Chapter 11

Arthropod Pests

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Introduction

The dynamics of cassava production, utilization and marketing vary considerably from one continent and country to another. In recent years there has been a shift in demand for particular cassava products in Latin America with a noticeable trend towards the production of chips and pellets for animal feed, as well as high-quality flours for human consumption (Henry and Gottret, 1995). This could induce a trend towards plantation-size production units.

World cassava production, which is concentrated in Latin America, Asia and Africa, can be divided into five principal agroecosystems (Henry and Gottret, 1995):

- the lowland humid tropics;
- the lowland subhumid tropics;
- the lowland semiarid tropics;
- the highland tropics; and
- the subtropics.

Approximately 65% of the area under cassava production occurs in the lowland humid and subhumid agroecosystems (Henry and Gottret, 1995). Arthropod pests do not appear to cause significant damage in the lowland humid or the highland tropical agroecosystems, where there is considerable and consistent rainfall (Montagnini and Jordan, 1983; Bellotti *et al.*, 1999). Moderate levels of crop damage can occur in the mid-altitude (1000–1400 m) tropics, especially if there is a dry season of 3 months or more. When the crop is grown under conditions of irregular, limited rainfall as in the lowland subhumid and semiarid tropics, however, arthropod pest populations increase, causing considerable yield reduction (Bellotti *et al.*, 1999). Arthropod pests can cause low-to-moderate levels of crop damage in the subtropical regions of Latin America and Africa and in the highland regions of Africa (Henry and Gottret, 1995).

Most cassava is grown by small-scale farmers, often on marginal or fragile soils under rainfed conditions, using few purchased inputs such as fertilizers or pesticides. In these traditional farming systems where cassava is usually one of many crops being grown, pest control is often a low priority and so cassava receives minimal pesticide applications. Under such conditions, yields are often low, with a large gap between potential yield (21.3 t ha^{-1}) and that achieved by producers: a mean of 11.2 t ha^{-1} in Latin America and 9.0 in Africa (Henry, 1995). Arthropod pests and diseases are major factors in causing this yield reduction (Bellotti *et al.*, 1999); moreover, the vegetative nature of cassava propagation contributes to pest build-up and dissemination across regions and among countries and continents.

In Latin America there are indications of a shift towards large-scale production units, where cassava is grown as a plantation crop. This may result in new or worse pest problems than those

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found in small-scale production. Such a scenario is especially feasible in the Neotropics, where a large complex of arthropod pests has co-evolved with the crop. For example, increased frequency and severity of cassava hornworm (*Erinnyis ello* L.) attacks have been recorded, resulting in increased pesticide applications (LaBerry, 1997). In Asia, where there are extensive areas planted with cassava, major pest problems have been avoided as the most damaging pest species from the Neotropics have not been introduced.

The Cassava Arthropod Complex

Cassava (Euphorbiaceae: *Manihot esculenta* Crantz) is a perennial shrub grown commercially as an annual or biennial, throughout tropical and subtropical regions of the world. This vegetatively propagated crop has a long growth cycle and is drought-tolerant. As it is often intercropped and planting dates are staggered, cassava is almost always present in farmers' fields. These agronomic characteristics undoubtedly contribute to the considerable diversity of arthropod pests that feed on the crop.

Cassava originated in the Neotropics, although its exact centre of origin is equivocal (Renvoize, 1973; Allem, 1994; see Chapter 4); consequently, the greatest diversity of arthropods reported attacking the crop (Table 11.1) is from the region (Bellotti *et al.*, 1994). An estimated 200 species have been reported (Bellotti and Van Schoonhoven, 1978a,b), many of which are specific to cassava and have adapted in varying degrees to an array of natural biochemical defences in the host that include laticifers and cyanogenic compounds (Bellotti and Riis, 1994). The pest complex varies greatly between the main cassava-growing areas, indicating that careful quarantine measures could prevent pest introduction into uninfested areas (Frison and Feliu, 1991). The accidental introduction of the cassava green mite (CGM; *Mononychellus tanajoa* Bonder) and the cassava mealybug (*Phenacoccus manihoti* Mat. Ferr.) from the Americas into Africa has caused considerable crop loss throughout the cassava belt and has been the object of massive biological control efforts (Herren and Neuenschwander, 1991; Neuenschwander, 1994a). In Asia none of the major neotropical cassava pests has become established and native arthropod pests that have adapted to cassava have not been reported as causing serious yield losses (Maddison, 1979).

Recent explorations in cassava-growing regions of the Neotropics indicate that the arthropod pest complex is not geographically uniform. The evidence suggests that the mealybug *Phenacoccus herreni*, which has caused considerable damage in northeast Brazil, was probably introduced from northern South America (Venezuela or Colombia), where mealybug populations are controlled by natural enemies not found in Brazil (Bellotti *et al.*, 1994; Smith and Bellotti, 1996). *P. manihoti*, which has caused severe crop damage in Africa, occurs only in Paraguay, the Mato Grosso area of Brazil and the Santa Cruz area of Bolivia (Lohr and Varela, 1990).

Studies on the CGM demonstrate a higher degree of morphological polymorphism and a greater *Mononychellus* species complex in northern South America than elsewhere in the Neotropics (Bellotti *et al.*, 1994). This diversity is associated with greater species richness within the phytoseiid complex that preys upon *Mononychellus* spp. in cassava (Bellotti *et al.*, 1987, 1999). The cassava pest complex can be divided into two groups:

- those that appear to have co-evolved with cassava, which is their primary or only host; and
- generalist feeders that may attack the cassava crop opportunistically, especially during seasonally dry periods when cassava is one of the limited food sources available.

The former group includes the *Mononychellus* mite complex, mealybugs (*P. herreni* and *P. manihoti*), the hornworm (*E. ello*), lacebugs (*Vatiga illudens*, *Vatiga manihotae*, *Amblystira machalana*), whiteflies (*Aleurotrachelus socialis* and *Aleurothrixus aepim*), the stemborer (*Chilomima clarkei* and those of the genus *Coelosternus*), fruitflies (*Anastrepha pickeli* and *Anastrepha manihoti*), the shootfly (*Neosilba perezi*), the white scale (*Aonidomytilus albus*), thrips (*Frankliniella williamsi*) and the gallmidge (*Jatrophobia brasiliensis*; Bellotti *et al.*, 1999).

The generalist feeders primarily consist of whitegrubs (*Phyllophaga* spp. and several others), termites, cutworms, grasshoppers, leafcutting ants, burrower bugs (*Cyrtomenus bergi*),

crickets, *Tetranychus* mite species and stemborers (*Lagochirus* spp.) (Bellotti and van Schoonhoven, 1978a; Bellotti *et al.*, 1999).

Several pests found in the Neotropics could potentially cause severe crop losses if introduced inadvertently into Asian or African cassava-growing areas. They include the cassava hornworm, several mite species, lacebugs, whiteflies and stemborers. Moreover, a species which is considered to be a secondary or minor pest in the Neotropics (e.g. the cassava mealybug, which is found only in limited sites, as mentioned) could become a major pest if introduced into areas where native natural enemies and/or adapted or resistant germplasm are unavailable. *P. manihoti* has not yet reached other regions, although there are no evident natural barriers to prevent its movement, especially in Brazil, where cassava is grown extensively throughout most of the country. The Andean mountain range in western South America has undoubtedly affected the movement of cassava pests, although this is not well documented. For example, the lepidopteran stemborer *C. clarkei*, which has good flight

Table 11.1. Global distribution of important arthropod pests of cassava.

Pest	Major species	Americas	Africa	Asia
Mites	*Mononychellus tanajoa*	X	X	
	Tetranychus urticae	X		X
Mealybugs	*Phenacoccus manihoti*	X	X	
	Phenacoccus herreni	X		
Whiteflies	*Aleurotrachelus socialis*	X		
	Aleurodicus dispersus	X	X	X
	Aleurothrixus aepim	X		
	Bemisia tabaci	X	X	X
	Bemisia afer	X	X	
Hornworm	*Erinnyis ello*	X		
	Erinnyis alope	X		
Lacebugs	*Vatiga illudens*	X		
	Vatiga manihotae	X		
Burrower bugs	*Cyrtomenus bergi*	X		
Thrips	*Frankliniella williamsi*	X	X	
	Scirtothrips manihoti	X		
Scales	*Aonidomytilus albus*	X	X	X
Fruitflies	*Anastrepha pickeli*	X		
	Anastrepha manihoti	X		
Shootflies	*Neosilba perezi*	X		
	Silba pendula	X		
Gallmidge	*Jatrophobia* (*Eudiplosis*) *brasiliensis*	X		
White grubs	*Leucopholis rorida*	X	X	X
	Phyllophaga spp.	X	X	X
	Several others	X	X	X
Termites	*Coptotermes* spp.	X	X	X
	Heterotermes tenuis	X		
Stemborers	*Chilomima* spp.	X		
	Coelosternus spp.	X		
	Lagochirus spp.	X	X	X
Leaf-cutter ants	*Atta* spp.	X		
	Acromyrmex spp.	X		
Root mealybugs	*Pseudococcus mandioca*	X		
	Stictococcus vayssierei		X	
Grasshoppers	*Zonocerus elegans*	X	X	
	Zonocerus variegatus	X	X	

Source: Adapted from Bellotti *et al.* (1999).

capabilities and has spread through many regions of Colombia and Venezuela, is not reported west of the westernmost range of the Andean mountains, but has been reported from Argentina (B. Lohr, personal communication).

Crop damage and yield loss

Arthropod damage to cassava is often indirect because most pests are foliage or stem feeders, reducing leaf area, leaf life or photosynthetic rate. Field studies indicate that pests that attack the crop over prolonged periods (3–6 months) – such as mites, mealybugs, thrips, whiteflies and lacebugs – can cause severe root yield reductions (Table 11.2) as a result of their feeding on leaf cell fluids and the consequent decrease in photosynthesis. Severe attacks can induce premature leaf drop and death of the apical meristem. The potential for yield reduction by these pests is greater than that by cyclical pests such as hornworm and leaf-cutter ants, which cause sporadic defoliation. Nevertheless, these highly visible pests often cause farmers to apply insecticides (Braun *et al.*, 1993).

The burrower bug (*C. bergi*; Hemiptera: Cydnidae) is one of the few pests that damage cassava roots directly. Root punctures during feeding can introduce fungal pathogens that reduces root yield and quality (García and Bellotti, 1980). Grubs, millipedes and termites are reported occasionally as feeding on tuberous roots; however these may be secondary feeders, attacking already damaged and decaying roots.

In general, arthropod pests are most damaging to cassava during the dry season and do not appear to cause significant damage in areas of considerable and consistent rainfall (Bellotti *et al.*, 1999). The cassava plant is well adapted to long periods of limited water, responding to water shortage by reducing its evaporative (leaf) surface rapidly and efficiently and by closing the stomata partially, thereby increasing water use efficiency (Cock *et al.*, 1985; El-Sharkawy *et al.*, 1992). In water-deprived plants, both the accelerated shedding of old leaves and the pronounced decrease in their photosynthetic activity means that the younger leaves play a key role in the plant's carbon nutrition. Given that pests prefer the younger canopy leaves, dry-season feeding tends to cause the greatest yield losses in cassava. Once the crop enters into a wet cycle (following

Table 11.2. Yield losses due to major cassava pests.

Pest	Yield losses	References
Hornworm (*Erinnyis ello*)	In farmers' fields, natural attack resulted in 18% yield loss; simulated damage studies resulted in 0–64% loss, depending on no. of attacks, plant age and soil fertility.	Arias and Bellotti (1984); Bellotti *et al.* (1992)
Mites (*Mononychellus tanajoa*)	21, 25 and 53% yield loss during a 3-, 4- and 6-month attack, resp.; 73% for susceptible cultivars compared with 15% for resistant cultivars; 13–80% in Africa.	Bellotti *et al.* (1983b); Byrne *et al.* (1982); Herren and Neuenschwander (1991); Yaninek and Herren (1988)
Whiteflies (*Aleurotrachelus socialis*)	1-, 6-, 11-month attacks resulted in 5, 42 and 79% yield loss, respectively.	Bellotti *et al.* (1983b, 1999); Vargas and Bellotti (1981)
Mealybugs (*Phenacoccus herreni*, *Phenacoccus manihoti*)	68–88% loss depending on cultivar susceptibility (in Colombia); in Africa yield losses of ≈ 80% are reported.	Herren and Neuenschwander (1991); Schulthess (1987); Vargas and Bellotti (1984)
Burrower bugs (*Cyrtomenus bergi*)	Brown-to-black lesions render roots commercially unacceptable; > 50% reduction in starch content.	Arias and Bellotti (1985); Bellotti *et al.* (1999); Castaño *et al.* (1985)
Lacebugs (*Vatiga manihoti*, *Amblystira machalana*)	Field trials with *A. machalana* and *V. manihoti* resulted in 39% yield loss.	CIAT (1990)
Stemborers (*Chilomima clarkei*)	In Colombia, 45–62% loss when stem breakage exceeds 35%.	Lohr (1983)

rain or irrigation), it has the potential to recover and compensate for yield losses from severe drought, as well as from pest attack, because of the formation of a new leaf canopy and the higher photosynthetic rate in newly formed leaves (El-Sharkawy, 1993).

Major Pests; Bioecology Damage and Management

Cassava mites

Mites are a universal pest of cassava, causing serious yield losses in the Americas and Africa (Herren and Neuenschwander, 1991; Bellotti *et al.*, 1999). Of the > 40 species reported feeding on cassava (Byrne *et al.*, 1983), the most frequent are *Mononychellus tanajoa* (syn = *Mononychellus progresivus*), *Mononychellus carribbeanae*, *Tetranychus cinnabarinus* and *Tetranychus urticae* (also reported as *Tetranychus bimaculatus* and *Tetranychus telarius*). Cassava is the major host for the *Mononychellus* species, whereas the *Tetranychus* species have a wide host range. Other mite species (e.g. *Oligonychus peruvianus*, *Oligonychus biharensis*, *Eutetranychus banksi* or *Mononychellus mcgregori*) are not important economically and feed on cassava only sporadically (Byrne *et al.*, 1983).

CGM, the most important species, is reported causing crop losses in the Americas and Africa (Herren and Neuenschwander, 1991; Bellotti *et al.*, 1999), especially in seasonally dry regions of the lowland tropics (Yaninek and Animashaun, 1987; Braun *et al.*, 1989). In experimental trials fresh root yields were reduced by 21, 25 and 53% following 3-, 4- and 6-month attacks, respectively (Bellotti *et al.*, 1983b). Under field conditions with higher mite populations, there was a 15% yield reduction in resistant cultivars compared with a ≤ 73% loss in susceptible cultivars; 67% of the stem-cutting planting material was damaged (Byrne *et al.*, 1982, 1983).

M. tanajoa is native to the Neotropics and it was first reported from northeast Brazil in 1938. It first appeared in Africa (Uganda) in 1971 and by 1985 it had spread across most of the cassava belt, occurring in 27 countries (Yaninek, 1988) and causing estimated root yield losses of 13–80% (Yaninek and Herren, 1988; Herren and Neuenschwander, 1991; Skovgård *et al.*, 1993).

CGM populations feed preferentially on the undersides of young emerging leaves, which develop a mottled whitish-to-yellow appearance; and they may become deformed or reduced in size (Byrne *et al.*, 1983). The CGM is a serious problem only in dry regions, where heavy infestations cause defoliation which begins at the top of the plant, often killing apical buds and shoots. Regrowth may occur but if the rains are scarce, this new flush of leaves will also be attacked (Yaninek and Animashaun, 1987).

Control

Research into the control of *M. tanajoa* has had two main thrusts: host plant resistance (HPR) and biological control (Table 11.3). These two complementary strategies promise to reduce CGM populations below economic injury levels. The continual use of acaricides is not feasible for low-income farmers. Moreover, such use is not recommended because of adverse effects on natural enemies.

HPR. Substantial efforts have been made by both international research centres which have a mandate for cassava [Centro Internacional de Agricultura Tropical (CIAT) and International Institute for Tropical Agriculture (IITA)] and by national research programmes [e.g. Centro Nacional de Pesquisa en Mandioca y Fruticultura (CNPMF)/Empresa Brasileira de Pesquisa Agropecuaria (EMBRAPA)] to identify cassava cultivars and develop hybrids with resistance to CGM (Byrne *et al.*, 1983; Bellotti *et al.*, 1987; Hershey, 1987). Of nearly 5000 landrace cultivars in the CIAT cassava germplasm bank that were evaluated for CGM resistance, only *c.* 6% (300 cultivars) have been identified as having low-to-moderate levels of resistance (CIAT, 1999). After substantial effort, cultivars with moderate levels of resistance have been developed and released to farmers.

CIAT's mite-resistance research has traditionally been carried out at two sites: (i) CIAT, Palmira, located in the mid-altitude (1000 m) Andean highlands, where mite populations are moderate; and (ii) Pivijay, Magdalena, on the Colombian Atlantic Coast, in the lowland tropics with a prolonged (4–6 months) dry season and

Table 11.3. Control options for major cassava pests.

Pest/species	Control options	References
Hornworm (*Erinnyis ello*)	Biological control. Baculovirus biopesticide; monitoring of hornworm populations with light traps and field scouting.	Bellotti *et al.* (1992, 1999); Braun *et al.* (1993); Schmitt (1988)
Mites (*Mononychellus tanajoa*, *Mononychellus caribbeanae*)	Host plant resistance (HPR). Moderate levels of resistance available in cassava clones; effective breeding programme needed to incorporate resistance into commercial cultivars.	Bellotti *et al.* (1994); Braun *et al.* (1989); Byrne *et al.* (1982, 1983); CIAT (1999)
	Biological control. Large Phytoseiidae predator complex associated with mite complex that reduces mite populations effectively; fungal pathogen (*Neozygites*) and virus disease identified.	Bellotti *et al.* (1999); Yaninek and Herren (1988)
Whitefly (*Aleurotrachelus socialis*)	HPR. Several highly resistant varieties and hybrids available; natural enemies, especially parasitoids being surveyed and evaluated.	Arias (1995); Bellotti *et al.* (1994, 1999); Castillo (1996); CIAT (1999)
Mealybugs *(Phenacoccus herreni*)	Adequate HPR not available in cassava germplasm. Several natural enemies identified: 3 parasitoid species (*Acerophagus cocois, Aenasius vexans* and *Apoanagyrus diversicornis*) give good control.	Bellotti *et al.* (1983a, 1999); Van Driesche *et al.* (1990)
(*Phenacoccus manihoti*)	Parasite species *Apoanagyrus lopezi* provides good control in most regions of Africa.	Herren and Neuenschwander (1991); Neuenschwander (1994a)
Thrips (*Frankliniella williamsi*)	HPR. Pubescent cultivars have effective resistance and are available to farmers.	Bellotti and Kawano (1980); Bellotti and van Schoonhoven (1978a,b); van Schoonhoven (1974)
Burrower bug (*Cyrtomenus bergi*)	High-HCN cultivars less damaged than others. Several biological control agents including entomopathogenic nematodes and fungal pathogens give promising results in lab studies. Intercropping with *Crotalaria* sp. reduces damage.	Barberena and Bellotti (1998); Bellotti and Riis (1994); Bellotti *et al.* (1999); Caicedo and Bellotti (1994); Riis (1997)
Stemborers (*Chilomima clarkei*)	Cultural practices; maintain clean fields, destroy infested stems. HPR being investigated. Possible use of transgenic cultivars (Bt) being evaluated.	Bellotti and van Schoonhoven (1978a,b); Gold *et al.* (1990); Lohr (1983)
Lacebugs (*Vatiga manihotae*, *Vatiga illuden*, *Amblystira machalana*)	HPR evaluations have given some promising results. Natural enemies identified but not thoroughly investigated.	Bellotti *et al.* (1987, 1999); Calvacante and Ciociola (1993); CIAT (1990); Farias (1985)

high mite populations. Low-to-moderate levels of resistance are indicated by a 0–3.5 damage rating on a 0–6 evaluation scale.

Of the 300 cultivars selected as promising for mite resistance over several years (two to seven field cycles), 72 have consistently had damage ratings < 3.0 (CIAT, 1999). Most of these cultivars were collected from Brazil, Colombia, Venezuela, Peru and Ecuador, but there are also several hybrids.

Mechanisms of mite resistance have usually been expressed as antixenosis (preference versus non-preference) or antibiosis (Byrne *et al.*, 1982). Mites feeding on susceptible cultivars had greater fecundity, greater acceptability, a shorter development time, a longer adult life span and lower larval and nymphal mortality than those feeding on resistant cultivars (Byrne *et al.*, 1983). In more recent laboratory studies, *M. tanajoa* displayed a strong ovipositional preference for susceptible cultivars. When paired with the resistant cultivars M Ecu 72, M Per 611 and M Ecu 64 in free-choice tests, 95, 91 and 88%, respectively, of the eggs were oviposited on CMC 40, the susceptible cultivar (CIAT, 1999).

BIOLOGICAL CONTROL. Extensive surveys of cassava fields and experimental data indicate that although CGM is present throughout much

of the lowland Neotropics, severe outbreaks causing significant yield losses are rare, except in parts of Brazil. From 1983–1990 extensive evaluations of the natural enemy complex associated with cassava mites were carried out at 2400 sites in 14 countries of the Americas (Byrne *et al.*, 1983; Bellotti *et al.*, 1987). This led to the identification of the phytoseiid predator complex associated with the mites. The current predator mite reference collection held at CIAT conserves primarily those predators related to phytophagous mites found on cassava. Collecting zones were usually chosen for their similarity to ecological homologues in Africa and Brazil. Of the 87 species collected and stored, 25 are new or unrecorded species; 76% (66 species) were collected from cassava. A taxonomic key on phytoseiid species associated with cassava is being prepared as part of a collaborative project with Brazilian colleagues. The CIAT-Brazil collection is now organized into a true reference collection with accompanying database and can be used readily for species description or redescription, where types and paratypes may be found.

Of the 66 phytoseiid species collected on cassava, 13 occur frequently. *Typhlodromalus manihoti* was collected most frequently, being found in > 50% of the fields surveyed. This was followed by *Neoseiulus idaeus*, *Typhlodromalus aripo*, *Galendromus annectens*, *Euseius concordis* and *Euseius ho*, *T. aripo* and *N. idaeus* have played an important role in the successful control of *M. tanajoa* in Africa (Yaninek *et al.*, 1992, 1993).

Explorations also revealed several insect predators of CGM, especially the staphylinid *Oligota minuta* and the coccinellid *Stethorus* sp. These phytoseiids and insect predators have been studied extensively in the laboratory and field (Table 11.4). It is generally agreed that the phytoseiid predators are more efficient than the insect predators at controlling mites occurring in low densities (Byrne *et al.*, 1983).

Survey data also showed that CGM densities were much higher in northeast Brazil than in Colombia and that the richness of phytoseiid species was considerably higher in Colombia than in Brazil. Of the fields surveyed in Colombia, 92% were uninfested or had low CGM densities (< 25 mites per leaf) whereas in Brazilian fields only 12% were uninfested and 25% had intermediate or high densities (Bellotti *et al.*, 1994).

Data from field experiments in Colombia (Braun *et al.*, 1989) demonstrated the value and effect of the richness of phytoseiid species associated with CGM. Fresh and dry root yields in Colombia were reduced by 33% when natural enemies were eliminated, whereas applications of acaricides did not increase yields, indicating good natural biological control.

Since 1984 numerous species of phytoseiids have been shipped from Colombia and Brazil to Africa. Despite massive releases, none of the Colombian species became established, but three of the Brazilian species did (*T. manihoti*, *T. aripo* and *N. idaeus*; Yaninek *et al.*, 1992, 1993; Bellotti *et al.*, 1999). *T. aripo* appears to be the most successful of the three species. It has spread rapidly and is now in more than 14 countries. On-farm field trials indicate that *T. aripo* reduces CGM populations by 35–60% and increases fresh root yields by 30–37%.

Neozygites cf. *floridana*, a fungal pathogen (Zygomycetes: Entomophthorales), causes irregular or periodic mortality of mite populations in Colombia and northeast Brazil (Delalibera *et al.*, 1992). The pathogen has been found on mites throughout many cassava-growing regions of the Neotropics. Some strains appear to be specific to the genus *Mononychellus* (de Moraes *et al.*, 1990). The pathogen has also been found in CGM in Africa, but epizootics have not been observed (Yaninek *et al.*, 1996), indicating that Brazilian strains may be more virulent than the African strains. Molecular techniques are being used to determine taxonomic identification of fungal strains, and *in vitro* methodologies for rearing the pathogen are being developed. This fungus, which shows considerable promise for biological control of CGM, is being evaluated in Africa.

Cassava mealybugs

More than 15 species of mealybugs are reported feeding on cassava in Africa and South America. *P. herreni*, *P. manihoti*, *Phenococcus madeirensis*, *Ferrisia virgata* and *Pseudococcus mandio* are all reported from the Americas (Bellotti *et al.*, 1983a; Williams and Granara de Willink, 1992). Only *P. herreni* and *P. manihoti*, both of neotropical origin, are important economically (Table 11.2). *P. manihoti* was introduced inadvertently

Table 11.4. Life table data on selected Phytoseiidae predators of the cassava mites *Mononychellus tanajoa* (*Mt*), *Mononychellus caribbeanae* (*Mc*) and *Tetranychus urticae* (*Tu*).

	No. colony strains/species[a]	Tolerance to RH[b]	Egg consumption[b]	Development time (days)[c]			Fecundity[c]			Longevity (days)[c]		% Females[c]	
Phytoseiidae species	1986–1999	Egg eclosion	(24 h)	*Mt*	*Tu*	*Mc*	*Mt*	*Tu*	*Mc*	*Tu*	*Mc*	*Mt*	*Tu*
Typhlodromalus manihoti	31	+	68	4.9	4.1	5.5	14.2	–	3.5			74	88
Typhlodromalus aripo	9	+				6.8		13.0[d]	13.0[d]	14.0	20.9		
Typhlodromalus tenuiscutus	7	+	45.4	5.8	5.8	5.7	32.0	2.5	16.1	6.6	16.1	75	81
Neoseiulus idaeus	20	+++	26.8	4.6	4.6	5.1	13.8	32.3	12.5	21.6	27.8	73	84
Neoseiulus californicus	5	++	26.5	4.7	4.4	7.7	34.8	43.7	23.4			70	79
Typhlodromalus rapax	1			5.0	5.4	5.8	6.0	12.0	19.4			78	62
Neoseiulus anonymus	4			4.7	5.1	5.2	14.5	34.4	27.7	39.1	12.0	73	58
Galendromus helveolus	5	+		7.4	7.0		18.7[d]	8.0[d]	23.0[d]	14.2	19.0	64	66
Galendromus annectens	6	++	17.8	5.7	6.1		22.4[d]	19.0[d]	31.0[d]	23.0	27.7	74	85
Euseius concordis	1			5.7	5.0		12.7[d]					75	70

RH, relative humidity; + = 75%; ++ = 60%; +++ = 40–50%.
[a]CIAT (1994).
[b]CIAT (1999).
[c]CIAT (1990).
[d]Cuéllar *et al.* (1996).

into Africa in the early 1970s, where it spread rapidly, causing considerable yield loss. It has been the object of a successful biological control programme (Herren and Neuenschwander, 1991). In the Americas, *P. manihoti* is confined to Paraguay, certain areas of Bolivia and Mato Grosso do Sul State of Brazil, causing no economic damage (Lohr and Varela, 1990).

P. herreni is distributed throughout northern South America and northeast Brazil, where high populations can cause considerable yield losses (Table 11.2). Damage caused by both species is similar: feeding by nymphs and adults causes leaf yellowing, curling and cabbage-like malformation of the growing points. High densities lead to leaf necrosis, defoliation, stem distortion and shoot death. Reductions in photosynthetic rate, transpiration and mesophyll efficiency – together with moderate increases in water pressure deficit, internal CO_2 and leaf temperature – were found in infested plants (CIAT, 1992).

P. manihoti is parthenogenic, whereas males are required for reproduction of *P. herreni*. *P. herreni* females deposit ovisacs containing several hundred eggs on the underside of the leaves, or around the apical bud. Eggs hatch in 6–8 days and there are four nymphal instars; the fourth instar is the adult stage. Males have four nymphal instars plus the adult stage. The third and fourth instars occur in a cocoon, from which the winged adult emerges. Adult males live only 2–4 days; the average life cycle of the female is 49.5 days, that of the male, 29.5. The optimal temperature for female development is 25–30°C (Herrera *et al.*, 1989).

P. herreni populations peak during the dry season. The onset of rains reduces pest populations and permits crop recovery. (Herrera *et al.*, 1989). Recent research shows that when the water supply is limited, the cassava leaves produce increased amounts of metabolites, which could favour mealybug growth and decrease parasitoid efficacy (CIAT, 1999; Polanía *et al.*, 1999; Calatayud *et al.*, 2002). These results could help explain the rapid mealybug population increases during the dry season.

Control

Considerable effort has been made to identify resistance to cassava mealybugs. Of > 3000 cultivars from the CIAT cassava germplasm bank screened for resistance to *P. herreni*, only low levels of resistance or tolerance were identified (Porter, 1988). Resistance studies at IITA in Africa and at ORSTOM have given similar results. Partial or low-to-weak levels of resistance have been reported in germplasm evaluations with *P. manihoti* (Le Ru and Calatayud, 1994; Neuenschwander, 1994a). It is suggested, however, that even low levels of plant resistance could enhance the impact of natural enemies in a biological control programme.

BIOLOGICAL CONTROL. Management of cassava mealybugs is a well-documented example of classical biological control, especially in Africa where *P. manihoti* is being controlled successfully through the introduction of the parasitoid *Apoanagyrus lopezi* from the Neotropics. Although *P. herreni* is distributed throughout northern South America, it causes serious yield losses only in northeast Brazil. Thus *P. herreni* may be an exotic pest in this region, probably coming from northern South America (Williams and Granara de Willink, 1992).

Approximately 70 species of parasites, predators and entomopathogens of *P. herreni* have been identified in the Neotropics. Many of these are generalist predators that feed upon numerous mealybug species. Nevertheless, several parasitoids show a specificity or preference for *P. herreni.* Parasitoids identified from northern South America include *Acerophagus coccois*, *Apoanagyrus diversicornis*, *Anagyrus putonophilu*, *Anagyrus insolitus*, *Apoanagyrus elegeri* and *Aenasius vexans*. The three encyrtid parasitoids (*Ap. diversicornis*, *Ac. coccois* and *Ae. vexans*) have been identified as effective parasitoids of *P. herreni* (Van Driesche *et al.*, 1988, 1990).

Ae. vexans and *Ap. diversicornis* display a marked preference for parasitizing *P. herreni*, although laboratory studies show they will also parasitize other mealybug species (Bellotti *et al.*, 1983a, 1994; Bertschy *et al.*, 1997). *Ac. coccois* showed equal preference for both *P. herreni* and *P. madeirensis*. All three parasitoids were attracted to *P. herreni* infestations (Bertschy *et al.*, 1997). Comparative studies on the life cycles of the three parasitoid species show that each would complete two cycles for each cycle of *P. herreni*, which is a favourable ratio for biological control.

Ap. diversicornis prefers third instar nymphs, whereas the much smaller *Ac. coccois* can parasitize male cocoons, adult females and second instar nymphs with equal frequency. Oviposition by *Ap. diversicornis* caused 13% mortality of first nymphal instars (Van Driesche *et al.*, 1990). *Ae. vexans* prefers second and third instar nymphs and adult females with equal frequency (CIAT, 1990). Field studies with natural populations of *Ap. diversicornis* and *Ac. coccois* determined percentage parasitism by using trap plants with mealybug hosts set out in cassava fields (Van Driesche *et al.*, 1988). *P. herreni* mortality was estimated at 55% for the combined action of the two parasitoids (Van Driesche *et al.*, 1990).

Through the combined efforts of CIAT and EMBRAPA, *Ap. diversicornis*, *Ac. coccois* and *Ae. vexans* were exported from CIAT and released in northeast Brazil, primarily in the states of Bahia and Pernambuco from 1994 to 1996. Prior to introduction, EMBRAPA scientists had conducted field surveys to measure damage and collect natural enemies. By the end of 1996, > 35,000 individuals of the three parasitoid species had been released. In Bahia *Ap. diversicornis* dispersed 130 km in 6 months, 234 km in 14 months and 304 km in 21 months after release. *Ac. coccois* also became established and was recovered in high numbers at ≤ 180 km from its release site 9 months later. *Ae. vexans*, although being consistently recaptured at its release site in Pernambuco, dispersed only 40 km in 5 months (Bellotti *et al.*, 1999; Bento *et al.*, 1999). Subsequently, personal observations indicate that mealybug populations have been reduced considerably and that cassava cultivation has returned to areas where it had been previously abandoned due to *P. herreni* outbreaks.

Whiteflies

Whiteflies cause major damage in cassava-based agroecosystems in the Americas, Africa and, to a lesser degree, in Asia as direct feeding pests and virus vectors. There is a large complex in the Neotropics, where 11 species are reported on cassava: *Al. socialis*, *Trialeurodes variabilis*, *Al. aepim*, *Bemisia tuberculata*, *Bemisia tabaci*, *Bemisia argentifolii*, *Trialeurodes abutiloneus*, *Aleurodicus dispersus*, *Paraleyrodes* sp., *Aleuronudus* sp. and *Tetraleurodes* sp. (Bellotti *et al.*, 1994, 1999; Castillo, 1996; França *et al.*, 1996). *A. socialis* is the predominant species in northern South America, where it causes considerable crop damage, but it is also found, to a lesser extent, in Brazil (Farias, 1994). *B. tuberculata* and *T. variabilis* are reported in low populations from Brazil, Colombia, Venezuela and several other countries (Farias, 1990a; Bellotti *et al.*, 1999). The spiralling whitefly *A. dispersus* is reported causing conspicuous damage on cassava in West Africa (Neuenschwander, 1994b; D'Almeida *et al.*, 1998); *Bemisia afer* occurs in Kenya (Munthali, 1992) and the Côte d'Ivoire and in other countries of sub-Saharan Africa (J. Legg, personal communication).

B. tabaci has a pantropical distribution, feeding on cassava throughout Africa and several countries in Asia including India (Lal and Pillai, 1981) and Malaysia. Before 1990, the *B. tabaci* biotypes found in the Americas did not feed on cassava. Whiteflies are known to transmit the viruses causing two diseases of cassava:

- cassava mosaic disease (CMD) in Africa, India and Sri Lanka, caused by geminiviruses that are transmitted by *B. tabaci* (Thresh *et al.*, 1998; see Chapter 11).
- *B. tuberculata* is the reported vector of cassava frog skin disease in the Neotropics (Angel *et al.*, 1990; see Chapter 11).

It has been speculated that the absence of CMD in the Americas may be related to the inability of its vector, *B. tabaci*, to colonize cassava. Since the early 1990s a new biotype (B) of *B. tabaci*, regarded by some as a separate species (*B. argentifolii*), has been found feeding on cassava in the Neotropics. It is considered that CMD now poses a more serious threat to cassava production given that most traditional cultivars in the Neotropics are highly susceptible to the disease. In addition the *B. tabaci* biotype complex is the vector of several viruses of crops often grown in association with or near cassava. The possibility of viruses moving between these crops or the appearance of new viruses presents a potential threat.

Whiteflies cause direct damage to cassava by feeding on the phloem of leaves, inducing leaf chlorosis and abscission, which results in

considerable reduction in root yield if feeding is prolonged. Yield losses of this type are common due to *Al. socialis* and *At. aepim*. There is a correlation between duration of whitefly attack and root yield loss (Table 11.2).

Research efforts in the Neotropics have concentrated on *Al. socialis* and *At. aepim*. Populations of both species are highest during the rainy season, but may occur throughout the crop cycle (Farias *et al.*, 1991; Gold *et al.*, 1991). *Al. socialis* females oviposit individual banana-shaped eggs on the undersides of apical leaves. Eggs hatch in *c.* 10 days and pass through three feeding nymphal instars and a pupal stage (fourth instar) before reaching the winged adult stage. During the third instar, the body colour changes from beige to black, surrounded by abundant waxy white cerosine. The black pupal stage makes this species easy to distinguish from other whitefly species feeding on cassava. Egg-to-adult development time of *Al. socialis* in the growth chamber (28 ± 1°C, 70% relative humidity (RH)) was 32 days (Arias, 1995).

Control

HPR and biological control agents are accepted increasingly as complementary pest-control tactics that reduce environmental contamination and other disadvantages that arise from the excessive use of chemical pesticides. Research on cassava whitefly control in the Neotropics initially emphasized activities in HPR and cultural practices. More recently, a concentrated effort is being made to identify and evaluate the use of natural enemies in an IPM context.

CULTURAL CONTROL. In traditional cropping systems, cassava is often intercropped, a practice that has been shown to reduce populations of many pests (Leihner, 1983). Intercropping cassava with cowpea reduced egg populations of *Al. socialis* and *T. variabilis*, compared to those in monoculture (Gold *et al.*, 1990). These effects were residual and persisted up to 6 months after harvest. Yield losses in cassava/maize, cassava monoculture and mixed cultivar systems were *c.* 60%; whereas in cassava/cowpea intercrops, yield losses were only 12% (Gold *et al.*, 1989a). Intercropping with maize did not reduce egg populations (Gold, 1993), indicating that this technique can depend on the intercropped species for success, thereby limiting its effectiveness and acceptance by farmers. However, it is a promising means of reducing pest populations for small-scale farmers.

HPR. Stable HPR offers a practical, low-cost, long-term solution for maintaining reduced whitefly populations. Whitefly resistance in agricultural crops is rare, although several good sources of resistance have been identified and high-yielding, whitefly-resistant cassava hybrids are being developed. HPR studies initiated at CIAT > 15 years ago are evaluating systematically the 6000 cultivars in the germplasm bank for whitefly resistance (CIAT, 1999), especially to *Al. socialis*. In Brazil some HPR research has been done with *At. aepim* (Farias, 1990a).

Several sources of resistance to *Al. socialis* have been identified. The clone M Ecu 72 has consistently expressed the highest level of resistance. Additional cultivars expressing moderate-to-high levels of resistance include M Ecu 64, M Per 335, M Per 415, M Per 317, M Per 216, M Per 221, M Per 265, M Per 266 and M Per 365. Based on these results, *Al. socialis* resistance appears to be concentrated in germplasm originating from Ecuador and Peru, but this phenomenon needs to be investigated further.

M Ecu 72 and M Bra 12 (an agronomically desirable clone with field tolerance to whiteflies) were used in a crossing programme to provide high-yielding, whitefly-resistant clones that showed no significant differences in yield between insecticide-treated and untreated plots (CIAT, 1992; Bellotti *et al.*, 1999). Greenhouse and field studies showed that *Al. socialis* feeding on resistant clones had less oviposition, longer development periods, reduced size and higher mortality than those feeding on susceptible ones. *Al. socialis* nymphal instars feeding on M Ecu 72 suffered 73% mortality, mostly in the early instars (CIAT, 1994; Arias, 1995; Fig. 11.1). The progeny (CG 489–34, CG 489–4, CG 489–31 and CG 489–23) selected from the M Ecu 72 × M Bra 12 cross have consistently displayed moderate levels of whitefly resistance. Three of these hybrids are currently being evaluated for release to producers in Colombia.

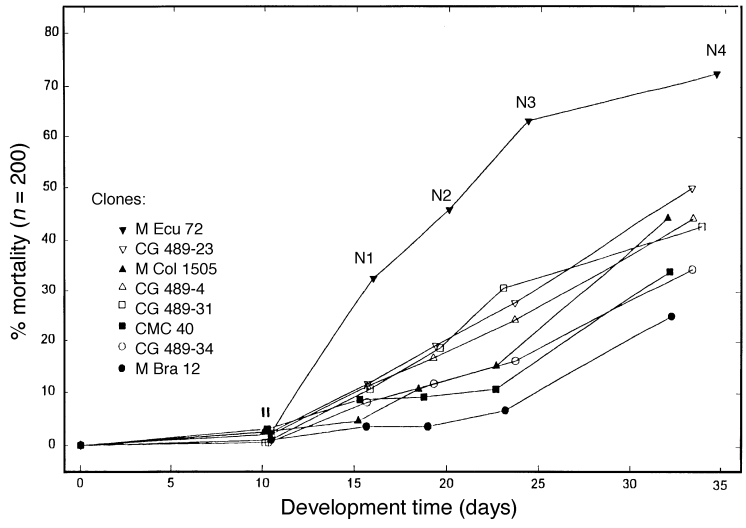

Fig. 11.1. Whitefly (*Aleurotrachelus socialis*) nymphal development and mortality on resistant and susceptible cassava clones. Source: Arias, 1995.

Resistance screening using natural *Al. socialis* populations is done in the field at two sites in Colombia:

- Nataima, Tolima, in cooperation with CORPOICA, the Colombian Agricultural Research Corporation. *Al. socialis* populations at Nataima have consistently been at moderate to high levels for nearly 15 years, offering the opportunity for sustained research over a long period.
- CIAT, Palmira, Valle del Cauca. Initially, *Al. socialis* populations at CIAT were low; however, since 1994, populations have increased dramatically and are presently higher than in Tolima. The reason for this sudden increase in *Al. socialis* populations is not understood, but is evidence of the dynamics of cassava pest eruptions, emphasizing the present and potential severity of whiteflies as cassava pests.

Research is also being done at CIAT to identify molecular markers linked to genes conferring resistance to *Al. socialis* in order to evaluate further and understand the genetics of whitefly resistance in cassava. Different breeding populations have been obtained from crosses between resistant (CG 489–34) and susceptible (M Col 2026) genotypes. Amplified fragment length polymorphism (AFLP) and simple sequence repeat (SSR) markers with bulk segregant analysis (BSA), are being used to locate markers linked with resistance for mapping and ultimately cloning the resistant genes. Co-segregating AFLP bands with resistance to *Al. socialis* have been identified and are being sequenced to generate sequence-characterized amplified region (SCARs) markers. The PCR-based marker will be the basis for the molecular mapping and used in breeding.

BIOLOGICAL CONTROL. Surveys in recent years in the Neotropics – especially in Colombia, Venezuela, Ecuador and Brazil – have identified a considerable number of natural enemies associated with the cassava whitefly complex. Gaps in knowledge about the natural enemy complex associated with the different whitefly species have limited their effectiveness in biological control programmes. Although a large complex of parasitoids has been identified, there is limited knowledge about levels of parasitism, parasitism rates for individual species, host specificity and their overall effect on regulating whitefly populations.

Since 1994, CIAT has carried out surveys in northern South America for natural enemies. The most representative group is the microhymenopteran parasitoids (Gold *et al.*, 1989c; Castillo, 1996; Evans and Castillo, 1998). In

Colombia, species richness – primarily from the genera *Encarsia*, *Eretmocerus* and *Amitus* – was most frequently associated with *Al. socialis*, *B. tuberculata* and *T. variabilis* (Castillo, 1996). More than ten species – several unrecorded – were collected. Three of the *Encarsia* spp. were identified as *Encarsia hispida*, *Encarsia pergandiella* and *Encarsia bellottii* (Evans and Castillo, 1998). None of the *Eretmocerus* and only one *Amitus* (*Amitus macgowni*) have been identified. The predominant species were *E. hispida*, *Amitus* sp. and *Eretmocerus* sp. The highest levels of parasitism observed for *Al. socialis*, *B. tuberculata* and *T. variabilis* were 15, 14 and 12%, respectively, although this varied according to geographic region (Castillo, 1996). Parasitism was higher in the Andean zone than in the coastal and eastern plains regions of Colombia. In surveys conducted between 1997 and 1999 in Colombia, *Encarsia* was the genus most frequently collected from the Andean highlands, while *Eretmocerus* predominated at lower altitudes on the Caribbean coast (CIAT, 1999). Moreover, the parasitoid species complex associated with each whitefly species can be influenced by geographic area. On the Caribbean coast, *Al. socialis* was most frequently parasitized by *Eretmocerus*, while in the Andean highlands it was *Encarsia*. In Valle del Cauca (1000 m altitude), 99.6% of the parasitism of *Al. socialis* was by *Encarsia* and 0.4% by *Eretmocerus*. The most numerous complex of parasitoids species was found associated with *B. tuberculata*.

Greenhouse studies with *E. hispida* parasitizing *Al. socialis* show that the third whitefly instar is preferred. Parasitism rates reached 75% in the third instar and 16, 45 and 43% in the first, second and fourth instars, respectively. The average parasitism rate was 45%, and peak parasitism occurred 72–96 h after exposure (CIAT, 1999). *E. hispida* is the most frequent parasitoid observed when there are high populations of *Al. socialis*, but its effectiveness in regulating the populations in the field is not known.

The influence of *Al. socialis*-resistant cassava cultivars on parasitoid behaviour has also been evaluated. Survival of *E. hispida* was not adversely affected by resistant genotypes. Parasitoid emergence was, however, considerably lower from pupae of *Al. socialis* that fed on the resistant cultivar M Ecu 72 than on the susceptible CMC 40 (CIAT, 1999).

Lepidoptera

Several species of Lepidoptera feed on cassava, including *E. ello* (L), *Erinnyis alope*, *Chilomima clarkei* (Amsel), *Chilozela bifilalis* (Hampson), *Phyctaenodes fibilialis*, *Agrotis ipsilon*, *Prodenia eridania* and *Phoenicoprocta sanguinea* (Bellotti and van Schoonhoven, 1978a,b; Bellotti *et al.*, 1999). The stemborer *Cm. clarkei* causes breakage of cassava stems. *A. ipsilon* and *Pr. eridania* attack recently planted stem cuttings, resulting in poor establishment; *Ph. sanguinea* is a leaf feeder. Yield reductions attributable to these last three species have not been documented. Attacks by *E. ello* and *Cm. clarkei* can reduce yields and are discussed in detail.

Cassava hornworms

E. ello (Sphingidae) is one of the most serious pests of cassava in the Neotropics (Bellotti *et al.*, 1992, 1999). It has a broad geographic range, extending from southern Brazil, Argentina and Paraguay to the Caribbean basin and the southern USA. The migratory flight capacity of *E. ello*, its broad climatic adaptation and wide host range probably account for its wide distribution and sporadic attacks (Janzen, 1987). Several other species of *Erinnyis* feed on cassava. The subspecies *E. ello ello* and *E. ello encantado* and the closely related species *E. alope* are all reported from the Neotropics.

Hornworm larvae feed on cassava leaves of all ages as well as on young, tender stems and leaf buds. Severe attacks cause complete plant defoliation, bulk root loss and poor root quality (Table 11.2). Although yield losses may be severe, complete defoliation due to hornworm attack, or even repeated attacks, do not kill cassava. The carbohydrates stored in the roots enable the plant to recover, especially under the more favourable conditions of the tropical rainy season. Repeated attacks are most common when ill-timed pesticide applications destroy natural enemies, but not fifth instar larvae or prepupae of the pest (Braun *et al.*, 1993). Moreover, large plantations of cassava are more prone to frequent and repeated hornworm attacks.

E. ello adults are grey nocturnal moths that oviposit small, round, light green-to-yellow eggs individually on the upper surface of cassava leaves. In field cage studies as many as 1850

eggs were laid per female. This high oviposition, combined with the migratory behaviour of adults, helps explain the rapid build-up of hornworm populations and their sporadic occurrence (Janzen, 1987; Bellotti *et al.*, 1992). During the larval period, each hornworm consumes *c.* 1100 cm^2 of leaf foliage; *c.* 75% of this during the fifth instar. At 15, 20, 25 and 30°C the mean duration of the larval stage is 105, 52, 29 and 23 days, respectively, indicating that peak hornworm activity may occur at lower altitudes (< 1200 m), or during the summer in the subtropics (Bellotti and Arias, 1988).

CONTROL. *E. ello*'s strong flight abilities and migratory flight capacity, combined with its broad climatic adaptation and wide host range (Janzen, 1986, 1987), often make effective control difficult to achieve. Pesticides give adequate control if hornworm populations are detected and treated while at the first three instar stages. However, farmers often react to attacks with excessive, ill-timed applications of pesticides, leading to repeated and more severe attacks (LaBerry, 1997). Larval populations in the fourth and fifth instar stages are not only difficult to control but also uneconomical, because considerable defoliation has already occurred. Pesticide use also disrupts natural enemy populations, leading to more frequent attacks (Urias López *et al.*, 1987).

An extensive complex of natural enemies is associated with *E. ello*. Nevertheless, their effectiveness is limited, most likely because of the migratory behaviour of the hornworm adults. Adults migrating *en masse* will oviposit a considerable number of eggs in cassava fields (up to 600 per plant), where natural enemy populations are too low to prevent an explosion of hornworm larvae, which can cause severe crop defoliation. Because their rate of reproduction is limited, predators and parasites cannot usually compensate sufficiently quickly to suppress dramatic hornworm eruptions (Bellotti *et al.*, 1992).

Approximately 35 species of parasites, predators and pathogens of the egg, larval and pupal stages have been recorded and reviewed extensively (Bellotti and van Schoonhoven, 1978a,b; Schmitt, 1983; Farias, 1990b; Bellotti *et al.*, 1992, 1999). Eight microhymenopteran species of the families Trichogrammatidae, Scelionidae and Encyrtidae are egg parasites, of which *Trichogramma* and *Telenomus* are the most important. Tachinid flies are the most important group among the dipteran larvae parasitoids; the Braconidae, particularly *Cotesia* spp., are the most important hymenopteran (Bellotti *et al.*, 1992, 1994). The commonest egg predators are *Chrysopa* spp. Important larval predators include *Polistes* spp. (Hymenoptera: Vespidae), *Podisus* spp. (Hemiptera: Pentatomidae) and several spider species (Bellotti *et al.*, 1992). Important entomopathogens include *Cordyceps* sp. (Aconycetes: Clavicipitaceae), a soil-borne fungus that invades hornworm pupae, causing mortality. More recently, isolates of *Beauveria* sp. and *Metarhizium* sp. were found to cause high larval mortality in laboratory studies (Múnera *et al.*, 1999).

The key to the effective use of biological control agents is the ability to synchronize the release of large numbers of predators or parasites during the early stages, preferably the egg or the first to third larval instars. Predator and parasite effectiveness is limited by poor functional response during hornworm outbreaks, which are of short duration (15 days). Successful control, therefore, requires monitoring of field populations to detect immigrant adults or larvae in the early instars. This can be done with black lights (Type T20T12BLT), which trap flying adults, or by scouting for the presence of eggs or larvae (Braun *et al.*, 1993). The complexities of synchronizing inundative releases of parasites and predators with peak pest populations, suggests the need for a cheap, storable biological pesticide.

A granulosis virus species of the family *Baculoviridae* was found attacking *E. ello* in cassava fields at CIAT in the early 1970s. Pathogenicity studies in the laboratory and field resulted in nearly 100% mortality of hornworm larvae (Bellotti *et al.*, 1992; Braun *et al.*, 1993; Table 11.3). Infested larvae are collected from the field, macerated in a blender, filtered through cheesecloth, mixed with water and applied to hornworm-infested fields. Studies on the effect of virus concentration on mortality of larval instars showed a sigmoidal relationship for the first, second and fourth instars. LC_{50} studies indicate that progressively higher concentrations are needed for adequate control of each succeeding larval instar. Most fifth instar larvae reached the prepupal state, but few female adults emerged and those that did had wing deformities

and died without producing progeny (Bellotti *et al.*, 1992).

The hornworm baculovirus can be managed by cassava growers themselves. They can collect and macerate diseased larvae and apply the virus suspension to their fields. The virus can be stored at low cost by refrigeration and wettable powder formulations of the virus are being developed. Hornworm management with the virus was first implemented in southern Brazil, where light traps were used to detect adult movement and invasions. Virus applications, made when populations were in their early instars, resulted in almost complete control (Schmitt, 1988) and pesticide applications were reduced by 60%.

The hornworm virus is an especially attractive option for use on large cassava plantations, where pesticide applications have proved ineffective. In Venezuela, where the hornworm is endemic, the virus preparation was applied (70 ml ha^{-1}) to 7000 ha via overhead sprinkler irrigation systems when larvae were in the first and second instars, resulting in 100% control. The virus has replaced pesticides and the cost of gathering, processing, storing and applying it is only US$4 ha^{-1} (LaBerry, 1997).

Stemborers

A complex of arthropod stemborers, which includes both coleopteran and lepidopteran species, feed on and damage cassava. Long-horned beetles (*Lagochirus* spp.) are distributed worldwide, but do not appear to cause yield losses. Stemborers are most important in the Neotropics, especially in Colombia, Venezuela and Brazil. Seven species of *Coelosternus* (Coleoptera: Curculionidae) are reported reducing cassava yields and quality of planting material in Brazil. However, the damage is generally sporadic or localized and does not significantly reduce yield (Bellotti and van Schoonhoven, 1978a,b).

Populations of the stemborer *C. clarkei* (Lepidoptera: Pyralidae) have increased dramatically in Colombia and Venezuela in recent years and the species is now a major pest of cassava (Vides *et al.*, 1996). The nocturnal adult females oviposit in cassava stems, usually around the bud or node. The egg stage is ~6 days (28°C). Upon hatching, first instar larvae feed on the outer bark or stem epidermis. They are very mobile and search for an appropriate feeding site, generally around axillary buds. They form a protective web, under which the first four instars feed, enlarging the web with each instar. In the fifth instar the larvae penetrate the stem, where they complete their cycle (6–12 instars), pupate and emerge as winged adults (Lohr, 1983). The larval stage lasts 32–64 days; the pupal stage within the stem is 12–17 days. Female adults live 5–6 days (males 4–5 days), each ovipositing an average of 229 eggs.

Ch. clarkei populations occur throughout the year but are highest during the rainy season. From 4–6 overlapping cycles can occur during the 1-year crop cycle, increasing potential damage and making control more difficult. Extensive tunnelling by the larvae (> 20 can be found in one stem) cause stem breakage, leading to stem rot and a reduction in the quality and quantity of planting material (Table 11.3). Field studies show that when > 35% of the plants suffer stem breakage, significant yield loss can occur (45–62%) (Lohr, 1983). On the Colombia Caribbean coast, 85% of the cassava fields had *Ch. clarkei* damage (Vides *et al.*, 1996).

CONTROL. Once larvae enter the stem, control is very difficult. Moreover the web that covers the early larval instars offers protection from both natural enemies and pesticide applications. The highly mobile early-instar larvae are more vulnerable and can be controlled by *Bacillus thuringiensis* [Bt]. Given the overlapping generations, however, several applications would be necessary and they would be too costly for producers to adopt. Field research by Gold *et al.* (1990) showed that intercropping with maize reduced stemborer populations until the intercrop was harvested.

Several natural enemies have been identified, including the hymenopteran parasitoids *Bracon* sp., *Apanteles* sp. and *Brachymeria* sp. (Lohr, 1983). More recently emphasis has been placed on identifying resistant cassava germplasm. Approximately 1000 clones have been evaluated on the Colombia Caribbean coast, where *Ch. clarkei* populations are high. Evaluations are based on the number of *Ch. clarkei* holes and tunnels in the stems and percentage stem breakage. A number of clones with only 0–1 hole per stem have been identified, indicating varietal influence (CIAT, 1999). Nevertheless,

field evaluations of germplasm using natural populations of a highly mobile pest can often give misleading results due to 'escapes' (plants that have avoided damage by chance). Thus these cultivars will need to be evaluated over several cycles.

CIAT has initiated research based on introducing insect-resistant Bt genes through *Agrobacterium*-mediated transformation into cassava embryonic tissue to develop *Ch. clarkei*-resistant cultivars. Initial results are promising (CIAT, 1999).

Cassava burrower bug: C. bergi

C. bergi is one of the few arthropod pests that feed directly on the tuberous roots of cassava, but this polyphagous species has not co-evolved with cassava. It was first recorded as a cassava pest in Colombia in 1980 (García and Bellotti, 1980) and more recently it has been reported causing commercial losses in Panama, Costa Rica and Venezuela (Riis, 1997). *C. bergi* is probably present in many other areas of the Neotropics, but feeding on other hosts including onion, groundnut, maize, potato, *Arachis pintoi* (forage groundnut), sorghum, sugarcane, coffee, coriander, asparagus, beans, pea, pastures and numerous weeds (Riis, 1997; Bellotti *et al.*, 1999).

Some hosts are strongly preferred over others. Laboratory experiments indicate that cassava is not the optimal host. *C. bergi* develops faster on maize and groundnut than on cassava and prefers maize to cassava (78 versus 22%) in free-choice feeding tests. The LD_{50} for adults was 95 days on maize, 69 on onion and 66 and 64 days, respectively, on sweet (CMC 40) and bitter (M Col 1684) cassava (Riis, 1990). Optimal fecundity, survival and intrinsic rate of population increase occurred on groundnut and peanut, not on maize. Sweet cassava, sorghum and onions were not favourable hosts and *C. bergi* could not complete its life cycle on bitter cassava (Riis, 1997).

C. bergi nymphs and adults feed on cassava roots by penetrating the peel and parenchyma with a thin strong stylet. This feeding action can introduce several soil-borne pathogens (e.g. *Aspergillus*, *Diplodia*, *Fusarium*, *Genicularia*, *Phytophthora* and *Pythium* spp.) into the root parenchyma (Bellotti and Riis, 1994). Brown-to-black lesions begin to develop on the roots within 24 h after feeding is initiated, resulting in starch reduction and a serious loss in commercial value (Table 11.2). As damage is not detected until roots are harvested and peeled, producers can lose the value of the crop and also labour, time and land use.

C. bergi has five nymphal instars; nymphs and adults can live for more than 1 year feeding on cassava roots (García and Bellotti, 1980). *C. bergi* had a lifespan of 286–523 days when fed on slices of low-HCN cassava roots in the laboratory (23°C, 65 ± 5% RH). Egg eclosion averaged 13.5 days; mean development time of the five nymphal stages was 111 days; mean longevity for adults was 293 days.

C. bergi populations occur in the soil throughout the crop cycle and root damage starts in the first month of plant growth. Feeding can continue throughout the crop cycle and can result in 70–80% total root damage and > 50% reduction in total starch content. *C. bergi* can cause serious economic damage, even if populations are not high (Arias and Bellotti, 1985). Riis (1990) showed that even when populations were very low (~0), 22% of the roots were damaged. The economic injury threshold – the point where cassava root purchasers will reject a consignment – is when 20–30% of the roots are damaged, given that the 'cosmetic' damage of rot spots is not acceptable for the fresh food market.

C. bergi is strongly attracted to moist soil; it will migrate when soil moisture content is below 22% and is most persistent when it exceeds 31%. The rainy season greatly favours adult and nymphal survival, behaviour and dispersal; whereas low soil water content during the dry season restricts adult burrowing and migration and increases nymphal mortality (Riis, 1997).

Field trials and laboratory studies strongly suggest that feeding preferences of *C. bergi* may be related to the levels of cyanogenic glucosides in cassava roots. Adults and nymphs that fed on a high-HCN (> 100 mg kg^{-1} HCN) cultivar had longer nymphal development, reduced egg production and increased mortality. Oviposition on CMC 40 (43 mg kg^{-1} HCN) was 51 eggs per female versus only 1.3 on M Col 1684 (627 mg HCN equivalent kg^{-1}). Adult longevity on CMC 40 (235 days) was more than twice that on M Col 1684 (112 days; Bellotti and Riis, 1994). Riis (1997) showed that oviposition on clones with a

cyanogenic potential (CNP) of < 45 p.p.m. (fresh weight) was significantly higher than on clones with a CNP > 150 p.p.m., while oviposition varied considerably on clones with CNPs between 45–150 p.p.m. Additional studies indicate that the earliest instars are most susceptible to root CNP. Due to the short length of the stylet, feeding during the first two nymphal instars is confined mainly to the root peel (Riis, 1990; Riis *et al.*, 1995), whereas third to fifth instars can feed on the root parenchyma. CMC 40 has a low cyanogen level in the root parenchyma, but a high level in the root peel (707 mg kg^{-1} HCN). Laboratory feeding experiments resulted in 56% mortality of first and second instar nymphs feeding on CMC 40 and 82% for those feeding on M Col 1684. The high cyanogen level in the peel of CMC 40 is probably responsible for the high mortality rate (Bellotti and Riis, 1994).

Feeding preference studies carried out in cassava fields in Colombia resulted in considerably more damage to CMC 40 (the low-HCN clone) than to M Col 1684. M Mex 59, with an intermediate cyanogen content (106 mg kg^{-1} HCN) suffered moderate damage. These data indicate that CNP may act as a feeding deterrent and the *C. bergi* damage should not be a problem where cassava clones with high CNP are cultivated (i.e. northeast Brazil and many parts of Africa; Bellotti and Riis, 1994).

CONTROL. Control of *C. bergi* is difficult due to the polyphagous nature of the pest and its adaptation to the soil environment. Measures should be taken early in the crop growth cycle, either during planting or within the first 2 months, given the fact that initial damage can occur during this period. Pesticide applications can reduce pest populations and damage. However, frequent applications may be required, and these are costly, environmentally hazardous, and often fail to reduce damage below economic injury levels (Castaño *et al.*, 1985). Intercropping cassava with *Crotalaria* sp. (sunn hemp) reduced root damage to ~4% compared to 61% damage in cassava monoculture (Table 11.3). However, cassava yields were reduced by 22% when intercropped and as *Crotalaria* has little commercial value, producers are reluctant to adopt this technology.

Experimental data and field observations show that high CNP cultivars are resistant to *C. bergi* feeding and damage. However, in many cassava-producing regions, low CNP or 'sweet' cultivars are preferred, especially for fresh consumption. Recent studies indicate a potential resistance/tolerance to *C. bergi* in 15 low-CNP cultivars (Riis, 1997). The potential employment of this resistance justifies research on pest behaviour, resistance mechanisms, biochemistry and genetics.

The potential for biological control of *C. bergi* is being investigated and recent studies with entomopathogenic nematodes and fungi indicate a possible solution. This research, however, has been done only in the laboratory/greenhouse and field studies are required before acceptable technologies can be recommended.

The nematode *Steinernema carpocapsae* successfully parasitized *C. bergi* in the laboratory, infecting it 5–8 days after exposure. The adult was most sensitive to infection (59% parasitism after 10 days); the least sensitive were the first and second instars, with 17 and 31%, respectively (Caicedo and Bellotti, 1994). A native species, *Heterorhabditis bacteriophora*, found parasitizing *C. bergi* in the field in Colombia, resulted in 84% parasitism of the instars (Barberena and Bellotti, 1998). Isolates of the entomopathogenic fungus *Metarhizium anisoplae* have been recovered parasitizing *C. bergi* in the field. In laboratory studies mortality was highest (61%) during the fifth instar, overall average mortality was 33% (CIAT, 1994).

Cassava lacebugs

Lacebugs (Hemiptera: Tingidae) are neotropical cassava pests. Froeschner (1993) identified five *Vatiga* species that show a decided preference for cassava: *Vatiga illudens*, *Vatiga manihotae*, *Vatiga pauxilla*, *Vatiga varianta* and *Vatiga cassiae*. The first two are the most widely distributed. *V. illudens* predominates in Brazil, but also occurs throughout the Caribbean area. *V. manihotae* predominates in Colombia and Venezuela, but is also reported from Cuba, Trinidad, Peru, Ecuador, Paraguay, Argentina and Brazil. *V. varianta* is reported from Brazil and Colombia, *V. cassiae* from Brazil, and *V. pauxilla* from Argentina. Moreover, *A. machalana*, referred to as the black lacebug, damages cassava in Colombia, Venezuela and Ecuador (CIAT, 1990).

A prolonged dry period is favourable for increasing lacebug populations (Salick, 1983). Adults and nymphs feed on the undersurface of lower leaves. Initially, white feeding spots appear, increasing in number and area until the leaf centres turn white and eventually darken. High lacebug populations will cause leaves to curl and die. Younger plants (4–5 months old) attract higher populations, which tend to decline on older plants (Salick, 1983).

The relationship between damage, population density and duration is unknown. A field trial at CIAT with natural populations of *A. machalana* resulted in 39% yield reduction compared with pesticide-treated plots (CIAT, 1990).

Field observations in Colombia indicate a shift in populations of lacebug species. In CIAT cassava fields *V. manihotae* predominated until the mid-1980s. By 1990, *A. machalana* populations were considerably higher than *V. manihotae* and remained so for several years. Currently, *V. manihotae* is again the predominant species and it is difficult to find *A. machalana* in Colombian cassava fields (B. Arias, personal observation). The cause of this shift in populations is not understood. In Ecuador populations of *A. machalana* remain high.

Lacebugs are the least studied of the important cassava pests. Populations of *V. illudens* in Brazil are endemic and appear to be causing yield losses, especially in the central Campo Cerrado region and more recently in the south. Nevertheless, a sustained research effort has not been attempted in order to understand fully the dynamics of lacebug populations, yield losses and control. Considering the present and potential importance of lacebugs, there is a dearth of published information.

BIOLOGY. The egg stage of *V. manihotae* is 8–15 days, followed by five nymphal stages averaging 16–17 days. Adult longevity under field conditions averages 40 days (Borrero and Bellotti, 1983). Laboratory studies with *V. illudens* in Brazil show a nymphal duration of 13.5 days and an average adult longevity of 27 days (Farias, 1987). In laboratory studies with *A. machalana*, the egg stage averaged 8.2 days, the five nymphal instars 14 days and adult longevity was 18 and 22 days for females and males, respectively (CIAT, 1990).

CONTROL. Lacebug control appears to be difficult as few natural enemies have been observed (Borrero and Bellotti, 1983; Salick, 1983; Farias, 1985). Preliminary screening of cassava germplasm indicates that HPR may be available (CIAT, 1990; Calvacante and Ciociola, 1993), but considerable research is still required before implementation is possible.

Secondary pests

The cassava arthropod pest complex includes numerous species that feed on cassava but they do not generally cause major economic damage to the crop. These 'occasional' or 'incidental' pests either occur sporadically or at such low population levels that yield is unaffected. Outbreaks may occur in localized areas, and populations may increase to the point where they cause yield reductions. Moreover, changes in agronomic practices or varietal selection could influence pest populations, causing more crop damage (Table 11.5).

The thrips *F. williamsi* can reduce crop yields of cassava by 5–28%, depending on varietal susceptibility (Bellotti and van Schoonhoven, 1978a,b), especially in the seasonally dry tropics having a dry season of at least 3 months. *F. williamsi* can be controlled easily by using the resistant pubescent cultivars that are readily available and commonly grown in these areas (van Schoonhoven, 1974). If non-pubescent cultivars are introduced, thrips populations and damage increases, resulting in yield losses.

The fruitflies *A. pickeli* and *A. manihoti* normally attack cassava fruit. This is a problem for plant breeders, but of no concern to producers. In certain areas during the rainy season, however, females will oviposit in the tender upper portion of the cassava stem. The larvae tunnel into the stem, providing an entrance for soft rot bacteria such as *Erwinia carotovora*. The bacteria can cause severe rotting of the stem tissue, resulting in apical dieback. Yield losses due to this damage have not been reported, although there is a reduction in the quality of planting material, which may result in decreased establishment and yield in the subsequent crop cycle (Bellotti and van Schoonhoven, 1978a,b).

Shootfly (*N. perezi*) damage to the growing points of cassava breaks apical dominance,

Table 11.5 Occasional and incidental pests of cassava.

Common name	Important species	Region	Type of damage	Reported yield loss	Control strategy	References
Scales	*Aonidomytilus albus*, *Saissetia miranda*	Americas, Africa, Asia	Attack stems causing leaf fall; use of infested stems reduces establishment	< 20% fresh root yields; 50–60% loss in stem cutting	Destroy infested stems; use scale-free planting material	Bellotti and van Schoonhoven (1978a,b); Frison and Feliu (1991); Lozano *et al.* (1981); Bellotti and Peña (1978); Bellotti and van Schoonhoven (1978a,b); Lozano *et al.* (1981)
Fruitflies	*Anastrepha pickeli*, *Anastrepha manihoti*	Americas, Costa Rica, Panama, Venezuela, Colombia, Brazil, Peru	Bore fruit (seed) and stems, causing rotting of pith area	0–30% when infested stems used as planting material	Use of damage-free planting material	
Shootflies	*Neosilba perezi*	Americas	Larvae kill apical buds, retarding plant growth, inducing lateral branching	Not reported; reduced quality of planting material	None required	Bellotti and van Schoonhoven (1978a,b); Cock (1978); Lozano *et al.* (1981); Peña and Waddill (1982)
Gallmidges	*Jatrophobia* (*Eudiplosis*) *brasiliensis*	Americas	Yellowish green to red galls on upper leaf surface	Not reported	None required	Bellotti and van Schoonhoven (1978a,b); Lozano *et al.* (1981); Samways (1980)
White grubs	*Leucopholis rorida*, *Phyllophaga* spp., several others	All regions	Feed on planting material, roots	95% loss in germination	Soil pesticide treatment at planting	Bellotti and van Schoonhoven (1978a,b); Lal and Pillai (1981); Peña and Waddill (1982)
Termites	*Coptotermes voltkevi*, *Coptotermes paradoxis*	All regions	Tunnel in planting material, roots, stems, swollen roots	46–100% loss of planting material	Dusting of planting material with pesticide	Bellotti and van Schoonhoven (1978a,b); Lal and Pillai (1981); Lozano *et al.* (1981)
Stemborers	*Coelosternus* spp.	Americas, Brazil	Tunnel stems, stem breakage	Unknown	Cultural practices to maintain clean fields; destroy infested stems	Bellotti and van Schoonhoven (1978a,b); Lozano *et al.* (1986); Samways (1980)
	Lagochirus sp.	All regions	Tunnel stems, stem breakage	Unknown		Villegas and Bellotti (1985)
Leaf-cutting ants	*Atta* spp., *Acromyrmex* spp.	Americas	Foliage removed	Unknown	Toxic baits	Bellotti and van Schoonhoven (1978a,b); Diehl-Fleig *et al.* (1988); Samways (1980)
Grasshoppers	*Zonocerus elegans*, *Zonocerus variegatus*	Mainly Africa, occasionally Americas	Defoliation, stripping of bark	Unknown	Entomopathogens being investigated	Bellotti and Riis (1994); Bellotti and van Schoonhoven (1978a,b); Lomer *et al.* (1990); Modder (1994)
Thrips	*Frankliniella williamsi*	Americas, Africa	Leaf distortion, bud reduction	17–25%	Host plant resistance	Bellotti and Kawano (1980); Bellotti and van Schoonhoven (1978a,b); van Schoonhoven (1974)

retards plant growth and causes excessive branching. When younger plants are attacked, there is a reduction in the growth of the stems used as planting material, but seldom in yield. If plants are being grown for quality cutting production, then the crop needs to be protected only during the first 3 months of growth. Usually one timely pesticide application suffices to protect the crop.

Mealybugs feeding on and damaging cassava roots have been reported in recent years from two continents. In South America, *P. mandio* has been reported from southern Brazil, Paraguay and Bolivia (Williams, 1985; Pegoraro and Bellotti, 1994), and *Stictococcus vayssierei* is reported from the Cameroon, Africa (Ngeve, 1995). Mealybug feeding can result in reduced quality of tuberous roots and some plant defoliation. *P. mandio* females have three nymphal instars and adults oviposit an average of 300 eggs, accounting for rapid population build-ups. The life cycle from oviposition to adult was 25 days for females and 30 for males (Pegoraro and Bellotti, 1994). Yield losses of 17% have been reported; control through crop rotation is suggested.

Severe attacks of white grubs (Scarabaeidae) and termites can destroy the cuttings used to establish new plantations (Bellotti and van Schoonhoven, 1978a,b). Populations of scale insects, normally under natural biological control, can occasionally increase rapidly, especially if infested stakes are planted, causing yield losses and reduced availability of stems for use as planting material. Leaf-cutting ants can defoliate part or all of small plantations, possibly reducing yields.

Grasshopper (*Zonocerus elegans*, *Zonocerus variegatus*) attacks in Africa are reported as causing severe crop damage, but reliable data on actual root yield loss are scarce. Several countries including Nigeria, Congo, Benin, Uganda, Côte d'Ivoire and Ghana report thousands of hectares of cassava defoliated in some years, probably causing yield reductions (Modder, 1994). Simulated damage studies indicate a reduction in root yield (Toye, 1982) and in Nigeria, > 50% of the cassava crop is estimated to be lost in years of high grasshopper populations (Modder, 1994).

In Nigeria grasshopper oviposition usually occurs at the onset of the wet season and eggs hatch 6–7 months later, at the start of the dry season. This population will attack cassava toward the latter part of the dry season when preferred herbaceous food plants become scarce (Modder, 1994). Experiments show that grasshoppers are deterred from feeding on cassava by the production of large amounts of HCN. The early instars (I-IV) will not consume growing cassava and instars V and VI will eat growing cassava only if they have been deprived of food for a considerable period. Wilted cassava leaves are readily eaten by all stages and result in high grasshopper growth rate and high oviposition (Bernays *et al.*, 1977; Bellotti and Riis, 1994).

Chemical control of grasshoppers has been attempted in Africa. Although feasible, it does not appear to be financially or ecologically sustainable, and in the mid-to-long term is not effective (Modder, 1994).

Biological control using entomopathogens offers a more practical, safer and effective long-term solution for grasshopper control. The entomopathogens *Metarhizium flavoviride*, *Beauveria bassiana* and *Entomophaga grylli* have been identified infecting *Z. variegatus*. Currently, a considerable effort is being made to develop effective biopesticides and application technologies for grasshopper control. Results to date are encouraging, especially with *M. flavoviride* (Lomer *et al.*, 1990; Modder, 1994; Langewald *et al.*, 1997).

Trends in Pest Management

A successful integrated pest management (IPM) programme in cassava will depend on having effective, environmentally sound, low-cost pest management technologies available to cassava farmers in developing countries. Currently available biotechnology tools offer the potential to develop improved pest-resistant cultivars and to enhance the effectiveness of natural control organisms, including parasitoids and entomopathogens. The new generation of genetic pest management technologies presently being integrated with traditional IPM offers alternative technologies for controlling stemborers, leaf-cutting ants, grasshoppers, white grubs and other pests that are difficult to control. Research activities in these areas are already under way and recommendations should soon be available to farmers.

Pesticides

Pesticide use in traditional cassava agroecosystems is minimal due to their prohibitive costs and the long crop cycle of cassava, which may necessitate several applications. Farmers in the Neotropics, however, may respond to pest outbreaks with pesticides. As cassava production shifts to larger plantations, there may be a greater tendency to apply pesticides to control outbreaks, as already occurring in certain areas of Colombia, Venezuela and Brazil (Bellotti *et al.*, 1990).

There is considerable potential for the use of biopesticides to replace chemical pesticides in cassava pest management. The effectiveness of the hornworm baculovirus and its successful implementation, especially on large plantations (LaBerry, 1997), exemplifies this possible trend. Entomopathogens have been identified for mites, mealybugs, whiteflies, hornworms, burrower bugs, white grubs, grasshoppers and others. Further research is required to develop biopesticides and methodologies for their effective implementation. This will probably require a link to and collaboration with the biopesticide industry. This has been initiated already in Colombia.

Cultural practices

Traditional farmers in most cassava-growing regions have relied on an array of cultural practices that have often been effective in reducing pest populations (Lozano and Bellotti, 1985). Intercropping, as commonly practised by small farmers, has been shown to reduce populations and damage of whiteflies, hornworm and burrower bugs (Castaño *et al.*, 1985; Gold *et al.*, 1989b, 1990). Farmers may, however, be reluctant to adopt this practice if the intercrop species has little or no commercial value, or if cassava yields are reduced considerably (see 'cassava burrower bug'). On larger plantations where mechanization is a standard practice, there may be a reluctance to adopt intercropping. Additional cultural practices that can reduce pest populations include use of varietal mixtures, destruction (burning) of plant debris, crop rotation, changed planting dates and high-quality, pest-free planting material (Lozano and Bellotti, 1985).

Biological control

Classical biological control has been highly successful in Africa against introduced pests. Management of many cassava pests in the Neotropics will require greater farmer involvement for the effective implementation of solutions (Bellotti *et al.*, 1999). Numerous surveys of cassava fields in various regions of the Neotropics have revealed a species-rich complex of natural enemies of important cassava pests (see sections on individual pests). CIAT maintains a taxonomic and working collection, with an accompanying computerized database, for cassava pests and their natural enemies. This information is available to producers and staff of national agricultural research and extension programmes, taxonomists and museums (Hernández *et al.*, 1995).

Results from explorations and surveys indicate that considerable natural biological control may be occurring in the Neotropics. This is to be expected because in many cropping systems, cassava is grown as a functional perennial and certain pests and associated natural enemies may be in equilibrium. A disruption of this system by, for example, the use of pesticides could cause pest outbreaks. As previously described, the CGM populations in northern South America appear to be regulated by a complex of phytoseiid predators, which, if disturbed, results in reduced yields (Braun *et al.*, 1989). The potential for enhancing the effectiveness or virulence of natural enemies through genetic engineering offers further exploitation of this rich complex.

Host plant resistance

CIAT's germplasm bank of more than 6000 landrace cassava cultivars offers entomologists and breeders a potential pool of pest-resistance genes. As previously described, differing levels of resistance have been identified for mites, whiteflies, thrips, burrower bugs, lacebugs and stemborers. The novel biotechnology tools now available facilitate access to resistance genes and more efficient, quicker manipulation at the molecular level. A considerable portion of this germplasm bank is grown continually in the field and is available for systematic evaluation for pest resistance. Techniques and

methodologies are now available for mass rearing of most major cassava pests and damage and population scales have been described to identify resistant and susceptible germplasm. Accurate germplasm evaluation needs to be done in the field using natural or artificial infestations. Damage symptoms of most cassava pests are not expressed accurately on plants grown in the greenhouse or screen house, resulting in the misidentification of resistance.

Cultivars that possess multiple resistance (i.e. to more than one pest) have also been identified. For example, M Ecu 72 has high levels of resistance to whiteflies and thrips, and moderate levels to mites. One of the challenges confronting geneticists and plant breeders will be to include both disease and arthropod pest resistance in the same cultivar.

Perhaps the greatest source of pest resistance is contained in wild *Manihot* species. More than 100 of these species have been identified (Allem, 1994) and small collections exist at several locations including CIAT, EMBRAPA/Brazil and IITA. The cassava molecular genetic map has been developed (Fregene *et al.*, 1997), and this should provide a useful tool for developing transgenic cassava plants (using other *Manihot* species) having pest resistance.

Cassava IPM projects are few and the decision-making guides and strategies required for appropriate implementation of control options are seldom available to small farmers in traditional production systems (Bellotti *et al.*, 1999). It is felt strongly that for large cassava plantation systems to succeed – especially in the Neotropics where there is a large complex of arthropod pests and diseases – the implementation of an effective IPM system based on biological control and varietal resistance is critical for sustaining high yields. A promising approach to overcome the slow technology diffusion inherent with cassava producers is through the use of farmer participatory methods and the inclusion of the private sector in setting the research agenda and objectives. The successful implementation of an integrated crop and pest management pilot project with traditional farmers in northeast Brazil (Bellotti *et al.*, 1999; Ospina *et al.*, 1999) provides an example of how this can be accomplished.

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