* (Maskell). However, they are considered of secondary importance.

One particular situation of Brazilian viticulture is the use of *Vitis labrusca* L. cultivars Niagara, Isabel and Ives for juice, wine, and table grapes, representing about 50% of all grape cultivars. The importance of these *V. labrusca* cultivars is that, in many regions, they are grown next to *Vitis vinifera* L., but as *V. labrusca* can host but not show GLD symptoms, they may provide an undetected refuge for these pathogens. Currently, researchers in Brazil are working to improve wine quality where the presence and spread of GLRaV is considered a primary issue for replanting vineyards and the future development of the wine industry. Because *D. brevipes* is a root mealybug, this species may be an issue (if it is also a vector of a GLRaV) for replanting *V. labrusca* with *V. vinifera*.

Mealybug management is based on chemical treatments, primarily with neonicotinoid insecticides (e.g. imidacloprid and thiamethoxam). These are typically applied as a soil drench directed to the grape roots. Many Brazilian researchers suggest that the previous use of broad spectrum pesticides to control other vineyards pests (e.g. South American fruit fly, thrips) have destroyed much of the natural enemy population that attacks *D. brevipes* and other vineyard pests. Future research will investigate improving natural controls and monitoring programs, as well as testing novel insecticides such as spirotetramat. Because mealybugs were an often overlooked pest group in Brazilian vineyard management, another goal is to survey and correctly identify mealybug pests and to extend information on mealybugs as vectors of plant pathogens.

12.5.3 Europe

Modern studies of mealybugs in European vineyards began in the 1980s with the examination of *Planococcus* spp. in the transmission of GLRaV (Rosciglione and Castellano 1985) and the serological characterization of GLRaVs. Because grape cultivation in Europe is dominated by wine rather than table grapes, GLD is the main concern with mealybugs. Besides the outward GLD symptoms mentioned earlier, leafroll damage is considered to be the reduction in sugar content and an increase in acidity in the berries. Nevertheless, it is commonly accepted by European growers that GLD is not as severe as grapevine yellows (induced by phytoplasmas and transmitted by leafhoppers and planthoppers) or grapevine fanleaf disease (induced by viruses and transmitted by nematodes). In Europe, four mealybug species are known to develop on grapes: *Pl. ficus*, *Pl. citri*, *H. bohemicus*, and *Ph. aceris* (Sforza et al. 2003; Bertin et al. 2010; Cid et al. 2010), along with four coccid scales and a diaspid scale. For example, in vineyards of France (Champagne, Burgundy, Alsace), four hemipterans are sympatric in leafroll-infected vineyards, namely the mealybugs *H. bohemicus*, *Pl. ficus*, and *Ph. aceris* and the coccids *Pa. corni* and *Pu. vitis* (Sforza et al. 2003).

The biology of *Pl. ficus* and *Pl. citri* is poorly known even though they are natives of Eurasia and polyphagous in European agroecosystems. These pseudococcids were only recently considered as economically important pests. *Planococcus ficus* is present throughout the Mediterranean Basin, and often sympatric and misidenti-fied, with the closely related *Pl. citri*, as discussed previously. Both mealybugs are reported as vectors of GLRaV-3,-5 in several European countries (Cabaleiro and Segura 1997). *Planococcus ficus* may be the only European GLRaV vector with multiple generations. There have been no concerted control programs for either *Pl. ficus* or *Pl. citri*. Survey studies have identified natural enemies and quantified their abundance during the growing season (Sforza et al. 2003), in order to improve the understanding of resident biological control agents. Currently, natural regula-tion of *Pl. ficus* and *Pl. citri* is primarily provided by the activity of resident *A. pseudococci*.

Heliococcus bohemicus became a primary vineyard pest in the last two decades in Hungary, Switzerland, Italy, France, and Germany, but it is only reported as a GLRaV vector on grape in France (GLRaV-1) and Italy (GLRaV-1 and GVA) (Kozar et al. 1994; Sforza et al. 2003; Zorloni et al. 2006). This mealybug is univoltine in France, and bivoltine in Italy. A natural enemy survey showed parasitism levels of at least 35%, attributed to the encyrtids *Leptomastidea bifasciata* (Mayr) and *Anagyrus szodensis* Erdös, with activity from spring through summer.

Phenacoccus aceris is common on vines as well as some tree species (e.g., oak, apple, chestnut). This is a univoltine species, with a high fecundity rate that is reported to range from 800 to 3,600 eggs per female. It is found throughout Eurasia, where it is reported as a virus vector on grapes, as well as 'little cherry disease' on cherry (Kosztarab and Kozar 1988). In French vineyards, it transmits GLRaV-1, GLRaV-3, and GVA, and GVB from grape to grape (Sforza et al. 2003). The encyrtid *Anagyrus schoenherri* (Westwood) has been reported attacking second instar *Ph. aceris* (Sforza et al. 2003) and releases of *C. montrouzieri* have shown promise.

12.5.4   New Zealand

Three introduced mealybug species, *Ps. calceolariae*, *Ps. longispinus* and *Ps. viburni*, have been primary pests in New Zealand vineyards (Charles 1993). A more recent survey revealed that only *Ps. calceolariae* and *Ps. longispinus* were commonly encountered, with *Ps. viburni* now regarded as an insignificant component of the mealybug fauna, resulting from a successful biological control program (Charles et al. 2010). Damage from these pests includes berry contamination with insects, honeydew and sooty molds (Charles 1982). However, as New Zealand production is primarily for wine grapes, the mealybugs are more recognized as vectors of GLRaVs (Petersen and Charles 1997). Indeed, mealybugs and GLD are considered the pri-mary destructive pests and disease affecting vines (Charles et al. 2006).

In the North Island of New Zealand, *Ps. calceolariae* and *Ps. longispinus* have three generations per year (Charles 1981) and it is likely that the same number of

generations occur in Marlborough in the South Island, the major wine grape region. However, other aspects of the biology of these pests remain poorly understood. For example, *Ps. calceolariae* is frequently found on vine roots but the proportion of the population on roots at any point in time and its relative mobility in this environment remain unknown. Subterranean mealybugs hamper monitoring, may limit the effectiveness of contact insecticides and some natural enemies, and may also reduce the effectiveness of programs to remove GLRaV-infected vines, which is commonly practiced in New Zealand wine regions (Bell et al. 2009). Given what is known of *Ps. calceolariae*, it is conceivable that their survival on remnant roots could, in part, explain the relatively rapid reappearance of GLDs observed in replanted vineyards. Research is now underway to assess the likelihood of this mechanism perpetuating a renewed incidence of leafroll virus in re-plants.

Grapes in New Zealand are primarily grown for wine production, and as mentioned, the goal of mealybug control is not so much on preventing crop damage from mealybug infestations, but in managing the incidence and spread of GLRaVs (Charles et al. 2009). Consequently, tolerance for mealybugs is very low, especially where they co-exist with leafroll virus. The use of insecticides for mealybug control is largely limited to North Island vineyards, and includes an organophosphate (e.g., prothiofos) near budbreak and two in-season applications of an insect growth regulator (e.g., buprofezin). In 2008, the average number of buprofezin applications per block was 0.31, whereas applications of prothiofos (not endorsed under the Sustainable Winegrowing Program, SWNZ) averaged just 0.15 per block. Research into other insecticides, including systemic products, is underway. Recently, the label claim of one such active ingredient, imidacloprid, was extended to include vines but its use in New Zealand is restricted to that of a soil drench that can only be applied to non-cropping vines infected with leafroll virus and about to be removed (Lo and Walker 2010). This strategy attempts to reduce the incidence of viruliferous mealybugs on the remnant roots of rogued vines.

In New Zealand, three important issues are the likely focus of future vineyard pest management research: (1) the development of efficient mealybug monitoring systems, (2) the determination of the role of biological control in regulating mealybug populations, and (3) control measures based on treatment thresholds and the use of novel insecticides. First, the recent identification of the sex pheromone for *Ps. calceolariae* and *Ps. longispinus* (Millar et al. 2009; El-Sayed et al. 2010) will enable researchers to develop monitoring programs, better study pest phenology, and detect new mealybug incursions. Sex pheromones may also offer the potential to control these mealybug pests through mating disruption and/or male 'lure and kill'. Second, the potential for biological control of *Ps. calceolariae* and *Ps. longispinus* in New Zealand has not been fully explored, despite a good understanding of the species composition and regional distribution of many mealybug natural enemies (Charles 1981, 1985, 1993; Charles et al. 2010). Still, the current changes in pesticide use patterns, particularly the virtual elimination of mid- to late season organophosphate applications, may improve the vineyard ecosystem for natural enemy use (Charles et al. 2010). Third, the long-term challenge facing the wine sector is the development and implementation of a leafroll virus program. New Zealand

operates a high-health plant program to ensure that vineyards receive virus-free plant material but has only recently increased the focus on roguing virus-infected vines and mealybug control. This situation not only demands a better understanding of mealybug ecology and cost-effective control measures but also an appreciation of the social and economic challenges confronting communities of growers that now need to share strategies when implementing area-wide virus-elimination programs.

12.5.5 India

Severe mealybug outbreaks have been reported in India's vineyards, adversely affecting grape production by as much as 90% in extreme cases in the state of Andhra Pradesh. Amongst the eight mealybug species that have been reported on vines in India, *M. hirsutus*, *Pl. citri*, *Nipaecoccus viridis* (Newstead) and the root mealybug, *X. annandalei*, are the primary mealybug pests. Cultivars harvested in late fall suffer heavily from mealybug damage. The increasing mealybug problem in recent years may be due to frequent and indiscriminate use of insecticides to control other pests, which may disrupt natural enemies responsible for the suppression of mealybugs. Although the root mealybug will not be covered here in detail, root damage by this pest reduces vine vigor and yield, and shortens fruit-bearing canes (Rajagopal et al. 1997).

Maconellicoccus hirsutus is the most important of the vineyard mealybugs in peninsular India, with severe infestations leading to berry and shoot damage. The mealybug occurs on the vine throughout the year (Mani and Thontadarya 1987c). After harvest, the mealybug population is confined to vegetative parts, where it overwinters. In spring, the vines are given a 'foundation pruning' (usually in April–May), and *M. hirsutus* remains on the leaves, stem, and trunk from this period until harvest. From mid- to late summer, the population density is typically low until late fall when the vines are given a 'berry pruning'. The mealybug population density starts increasing from mid-December onwards and by January (midwinter – but temperatures in India are, of course, different from most grape growing regions, as are the grape cultural practices) the *M. hirsutus* population migrates from the trunk, cordons, and shoots to developing berries. The pest population build-up coincides with high temperatures (30–40°C), low humidity (less than 40%) and berry development. Peak population is reached before harvest in spring (March–April). An early harvested crop usually reduces mealybug damage as compared to a late harvested crop. Also, heavy rains and cool temperatures of less than 20°C can result in a temporary reduction in the *M. hirsutus* population, often encountered in winter and rainy seasons.

For biological controls, six parasitoids and seven predators have been associated with *M. hirsutus*. The parasitoids are *Anagyrus dactylopii* (Howard), *Allotropa* sp. nr. *japonica* Ashmead, *Anagyrus mirzai* Agarwal & Alam, *Alamella flava* Agarwal, *Leptopilinia* sp., and *Chartocerus* sp. nr. *walkeri* Hayat. The predators are *Scymnus gratiosus* Wiese, *Scymnus coccivora* Ayyar, *C. montrouzieri*, *Chrysopa* sp., *Spalgis*

epius Westwood, *Cacoxenus perspicax* (Knab), and *Triommata coccidivora*. Among these, *A. dactylopii* and *S. coccivora* are the most important, causing up to 70% parasitism (Mani et al. 1987). Studies have investigated the biology of the more important natural enemies. For example, *A. japonica* can be reared on 15–20 day old *M. hirsutus* (Mani and Krishnamoorthy 1989) and larva of *S. coccivora* consumed 308 eggs or 62 nymphs (Mani and Thontadarya 1987a). The lady beetle *C. montrouzieri* showed the potential to consume about 1,000 eggs or 300-500 mealybug nymphs (Mani and Thontadarya 1987b). The augmentative release of this beetle showed promise against *M. hirsutus* in field trials (Mani and Thontadarya 1989). Studies also investigated the impact of various pesticides on these natural enemies. For example, application of dichlorvos, diazinon, phosalone, fish oil rosin soap, and the commonly used fungicides proved to be safe to *A. dactylopii* (Mani and Thontadarya 1988) and could be integrated with the release of *C. montrouzieri*.

Prevention is better than cure. Cultural, mechanical, biological, and chemical methods of control have to be integrated to reduce the mealybug populations and reduce berry damage. Cultural practices include: (1) the collection and destruction of the mealybug from infested clusters at harvest time (March–April), (2) the collection and destruction of all the pruned material from mealybug infested vines during the foundation pruning (April–May), (3) bark stripping – or the removal and destruction of loose bark (April–May), (4) a similar removal of weeds and other alternate host plants that harbor mealybugs in and around the vineyards (season-long), and (5) removal of ant colonies that tend the mealybugs.

Insecticide practices to manage mealybugs include the following: (1) drenching ant colonies with chlorpyrifos or malathion dust (April–May), (2) treating the trunk and cordons with dichlorvos (April–May), (3) systemic application of imidacloprid applied to basins in the soil around the trunk or through drip irrigation system (April–May), (4) foliar applications of buprofezin and/or methomyl (about 30 days of soil drenching, or 30–60 days before harvest), (5) foliar sprays of dichlorvos or azadirachtin (3–15 days before harvest), and (6) releasing of *C. montrouzieri* (at 5,000/ha from August–September) or foliar sprays of a mixture of *Verticillium lecanii* (Zimmerman) / *Beauveria bassiana* (Balsamo) Vuillemin at 15-day interval in the rainy season (July–August). These steps may also be repeated after the second harvest (October–November).

12.5.6 The Middle East

Planococcus ficus is the primary vineyard pest of the Middle East, and has been reported as a pest in Iran (Williams and Moghaddam 2000), Iraq, Israel, Lebanon, Libya, Egypt (Ben-Dov 1995), Syria, Tunisia (Mahfoudhi and Dhouibi 2009), and Turkey (Kaydan et al. 2005). For example, *Pl. ficus* is found in many vineyard and fig production areas and has become a serious vineyard pest in southern Iran

(Williams and Moghaddam 2000; Fallahzadeh et al. 2009). However, the pest distribution and pest status is uneven across the Middle East and, for example, *Pl. ficus* has never been reported to cause damage in northern Iran vineyards.

In southern Iran, *Pl. ficus* has five generations, with population density increasing rapidly from spring (May) into summer, and then declining after harvest (August to September). After the fifth generation, all developmental stages of *Pl. ficus* can be found overwintering on roots (November to March). Along with the change in population density is the expected change in feeding location. In spring, mealybugs are primarily found on the trunk and canes, while in summer they are primarily found on leaves, new canes, and berries. However, a portion of the population is always found in protected locations (Fallahzadeh et al. 2009).

Seven primary, two primary/secondary, three secondary parasitoid species, as well as two coccinellids, and four other predator species are associated with *Pl. ficus* in southern Iran (Fallahzadeh et al. 2011). The primary parasitoids are *A. pseudococci*, *L. dactylopii*, *A. dactylopii*, *A. mirzai*, *Anagyrus agraensis* Saraswat, *Leptomastix flava* Mercet, and *Chartocerus kurdjumovi* (Nikol'skaya). The primary/secondary parasitoids are *Prochiloneurus bolivari* Mercet and *Pachyneuron muscarum* (L.). The secondary parasitoids are *Marietta picta* (André), *Aprostocetus trjapitzini* (Kostjukov), and *Baryscapus sugonjaevi* (Kostjukov), and these attack either the *Anagyrus* or *Leptomastix* species.

In other Middle East regions, the encyrtid parasitoids *L. dactylopii*, *L. abnormis*, *Clausenia josefi* Rosen, and *Neoplatycerus* sp. nr. *palestinensis* (Rivnay) were found attacking *Pl. ficus* in Egyptian vineyards. In Tunisia, both *Pl. citri* and *Pl. ficus* were found in vineyard regions, where parasitoids were more frequently recorded than predators as natural enemies. *Anagyrus pseudococci* had a parasitism rate of 80.3%, followed by *L. abnormis* (12.1%), *C. perminutus* (4.5%), and *L. dactylopii*, whereas only two coccinellids (*Rhyzobius lophanthae* (Blaisdell) and *Scymnus* sp.) were associated with these mealybugs (Mahfoudhi and Dhouibi 2009). In Israel, both *Pl. citri* and *Pl. ficus* occur, with the former being primarily a citrus pests and the latter being more of a vineyard pest. Natural enemies attacking *Pl. ficus* include *C. josefi* and *A. pseudococci* (Berlinger 1977). More recently, the use of *A. pseudococci* against *Pl. ficus*, as well as the use of semiochemicals for monitoring *Pl. ficus*, has been undertaken in Israel (Franco et al. 2003; Zada et al. 2003).

Other mealybugs and scale insects have been reported from Middle East vineyards. The mealybug *Chorizococcus viticola* Kaydan & Kozár was collected on vineyards from southern Iran and a related species, *Chorizococcus shaferi* (Hollinger), found on grapes is a presumed invasive species from North America (Fallahzadeh et al. 2010). *Chorizococcus viticola* can reach damaging levels, and in some parts of Iran it is the most damaging vineyard pest, where it can reach high densities by midsummer (July), especially on berry clusters. The damage caused by this pest has increased in recent years in Beyza, Kavar and Akbar Abad (Fallahzadeh et al. 2010). Two encyrtid parasitoids, *Gyranusoidea iranica* Japoshvili & Fallahzadeh and *Anagyrus matritensis* (Mercet) and the lady beetle predator *Nephus bipunctatus* (Kugelann), were recorded as natural enemies of *C. viticola* (Fallahzadeh and Japoshvili 2010;

Fallahzadeh et al. 2010). Other mealybugs reported from Middle East vineyards include *M. hirsutus*, *N. viridis*, *Pl. citri* and *Ps. maritimus*, but these mealybugs are not regarded as important vineyard pests.

12.5.7   South Africa

Planococcus ficus is the key economic mealybug species occurring in vineyards in South Africa. *Planococcus ficus* was initially identified in the Western Cape Province as *Pl. citri* (Joubert 1943) after this pest was accidentally introduced to the area. Other pseudococcid species have since been recorded from vines in South Africa and include *Ps. longispinus* and *F. malvastra*. The most recent records of mealybugs as well as their distribution in South African vineyards can be found in Walton et al. (2009). As with many other regions, the primary concern of *Pl. ficus* is the transmission of GLRaVs.

In South Africa, the influence of temperature on the development of *Pl. ficus* was reported by Walton and Pringle (2005), who estimated up to six annual generations of *Pl. ficus*. Seasonal development showed an upward migration of the population on the trunk from spring or early summer, with populations starting to develop on new growth and continuing until near harvest, reaching peak population densities in mid- to late summer. Mealybugs found in the vine canopy after harvest formed the nuclei of winter colonies. Winter population levels of *Pl. ficus* were low and consisted mainly of non-ovipositing adult females. The most recent advance in *Pl. ficus* management is the development of pheromone monitoring for South African vineyards, which can aid with treatment decisions (Walton et al. 2004).

Planococcus ficus populations are attacked by a range of natural enemies (Walton and Pringle 2004a, b). These include, in descending order of abundance, *Anagyrus* spp., *C. perminutus*, and *L. dactylopii* for parasitoids, and *Nephus bineavatus* (Mulsant), *Nephus angustus* (Casey) and *Nephus quadrivittatus* (Mulsant) for predatory beetles. Biological control is severely hampered by the presence of ants, such as *L. humile*, *Formica perpilosa* Wheeler, and *Crematogaster peringueyi* Emery as they provide biological refuges for the mealybugs (Addison and Samways 2000; Mgocheki and Addison 2009b). Management of ant colonies has led to marked increases of parasitism and ultimately biological control of these pests (Mgocheki and Addison 2010).

Chemical control of *Pl. ficus* is based on two treatments of organophosphates applied 2 weeks apart, just before bud burst. An additional supplementary treatment of a chemical with a short residual period is sometimes applied prior to harvest. The use of insect growth regulators and systemic neonicotinoids has increased and these are currently being used as in-season pest control options. Mating disruption by use of pheromone impregnated dispensers for *Pl. ficus* (Walton et al. 2006) is being investigated as an alternative in high value grape production units. Because ants impact mealybug densities and damage, chemical control measures for ants using directed sprays or chemical barriers have also been developed (Addison 2002).

12.6   Conclusion

Mealybugs may be the most universally important vineyard insect pest, causing crop damage through their presence, as well as the accumulation of honeydew and sooty molds. They also reduce vine vigor through repeated annual infestations and vector grapevine leafroll associated viruses. These innocuous-looking insects can be found in most of the world's vineyard regions. Although the mealybug species and their level of damage often vary, this review of vineyard mealybugs in Europe, the Middle East, North America, New Zealand, South Africa, South America, and India reveals remarkable similarity in pest issues and control strategies. For the most part, biological controls are a key component of mealybug pest suppression measures. In most regions there is still a reliance on insecticides when mealybug densities become too high, and vineyard managers worldwide have moved along similar lines of insecticide materials, with most regions now using organophosphates more sparingly and developing new programs based on neonicotinoids, insect growth regulators, and/or tetramic acid derivatives. Cultural practices can be used to enhance both biological controls and insecticide measures, but appear to be relatively labor intensive, and therefore, too costly in some regions. Future control measures will focus on novel methods to monitor mealybugs, using synthetic sex pheromones that may even find commercial use in mating disruption programs. For most wine grape regions, there is a need to better understand grapevine leafroll disease and the role of mealybugs and other scale insects in the dispersion of this important plant pathogen. It is towards this goal that grape pest researchers have joined a cosmopolitan effort towards the study and control of mealybugs.

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