

# Cassava Production and Pest Management: Present and Potential Threats in a Changing Environment

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**Abstract** Cassava is attacked by a complex of arthropod pests across the tropical regions of the world where the crop is grown. Root yield losses have been recorded for several pests, including mites, mealybugs, whiteflies, hornworm, lacebugs, thrips and burrower bugs. Agronomic characteristics such as vegetative propagation, a long growth cycle, drought tolerance, staggered planting dates and intercropping contribute to the considerable diversity of pests that feed on the crop. The dynamics of cassava production are evolving as trends in the food, feed and industrial starch sector are leading to an increased demand for high quality starches. The resulting shift to larger scale production units, expansion of cultivated area and modifications in crop management combined with the effects of climate change, especially warmer temperatures and altered rainfall patterns, affect the occurrence and dynamics of arthropod pests in cassava agro ecosystems. Data is presented to describe the effects of temperature and dry seasons on key pest species. Whiteflies, mites and mealybugs register a suitability increase in the same areas in South America: Northeastern Brazil, Northern Argentina, South-Central Bolivia, and Southwest Peru. In Africa increases are projected in Southeast Africa and Madagascar. In Asia, regions with greater projected suitability for these pest species are Coastal India and Southeast Asia. Future trends and important criteria that will influence the severity and management of key pests are discussed.

**Keywords** Cassava arthropod pests · Mites · Mealybugs · Whiteflies · Hornworms · Climate change · Bioecology · Pest management · Pest distribution · Weighted overlay

## Abbreviations

BCCR-	Bjerknes Centre for Climate
BCM	Research-Bergen Climate Model
CBSD	Cassava Brown Streak Disease
CCCMA-	Canadian Centre for Climate Modelling and
CGSM	Analysis
CGM	Cassava Green Mites
CIAT	International Center for Tropical Agriculture
CMD	Cassava Mosaic Disease
CNFM	<i>Centro Nacional de Pesquisa de Mandioca e</i> <i>Fruticultura</i> (National Cassava & Fruits Research Center)
CNRM	Centre National de Recherches Météorologiques
CORPOICA	Colombian Corporation for Agricultural Research
CSIRO	Commonwealth Scientific and Industrial Research Organisation
EMBRAPA	<i>Empresa Brasileira de Pesquisa Agropecuária</i> (Brazilian Agricultural Research Corporation)
GFDL	Geophysical Fluid Dynamics Laboratory
GISS	Goddard Institute for Space Studies (NASA)
HPR	Host Plant Resistance
IAP-	Institute of Atmospheric Physics
FGOALS	
IIBC	International Institute of Biological Control
IITA	International Institute for Tropical Agriculture
IPM	Integrated Pest Management

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MADR	Ministry of Agricultural and Rural Development
MIROC	Model for Interdisciplinary Research on Climate
MIUB-ECHO-G	Meteorological Institute of the University of Bonn
MPI	Max Planck Institute for Meteorology
MRI	Meteorological Research Institute
NCAR-PCM	National Center for Atmospheric Research-Parallel Climate Model
NIES	National Institute for Environmental Studies

## Introduction

Agricultural research systems both internationally and nationally in key cassava-producing countries have focused on cassava pests over the last half century, and with good reason. Cassava is important for food security and livelihoods, and pests have caused enormous losses to farmers in the tropics.

The cassava pest complex varies considerably among the major cassava growing regions of the Americas, Africa and Asia. The greatest diversity of arthropod pests attacking cassava is in the Neotropical Americas, the center of origin of this crop. An estimated 200 species have been reported, several of which are specific to cassava (Bellotti et al. 1999, 2010; Bellotti 2008) and adapted in varying degrees to the array of natural biochemical defenses in the host, which include laticifers and cyanogenic compounds (Bellotti and Riis 1994; Riis et al. 2003). The arthropod pests that attack and damage cassava in the Americas includes several species of whiteflies, mites, mealybugs, stemborers, thrips, and the cassava hornworm (Bellotti 2008; Bellotti et al. 1999). In Africa, the whitefly *Bemisia tabaci* is presently considered to be the major pest of cassava, as it is the vector of Cassava Mosaic Disease (CMD) and Cassava Brown Streak Disease (CBSD; Calvert and Thresh 2002; Legg and Hillocks 2003). Recent reports indicate that high populations of *B. tabaci* are also causing root yield reductions due to direct feeding on the cassava crop (Liu et al. 2007). The accidental introduction of the cassava green mite (CGM; *Mononychellus tanajoa*) and the cassava mealybug (*Phenacoccus manihoti*) from the Americas into Africa has caused severe damage and considerable yield losses on that continent (Herren and Neuenschwander 1991).

In Asia, until recently, none of the major Neotropical cassava pests had become established, although native arthropods, including red spider mite, mealybug and whitegrub species, have adapted to cassava and are reportedly causing yield losses in localized areas (Bellotti et al. 2010). However, recent surveys in Asia indicate that pest species originally from the Neotropics are causing crop losses. The cassava

mealybug, *P. manihoti*, was first observed in Thailand in 2008, causing severe crop losses in several regions, and has spread to Cambodia. The whitefly species *Aleurodicus dispersus* has been observed in moderate to high populations in several Southeast Asian countries (Bellotti et al. 2010), while the green mite species *Mononychellus mcgregori* was recently identified in Vietnam and is reported to be in Cambodia (Bellotti, personal observation).

The problems caused by cassava pests over the last half century have been substantial. Research and development programs have addressed these problems, especially through biological control programs and breeding pest and disease resistance into new cassava varieties. Many of the problems addressed in the past are simply moving from one region to another, such as mealybugs and mites in Asia. However, developing trends in cassava production are likely to influence pest incidence and severity in the future. Three major trends are: (1) movement of exotic or introduced species, (2) the effects of climate change on pest populations, and (3) the growing industrialization of cassava and associated changes in crop management.

There is a long history of problems associated with the movement of exotic or introduced species. This trend is likely to intensify given globalization and the growing movement of goods and people across international borders and continents. The implications for cassava pests include the possibility of new outbreaks, the spread of diseases using pests as vectors and the lack of natural enemies that could hold pest problems in check. Future challenges will include control of this movement through prevention and adaptation to pest outbreaks once they become apparent.

Higher temperatures and changing rainfall patterns could have substantial impacts on the cassava pest complex. Climate change predictions indicate that certain agricultural lands will receive less rainfall in the future. The cassava crop may have an advantage compared to other crops in regions with extended dry seasons; however, increased cassava production in these drier regions of the Americas, Africa and Asia could result in dangerous pest outbreaks, reducing yields and/or increasing pesticide use. In general, arthropod pests, such as mites, mealybugs, thrips and lacebugs, are more damaging to cassava during the dry seasons (Polanía et al. 1999; Yaninek and Animashaun 1987). Warmer temperatures may also have an effect on the developmental cycle of the pest. It has been documented that the intrinsic rate of increase for mites, whiteflies, hornworms and mealybugs is more rapid as temperatures increase (Holguín et al. 2006; Herrera et al. 1989; Bellotti et al. 1992; Mesa et al. 1987).

The dynamics of cassava production are changing as trends in food, feed, biofuel and other industrial uses are leading to an increased demand for high-quality cassava starches (Ceballos et al. 2010). In Latin America and Asia there are indications of a shift toward larger production units, where cassava is grown

as a plantation crop or where numerous small units (3–5 ha) cohere to form a monoculture of cassava over an extensive area. Under these conditions, it becomes advantageous for farmers to employ a multiple planting and harvesting production system in order to meet the constant market demands imposed by the processing industries. In this type of production system, the cassava crop will be at several different growth stages in the same or surrounding fields. Evidence now indicates that pest problems can be compounded in these overlapping production systems. Populations of certain pests such as whiteflies, hornworms and mealybugs tend to increase when a constant food supply (e.g. young cassava foliage) is available. Given this trend, with the concomitant increase in pest populations and damage, there is a greater tendency to apply pesticides to control pest outbreaks (Holguín and Bellotti 2004). This paper will discuss these and other implications of the industrialization of cassava.

The paper is organized around important cassava pests and the major trends that affect them and the crop. The following sections of this paper describe the cassava pest complex and deal primarily with four important pests of cassava—mites, mealybugs, whiteflies and the hornworm. The first three are global pests across the cassava growing regions of the Americas, Africa and Asia, while the hornworm (*Erinnyis ello*) is confined to the Americas. Next the paper deals with the movement of exotic or introduced cassava pest species and their impacts on productivity. Then, the effects of climate change are discussed; especially the effects of increased temperatures and prolonged dry seasons on pest population dynamics and crop management. Finally, the potential for increased pest incidence and more severe damage in large or extensive cassava plantations feeding into industrial markets will be analyzed.

### The Cassava Pest Complex and Crop Damage

The cassava pest complex can be divided into two groups: (1) those that likely co-evolved with cassava, which is their primary or only host, and are Neotropical in origin; and (2) generalist feeders or newly adapted pests, which may attack the cassava crop sporadically or opportunistically, and are often limited in geographic distribution. The first group includes the *Mononychellus* mite complex (*M. tanajoa*, *M. mcgregori*, *M. caribbeanae*), mealybugs (*Phenacoccus herreni* and *P. manihoti*), the hornworm (*Erinnyis ello*), lacebugs (*Vatiga illudens*, *V. manihotae*), whiteflies (*Aleurotrachelus socialis*, *Aleurothrix aepim*, *Trialeurodes variabilis*, *Bemisia tuberculata*), stemborers (*Chilomima clarkei*, *Coelosternus* spp), thrips (*Frankliniella williamsi*), scale (*Aonidomytilus albus*), fruitflies (*Anatrepha pickeli*, *A. manihoti*), shootflies (*Neosilva perezii*, *Silva pendula*) and gallmidges (*Latrophobia brasiliensis*) (Bellotti 2008; Bellotti et al. 2010).

The generalists—species feeding on cassava among other plants—and those species that have adapted to cassava include several *Tetranychus* mite species (especially in Asia), certain whitefly species (*Bemisia tabaci*, *Aleurodicus disperses*, *B. afer* and others), a complex of whitegrub species (*Phyllophaga* spp, *Leucopholis rorida*, *Euchlora viridis* and several others), mealybugs (*Ferrisia virgata*, *Pseudococcus jackbeardsleyi*, *Pseudococcus elisae*), burrowing bugs (*Cyrtomenus bergi*), termites, cutworms, grasshoppers, leaf-cutting ants, stemborers and others (Bellotti et al. 2010).

The most serious pests of cassava—those causing economic damage or yields losses—are generally those that have co-evolved with the crop, especially the cassava green mite (CGM; *M. tanajoa*), mealybugs (*P. herreni*, *P. manihoti*), whitefly (*A. socialis*, *A. aepim*), hornworm (*E. ello*), lacebugs (*V. illudens*) and stemborers (*C. clarkei*). Several generalist feeders are reported causing serious yield losses. The whitefly *B. tabaci* is the vector of Cassava Mosaic Disease (CMD) and a major pest of cassava in Africa, causing severe crop losses (Calvert and Thresh 2002). Yield losses due to Tetranychid mites feeding on cassava have been reported from the Philippines, Indonesia and India, ranging from 14 to 47% in field trials. The mite species involved include *T. kawganai* (Philippines), *Eutetranychus orientalis*, *T. neocalidonicus* and *Oligonychus biharensis* (India) and *Tetranychus* sp (Indonesia; Palaniswami et al. 1995; Bernardo and Esguera 1981).

The potential establishment of exotic cassava pests into areas where they do not presently exist is of great concern. Two major species, the cassava green mite (*M. tanajoa*) and the cassava mealybug (*P. manihoti*) were inadvertently introduced into Africa in the early 1970s, where they caused considerable crop damage (Herren and Neuenschwander 1991). More recently, *P. manihoti* has invaded cassava fields in Thailand and Cambodia and threatens several other cassava producing countries in the region (Laos, Vietnam, China and Indonesia; Howeler 2010; Winotai et al. 2010). In addition, in 2009 a member of the cassava green mite complex, *Mononychellus mcgregori*, was collected from cassava fields in Vietnam (Bellotti, personal observation) and has recently been reported (2011) in Cambodia. These invasive and exotic pest species pose a considerable threat and challenge to the cassava starch processing industries in Asia.

The vegetative propagation of cassava facilitates the movement of arthropod pests between countries and continents. Stem cuttings are often transported across land borders by farmers seeking higher yielding or improved varieties (Frison and Feliu 1991). In addition, transcontinental travelers can easily include small stem pieces in checked luggage that may not be detected by customs authorities (Fieselmann 1999), leading to the introduction of exotic pests. Pests such as mites, mealybugs, thrips,

stem borers and scale insects can be disseminated across land and ocean boundaries (Herren and Neuenschwander 1991; Frison and Feliu 1991). The increased demand for cassava as a multipurpose industrial crop will inevitably result in the increased movement of germplasm. This involves the risk of inadvertently introducing exotic pests and diseases along with the movement of cassava stems and may lead to more pest outbreaks in the future.

#### Bioecology and Management of Major Cassava Pests

Crop damage from cassava pests can be reduced through an improved understanding of the pest's bioecology and through the development of strategies to control them. Integrated Pest Management (IPM) strategies are described for each of the major cassava pests. Four tactics are generally highlighted or mentioned: host plant resistance (HPR), biological control, cultural or agronomic practices and the use of chemicals (insecticides). Biological control, the employment of natural enemies and HPR are emphasized. As previously mentioned biological control has played a major role in the management of mites, mealybugs and the cassava hornworm and is described in detail for each of these pests.

**Host plant resistance** offers an economical, practical, environmentally sound and farmer-friendly approach for controlling certain cassava pests. Although considerable effort has gone into evaluating and screening cassava genotypes to identify pest resistance, few pest resistant, commercial varieties are being cultivated over extensive areas. In traditional cassava production systems, numerous, perhaps hundreds, of landrace varieties are being grown by farmers in any given region, making it very difficult and strategically impractical to incorporate resistance into all landraces. In many cases six or more varieties might be grown on a single plantation (Lozano et al. 1980); this considerable genetic diversity can be seen as a defense against pest outbreaks. In regions where cassava is being commercially produced for the large starch or industrial market, few varieties are often being grown and a more uniform germplasm is preferred. The lack of genetic diversity in these systems could favor more severe pest outbreaks. For example, cassava plantings in Southeast Asia and South-Central Brazil, where the industrial starch market predominates, have experienced more severe mealybug and whitefly outbreaks in recent years. (Pietrowski et al. 2010; Winotai et al. 2010) In these regions it is common to find only a few varieties being grown over an extended area. For example, 1.2 million ha of cassava are grown in Thailand, but only 4 or 5 varieties predominate (Chareinsak et al. 2010).

In these industrial cassava production regions the possibility of incorporating host plant resistance into cassava germplasm becomes more feasible and a more strategically

practicable option for controlling cassava pests. Moderate levels of resistance to pests such as whiteflies, mites and mealybugs would be compatible with biological control and crop management practices, as well as reducing pesticide use. Research in host plant resistance, including the use of wild *Manihot* species as a source of resistant genes, would be a sound economical and environmentally friendly investment.

**Biological control** involves the employment, in some manner, of natural enemies to suppress pest population densities to levels lower than they would otherwise occur. In agricultural ecosystems it involves the use of parasitoids, predators, pathogens or other antagonistic organisms to maintain pest populations below economically damaging levels. There are three major methods for the use of natural enemies—*introduction*, *conservation* and *augmentation* (Van Driesche and Bellows 1996).

*Introduction* is one of the most successful methods in solving arthropod (insects and mites) pest problems, especially where introduced or exotic species comprise the major pests causing economic damage (yield losses) to the crop. The introduction of new, natural enemy species, often from the center of origin of the crop and pest, can be essential for managing pest populations and has historically been very effective. The introduction of the key parasitoid *Anagyrus lopezi* to control the cassava mealybug (*P. manihoti*) in Africa is an excellent example of this method (Herren and Neuenschwander 1991) and resulted in one of the most successful, cost effective and best documented examples of classical biological control (Renkow and Byerlee 2010). The identification of the pest's key natural enemy, a parasitoid, in its region of origin, Paraguay, South America, and its introduction into the invaded region, Africa, reduced yield losses from as high as 80% to 5 to 10%.

*Augmenting* the wild population of predators can be effective biological control as part of an IPM approach if it is deemed cost effective. Yield losses in the millions of dollars can be attributed to pest damage in regions, such as Southeast Asia and southern Brazil, where cassava is grown for the starch processing industry, which does not tolerate 5 to 10% yield losses. In Thailand, for example, the introduction of the cassava mealybug (*P. manihoti*) has caused yield losses estimated at more than US \$30 million (TTTA 2011). The industrial sector in Thailand has developed facilities for mass rearing of the parasitoid (*A. lopezi*) and sufficient numbers are made available to cassava producers for release into their mealybug-infested fields (Bellotti, personal observation, 2011). It is expected that this augmentation of the natural parasitoid population in the field will further depress mealybug populations. Natural enemies for the major cassava pests have been identified, including parasitoids, predators and entomopathogens (Table 1).

**Table 1** Natural enemies of important cassava pests

Species	Parasitoids	Predators	Entomopathogens
<i>Aleurotrachelus sociales</i>	<i>Amitus macgowni</i>	<i>Delphastus sp</i>	<i>Beauveria bassiana</i>
	<i>E. americana</i>	<i>D. quinculus</i>	<i>lecanicillium lecani</i>
	<i>E. bellotti</i>	<i>D. pusillus,</i>	<i>Aschersonia aleyrodes</i>
	<i>E. cubensis</i>	<i>Chrysopa sp. nr. cincta, Condylostylus sp.</i>	
	<i>Encarsia hispida</i>		
	<i>E. luteola</i>		
	<i>E. sophia</i>		
	<i>Encarsia sp. nr. variegata</i>		
	<i>Encarsia sp.</i>		
	<i>E. tabacivora</i>		
	<i>Euderomphale sp.</i>		
	<i>Eretmocerus spp.</i>		
	<i>Metaphycus sp.</i>		
	<i>Signiphora aleyrodis</i>		
	<i>Aleurothrixus aepim</i>	<i>Encarsia porteri</i>	
<i>E. aleurothrixi</i>			
<i>E. hispida</i>			
<i>Eretmocerus sp.</i>			
<i>Aleurodicus dispersus</i>	<i>Aleurotonus vittatus</i>		
	<i>E. haitiensis</i>		
	<i>Encarsia sp.</i>		
	<i>Eretmocerus sp.</i>		
<i>Bemisia tuberculata</i>	<i>E. hispida</i>	<i>Condylostylus sp.</i>	
	<i>E. pergandiella</i>		
	<i>E. sophia</i>		
	<i>Encarsia sp. prob. variegata</i>		
	<i>E. tabacivora</i>		
	<i>Eretmocerus sp.</i>		
	<i>Euderomphale sp.</i>		
<i>Bemisia tabaci</i>	<i>Encarsia sophia</i>	<i>Delphastus pusillus</i>	
	<i>E. lutea</i>	<i>Condylostylus sp.</i>	
	<i>E. Formosa</i>		
	<i>E. mineoi</i>		
	<i>Encarsia sp.</i>		
<i>Trialeurodes variabilis</i>	<i>Eretmocerus mundus</i>		
	<i>E. bellotti</i>	<i>Chrysopa sp. nr. cincta</i>	<i>Aschersonia aleyrodes</i>
	<i>E. hispida</i>	<i>Condylostylus sp.</i>	<i>Beauveria bassiana</i>
	<i>E. luteola</i>		<i>Lecanicillium lecani</i>
	<i>E. nigricephala</i>		
	<i>E. pergandiella</i>		
	<i>Encarsia sp.</i>		
	<i>E. sophia</i>		
	<i>E. strenua</i>		
	<i>E. tabacivora</i>		
	<i>Eretmocerus spp.</i>		
<i>Mononychellus tanajoa</i>		Insects:	<i>Hirsutella thompsoni</i>
		<i>Stethorus tridens</i>	<i>Neozygites floridana</i>
		<i>S. darwin</i>	<i>N. tanajoeae</i>

**Table 1** (continued)

Species	Parasitoids	Predators	Entomopathogens
		<i>S. madecassus</i> <i>Oligota minuta</i> <i>O. gilvifrons</i> <i>O. centralis</i> <i>O. pigmaea</i> <i>Delphastus argentinicus</i> , <i>Chrysopa</i> sp. Mites/Phytoseiidae: <i>Typhlodromalus manihoti</i> ; <i>T. aripo</i> ; <i>T. rapax</i> <i>E. lokole</i> ; <i>E. ncholsi</i> ; <i>E. baetae</i> , <i>Neoseiulus idaeus</i> <i>Galendromus annectes</i> <i>Euseius concordis</i> ; <i>E. ho</i> ; <i>E. fustis</i> <i>Neoseiulus anonymus</i> <i>Galendromus helveolus</i> <i>Phytoseiulus macropilis</i> <i>Typhlodromalus aripo</i> <i>T. manihoti</i> <i>T. rapax</i> <i>Cleothera onerata</i> , <i>Hyperaspis</i> sp.	
<i>Tetranychus urticae</i>			
<i>Phenacoccus manihoti</i>	<i>Anagyrus lopezi</i> <i>Acerophagus</i> sp.	<i>Nephus</i> sp. <i>Chrysopa</i> sp. <i>Symphorobius</i> sp., <i>Typhlodromalus aripo</i> <i>Ocyptamus</i> sp. <i>Symphorobius</i> sp. <i>Hyperaspis</i> sp.	<i>Cladosporium</i> sp. <i>Neozygites fumosa</i>
<i>Phenacoccus herreni</i>	<i>Acerophagus coccois</i> <i>Anagyrus diversicornis</i> <i>Aenasius vexans</i> ,  <i>Anagyrus insolitus</i> <i>A. thyridopterygis</i> <i>A. pseudococci</i> <i>Anagyrus</i> sp. nr. <i>greeni</i> <i>Aenasius</i> sp. nr. <i>putonophylus</i>  <i>Prochiloneurus dactylopii</i> <i>Chartocerus</i> sp.  <i>Hexacnemus</i> sp. <i>Eusemion</i> sp.	<i>Nephus</i> sp.  <i>Cleothera onerata</i>  <i>C. notata</i> <i>Diomus</i> sp. <i>Coccidophylus</i> sp. <i>Scymnus</i> sp. <i>Olla</i> sp. <i>Curinus colombianus</i> , <i>Cycloneda sanguinea</i> , <i>Hippodamia convergens</i> <i>Azya</i> sp. <i>Chrysopa</i> sp. <i>Kalodiplosis coccidarum</i> , <i>Zelus</i> sp.	
<i>Erinnyis ello</i>	<i>Trichogramma</i> sp. <i>Telenomus</i> sp. <i>Cortesia</i> spp.	<i>Chrysopa</i> spp. <i>Polistes</i> spp.	<i>Cordyceps</i> sp. <i>Beauveria</i> sp. <i>Metarhizium</i> sp. <i>Bacillus thuringiensis</i>

**Cultural Practices** There are numerous agronomic practices that cassava farmers might utilize to reduce pest populations. These include intercropping, varietal mixtures, crop rotation, altered planting dates, destruction (burning) of plant debris (especially after harvest), fertilization, and most importantly, the selection and use of high quality, pest- and disease-free planting material (stem cuttings). Traditional farmers in many of the cassava growing regions have employed several of these practices, especially the use of varietal mixtures and intercropping (Lozano and Bellotti 1980; Gold et al. 1990). On larger plantations where uniformity in planting, weed control, harvesting and root quality characteristics are desired, these types of agronomic practices might not be favored. However, the use of high quality planting material, destruction of pest- and disease-infested plant debris and proper implementation of crop management practices are accepted strategies across cassava crop agroecosystems.

**Pesticides** The success of an ecologically sound and economically profitable IPM program for cassava requires the implementation of a strategy that minimizes or prevents chemical pesticide use (Braun et al. 1993). The continual or frequent use of pesticides on a long season crop like cassava is prohibitively expensive for the small traditional farmer and reduces profit for the larger farmer (Holguín and Bellotti 2004). Foliar applications of pesticides can be effective in reducing pest populations; however, they can also be disruptive to natural or augmentative biological control. The increase in mealybug populations and damage in southern Brazil has been attributed, at least in part, to the use of pesticides to control whiteflies and lacebugs.

As cassava production shifts to larger plantations—especially those in the Americas and Asia—farmers may respond to pest outbreaks with increased pesticide use. At the onset of the mealybug outbreak in Thailand, cassava farmers resorted to the considerable use of chemical insecticides to control the pest (Bellotti, personal observation, 2009–2010). As cassava attains a higher commercial value and higher yielding varieties are desired, there will be an increased tendency and pressure to apply pesticides instead of relying on biological control or improved crop management practices to control pest outbreaks. Pests that trigger pesticide applications include the cassava hornworm, whiteflies, lacebugs, mites, burrower bugs and mealybugs (Bellotti 2002). The treatment of cassava planting material (stem cuttings) with a 5 to 7 min emersion in a pesticide solution, such as thiamethoxam (1 g/lit. H<sub>2</sub>O), prior to planting is effective in producing pest-free cuttings and providing some control during the early growth period (15 to 45 day) of the crop (Bellotti 2008). Pesticides, when properly employed, can also be used effectively to control localized outbreaks of pests such as mealybugs and mites.

## Cassava Mites

Approximately 45 species of phytophagous mites have been reported to feed on cassava in the Americas, Africa and Asia (Bellotti 2008; Bellotti et al. 2010). The most important are *Mononychellus tanajoa* (syn = *M. progresivus*), *M. caribbeanae*, *M. mcgregori*, *Tetranychus cinnabarinus*, *T. urticae* (also reported as *T. bimaculatus* and *T. telarius*), *T. truncates*, *T. kanzawai*, *T. neocalidonicus*, *Oligonychus biharensis* and *O. peruvianus*. Cassava is the major host for the *Mononychellus* species, while the *Tetranychus* species tends to have a wide host range. *M. tanajoa*, the Cassava Green Mite (CGM), is native to the Neotropics and is the most important mite species, causing crop losses in both the Americas and Africa. *M. tanajoa* has not been reported in any of the Asian cassava-producing countries, but the closely related species *M. mcgregori* was recently (2009) found feeding on cassava in Vietnam and Cambodia (Bellotti, personal observation). Climatic conditions in several Asian cassava growing countries are favorable for rapid dissemination and high population buildup of the CGM complex. The *Tetranychus*, or red spider mite complex, predominates in Asia, where more than 10 species are reported feeding on cassava (Bellotti et al. 2010).

**Bioecology** Mites are dry season pests and thrive in the lowland tropics where high temperatures prevail. At the onset of the rainy season mite populations decrease and cassava plants recover, producing new foliage (Yaninek and Animashaun 1987). *M. tanajoa* adults are green in color with an average body length of about 350  $\mu$ m. Females oviposit on the leaf undersurface; eggs hatch in 3–4 day (at 30°C and 70±5% RH). At 15, 20, 25 and 30°C, egg-to-adult stage duration is 41, 20, 10 and 8 day, respectively (Mesa et al. 1987; rounded to nearest whole numbers). In a study with the CGM in Africa, temperatures of 20, 24, 27, 31 and 34°C resulted in 21, 16, 12, 8 and 7 day egg-to-adult stage, respectively (Yaninek et al. 1989a). These data indicate that CGM populations can increase rapidly as temperatures increase in warmer regions of the lowland tropics. At 30°C, each female oviposits 90–120 eggs; during the initial population buildup, females are mostly produced, adding to the rapid population increase (Bellotti 2008). In a separate study in Africa, *M. tanajoa* (= *M. progresivus*) development was evaluated at five constant temperatures, 16, 22, 26, 31 and 36°C (Bonato et al. 1995). The lower thermal threshold for the mite was 13°C and at 16°C none of 117 eggs hatched. At 22, 26, 31 and 36°C, the developmental (egg-to-adult) times were 14, 10, 7 and 8 day, respectively. The lowest mortality occurred at 26°C (15%) and the highest (88%) at 36°C. These results indicate that there is an upper thermal threshold and that very high temperature could have an adverse effect on *M. tanajoa* population dynamics.

Developmental time of the red spider mite, *T. urticae*, follows a similar pattern to that of *M. tanajoa* in relation to temperature. Temperatures of 15, 20, 25 and 30°C resulted in an egg-to-adult developmental period of 30, 16, 9 and 7 day, respectively (Mesa et al. 1987). These data indicate that higher temperatures may be more favorable to population buildups of red spider mites (*Tetranychus* spp.).

CGMs show a wide potential distribution in the Americas, Africa and Asia (Herrera Campo et al. 2011). The lowland tropics provide favorable conditions for CGM, especially the distinct dry season of 3 to 6 month when average temperatures are 24 to 31°C and relative humidity values are 50 to 70% (Yaninek et al. 1989b). Low temperatures (15–20°C) or intense and constant rainfall increase mite mortality and inhibit population build up. For both the red spider and green mites, higher temperatures favor a higher net reproduction rate, a shorter generational time, a higher intrinsic rate of population growth and a shorter doubling time of the population (Mesa et al. 1987). However, when the *M. tanajoa* developmental period was evaluated at very high temperatures (34°C), the number of average eggs per female was reduced by nearly 80% and the population doubling time increased from 2.5 day (at 31°C) to 5.8 day (Yaninek et al. 1989a).

**Damage** CGMs prefer to feed on the underside of young, emerging leaves and use their stylets to penetrate leaf tissue and remove cell content. Leaves develop a mottled whitish-to-yellow appearance and may become deformed or reduced in size. Heavy infestations cause defoliation, beginning at the top of the plant, and often kill apical and lateral buds and shoots (Bellotti 2002). In contrast, mites of the *Tetranychus* complex tend to first attack the mature leaves at the base of the plant and then move to the upper leaves. Symptoms generally are first seen at the base of the leaf and along the midrib, but eventually cover the whole leaf. *Tetranychus* mite colonies feed on the lower leaf surface but, in the case of heavy infestations, can attack both leaf surfaces, often causing considerable webbing. Initial spotting becomes reddish or rust-colored as the infestation increases; defoliation occurs from bottom to top leaves and, if dry conditions persist, plants may die (Bernardo and Esguera 1981; Bellotti et al. 2010).

The CGM is reported to cause the greatest yield losses in the Americas and Africa (Herren and Neuenschwander 1991; Bellotti et al. 1999), especially in the seasonally dry regions of the lowland tropics. Under field conditions, high CGM populations in the Colombian north coast region caused a 15% yield reduction in resistant cultivars compared to an average 73% loss in susceptible cultivars (Byrne et al. 1982a). *M. tanajoa* first appeared in Africa (Uganda) in 1971 and by 1985 had spread to 27 countries, causing estimated loss in root yield of 13–80% (Yaninek and Herren 1988; Skovgard et al. 1993). Yield losses caused by

tetranychid mites feeding on cassava in Asia have been reported from the Philippines, Indonesia and India. Yield losses ranging from 18 to 47% have been recorded in field trials. The mite species involved include *T. kanzawai* (Philippines), *E. orientalis*, *T. neocalidenicus* and *O. biharensis* (India) and *Tetranychus* sp. (Indonesia; Bernardo and Esguera 1981).

*M. mcgregori* is Neotropic in origin and has been reported in several countries in the Americas, including Colombia, Brazil, Ecuador, Peru, Venezuela and the Caribbean region (Fletcher and Baker 1970; Byrne et al. 1983). It generally occurs at low densities, and there is little information in the literature on its biology, ecology or behavior. *M. mcgregori* can be found throughout the cassava plant, but densest populations occur near the apex or upper leaves. Its biology and behavior appear to be similar to that of *M. tanajoa*, but yield losses due to *M. mcgregori* have not been reported in the Americas (Braun 1993). Its recent introduction into Asia (Vietnam and Cambodia) indicates the need for increased knowledge on its biology, behavior, population dynamics, natural enemies and potential for damage to the cassava crop.

**Management** Pesticide applications for controlling mites on a long-cycle crop such as cassava are not a feasible or economic option for low-income farmers. Moreover, even low doses of pesticides have adverse effects on natural enemies (Braun et al. 1987a). Cultural control methods have not sufficiently been explored, and there is little mention of their use in the literature. Research into the control of *M. tanajoa* and *T. urticae* has followed two main thrusts: host plant resistance and biological control. It is expected that these two complementary strategies can reduce mite populations below economic injury levels.

**Host Plant Resistance** Immunity or even high levels of resistance do not appear to be available in *M. esculenta* germplasm. However, it is hypothesized that in the presence of effective natural enemies only low-to-moderate levels of HPR are needed to reduce CGM populations below economic injury levels. A level of resistance that would hinder, delay or suppress the initial buildup of CGM populations could provide sufficient opportunity for establishing effective natural enemy populations that could prevent an outbreak of the CGM population. Therefore, an important objective of an HPR strategy is to develop cultivars that are not highly susceptible to the CGM and that hopefully contain low-to-moderate levels of resistance.

Considerable efforts have been made to identify CGM resistance in cultivated cassava. The International Center for Tropical Agriculture (CIAT), the International Institute for Tropical Agriculture (IITA) and several national research programs in the Americas and Africa have screened cassava



germplasm for CGM resistance. Of the more than 5,000 landrace cultivars in the CIAT cassava germplasm bank, only 6% (300 cvs.) were identified as having low-to-moderate levels of resistance. A select number of cultivars with moderate levels of resistance have been released to farmers by plant breeders and entomologists. Two hybrids (ICA Costeña and Nataima 31), both with low levels of mite resistance, are being grown by cassava farmers in Colombia (Bellotti 2008).

Most field evaluations for mite-resistance by CIAT have been carried out in the lowland tropics with a prolonged dry season (4–6 month) and high mite populations (Colombian Atlantic Coast). In Brazil CGM evaluations were conducted by the National Cassava and Fruit Research Center (CNPMP) of the Brazilian Corporation for Agricultural Research (EMBRAPA), primarily in the semiarid regions of northeastern Brazil. Of the 300 cultivars identified by CIAT as promising for CGM resistance (over several years and 2–7 field cycles), 72 have consistently had damage ratings below 3.0 on a 1–6 damage scale, with low-to-moderate levels of resistance indicated by damage ratings of 1–3.5.

Mite resistance-mechanism studies indicate strong anti-xenosis (preference vs. nonpreference) for oviposition, as well as moderate antibiosis. In laboratory studies, *M. tanaioja* displayed a strong ovipositional preference for susceptible varieties. When paired with the moderately resistant cvs. MEcu 72, MPer 611 and MEcu 64 in free-choice tests, 95, 91 and 88%, respectively, of the eggs were oviposited on the susceptible cv. CMC 40. Antibiosis is expressed by mites having lower fecundity, a longer development time, a shorter adult life span, and higher larval and nymphal mortality when feeding on resistant vs. susceptible cultivars (Byrne et al. 1982b).

Host plant resistance studies for *Tetranychus* mite species have been less intensive than those carried out for CGM. Field evaluations of cassava germplasm by CIAT in Colombia have been hindered by low *Tetranychus* mite field populations. However, some laboratory studies have been conducted. *T. urticae* larval and nymphal mortality was 68% higher on the cultivar MBra 12 than on the susceptible cultivar MCol 22. Mortality on the cultivar MCol 1434 was 50% higher than that on MCol 22. Egg eclosion and larval survival were significantly lower (25%) on MCol 1351 than on MCol 22. Germplasm evaluations for resistance to *Tetranychus* mites need to be carried out in regions where high mite populations occur. The opportunity for this line of research is better in Asia where *Tetranychus* mite species are reported to be causing economic damage (CIAT 1980).

Several wild *Manihot* species have been evaluated as a potential source of resistance to cassava mites by CIAT in Colombia. Moderate levels of resistance (2.0 on a 1.0 to 6.0 damage scale) to *M. tanaioja* have been found for some

accessions of *M. esculenta* subsp. *flabellifolia* (Burbano et al. 2007). In laboratory studies, *M. tanaioja* oviposition was considerably reduced on some accessions of *M. tristi*, *M. filamentosa* and *M. alutacea*, when compared to a susceptible *M. esculenta* (CMC 40) cultivar. In addition, microsatellite markers associated with *M. tanaioja* resistance have been identified in segregating accessions of a cross between *N. flabellifolia* and *M. esculenta* (Mtai 8; Macea Choperena 2007). These results indicate that a research effort to utilize wild *Manihot* species as a source of resistance to cassava mites would be potentially effective. This effort could also be extended to include *Tetranychus* mite species.

**Biological Control** Biological control offers an alternative and practical solution for management of cassava mites, provided that chemical pesticides are not being employed to control other arthropod pests, such as whiteflies and mealybugs. Beginning in the early 1980s, extensive evaluations of the natural enemy complex associated with cassava mites were conducted at more than 2,400 sites in 14 countries of the Neotropics (Bellotti et al. 1987). The primary target in most of these field and laboratory studies was the CGM. Predator species feeding on *Tetranychus* mite species were also collected and evaluated. These ongoing, extensive surveys indicate that the CGM is present throughout much of the lowland Neotropics; however, high populations causing significant yield loss are localized and occur most frequently in northeastern Brazil and the Caribbean coast of Colombia and Venezuela (Doreste 1982; Byrne et al. 1983).

Geographic regions of the Americas were identified and prioritized using GIS support, to target specific areas for exploration. Homology maps—based on agrometeorological data and microregional classification comparing Africa and the Neotropics—were prepared to target natural enemies of CGM found in South America to those areas of Africa where the CGM was causing economic damage.

A total of 87 phytoseiid species were collected and stored; 25 were new or unrecorded species and 66 were collected from cassava. The predator mite reference collection at CIAT conserves primarily those predators attacking phytophagous mites found on cassava. Explorations also identified several insect predators of cassava mites, especially the staphylinid *Oligota minuta* and the coccinellid *Stethorus* sp (Table 1). After extensive laboratory and field studies of this predator complex, it was generally agreed that the phytoseiid predators offered the best potential for controlling mites, especially when prey mites occur at low densities. The phytoseiid development period is shorter than that of CGM or *Tetranychus* mites. In studies at CIAT with the species *Neoseiulus anonymus*, the egg-to-adult development period at 25 and 30°C was 4.7 and 4.0 day, respectively (Mesa and Bellotti 1986). This is approximately half

the development period of CGM or *T. urticae* at those temperatures. Survey data also revealed that CGM densities were much higher in northeastern Brazil than in Colombia, but the richness of phytoseiid species was greater in Colombia.

Field data from experiments in Colombia demonstrated that a rich phytoseiid species complex could reduce CGM populations and prevent cassava yield loss. When natural enemies were eliminated by applying low doses of an acaricide that did not affect the CGM population, cassava root yields were reduced by 33%. Application of an acaricide did not increase yields, indicating the effectiveness of biological control (Braun et al. 1989).

A major objective of the surveys for CGM natural enemies and the substantial research that followed was to identify the key phytoseiid species controlling CGM populations and introduce them into Africa. This was a collaborative effort between CIAT and EMBRAPA in the Americas and IITA in Africa. Of the phytoseiid species identified as feeding on CGM, those most frequently collected were *Typhlodromalus manihoti* (found in >50% of the fields surveyed), *Neoseiulus idaeus*, *Typhlodromalus aripo*, *Galendromus annectens*, *Euseius concordis* and *Euseius ho* (Bellotti et al. 1987).

Six phytoseiid (Acari: Phytoseiidae) collected in South America, *E. ho*, *T. aripo*, *Typhlodromalus tenuiscutus*, *Neoseiulus californicus*, *N. idaeus*, and *G. annectens*, were evaluated as biological control agents of *M. tanajoa*. Their effectiveness was estimated by measuring rates of prey consumption and oviposition in relation to prey density under optimal laboratory conditions. Prey consumption by *E. ho*, *T. aripo* and *T. tenuiscutus* continued increasing linearly up to the highest density of prey evaluated (200 prey eggs) for a maximum of 93, 101 and 59 prey, respectively, in 24 h. For the remaining predators, prey consumption leveled off at prey density of 30 or more. Higher maximum daily oviposition rates were registered for *T. tenuiscutus*, *N. californicus*, *N. idaeus* and *G. annectens*, ovipositing 3.9, 3.6, 2.9 and 2.8 eggs, respectively, whereas *E. ho* and *T. aripo* oviposited a maximum of 2.2 and 1.4 eggs in 24 h, respectively (Cuellar et al. 2001). The high prey consumption rates of *T. aripo*, *T. tenuiscutus* and *E. ho* suggests that these species are the best predators in regard to the attack of pest eggs and could be effective agents for biological control of *M. tanajoa*. More than ten species of phytoseiids were shipped from Colombia and Brazil to Africa, via quarantine in England (IIBC-International Institute of Biological Control). None of the Colombian species became established, but three of the Brazilian species did (*T. manihoti*, *T. aripo* and *N. idaeus*). *T. aripo*, the most successful of the three species, was released in Africa in 1993 and became established in more than 14 countries (Yaninek et al. 1993). *T. aripo* inhabits the tips of cassava plants during the day and forages on leaves

at night and can persist during periods of low CGM densities by consuming alternative food sources (e.g., maize pollen). On-farm trials in Africa indicated that *T. aripo* reduced CGM populations by 30–90% and increased fresh root yield by 30–37%. This was an increase of US\$60/ha for cassava producers (Yaninek et al. 1993; Onzo et al. 2005).

Many predacious mite species (Phytoseiidae) have been observed feeding on *Tetranychus* mites, and several species have been evaluated for feeding on *T. urticae* (Mesa and Duque 1994). These include *G. annectens*, *E. concordis*, *Phytoseiulus pessimilis*, *Neoseiulus anonymous*, *N. chilensis*, *N. idaeus* and *P. macropilis* (Bellotti 2002; Mesa et al. 1990). The development time (egg-to-adult) for the seven species ranged from 4.2 day (*N. idaeus*) to 6.1 day (*G. annectens*; 25°C, 70±5% RH and 12:12 h photoperiod) when feeding on *T. urticae*. The development time for these seven species when feeding on *M. tanajoa* ranged from 4.0 (*P. pessimilis*) to 5.8 day (*G. annectens*). The development time during these experiments for the phytophagous species, *T. urticae* and *M. tanajoa*, was 9.1 and 10.7 day, respectively. The development times of three predator species, *N. chilensis* (4.4 day), *P. macropilis* (4.3 day) and *N. idaeus* (4.2 day) were less than one-half that of *T. urticae* (9.1 day). The *Neoseiulus anonymous* development time when feeding on *T. urticae* was 4.7 day, nearly one-half that of the prey species (Mesa et al. 1990). Adult longevity of the phytoseiid species when feeding on *T. urticae* ranged from 17.4 day (*N. idaeus*) to 54.8 day (*N. chilensis*). When feeding on *M. tanajoa*, adult longevity ranged from 18.2 day (*N. idaeus*) to 44.1 day (*P. macropilis*). In general, the data for both species were similar (Mesa et al. 1990).

Predation consumption studies were carried out with the phytoseiid *N. anonymous* on both prey species. *N. anonymous* consumed mites at all four developmental stages (egg, larva, nymph and adult) of *T. urticae* and *M. tanajoa*. *N. anonymous* consumed an average of 78.3 *T. urticae* eggs, compared to only 10.3 *M. tanajoa* eggs. However, *N. anonymous* showed a higher average consumption of larvae (20.0 vs. 2.8), nymphs (9.0 vs. 5.1) and adults (21.0 vs. 4.7) when feeding on *M. tanajoa* compared to *T. urticae* (Mesa and Bellotti 1986). These results indicate that *N. anonymous* could play an effective role in the biological control of both prey species, especially that of *T. urticae* because of the high egg consumption.

As noted, cassava mite populations can increase rapidly in regions where temperatures may be on the rise. Studies also indicate that certain natural enemies employed in a biological control program can be affected by rising temperatures. The development time (egg-to-adult) of *Oligota centralis* (Coleoptera: Staphylinidae), a mite predator, at 15, 20, 25 and 30°C, was 59, 32, 19 and 17 day, respectively. Egg eclosion remained high (79 to 86%) at all temperatures

(Lenis et al. 1989). At temperatures of 15, 20, 23 and 25°C, egg-to-adult developmental times of *Typhlodomulus manihoti* were 14.7, 6.1, 6.8 and 4.8 day, respectively (Mesa and Bellotti 1986). However, average oviposition decreased from 8.2 to 2.3 per female. A similar study with *N. anonyms* at temperatures of 20, 23, 25 and 30°C gave developmental times of 8.9, 6.1, 4.7 and 4.0 day, respectively. There was no significant change in oviposition at the higher temperatures (Mesa and Bellotti 1986). These data indicate that several cassava mite natural enemies can survive, reproduce and consume prey at higher temperatures.

*Neozygites* spp. are fungal pathogens (Zygomycetes: Entomophthorales) found on mites throughout cassava-growing regions of the Neotropics. Isolates of *Neozygites floridana* from Brazil, Colombia and Benin were evaluated on CGM in Africa. Laboratory and field studies indicate that the Brazilian strain of *N. floridana* was the most virulent. Although this fungus shows considerable promise for biological control of CGM, further research and field evaluations are needed (Delalibera et al. 1992).

Exotic phytoseiid mite predators can play an important role in reducing CGM populations in Africa and Asia (*M. mcgregori*) and *Tetranychus* spp. in Asia. However, field observations in the Neotropics indicate that they are very sensitive to disturbances in the agroecosystems, especially the use of pesticides. For example, when insecticides were applied at CIAT for controlling thrips, CGM populations erupted, and few phytoseiid predators were detected in the fields. Studies in Colombia showed that low acaricide doses that did not cause mortality to CGM were lethal to phytoseiids, causing a considerable increase in mite populations and cassava yield losses (Braun et al. 1987a, b). In the Neotropics, especially on larger plantations, cassava farmers may use pesticides to control hornworm, whitefly or thrips outbreaks. This could result in mite outbreaks and yield losses if biological control is the only mite control measure employed and highly susceptible cultivars are being grown.

In Asia, few phytoseiid mites have been collected and identified as preying on phytophagous mites on cassava (Moraes et al. 1989). Considering the many mite species feeding on cassava in Southeast Asia and the recent introduction of *M. mcgregori* into the region, biological mite control research needs to become a priority in Asia. The predicted increases in temperature in the region will favor increased populations and greater plant damage from mites on cassava (Herrera Campo et al. 2011).

CIAT maintains a cassava phytophagous mite and a phytoseiid predator mite collection that has been sourced from many of the cassava growing regions of the Americas, Asia and Africa. The collection contains more than 20,000 specimens and is utilized by cassava scientists for comparative taxonomic purposes. The collection is accompanied by a computerized database that allows researchers to identify

the geographic location of cassava mite species and their natural enemies. It also allows us to predict the climatic parameters that might favor outbreaks or spread of phytophagous mite species and the potential adaptability of their natural enemies (Hernandez et al. 1995).

### Cassava Mealybugs

More than 15 species of mealybugs are reported to attack cassava in the Americas, Africa and Asia. *Phenacoccus manihoti* and *Ph. herreni*, both of Neotropical origin, are the most important economically, causing severe yield reductions (Herren and Neuenschwander 1991; Bellotti 2002). *Ph. manihoti* was introduced inadvertently into Africa in the early 1970s, where it spread rapidly across the cassava-growing regions and caused considerable yield loss. In 2008, *P. manihoti* was collected from cassava fields in Thailand and has subsequently caused damage estimated to be in the millions of dollars (Winotai et al. 2010). Recent reports indicate that *P. manihoti* is also present and causing damage to cassava in Cambodia and Indonesia.

*Ph. manihoti* was first recorded in the Americas in Paraguay in 1980 and was later collected from certain areas of Bolivia and Mato Grosso do Sul state of Brazil, where it caused no economic damage (Lohr and Varela 1990). More recently, *Ph. manihoti* has also been collected from the Brazilian states of Paraná, Sao Paulo, Bahia and Pernambuco, where it appears to be reducing cassava yields. The origin of *Ph. herreni* is probably in northern South America, where it was found in the cassava growing regions of Colombia and Venezuela. It was first reported causing severe damage and yield losses in cassava during the mid-1970s in northeastern Brazil. Surveys in the region found high mealybug populations but few parasitoid natural enemies, suggesting that *Ph. herreni* is an introduced or exotic pest, probably originating from northern South America, where several parasitoid species are frequently observed (Bento et al. 2000).

Recent mealybug collections from cassava fields in Asia, especially in Thailand, indicate that there is a complex of mealybug species in that region (Bellotti et al. 2010). There is an urgent need to continually survey the situation in order to better understand the distribution of the cassava-infesting mealybug in Southeast Asia and the damage or yield losses that may result. The striped mealybug, *Ferrisia virgata*, has been reported feeding on cassava in Asia for many years but, until recently, was seldom observed in very high densities (Schreiner 2000). Recent observations in Thailand and Vietnam indicate that populations have increased dramatically and are now causing yield losses (Bellotti, personal observation, 2010). Additional mealybug species that have been recently collected from cassava in Asia include

*Pseudococcus jackbeardsleyi* (Thailand, Philippines, Malaysia and Vietnam), *Ps. elisae* (Thailand), *Phenacoccus solenopsis* (Thailand, Vietnam), *Paracoccus marginatus* (Thailand, India), and *Ps. longispinus* (China, Vietnam, Thailand). *Ph. hirsutus* is reported feeding on cassava in the Philippines. *Ps. elisae* is described as very similar to *Ps. jackbeardsleyi* and has been collected from cassava in Papua New Guinea, the Philippines and Thailand (Williams 1988, 2004).

**Biology and Behavior** In general, mealybugs are very much alike in their biology. Mealybugs can be placed into two groups: The short-tailed mealybugs and the long-tailed mealybugs. The short-tailed mealybugs reproduce by laying eggs, often in an ovisac. The filaments that surround the body are of about equal length and none more than one-fourth the length of the body. The long-tailed mealybugs generally do not form an egg sac, giving birth to live nymphs. This group derives its name from the four filaments near the tip of the abdomen, which may be as long as the body. *Phenacoccus herreni* and *Ph. manihoti* are short-tailed species, while *F. virgata* is a long-tailed species. In general, mealybugs are oval, flattened, soft-bodied insects, distinctly segmented but without a clear definition between the head, thorax and abdomen. The aforementioned species pass through four stages: egg, 2 nymphs and adults. Although sedentary, nymphs and adults do not remain fixed and may move about on the plant.

*F. virgata* females are described as flat bodied, 1.8 × 3.0 mm long with tail filaments about 1.6 mm long. The winged male body is about 0.5 × 1.3 mm. The life cycle has been recorded as 35 to 92 day and females oviposit an average 364 eggs. The adult female is covered with a powdery white wax and has a pair of purplish dorsal stripes along the back. Long, glossy white wax threads extend from the body to form two long waxy tails. Although mobile, these mealybugs generally do not move very far and form large clusters (Schreiner 2000).

Both *Ph. herreni* and *Ph. manihoti* are morphologically similar and were originally thought to be one species. *Ph. manihoti* is parthenogenic, whereas males are required for reproduction by *Ph. herreni* (Bellotti 2008). The females deposit ovisacs containing hundreds of eggs on the undersides of leaves and around apical and lateral buds. Eggs hatch in 6–8 day, followed by four nymphal instars. The first instars are highly mobile and will spread over the plant or between plants. The fourth instar is the adult stage for females, while males have four nymphal instars plus the adult stage. The third and fourth instars occur in a cocoon, from which the winged male adults emerge, living only 2–4 day. The life cycle of the female is 49.5 day; that of the male, 29.5. The optimal temperature for female development is 25–30°C (Herrera et al. 1989). Populations of both

species peak during the dry season. The onset of seasonal rains reduces pest populations and plant damage, permitting some crop recovery.

Life table studies with *Ph. manihoti* conducted at four constant temperatures, 20, 23.5, 27 and 30.5°C, resulted in development times of 50, 36, 27 and 29 day, respectively (Lema and Herren 1985; rounded to nearest whole number). However, an inverse relationship was observed between adult longevity and temperature. Mean adult longevities at 20, 23.5, 27 and 30.5°C were 35, 23, 20 and 18 day, respectively. The mean fecundity (eggs/female) decreased at higher temperatures; 585 (±29) eggs were oviposited at 20°C vs. 425 (±26) at 30.5°C. However, population doubling times were 6.1, 4.1, 3.7, and 3.8 day at 20, 23.5, 27 and 30.5°C, respectively, indicating that *Ph. manihoti* populations can persist and expand within a range from 20 to 30.5°C. A separate, more recent study to determine the influence of temperature on *Ph. manihoti* development gave similar results. The development times (egg-to-adult) were 50, 31, 27 and 24 day at 20, 25, 27 and 30°C (Minko 2009). The results from these studies indicate that the optimal temperature for *Ph. manihoti* development is probably around 27 to 30°C and that 30.5°C may be near the upper thermal threshold for development of *Ph. manihoti* (Lema and Herren 1985).

The developmental times (egg-to-adult) for *Ph. herreni* females at 20, 22, 25 and 30°C were approximately 44, 30, 14 and 15 day, respectively (Herrera et al., 1989). Total life durations, including the adult stage, were 90, 68, 38 and 39 day, respectively, at the above noted temperatures. Highest mortality occurred during the first instar, especially at the higher temperatures. The average developmental times for males (including adult stage) were 52, 33, 22 and 20 day at the same respective temperatures. These data indicate that the optimal development temperature for *Ph. herreni* is between 25 and 30°C, similar to that of its close relative *Ph. manihoti*. It could be considered, therefore, that very high temperatures, above 30°C, may be detrimental to the development of both *Ph. manihoti* and *Ph. herreni*.

*Pseudococcus jackbeardsleyi* has not been reported as a serious pest and there is little information available on this species feeding on cassava. It has both a wide distribution and wide host range. Commonly known as the Jack Beardsley mealybug, it is reported to feed on a diverse range of fruits, vegetables, and ornamentals, as well as cassava. Hosts include pineapple, cherimoya, celery, cabbage, pigeon pea, bell peppers, star apple, grapefruit, melon, banana, beans and numerous others (from 88 genera and 38 plant families). It has been reported from nearly all countries in tropical Americas and several countries in Africa and Asia (Williams 2004).

Mealybug dissemination between regions, countries or continents occurs through movement of infested stem cuttings, as mealybug immature stages can be found around the

lateral buds on cassava stems. The introduction of *Ph. manihoti* into northeastern Brazil from southern Brazil can probably be traced to the movement of cassava varieties between these two regions. In addition, the introduction of stem cuttings from Africa likely explains the recent outbreaks of *Ph. manihoti* in Thailand. The frequent movement of cassava stems between Thailand and Cambodia has most certainly contributed to the presence of *Ph. manihoti* in Cambodia (Bellotti, personal observation, 2010). The planting of infested cuttings can also carry mealybug infestations from one crop cycle to the next.

**Damage** *Phenacoccus manihoti* and *Ph. herreni* cause similar damage: feeding by adults and nymphs causes leaf yellowing, curling and cabbage-like malformation of the apical growing points. High populations 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<sub>2</sub> and leaf temperature—were found in infested plants (Polanía et al. 1999). Experimental fields at CIAT infested with *Ph. herreni* suffered 68–88% yield loss, depending on cultivar susceptibility. Farmers in northeastern Brazil estimated their losses to be over 80%, and cassava production decreased in the region during the 1980s. In Africa, yield losses due to *Ph. manihoti* feeding and damage ranged from 9 to around 80% (Nwanze 1982; Schulthess 1987; Neuenschwander and Hammond 1989; Herren and Neuenschwander 1991). Cassava field losses in Thailand during a recent (2010) infestation of *Ph. manihoti* were estimated as high as 50% (Winotai et al. 2010), and the loss in crop value was as high as US\$30 million (TTTA 2011). *Ph. manihoti* populations in south-central Brazil have increased in recent years and are probably causing yield losses; studies have been initiated to quantify these losses (Bellotti, per. observ. 2010; Pietrowski et al. 2010).

In general mealybugs can cause two types of damage to cassava: (1) a mechanical or direct damage caused by their sucking feeding habits and (2) an indirect damage produced by the build-up of sooty mold on the leaf surface due to mealybug honeydew. Fungal growth reduces leaf photosynthesis. *Ferrisia virgata*, the striped mealybug, can often be found in high populations feeding on the undersurface of leaves and in clusters along the stems and branches of the cassava plant. When high populations occur, considerable sooty mold can be observed. *F. virgata* causes leaf yellowing and eventually defoliation, usually beginning with the basal leaves. Striped mealybug infestations can spread rapidly, eventually covering most leaves, stems and shoots. When high populations occur on young plants, growth is slowed, resulting in stunted plants. Stems will have shortened internodes. Shoots and leaves are deformed and wilting occurs, eventually leading to leaf and shoot desiccation or defoliation.

High *F. virgata* populations have occurred in certain regions of Thailand in recent years, especially in areas where the rainy season was delayed, prolonging the dry season. It was estimated by farmers that yields were reduced by 20 to 80% in fields with high striped mealybug populations.

**Management** Mealybugs can be effectively controlled through use of biological control agents, especially parasitoids (Table 1). Pesticide control of mealybugs can be both difficult and costly. The objective is to prevent mealybug populations from reaching economically damaging levels. Therefore, any mealybug management actions need to be employed when pest populations are still low. Unless there is constant monitoring of pest populations in the field, it is often difficult to detect the initial increase in mealybug populations. This is especially true on larger cassava plantations, where monitoring schemes are not often implemented. If effective natural enemies, especially parasitoids, are present, they can prevent or retard the initial buildup of the mealybug populations. Use of pesticides can be disruptive to the natural biological control agents that exist in or are introduced into a field. Most natural enemies, especially parasitoids, are very sensitive to pesticides, even at low doses. Effective biological control requires considerable knowledge and information on the origin, biology, ecology, behavior and taxonomy of both the pest and their natural enemies (Van Driesche and Bellows 1996). Cassava mealybug management is a well-documented example of classical biological control, in both Africa and the Americas. In Africa, *Ph. manihoti* is being controlled successfully after introducing the parasitoid *A. lopezi* from the Neotropics. After several years of exploration in the Neotropics by scientists from IIBC, IITA and CIAT, the target species *Ph. manihoti* was finally located by a CIAT scientist (A.C. Bellotti) in Paraguay in 1980. IIBC collected natural enemies of *Ph. Manihoti* which were then sent via quarantine in London to IITA in Benin for multiplication and release in Africa. The encyrtid parasitoid *A. lopezi* and the coccinellid predators *Hyperaspis notata*, *H. raynevali*, and *Diomus* sp. became established in Africa. The parasitoid is credited with being the principal agent reducing mealybug populations. *Anagyrus lopezi* became established in all ecological zones occupied by *Ph. manihoti* and is now found in 27 countries, covering an area of 2.7 million km<sup>2</sup>. Cassava losses have been reduced by 90–95%, with an estimated savings of US\$7.971 to 20.226 billion (Neuenschwander 2004).

*Ph. manihoti* has caused severe crop losses in Thailand and Cambodia. Having first been identified in Thailand in 2008 (Bellotti pers. observ. 2008), it has since spread widely in the cassava growing regions of Thailand and Cambodia. In 2009 the Thai Department of Agriculture (DOA) imported the parasitoid *A. lopezi* from IITA, in Benin, Africa. It was mass reared and released in December 2009

(Winotai et al. 2010) and became well established in various cassava growing regions of the country. At present *A. lopezi* is being reared by both the Thai DOA and the private sector, especially the industrial starch processing industry, and is being made available to cassava producers. Damage due to *Ph. manihoti* has decreased significantly in Thailand since the release and establishment of *A. lopezi* (Bellotti, personal observation, 2011).

If mealybug (*Ph. manihoti*) populations in a given region are not reduced to economically acceptable levels by the establishment of *A. lopezi*, periodic releases of the parasitoid may be made. Such augmentative biological control requires careful monitoring of cassava fields during times of highest mealybug numbers, usually at the onset of and during the dry season. This strategy requires that the private processing industry and government laboratories maintain mass rearing operations so that sufficient parasitoids are available for farmers during mealybug outbreaks. Monitoring of cassava plantations can identify mealybug “hot spots” (those sections of the field where the initial mealybug eruptions occur). A foliar pesticide application applied to these “hot spots” can reduce these initial outbreaks, and parasitoids can be released into surrounding areas. In this manner, pesticides and augmentative biological control may be complementary.

Surveys in Colombia and Venezuela identified many parasitoids, predators and entomopathogens associated with *Ph. herreni*. Several parasitoids showed a specificity or preference for *Ph. herreni*: *Acerophagus coccois*, *Anagyrus diversicornis*, *An. putonophilus*, *An. isolitus*, *An. elegeri* and *Aenasius vexans*. Based on many field and laboratory studies, three encyrtid parasitoids (*An. diversicornis*, *Ac. coccois* and *Ae. vexans*) were identified as likely to be effective in reducing *Ph. herreni* infestations (Van Driesche et al. 1988). These parasitoids completed two generations for each one of *Ph. herreni*—a favorable ratio for biological control. *An. diversicornis* prefers third instar nymphs, whereas the smaller *Ac. coccois* parasitizes male cocoons, adult females, and second instar nymphs. *Ae. vexans* prefers second and third instar nymphs. Field studies with natural populations of *An. diversicornis* and *Ac. coccois* estimated 55% mortality to *Ph. herreni* from the combined actions of these parasitoids.

Through the combined efforts of CIAT and CNPMF/EMBRAPA, these three parasitoids were exported from CIAT to EMBRAPA, Brazil, where they were mass reared and released into *Ph. herreni*-infested cassava fields, primarily in the northeastern states of Bahia and Pernambuco from 1994 to 1996. More than 35,000 parasitoids were released, and all three species became established. Studies before release had determined that none of these species existed in this region. In Bahia, *An. diversicornis* dispersed 120 km in 6 month. after release and 304 km in 21 month. *Ac. coccois* was recovered in large numbers 9 month later,

180 km from its release site. *Ae. vexans* was consistently recaptured at its release site in Pernambuco, having dispersed only 40 km in 5 month (Bento et al. 2000).

*Ph. herreni* populations have decreased considerably in northeastern Brazil as cassava farmers in the region have not reported severe outbreaks and cassava cultivation has returned to areas where it had been previously abandoned due to *Ph. herreni* damage (Bellotti pers. observ. 2010–2011). However, the recent introduction of *Ph. manihoti* into the region has resulted in reports of severe mealybug damage in Bahia, causing alarm among cassava producers. Efforts by local institutions and researchers are underway to determine if key *Ph. manihoti* parasitoids are present or need to be introduced into the region. *Ph. manihoti* was probably introduced into northeastern Brazil on infested cassava stems transported from southern Brazil as planting material.

South-central Brazil (the States of Paraná, Sao Paulo and Mato Grosso) has recently experienced considerable damage to cassava due to increased populations of *Ph. manihoti*. This species has been in the region for many years, and southern Brazil, Paraguay, and northern Argentina appear to be its center of origin. However, it was not previously observed at levels to cause economic damage to cassava. Explanations for this increase in pest importance may include (1) an increase in cassava monoculture production on large plantations, which has provided abundant vegetative material for mealybugs and (2) changes in climate, with a warmer “winter” period (June to August), which has altered crop management practices leading to staggered or more frequent plantings of cassava. Multiple planting systems of cassava at several different growth stages in the same or surrounding plantations is favorable for increases in mealybug populations. In addition, increased use of chemical pesticides to control whiteflies and lacebugs has probably reduced the effectiveness of the natural biological control agents, especially the parasitoid *A. lopezi* (Bellotti pers. observ. 2008–2010).

As stated earlier, mealybug populations in Asia, especially Thailand, have also increased in recent years. Factors such as warmer temperatures, a longer dry season, or greater use of pesticides may have contributed to this increase. Two important mealybug species collected from Thailand and Vietnam have been identified as *F. virgata* and *Ps. jackbeardsleyi*, both of neotropical origin. Several parasitoids of *F. virgata* have been reported, but there are few data on field efficacy (Bellotti et al. 2010). In addition, the species *Pa. marginatus* has been collected from several cassava fields in Thailand (Bellotti pers. observ. 2010–2011). Increased research and survey work are needed in order to identify and evaluate the most important natural enemies of these Asian mealybugs, especially parasitoids of *F. virgata* and *Ps. jackbeardsleyi*.

## Whiteflies

Whiteflies are one of the world's most damaging agricultural arthropod pests, both as direct feeders and virus vectors. This is especially true in the tropical and subtropical regions of the world (Anderson and Morales 2005). A complex of whitefly species attacks cassava-based agroecosystems in the Americas, Africa and Asia, causing crop damage and considerable yield losses, especially in the Americas and Africa (Bellotti 2008).

There is a large whitefly species complex associated with cassava, with the important species varying between regions or continents. The largest whitefly complex on cassava is in the Neotropics, where 11 species are reported, including *Aleurotrachelus socialis*, *Trialeurodes variabilis*, *Aleurothrixus aepim*, *Bemisia tuberculata* and *B. tabaci*, biotype B (syn = *B. argentifolii*). *Aleurotrachelus socialis* and *T. variabilis* cause considerable direct damage and yield losses in northern South America (Colombia, Venezuela and Ecuador) and in certain regions of Central America. *T. variabilis* is observed primarily at higher altitudes (>1,000 m), while *Aleurotrachelus socialis* is confined to lower altitudes (up to 1,200 m). *Aleurothrixus aepim* is found in high populations that cause yield losses in northeastern Brazil. *B. tuberculata* has recently been identified as causing yield losses in southern Brazil (Bellotti 2002, 2008).

*B. tabaci* is the most important whitefly species in Africa, where it is the vector of both cassava mosaic disease (CMD) and cassava brown streak disease (CBSD; Maruthi et al. 2005; Legg et al. 2011). CMD is caused by a complex of viruses of the family *Geminiviridae*, while CBSD is due to two distinct but similar virus species (Legg et al. 2011) that co-occur in infections (Mbanzibwa et al. 2010). *B. tabaci* and CMD are also distributed throughout parts of South Asia, especially India (Calvert and Thresh 2002) where moderate yield losses have been reported. More recently, *B. tabaci* pupa were collected from cassava from one region of Thailand (Bellotti, personal observation, 2011). *B. tabaci* is described as a complex of morphologically indistinguishable cryptic species that show distinct geographical, biological and genetic differences (Xu et al. 2010; De Barro et al. 2011). The most invasive form documented so far is the Middle East-Asia Minor 1(B) strain (also known as *B. argentifolii* and hereafter referred to as Biotype B), which affected cassava production in Africa, but has traditionally been recorded in the literature as *B. tabaci* (Anderson and Morales 2005; De Barro et al. 2011). *B. tabaci* is a polyphagous species that is known to colonize over 500 plant species, including several important food and fiber crops (Brown et al. 1995; Sseruwagi et al. 2006). 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 effectively. Before the early 1990s, the *B. tabaci*

biotypes found in the Americas did not feed on cassava. The B biotype of *B. tabaci*, regarded by some as a separate species (*B. argentifolii*), has been collected from cassava in several regions of the Neotropics, but seldom observed in high populations (Carabalí et al. 2005).

The potential adaptation of *B. tabaci* to cassava is considered a threat to cassava production in the Americas. A study was initiated to verify whether *B. tabaci* could gradually become adapted to *M. esculenta*. Trials were conducted in rearing chambers (growth rooms) measuring life cycle and population development of *B. tabaci* individuals that passed through a series of intermediate hosts, which had been selected based on phylogenetic proximity to *Manihot*. The ability of *B. tabaci* biotype B to gradually adapt to cassava (*M. esculenta*) was tested using individuals from a colony on a legume (*Phaseolus vulgaris*) that were then reared on either *Euphorbia pulcherrima* (poinsettia) or *Jatropha gossypifolia*, and finally assayed on a commercial cassava variety. The highest oviposition rate (2.66 eggs/female/2 day), the shortest development time (44.4 day) and the highest value of population growth rate ( $r_m$ ;  $0.48 \text{ day}^{-1}$ ) were for populations coming from *J. gossypifolia*. Whiteflies from *J. gossypifolia* survived on cassava at ~28%, whereas only 3.0% from *E. pulcherrima* and 2.0% from *P. vulgaris* survived (Carabalí et al. 2005). In addition to *J. gossypifolia*, two wild species of cassava, *Manihot flabellifolia* and *M. carthaginensis*, were compared to a commercial variety (MCol 2063) as hosts of biotype B (Carabalí et al. 2010a, b, c). Development time was highest on *M. flabellifolia* (47.2 day) and *M. esculenta* (44.4) and lowest on *J. gossypifolia* (27.5) and *M. carthaginensis* (33.3). Survival rate was highest on *M. carthaginensis* (0.6) and *J. gossypifolia* (0.55) and lowest on *M. flabellifolia* (0.08) and *M. esculenta* (0.275). The net reproductive rate ( $R_0$ ) was highest on *J. gossypifolia* (0.2) and *M. esculenta* (1.56). Population duplication time (TD) was highest on *M. esculenta* (49.5) and lowest on *J. gossypifolia* (12.6) and *M. carthaginensis* (21). Of the four hosts evaluated, *J. gossypifolia* was the most favorable, followed by *M. carthaginensis* (Carabalí et al. 2010a). The importance and potential impact of phylogenetically close plants as hosts facilitating the adaptation of *B. tabaci* to cassava is evident, especially in the Neotropics where cassava is not an efficient host for *B. tabaci*.

*Jatropha* species are being considered as a potential source for biofuels and plans call for the planting of large plantations of this crop. This could lead to “host shifting,” where *B. tabaci* adapts to cassava. This enhances the possibility of *B. tabaci* vectoring virus diseases to cassava. Studies in India (Raj et al. 2008) have identified a begomovirus from *Jatropha curcas* that possessed high identity with Indian and Sri Lankan cassava mosaic virus isolates. Precautions should be taken to insure that large *Jatropha*

plantations are not established near major cassava growing regions, such as in southern Brazil. These studies indicate that *B. tabaci* as a vector of CMD or CBSD may pose a more serious threat to cassava production in the Americas and Southeast Asia, given that most traditional and improved varieties grown in these regions are highly susceptible to these diseases.

The whitefly species *A. dispersus* (the spiraling whitefly) is found feeding on cassava in countries in Asia (Thailand, Laos, Vietnam, Cambodia, Sri Lanka and India) as well as Africa (Neuenschwander 1994; Mware et al. 2010) and several Pacific Islands (Martin 1987; Waterhouse and Novis 1989). Central America and the Caribbean Regions are considered to be the origin of this species. It is reported from several countries in the Americas, but it is seldom observed in high populations on cassava and no yield losses have been reported. *Aleurodicus dispersus* is a highly polyphagous species and has a wide host range that includes many vegetable, ornamental and fruit crops (bananas, citrus, avocado, guava, soybean), as well as cassava (Manzano et al. 1995; Legg et al. 2003; Aiswariaya et al. 2007). Many parasitoids of this whitefly have been observed in the Neotropics, and this may account for its low populations and lack of economic damage observed there. Yield loss studies on cassava with *A. dispersus* need to be carried out, especially in Asia and Africa, where high populations can often be observed (e.g., Thailand). The immature and adult stages cause direct feeding damage that can result in premature leaf-fall. Feeding damage is accompanied by a heavy production of honeydew and a white, waxy material produced by the insect. Sooty mold develops on the honeydew and decreases photosynthetic activity. *Aleurodicus dispersus* populations are also reported from Benin, Africa (D'Almeida et al. 1998). The wide host range of this species has probably contributed to its spread throughout much of the tropics.

**Bioecology** Research with the whiteflies *A. socialis* and *A. aepim* indicates that both species can occur throughout the cassava growing cycle (1 year or more) but that their numbers are usually highest during the rainy season, when there is considerable new growth (Farias et al. 1991; Gold et al. 1991). *Aleurotrachelus socialis* females prefer to oviposit on the undersides of young apical leaves, producing up to 244 eggs (avg 181, min. 155) per female. The individually oviposited banana-shaped eggs of this species hatch in ca. 10 day and pass through three feeding nymphal instars and a pupal stage (4th instar) before becoming adults. During the third instar, the body color changes from beige to black, and becomes surrounded by a waxy white cerosine, making this species easy to distinguish from other whitefly species feeding on cassava. *Aleurotrachelus socialis* egg-to-adult development was 32 day under growth chamber conditions (28±

1°C, 70% RH). *Aleurotrachelus socialis* may be specific to cassava, as populations have not been observed on other plant species (Holguín and Bellotti 2004).

The development of *B. tabaci* was studied on cassava under average maximum temperature of 31.5°C and average minimum of 23.6°C. The mean duration of development (days) was 6 day for eggs, and 4, 2, 3 and 6 day for instars I, II, III and IV, respectively. A total developmental time of 21 day was observed in Cote d' Ivore (Fishpool et al. 1995).

The bioecology of *B. tabaci* (biotype *B.*) has been studied in different regions and on different host species (Bosco and Caciagli 1998; Drost et al. 1998; Albergaria and Cividanes 2002; Yang and Chi 2006). The optimal temperatures for development fluctuate around 25–30°C. The maximum temperature threshold is about 35°C, with the minimal threshold temperature for development ranging between 8.3 and 14°C; however, Bosco and Caciagli (1998) found that at very low temperatures (0, 2, 4 and 6°C) eggs and nymphs of whiteflies can survive between 4 and 8 day, increasing the development time by 5 to 8 day. Yang and Chi (2006) found that at 15°C, oviposition was very low, but 90% of whiteflies survived more than a month and 20% more than 2 month. This rate of survivorship is sufficient for *B. tabaci* to survive short periods of low temperature.

*Aleurodicus dispersus* densities can reach hundreds of nymphs per leaf. Dense whitefly populations increase sooty mold cover. In general, whiteflies require high humidity, especially during their developmental stages. However, high *A. dispersus* populations have been recorded during dry periods (D'Almeida et al. 1998). The biology of *A. dispersus*, a polyphagous species, has not been extensively studied on cassava. Adults are white, large and easily observed on the undersurface of leaves where eggs are oviposited. Eggs are oviposited singly on stalks, in loose circular whorls and covered with a white wax. Eggs hatch in 4 to 10 day depending on the temperature and host plant. The nymphal period has four instars and may last 10 to 14 day or longer, depending on temperature. The pupal stage, which lasts 2 to 3 day, is covered with considerable white wax that may act as a protective shield against natural enemies. The total life cycle (egg-to-adult) ranges from 34 to 38 day (Palaniswami et al. 1995). Females can live up to 39 day and lay 80 or more eggs. Dense populations of *A. dispersus* can produce ample honeydew and sooty mold, leading to the abandonment of cassava fields. In Africa, this whitefly has been recorded on more than 100 host plants (Neuenschwander 1994) and in India on more than 250 (Ramani et al. 2002).

The egg-to-adult development period of *T. variabilis* feeding on cassava under laboratory conditions (25.5±.3°C and 73±27% RH, Var. MCol 1468) averaged 32 day (range 28 to 38 day). The egg-to-adult period of *B. tuberculata* studied under the same conditions averaged 39 day (range 32 to 46 day; CIAT 2007).



*Bemisia afer* is reported as a widespread pest species with numerous plant hosts, including cassava (Munthali 1992). It has been recorded in several countries in Africa, the Mediterranean region, the Middle east, Asia (India, Pakistan), Australia and South America (Anderson et al. 2001). *B. afer* is common along the coastal areas of eastern and southern Africa, where it readily feeds on cassava. The developmental period (egg-to-adult) on cassava ranged from 27 to 37 day (25°C mean temperature) depending on variety (Munthali 1992).

**Damage** Whiteflies can cause direct damage to cassava by feeding on the phloem of leaves, inducing leaf curling, chlorosis and defoliation. High populations, combined with prolonged feeding, result in considerable reduction in root yield. Yield losses resulting from *A. socialis* and *A. aepim* activity are common in Colombia and Brazil, respectively. With *A. socialis* feeding, there is a correlation between duration of attack and yield loss. Infestations of 1, 6 and 11 month. resulted in a 5, 42 and 79% yield reduction, respectively. More recently, yield losses of 58% due to *T. variabilis* feeding have been recorded in the Andean region of northern South America (Holguín and Bellotti 2004; Bellotti 2008).

*Aleurodicus dispersus* damage symptoms include yellowish speckling of the leaves and, with severe infestations, curling, crinkling and death of cassava leaves. Leaf damage and infestation progresses from the bottom of the plant to the top. Yield reduction up to 53% in cassava has been reported in Tamil Nadu (Ramani et al. 2002; Mware et al. 2010).

In several East African countries, yield losses due to direct feeding by *B. tabaci* have been recorded in recent years as a result of high populations attributed to new biotypes in the region. In Uganda, over 50% reduction in root yield has been recorded due to whitefly feeding and CMD (Calvert and Thresh 2002; Liu et al. 2007). Observations on large cassava plantations in south-central Brazil (states of Sao Paulo, Paraná and Mato Grosso do Sul) indicate that high *B. tuberculata* populations are reducing yields, but these losses have not been quantified (Bellotti, personal observation, 2009–2011).

**Management** A successful whitefly control program requires continual research in order to acquire the basic knowledge needed to develop the technologies and strategies for appropriate implementation. A recent survey in an important cassava-growing region of Colombia showed that 34% of the farmers surveyed applied chemical pesticides for whitefly control versus only 4.6% using biological products. Farmer field trials in the region revealed a 58% reduction in yield due to whitefly attack; however, 52% of the farmers surveyed employed no control measures. Pesticide applications have

not provided adequate control, probably for lack of farmer knowledge of whitefly biology, especially the immature stages (the presence of eggs and early-instar nymphs). This has resulted in inappropriate timing of applications and the misuse of chemical pesticides (Holguín and Bellotti 2004).

Recent research and field observations on cassava whiteflies in the Neotropics indicate that control measures, especially pesticide applications, are of limited value because of the whitefly's capacity for rapid population increases and its ability to develop high levels of pesticide resistance. When *A. socialis* feeds on a susceptible cassava variety, it can double its population every 4.2 day under ideal conditions (Holguín et al. 2006). Other whitefly species may follow a similar pattern.

However, we have not observed such rapid buildup for other whitefly species attacking cassava in the neotropics, such as *T. variabilis*, *B. tuberculata* and *A. aepim* (Farias and Bellotti 2006). When there are overlapping crop cycles (e.g., multiple plantings) and favorable rainfall patterns, such conditions are ideal for an increase in whitefly density, as a constant supply of young cassava leaves are available for adult feeding, oviposition and nymphal development. Field observations indicate that once whitefly populations begin this rapid increase, they are very difficult to control, requiring repeated pesticide applications that disrupt natural biological control and are uneconomical for small farmers (Holguín and Bellotti 2004). This capacity for rapid population buildup makes it urgent to begin efficient management practices early in the plant growth cycle, possibly during the first month of plant growth and before the economic threshold is reached.

Options for management of cassava whiteflies include host plant resistance (HPR) biological control, cultural or agronomic practices and chemical control.

**Host Plant Resistance** The large complex of whitefly species that attack and damage cassava complicates efforts to determine sources of resistance to all of the important species. Research at CIAT has concentrated on *A. socialis* (Bellotti and Arias 2001), while an effort has been made by IITA in Nigeria to identify *M. esculenta* genotypes resistant to *B. tabaci* (Ariyo et al. 2005). Host plant resistance to whiteflies is rare in cultivated crops (Bellotti and Arias 2001). HPR studies initiated at CIAT more than 25 years ago have systematically evaluated the accessions in the CIAT cassava germplasm bank for resistance to whiteflies, especially *A. socialis*. Of approximately 5,500 genotypes evaluated in the field in Colombia, about 75% are susceptible, with damage ratings above 3.5 (1 = no damage, 6 = severe damage). Emphasis was placed on those genotypes with damage ratings under 2.0 (ca. 8%). As there may be insufficient selection pressure in some selection trials, putatively resistant varieties must be reevaluated in subsequent

trials. Several sources of resistance to *A. socialis* have now been identified. Genotype MEcu 72 has consistently expressed a high level of resistance, while MEcu 64, MPer 334, MPer 415 and MPer 273 express moderate-to-high levels. When feeding on resistant genotypes, *A. socialis* experiences reduced oviposition, a longer development period, smaller size and higher mortality than when feeding on susceptible cassava genotypes. *Aleurotrachelus socialis* nymphs feeding on MEcu 72 and MPer 334 suffered 72.5 and 77.5% mortality, respectively, mostly in the early instars (Bellotti and Arias 2001).

On resistant cassava cultivars, a combination of reduced oviposition and high nymphal mortality depresses whitefly population increase. This allows other methods of control, such as biological control, to be more effective. The early establishment of natural enemies, especially parasitoids, can be more successful in maintaining whitefly populations below economic injury levels.

A cross between MEcu 72 (female parent, whitefly resistant) and MBra 12 (male parent, high yielding, good plant type) resulted in 128 progeny, four of which were selected for whitefly resistance, yield and cooking quality. These four hybrids, along with susceptible genotypes and local farmer varieties, were evaluated at three sites in Tolima Province in Colombia by CORPOICA-MADR (Colombian Corp. for Agricultural Research/Ministry of Agricultural and Rural Development) over a four-year period. CG 489-31 was selected for high whitefly resistance, high yield and good cooking qualities. In 2003, it was officially released by MADR under the name of Nataima-31. It has attained yields of 33 t/ha, outyielding the regional farmers' variety in Tolima by 34% with no pesticide applications. Nataima-31 is now being grown commercially in several areas of Colombia and has been introduced into Ecuador and Brazil.

Additional sources of resistance in cassava germplasm to *A. socialis* have been identified, and genomic regions responsible for the determination of whitefly resistance have been identified (Bellotti et al. 2005a). Exploratory research at CIAT indicates that wild *Manihot* species could provide new sources of genes for resistance to important cassava pests (Burbano et al. 2007). Accessions of two wild Brazilian species, *M. flabellifolia* and *M. peruviana*, were evaluated and compared to commercial genotypes of *M. esculenta* (CMC-40) to determine potential resistance to *A. socialis*. Evaluations of three genotypes, MFla444-002, MPer 417-003 and MPer 417-005, resulted in very low damage (1.0 on a 1 to 6 damage scale) and infestation ratings (1.0 to 1.5 on a 1 to 6 infestation scale) due to *A. socialis* feeding over a 55 day period (Burbano et al. 2007). There were no significant differences between the wild *Manihot* genotypes, but a considerable difference (6.0 rating for both damage and infestation) when compared to the *M. esculenta* check, CMC-40.

Subsequent studies characterized this new source of resistance by evaluating the biology and demographics of *A. socialis* on eight accessions of *M. flabellifolia*, a susceptible check (CMC-40) and a resistant check (MEcu 72). The averages of *A. socialis* longevity and fecundity on the *M. flabellifolia* accessions were not significantly different from MEcu 72 but were different from CMC-40 ( $P < 0.05$ ). For this same comparison, development times were not significantly different, ranging from 35 to 40 day on *M. flabellifolia* accessions and MEcu 72 and 33.5 day on CMC-40 ( $P < 0.05$ ). However, the population growth rate ( $r_m$ ) was significantly lower on *M. flabellifolia* accessions, with MFla61 displaying a growth rate 98 and 99% lower than that on MEcu 72 and CMC-40, respectively (Carabalí et al. 2010b). The accessions least preferred for oviposition by *A. socialis* were MFLA 21 (42.2 eggs) and MFLA 19 (53.4 eggs), with 78 and 72% lower oviposition, respectively, compared to the check (CMC-40). The combined results from these trials showed that the *M. flabellifolia* accessions expressed significant levels of resistance to *A. socialis* and that this resistance is characterized by antixenosis. Interspecific crosses of *M. flabellifolia* accessions with *M. esculenta* and backcrosses progeny are being created.

In addition, life history studies with *A. socialis* have been carried out on wild accessions of *M. tristis* (TST-26 and TST-18). The average longevity of whiteflies on TST-26 (4.1 day) and TST-18 (4.6 day) and oviposition rates (TST-26, 2.0; TST-18, 1.6 eggs/female/2 day) were not significantly different from MEcu 72 (5.1 day and 3.4 eggs/female/2 day). However, on CMC-40, longevity and oviposition rates were 11 day and 8.6 eggs/female/2 day (Carabalí et al. 2010c).

Generally, when an insect displays a longer development time together with low reproductive rates on a particular plant, then that plant is not an appropriate host for an insect (van Lenteren and Noldus 1990). Based on the above-cited results, the tested accessions of *M. flabellifolia* and *M. tristis* are not suitable hosts for *A. socialis*.

**Biological Control** Many natural enemies are found associated with whiteflies on cassava in the Neotropics (Table 1). In recent field explorations in Colombia, Ecuador, Venezuela and Brazil, a complex of parasitoids, predators and entomopathogens was collected from several whitefly species (Bellotti et al. 2005b), with parasitoids in the genera *Encarsia*, *Eretmocerus* and *Amitus* being frequently associated with *A. socialis*. Gaps in knowledge about this natural enemy complex have limited the determination of their effectiveness in biological control programs. There is little knowledge regarding rates of parasitism by species or host specificity and parasitoid effects on the regulation of whitefly densities.

Eleven species of parasitoids (in 5 genera) were collected from the cassava-growing regions of Colombia; an additional five species were collected from Ecuador and seven from Venezuela. On the Caribbean coast of Colombia, *A. socialis* was parasitized by eight species, with the genus *Eretmocerus* comprising 70% of the parasitoids. In Magdalena Province, 73% of *A. socialis* parasitism was by *Amitus macgowni*, followed by *Encarsia* sp. (26%). In the Andean region, *Eretmocerus* spp. parasitized all whitefly species, but *Encarsia pergandiella* was the predominant parasitoid of *T. variabilis* (Bellotti et al. 2005b).

Greenhouse studies with *E. hispida* parasitizing *A. 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 (Bellotti et al. 2005a, b).

Parasitoid species associated with *B. tuberculata* include *Encarsia hispida*, *E. pergandiella*, *E. sophia*, *E. tabacivora*, *Eretmocerus* spp.. However, there are no studies that indicate the effectiveness of these parasitoids. Research on the presence of *B. tuberculata* parasitoids in southern Brazil and their potential in biological control needs to be carried out. In northeastern Brazil, the predominant whitefly species on cassava is *Aleurothrixus aepim*. Several parasitoid species have been identified, including *Encarsia porteri*, *E. hispida*, *E. aleurothrixi* and *Eretmocerus* spp. However, there is little information available on the effectiveness of these natural enemies (Farias and Bellotti 2006).

Several parasitoid species have been recorded parasitizing *A. dispersus*; these include *Aleurotonus vittatus*, *Encarsia* spp., *E. haitiensis*, *E. guadeloupeae*, *Eretmocerus* spp. and *Euderomphale* spp. *Encarsia haitiensis* and *E. guadeloupeae* (both species probably from the Caribbean region) have been shown to be effective in reducing *A. dispersus* populations in Benin, Africa (D’Almeida et al. 1998; Legg et al. 2003). It is estimated that these two species were accidentally introduced, along with *A. dispersus*, into Benin during the early 1990s. *Aleurodicus dispersus* populations in Asian countries need to be surveyed in order to determine if these two parasitoids, or other parasitoids, are present and evaluated for effectiveness. *Encarsia haitiensis* and *E. guadeloupeae* are both reported as parasitoids of *A. dispersus* in the Philippines and Malaysia.

More than 20 species of entomopathogens have been reported infecting whiteflies on cassava, including *Aschersonia* sp., *Lecanicillium (Verticillium) lecani*, *Beauveria bassiana* and *Paecilomyces fumosoroseus*. However, when these are to be used as biopesticides there has to be a careful selection of the species, as well as the identification of native isolates of entomopathogenic fungi already present locally. Greenhouse experiments at CIAT with an isolate of *L. lecani* resulted in 58–72% mortality of *A. socialis*

nymphs and 82% mortality to eggs (Alean et al. 2004). An *L. lecani* isolate has been formulated into a commercial biopesticide (BioCanii®). The commercial biopesticide Mycotrol® (isolate of *B. bassiana*, a product of Laverlam S.A.), gave very effective control (>90% mortality of the eggs and first two nymphal instars) of *A. socialis* in greenhouse experiments at CIAT. Mycotrol® was also effective against *B. tabaci* and *T. variabilis* but needs to be evaluated in field trials.

Fungal entomopathogens as biopesticides for whitefly control appears to be most effective if applied when whitefly populations are low and most individuals are in the egg and nymphal stages. Field experiments indicate that biopesticides are ineffective if applied when whitefly population densities are high. The combination of a resistant cassava variety with applications of a biopesticide (if needed) would probably be very effective in maintaining whitefly populations below economic injury levels.

The most frequently observed predators feeding on cassava whiteflies are chrysopids (Neuroptera: Chrysopidae). These generalist predators feed on eggs and immature stages of many kinds of arthropods. *Chrysoperla carnea* is frequently collected feeding on *A. socialis* in cassava fields. In laboratory studies at CIAT, the level of consumption by *C. carnea* of *A. socialis* eggs and nymphs was measured by recording the time required for 50% of the prey offered to be consumed. *Chrysoperla carnea* adults required 80 h to consume 50% of the nymphs and pupae and 77 h to consume 50% of the eggs (Holguín et al. 2003).

**Cultural Control** In traditional cropping systems cassava is often intercropped, a practice that has been shown to reduce populations of certain pests (Gold et al. 1989). Intercropping cassava with cowpeas reduced *A. socialis* and *T. variabilis* egg populations by 70%, compared to those in cassava monoculture. Yield losses in cassava/maize, cassava monoculture and mixed cultivar systems were ca. 60% versus only 12% in cassava/cowpea intercrops. Significantly lower numbers of *B. tabaci* eggs, nymphs and adults were observed in cassava plots surrounded on all sides by five rows of cotton or *Jatropha curcas*, demonstrating the potential of strip cropping for *B. tabaci* management (Ewusie et al. 2010).

When cassava is grown in overlapping cycles or multiple plantings, favorable host material is available continually, making it difficult to ‘break’ the whitefly development cycle. Upon emerging from the pupal stage, adults migrate to feed and oviposit on recently germinated young plants in adjacent fields. A successful tactic for countering this situation is to implement a ‘closed season’, defined as an interdiction or prohibition when cassava cannot be present in the field. Field observations at CIAT have shown that a 1- to 2-month period with no cassava in the field decreases

whitefly populations dramatically over a four-year period. The success of this ban is enhanced by the fact that *A. socialis* does not appear to have suitable alternate hosts, and therefore their populations decline sharply. Nevertheless, the economic practicality of this strategy for producers is debatable. In many regions, a constant supply of cassava roots is economically desirable for meeting the demands of local fresh and processing markets. This same tactic would not be as effective for a species such as *A. dispersus* and *B. tabaci*, both of which have many alternate hosts.

**Chemical Control** Several products with new or novel active ingredients have been evaluated for control of *A. socialis* and *T. variabilis*. Foliar applications of thiamethoxam and imidacloprid were most efficient in reducing whitefly populations. Best control was obtained when applied as a drench at high doses (0.8 and 0.6 l/ha) on young plants (Holguín and Bellotti 2004). The treatment of cassava planting material (stem cuttings) with a 7-min emersion in a solution of thiamethoxam (Actara®; 1 g/l water) also gives promising results (CIAT 2007). More than two pesticide applications during the crop cycle should be avoided. Pesticide application should be made when whitefly populations are still low and to delay increase of whitefly populations. Field experiments have shown that high whitefly populations are difficult to control with chemical pesticides, even when applied at high doses. Field experiments have also shown that pesticides need not be applied after 6 months of crop growth as yield loss due to whitefly attack will not occur. A cost-benefit analysis indicates that chemical pesticide applications for whitefly control in cassava are generally uneconomical for small farmers and only slightly beneficial for large farmers who can generally receive a higher price for the product. Research is under way to evaluate the feasibility of substituting entomopathogens as biopesticides to replace chemical pesticide applications (Holguín and Bellotti 2004).

#### Cassava Hornworms

Several lepidopterans feed on cassava, the most important being the cassava hornworm, *Erinnyis ello*, which causes serious damage to cassava in the Neotropics and has a broad geographic range, extending from southern Brazil, Argentina and Paraguay to the Caribbean basin and southern USA. The migratory flight capacity of *E. ello*, its broad climatic adaptation and wide host range probably account for its wide distribution. Several other species of *Erinnyis* (*E. alope*; and subspecies *E. ello ello* and *E. ello encantado*) are reported feeding on cassava in the Neotropics, but they appear to be of minor importance, with no economic damage to the crop. *Erinnyis ello* is absent in both Africa and Asia.

**Bioecology** Although hornworm outbreaks are sporadic, they mostly occur during the rainy season when foliage is abundant. The grey nocturnal, migratory adult moths have strong flight abilities. *E. ello* females oviposit small, round, light green-to-yellow eggs individually on the upper surface of cassava leaves. In field cage studies, females oviposited an average of 450 eggs, although as many as 1,850 eggs/females were observed. This high oviposition capacity, combined with the mass migratory behavior of adults, helps explain the rapid buildup of hornworm populations and their sporadic occurrence. During the larval period, each hornworm consumes about 1,100 cm<sup>2</sup> of foliage; ca. 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 day, respectively, indicating that peak activity may occur at lower altitudes or during the summer in the subtropics. When considerable leaf area is present, up to 600 eggs may be found on a single plant, and larval populations may exceed 100/pl. It is estimated that 13 fifth instar larvae can defoliate a 3-month-old plant in 3–4 day, especially those grown in low fertility soils. Given this biology, hornworm outbreaks must be controlled when populations are in the early larval stages (Bellotti 2002; Bellotti et al. 1992).

**Damage** Hornworm larvae feed on cassava leaves of all ages, and high populations will also consume young, tender stems and leaf buds. Severe attacks cause complete plant defoliation, bulk root loss and poor root quality. In farmers' fields, natural attacks resulted in 18% yield loss; simulated damage studies resulted in 0–64% root loss, depending on cycles of defoliation, plant age and edaphic conditions. Repeated attacks are more common when poorly timed pesticide applications fail to destroy fifth instar larvae or prepupae. Frequent attacks often occur on larger plantations (>100 ha), where subsequent populations can oviposit and feed on areas not previously defoliated. Cassava can survive severe attacks and complete defoliation, as carbohydrates stored in the roots enable recovery, especially during the rainy season. However, severe defoliation can reduce the dry matter and starch quality of cassava roots (Arias and Bellotti 1984).

**Management** The migratory behavior of hornworm adults makes effective control difficult to achieve and reduces the impact of natural biological control. Insect migration has been described as an evolved adaptation for survival and reproduction, and some researchers speculate that the hornworm's migration evolved as a mechanism to survive low food availability, unfavorable environmental conditions and attack by natural enemies. It is important to detect hornworm outbreaks while in the early development stages. Successful control requires monitoring field populations to detect migrating adults, ovideposits or larvae in the early

instars (Braun et al. 1993). This can be done with black light traps for adults or by scouting fields for the presence of eggs and larvae.

Pesticides give adequate control if applied when hornworm populations are predominantly early instar larvae. Populations of fourth and fifth instars are difficult to control. Farmers often react only when considerable defoliation has occurred, with excessive, ill-timed and costly pesticide applications that can lead to repeated or even more severe attacks. Pesticide use may also disrupt natural enemy populations, leading to more frequent attacks, a common occurrence on larger plantations.

More than 30 species of parasitoids, predators and pathogens of the egg, larval and pupal stages have been identified and reviewed extensively (Table 1); however, their effectiveness is limited, most likely due to the migratory behavior of hornworm adults (Bellotti et al. 1992). Eight species of Trichogrammatidae, Scelionidae and Encyrtidae are egg parasitoids, of which *Trichogramma* spp. and *Telenomus* spp. are the most important. In recent field surveys during a hornworm outbreak at CIAT, egg parasitism reached 68%: 57% due to *Trichogramma* sp. and 11% to *Telenomus* sp. Tachinid flies are important dipteran larval parasitoids and the Braconidae, especially *Cotesia* spp., are the most important hymenopteran parasitoids. *Chrysopa* spp. are common egg predators, while important larval predators include *Polistes* spp. (Hymenoptera: Vespidae) and several spider species. Important entomopathogens include *Cordyceps* sp. (Aconycites: Clavicipitaceae), a soil-borne fungus that invades hornworm pupae, causing mortality. Recent laboratory studies show that certain isolates of *Beauveria* sp. and *Metarhizium* sp. cause high larval mortality. Hornworm outbreaks can be controlled with timely (early instars) applications of commercial formulations of *Bacillus thuringiensis* (Bellotti 2008).

The effectiveness of biological control agents in a hornworm management strategy depends on the ability to synchronize the release of large numbers of predators or parasitoids to augment natural biological control. Predator and parasitic effectiveness in hornworm control is limited by poor functional response during outbreaks, which are of short duration (15 day). In the absence of a reliable commercial source of *Trichogramma* or other parasitoid or predator species, the cost of maintaining these natural enemies in continuous culture to guarantee availability when an *E. ello* outbreak occurs is economically prohibitive and impractical for most cassava farmers (Braun et al. 1993).

The complexities of massive releases of parasitoid and predator species suggest the need for a cheap, storable biological pesticide. A granulosis virus of the family Baculoviridae was found attacking *E. ello* in cassava fields at CIAT in the early 1970s. Pathogenicity studies using virus material extracted from infected larvae collected in the field

were carried out on cassava plants in the laboratory and field. Larval mortality reached 100% 72 h after application. Studies on the effect of virus concentration on mortality of larval instars showed a sigmoidal relationship for the first, second and fourth instars. LD<sub>50</sub> studies show that progressively higher concentrations are needed for adequate control of each succeeding larval instar. Most fifth instar larvae reached the prepupal stage, but few female adults emerged and those that did had wing deformities and died without producing progeny (Bellotti et al. 1992).

Although the cassava hornworm baculovirus can be produced by small farmers, this technology has been most successful with larger producers or where research and extension services have provided viral preparations to farmers. Growers can collect and macerate diseased larvae and apply the virus/tissue suspension to cassava fields. The virus can be stored for several years under refrigeration, and for a few months at room temperature. Hornworm management with the baculovirus was implemented in southern Brazil during the late 1980s and early 1990s. Researchers and extension workers trained farmers in the handling and use of the virus and distributed free samples. By 1991, the virus was being applied on about 34,000 ha in Paraná State at a cost of only about US\$1/ha. In Santa Catarina state, virus applications to early instars resulted in almost complete control, and pesticide applications were reduced by 60%. The virus is at present being used to control the hornworm on large cassava plantations in southern Brazil.

In Venezuela, where the hornworm is endemic, the virus preparation was applied (at 70 ml/ha) to large cassava plantations (7,000 ha) via overhead sprinkler irrigation systems when larvae were in the first and second instars. This not only resulted in 100% control but also eliminated pesticides; the cost of gathering, processing, storing and applying the virus preparation was only US\$4/ha. The key to effective hornworm control is training farmers to detect outbreaks through light trapping of adults or field monitoring combined with the timely application of a biopesticide (or chemical insecticide) when larvae are in their early instars (1–3).

## Secondary Pests

This review has concentrated on the four major groups of cassava pests: mites, mealybugs, whiteflies and hornworm. There are several additional arthropod pests that attack the crop and can cause yield losses on a localized basis. These include thrips, stemborers, lacebugs, scale insects, shootflies, grasshoppers, leafcutter ants, the burrower bug and other soil-borne pests (Bellotti 2002, 2008). These “occasional” or incidental pests occur either sporadically or at such low population levels that yields are usually not affected. Changes in

agronomic practices, varietal changes or climate change (warmer temperatures or longer dry or rainy season) could influence pest populations, causing changes in the amount of crop damage and yield losses or lowering root quality.

Pest populations of thrips, lacebugs and scale insects tend to increase more rapidly during dry periods. The thrips, *Frankliniella williamsi*, can reduce cassava yields by 5 to 28%, depending on varietal susceptibility (Van Schoonhoven 1974). Warm temperatures and dry periods favor lacebugs (*Vatiga illudens*, *V. manihote*, *Amblystira machalama*; Salick 1983). *Vatiga illudens* predominates in Brazil, where it is reported to cause yield losses, especially in the Campo Cerrado region (Farias and Alves 2004). Yield losses due to *A. machalama* in Colombia have been measured at 39% (Bellotti 2002, 2008). Several scale insects (*Aonidonytilus albus*, *Saissetia Miranda*) are reported to attack cassava stems and leaves in the Americas, Africa and Asia, with more severe outbreaks during the dry season (Bellotti 2008). *Aonidonytilus albus* is the most important and widely disseminated scale species. Yield losses up to 20% in fresh roots and 50 to 60% in planting material (stem cuttings) have been documented in Colombia (Bellotti 2002).

The majority of cassava arthropod pests feed on leaves and stems, causing crop damage indirectly by reducing root yield. Few pests cause direct, irrevocable damage to the edible roots. The most important and damaging species appear to be generalist feeders, and the hypothesis is that the cyanogenic potential in cassava root peel and parenchyma is a defense mechanism against generalist root feeders (Bellotti and Riis 1994). Soil-borne pests such as burrower bugs (*Cyrtomenus bergi*) and several species of whitegrubs feed on and damage cassava roots, and these species require moist soil for optimal development. *Cyrtomenus bergi* is strongly attracted to moist soils. It will migrate when soil moisture content is below 22% and is most persistent when moisture content exceeds 31%. The rainy season greatly favors adult and nymphal survival, behavior and dispersal, in contrast to the dry season, when nymphal mortality increases (Riis et al. 2005a). *Cyrtomenus bergi* nymphs and adults feed on cassava roots by penetrating the peel and parenchyma with their strong thin stylets. Feeding permits the entrance of several soil-borne pathogens, causing rotten spots on the root parenchyma (Bellotti and Riis 1994; Riis et al. 2005b). Even low *C. bergi* populations can cause considerable root damage and the darkened lesions on the white root parenchyma are not acceptable for the fresh consumption market. Field trials in Colombia showed that damage can reach 70 to 80% of total roots with more than 50% reduction in starch content (Bellotti 2008).

A complex of root-feeding whitegrubs (Scarabacidae) damage cassava in many regions of the Americas, Africa and Asia (Bellotti 2008). Whitegrubs are classified as semi-edaphic (along with ants and termites) as they spend only a portion of their life cycle in the soil. It is during the larval

stages in the soil that they can damage cassava's tuberous roots. The genus commonly associated with damage to cassava in the Neotropics and Africa is *Phyllophaga* (Pardo-Locarno et al. 2005), while other grubs—*Leucopholis rorida*, *Lepidiota stigma*, *Aserica* sp and *Holotrichia* sp.—are reported damaging cassava in Asia (Pillai et al. 1993). Whitegrubs can also damage cassava by feeding on stem cuttings being used to establish new crop plantings, thereby reducing plant establishment and survival (Ortega-Ojeda et al. 2007). Damage to cassava occurs primarily during the rainy season. Grubs burrow deeper into the soil during dry periods and migrate upward when rains begin and soil moisture increases, allowing them to feed on cassava roots.

In recent years soil-borne pests have increased in importance in cassava plantations in southern Brazil. It is believed that warmer temperatures have contributed to this increase. The coleopteran *Migdalus fryanus* (Coleoptera: Vesperidae), an important pest of sugarcane, has been identified as causing considerable damage to cassava stem cuttings (for planting) and young tuberous roots (Machado et al. 2006; Pietrowski et al. 2010). *Migdalus fryanus* damages cassava during the larval stage by initially rasping the cortex of tuberous roots and later tunneling into the roots and by introducing soil pathogens that cause severe rotting. Adult and larval activity begin at the onset of the rainy season.

### Arthropod Pests under Climate Change

Temperature and precipitation changes will affect reproduction, mortality, development times and other important characteristics of cassava pests, which in turn will affect yields (Bale et al. 2002). To understand the general magnitude of these expected changes, we briefly review key interactions between cassava pests and climate. Then, climate change models based on the United Nations International Panel on Climate Change (IPCC) scenarios (Table 2) were analyzed in the context of temperature thresholds related with climatic conditions throughout the year and the length of the dry season.

In general, arthropod pests are more damaging in seasonally dry or semi-arid regions, being less severe in areas of considerable and consistent rainfall. Mites, mealybugs, lacebugs and thrips populations are higher and cause more severe yield losses during a prolonged dry season (3 to 6 month or longer). There are exceptions to this rule; hornworm attacks will frequently occur at the onset of the rainy season when there is considerable new growth and young foliage. Severe whitefly attacks often coincide with the rainy season when young, succulent leaves occur, which are preferred for oviposition and feeding by the immature and adult stages. Studies have also shown that whitegrubs and burrower bugs prefer soils with higher moisture content (Riis 1997; Riis et al. 2005a).

**Table 2** 13 different global climate models used

Model	Institute	Model name	Country
BCCR-BCM 2	Bjerknes Centre for Climate Research	Bergen Climate Model	Norway
CCCMA-CGSM3	Canadian Centre for Climate Modelling and Analysis	CCCMA- CGSM3	Canada
CNRM- CM3	Centre National de Recherches Météorologiques	CNRM	France
CSIRO-Mk3.5	Commonwealth Scientific and Industrial Research Organisation CSIRO	CSIRO Mark 3.5	Australia
GFDL-cm 2.1	Geophysical Fluid Dynamics Laboratory	(AOGCM) CGER 2002	USA
GISS-AOM	NASA Goddard Institute for Space Studies	AOM 4×3	USA
IAP- FGOALS	Institute of Atmospheric Physics	FGOALS1.0_g	China
MIROC3.2 h	Center for Climate System Research, U. National Institute for Environmental Studies, Frontier Research Center for Global Chance	Model for Interdisciplinary Research on Climate	Tokyo/ Japan
MIUB-ECHO-G	Meteorological Institute of the University of Bonn	ECHO-G = ECHAM4 + HOPE-G	Germany
MPI-ECHAMS MPI-OM	Max Planck Institute for Meteorology	ECHAM5/MPI-OM	Germany
MRI- GCDM2 3.2	Meteorological Research Institute	MRI-CGCM2.3.2 TAR = MRI-CGCM2.0	Japan
NCAR-PCM	National Center for Atmospheric Research	Parallel Climate Model	USA
NIES 99	Center for climate system Research (CCRS) National Institute for Environmental Studies	NIES 99	Japan

The cassava plant is well adapted to long periods of limited water and responds to water shortage by reducing its evaporative (leaf) surface rapidly and efficiently and by partially closing the stomata, thereby increasing water-use efficiency. The crop has the potential to recover from yield losses from seasonably dry periods and pest attack due to the higher photosynthetic rate in newly formed leaves (El-Sharkawy 1993). Younger leaves play a key role in plant carbon nutrition, and most pests prefer the young canopy leaves; thus, dry-season feeding tends to cause the greatest yield losses in cassava (Calatayud et al. 2002).

Climate change predictions indicate that certain agricultural lands will receive less rainfall or experience longer dry periods in the future. The cassava crop may have a comparative advantage in these extended seasonally drier areas; however, increased cassava production in extensive drier regions of the Americas, Africa and Asia may result in severe pest outbreaks or new pests adapting to cassava, resulting in reduced yields and/or increased pesticide use. Yield losses due to mites ranged from 21 to 80% depending on length of attack, varietal susceptibility, duration of the dry season and region. Whitefly attacks lasting 1-, 6- or 11 month resulted in 5, 42 and 79% yield losses, respectively, in Colombia. Mealybug attacks in Brazil and Africa during prolonged dry seasons resulted in yield losses as high as 80% (Bellotti 2008). More recently, mealybug (*P. manihoti*) attacks in Thailand have resulted in an estimated 50% yield loss.

Effects of climate change on cassava pests are due to a combination of higher temperatures with longer dry seasons. For example, populations of the cassava green mite (*M.*

*tanajoa*) increase dramatically, and remain high, during prolonged dry seasons, causing severe crop damage (Yaninek and Animashaun 1987). Yield trials in experimental cassava fields in Colombia resulted in 21, 25 or 53% root yield losses during 3-, 4-, or 6-month mite attacks that corresponded with the dry season (Bellotti 2002).

For each of the 13 global climate models (GCM; projected using the 2050 climate) and current conditions (Hijmans et al. 2005), we mapped four different temperature variables: (1) mean temperature of wettest quarter, (2) mean temperature of driest quarter, (3) mean temperature of warmest quarter and (4) mean temperature of coldest quarter, together with the length of the dry season, defined as the number of consecutive months with rainfall below 60 mm, as the precipitation variable. Temperature maps were combined using weighted overlay, where each map variable contributed 25% to the temperature result. Weights for variables were assigned according to Table 3. Finally, temperature and precipitation variables were overlaid with each layer contributing 50% to the final score, with the exception of hornworm, which has been assessed solely on the basis of temperature limits as no information on its precipitation requirements is available to, our best knowledge. Table 3 shows ranges of optimum temperature for survival and reproduction of green mites, whiteflies, mealybugs and hornworms. Temperature ranges were determined from different studies carried out under different environmental conditions (Lema and Herren 1985; Mesa et al. 1987; CIAT 1989; Yaninek et al. 1989a, b; Bosco and Caciagli 1998; Drost et al. 1998; Albergaria and Cividanes 2002; Yang and Chi 2006; Minko 2009).

**Table 3** Temperature and dry season ranges.

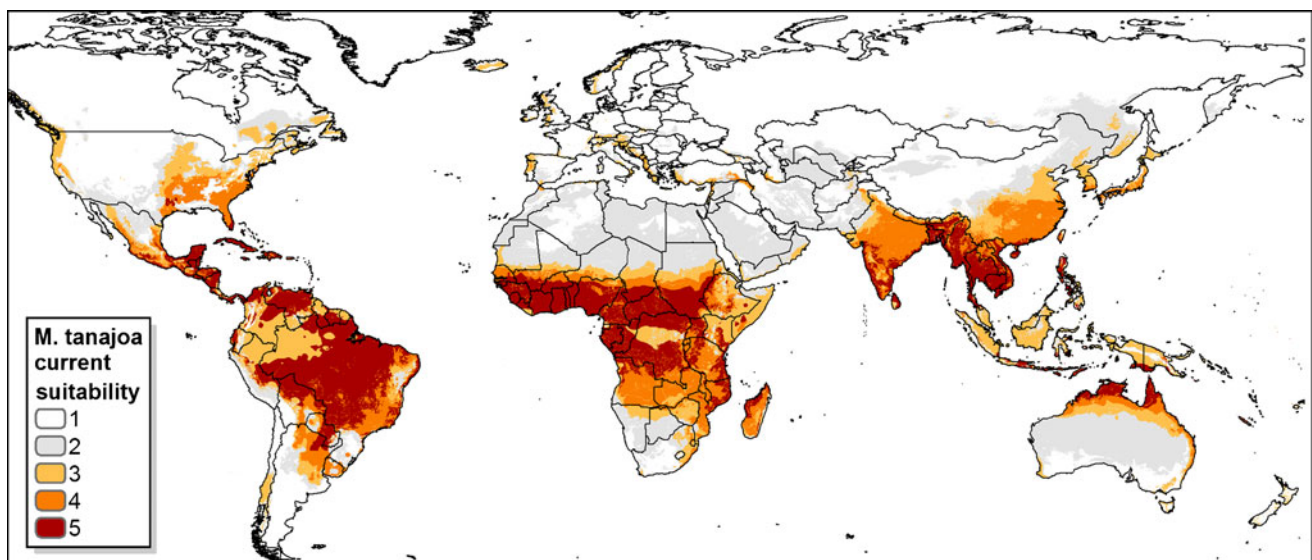
	GM		MB		Wh		HW	Weight
	Temp	Dry m	Temp	Dry m	Temp	Dry m	Temp	
Min. threshold	<12	0–3	<15	0–3	<8.3	0–4	<11.2	1
Range min temp	12–15	–	15	–	8.3–14	–	11.2	2
Range optimum min	15–22	–	15–23	–	14–24	–	11.2–20	3
Optimum	22–24	–	23–27	–	24–26	–	20.1–25	4
Range optimum max	24–31	3–6	27–30	3–6	26–29	5–6	25.1–30	5
Range max temp	31–33	7	30–30.5	7	29–33	7	30.1–31	4
Max. threshold	33–34	8–9	30.5–31	8–9	33–35	8	31–32	3
	34–36	10–12	31	10–12	34–36	10–12	32–34	2

(Lema and Herren 1985; Minko 2009; Yaninek et al. 1989a, b; Mesa et al. 1987; Bosco and Caciagli 1998; Drost et al. 1998; Albergaria and Cividanes 2002; Yang and Chi 2006; CIAT 1989)

The minimum temperature at which these pests can survive is 11.2°C for hornworm, 12 to 15°C for green mites, 15°C for mealybugs and between 8.3 and 14°C for whiteflies. Maximum temperatures are between 34 and 36°C for green mites and whiteflies, 31°C for mealybugs and between 32 and 34°C for the hornworm. Pests can survive at temperatures of roughly 15 to 20°C, but these are less than optimal conditions. All four pests survive and reproduce well at temperatures between 20 and 30°C at the lower end of the range and between 30 and 32°C at the higher end of the range. However, the best temperature conditions for survival and reproduction of these pests are between 24 and 30°C.

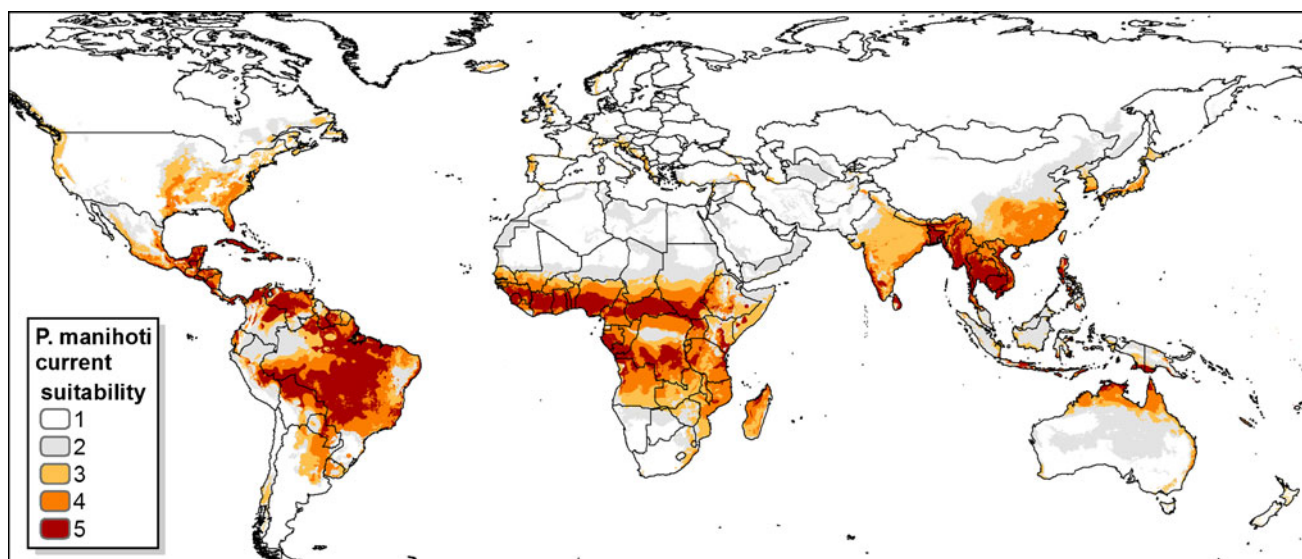
High populations and severe damage occur in the dry season between 3 and 6 mo. for green mites and mealybugs. Development rate decreases when the dry period is extended, due to feeding stress.

Figures 1 and 2 show the suitability scores for green mite and mealybug, respectively, for the current climate. Figures 3 and 4 show the projected 2050 climate. Difference maps are shown in Figs. 5 and 6. The insects are discussed together because the two species have similar distribution ranges, having co-evolved with the crop. In general, pest impacts between the current and projected 2050 climate appear similar for both the mealybug and green mite. In Latin America, the regions of eastern Brazil, northern Argentina, southern Bolivia, western Peru and the Ecuadorian coast are more suitable under the projected future scenario. The eastern Colombian plains, the northern coastal regions of the continent, southern Brazil and Paraguay appear less suitable. In Africa, suitability declines in much of northern Africa, in the Sahel, and in central Africa, but increases somewhat in southern and eastern Africa. In Asia, suitability decreases in northern India, but increases in the



**Fig. 1** Suitability of cassava green mite (*Mononychellus tanajoa*) for current conditions. Values of suitability show 1- No suitability, 2- Restricted, 3- Low, 4- Moderate, 5- Optimum





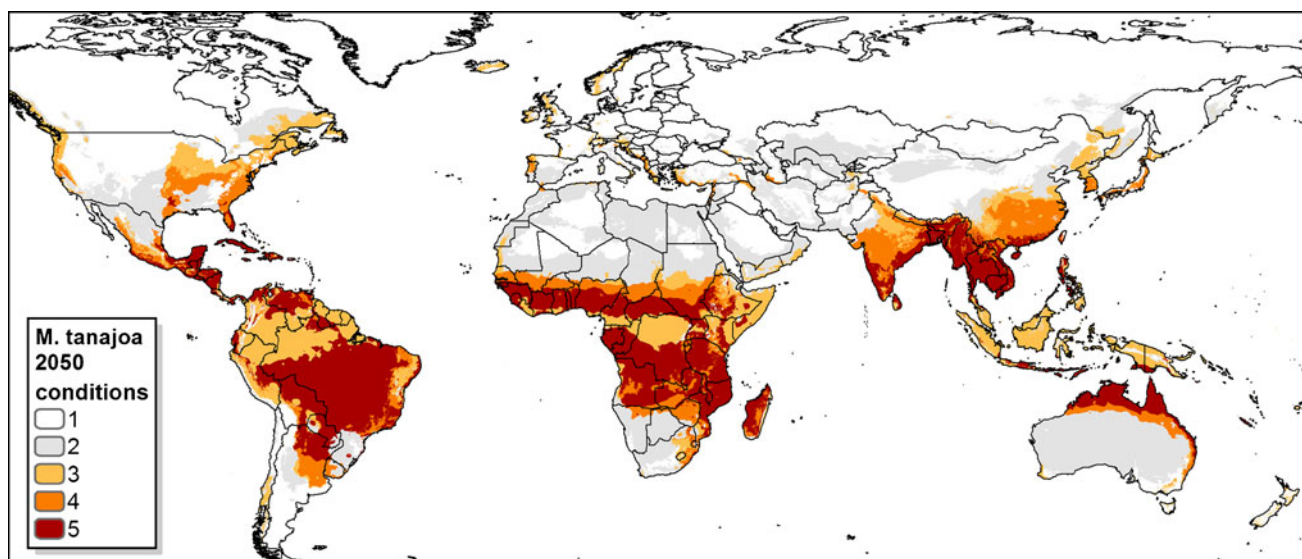
**Fig. 2** Suitability of cassava mealybug (*Phenacoccus manihoti*) for current conditions. Values of suitability show 1- No suitability, 2- Restricted, 3- Low, 4- Moderate, 5- Optimum

coastal regions and southeastern Asia. Suitability stays much the same in the rest of the continent.

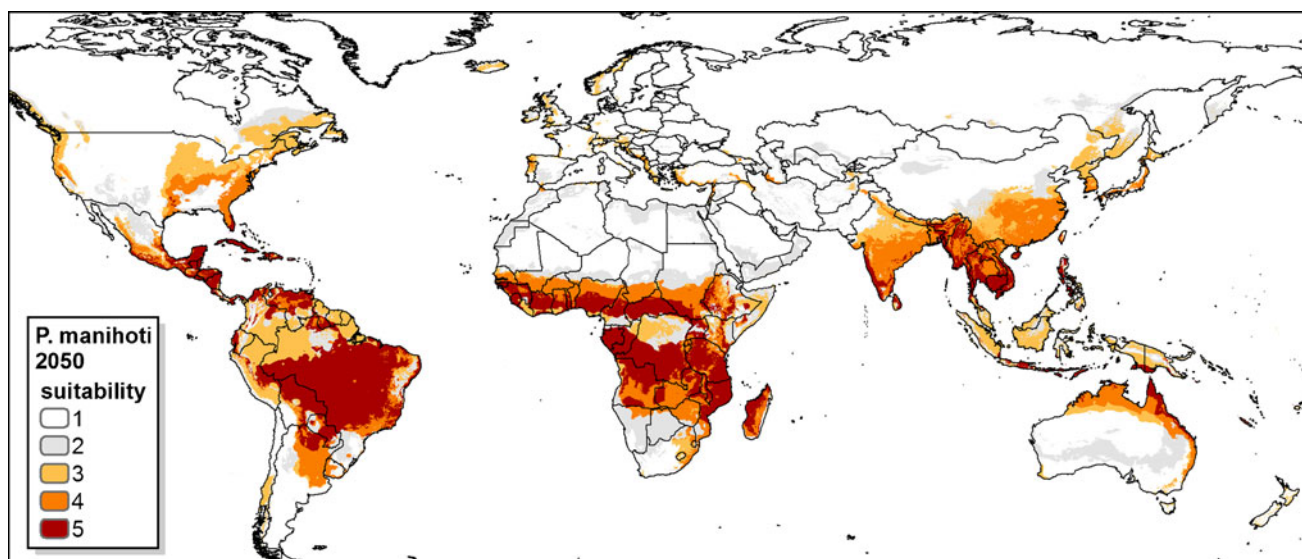
Figures 7 and 8 show the weighted overlay effects of temperature ranges on *B. tabaci* for current conditions and for the projected future climate, respectively. Figure 9 shows differences between current and future conditions. In the Latin American region, eastern and northeast Brazil, northern Argentina, southeastern Peru and central Bolivia increase their climatic suitability. In Africa, areas in the central and southern parts of the continent are projected to be more suitable for *B. tabaci* development. Losses of habitat could occur mainly in North Africa and the Middle

East, and to a lesser extent in northern India and some regions of northern South America.

*Erinnyis ello* is a pest specific to the Americas, perhaps due its difficulty in crossing ocean barriers. The current and projected distributions (Figs. 10 and 11) show that areas cultivated in cassava in Africa and Asia have suitable conditions for hornworm development. Overall, the difference maps shows that northern Africa, India, southeastern Asia and Australia are projected to be less suitable for hornworm development. But for large areas of the world there is little difference in suitability increases between the current and projected climates for the horn worm (Fig. 12).



**Fig. 3** Suitability of cassava green mite (*Mononychellus tanajoa*) for projected climate (2050). Values of suitability show 1- No suitability, 2- Restricted, 3- Low, 4- Moderate, 5- Optimum

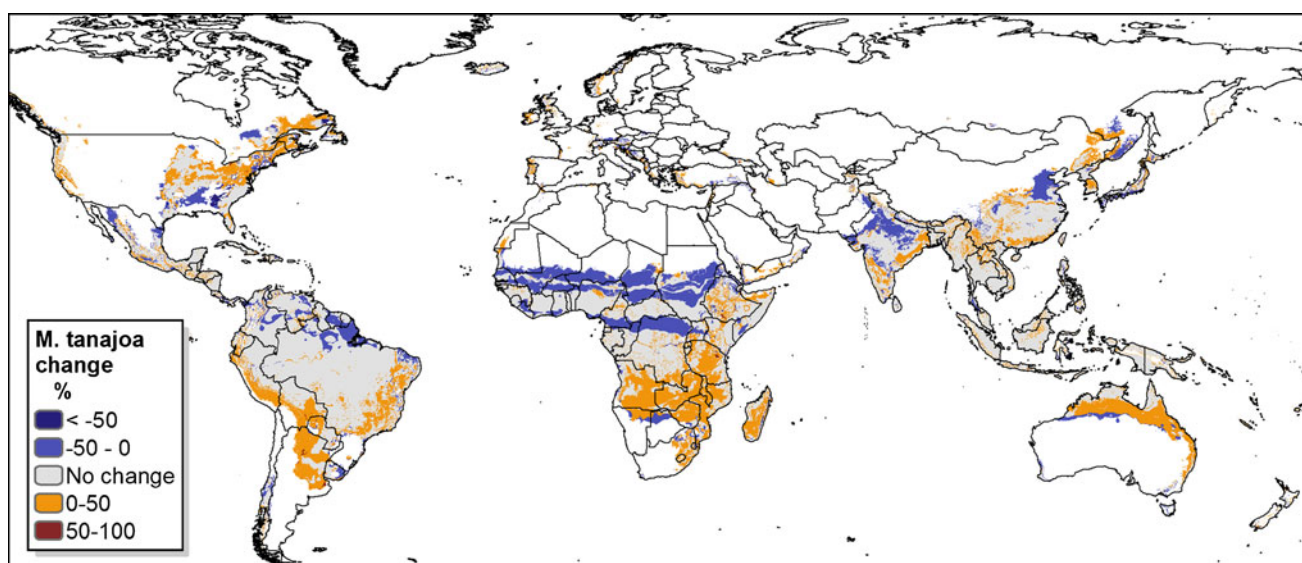


**Fig. 4** Suitability of cassava mealybug (*Phenacoccus manihoti*) for projected climate (2050). Values of suitability show 1- No suitability, 2- Restricted, 3- Low, 4- Moderate, 5- Optimum

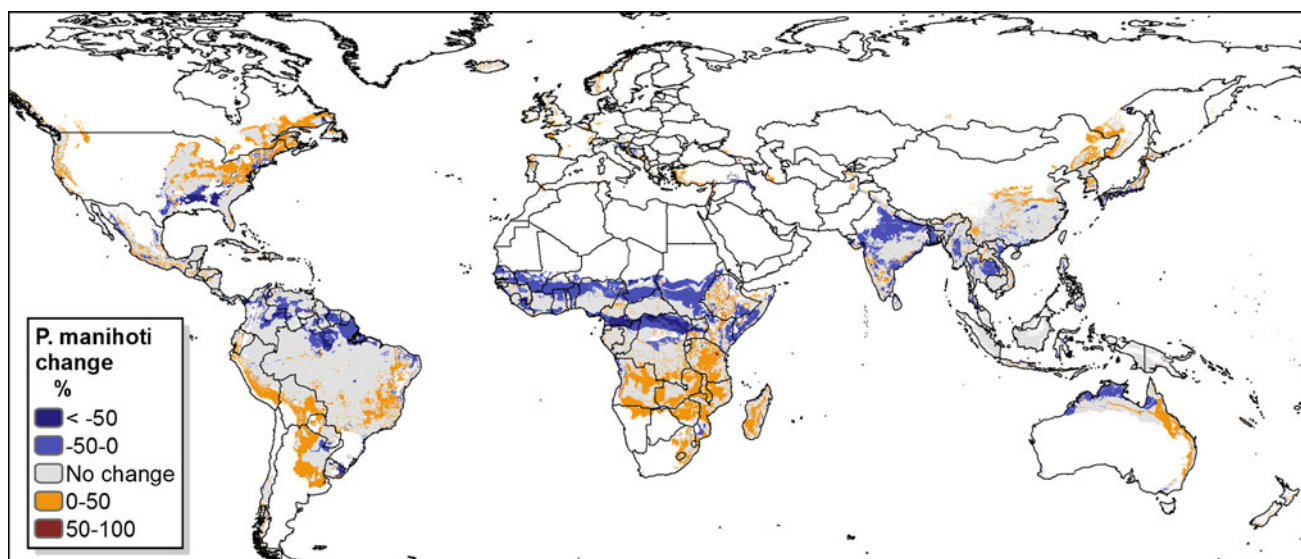
In general, whiteflies, green mites and mealybugs register a suitability increase in the same areas in South America: northeastern Brazil, northern Argentina, south-central Bolivia, and southwestern Peru. In Africa increases are projected in Southeast Africa and Madagascar. In Asia, regions with greater projected suitability for these pest species are coastal India and southeastern Asia.

Responses of species to changes in their environment depend on different evolutionary processes. Adaptation to new ranges could be determined by the relations

between host or pathogens (Peterson 2008) and biotic and abiotic limiting factors (natural enemies, competition, climate). For example, cassava green mite and cassava mealybug have had stable relationships in their center of origin. But when introduced to Africa, these pests devastated the cassava crop (Yaninek et al. 1989a, b). The same is true for the interaction between *B. tabaci* and cassava in Africa. Similarly, such could be the case for future accidental introductions in Asia for green mites and mealybugs, in Africa for hornworms and in the Americas for whiteflies with cassava.



**Fig. 5** Suitability change of cassava green mite (*Mononychellus tanajoa*). Blue tones represent less suitability and red tones increased suitability



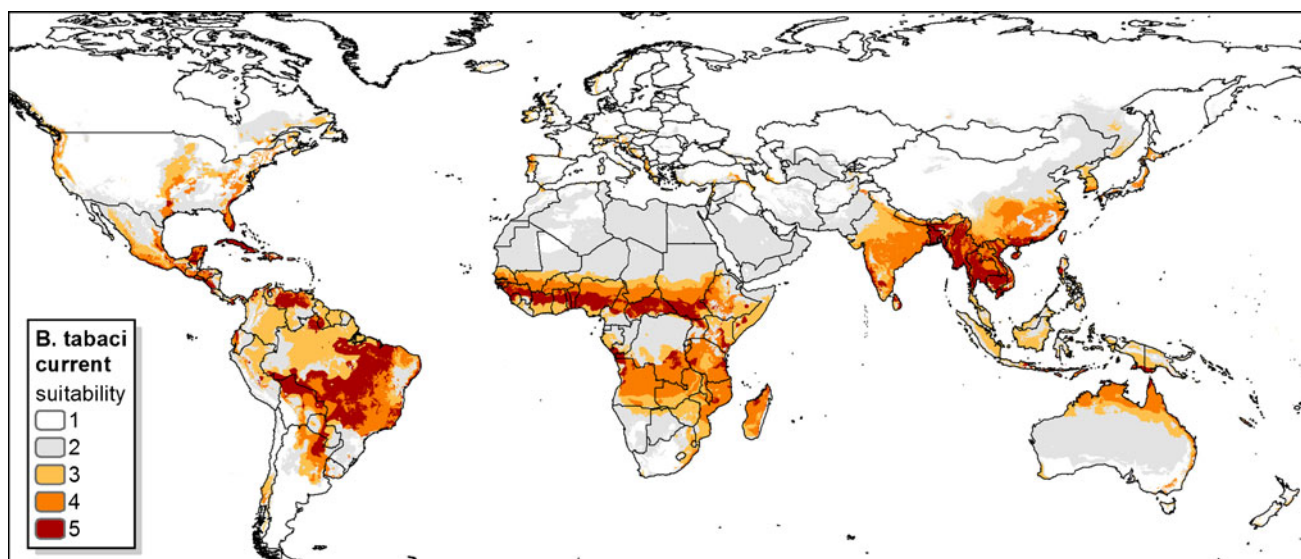
**Fig. 6** Suitability change of cassava mealybug (*Phenacoccus manihoti*). Blue tones represent less suitability and red tones increased suitability

### Industrialization of Cassava and Crop Management

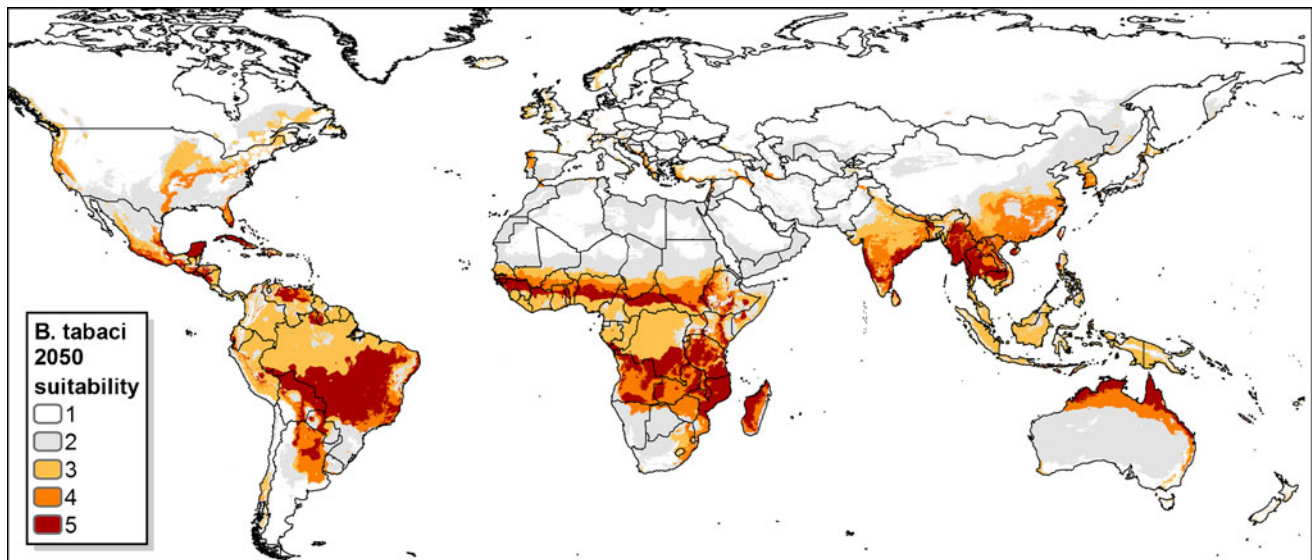
Much of the present increase in cassava production in Asia, Africa and the Americas is market driven and influenced by the processing and private sector (Howeler 2010). Cassava provides raw material for the animal feed, starch and biofuel industries as well as remaining an important food for human consumption. It can provide a stable income source for both small and larger farmers and increase job opportunities in the rural sector where connected to the private processing industries. The trend toward larger production units to

respond to the demands of the processing industries insures that integrated pest management (IPM) will continue to play an important role in sustaining high cassava production levels.

Advanced commercial-scale cassava production is characterized by greater farm size, mechanization (planting, harvesting, weed control), higher inputs (fertilizers, herbicides), increased pesticide use, improved, higher-yielding varieties, monoculture, staggered planting dates, overlapping crop cycles, and availability of technical assistance. In these cropping systems, cassava is grown as a functional perennial, and pest species may be continually present and



**Fig. 7** Suitability of whitefly (*Bemisia tabaci*) for current conditions. Values of suitability show 1- No suitability, 2- Restricted, 3- Low, 4- Moderate, 5- Optimum

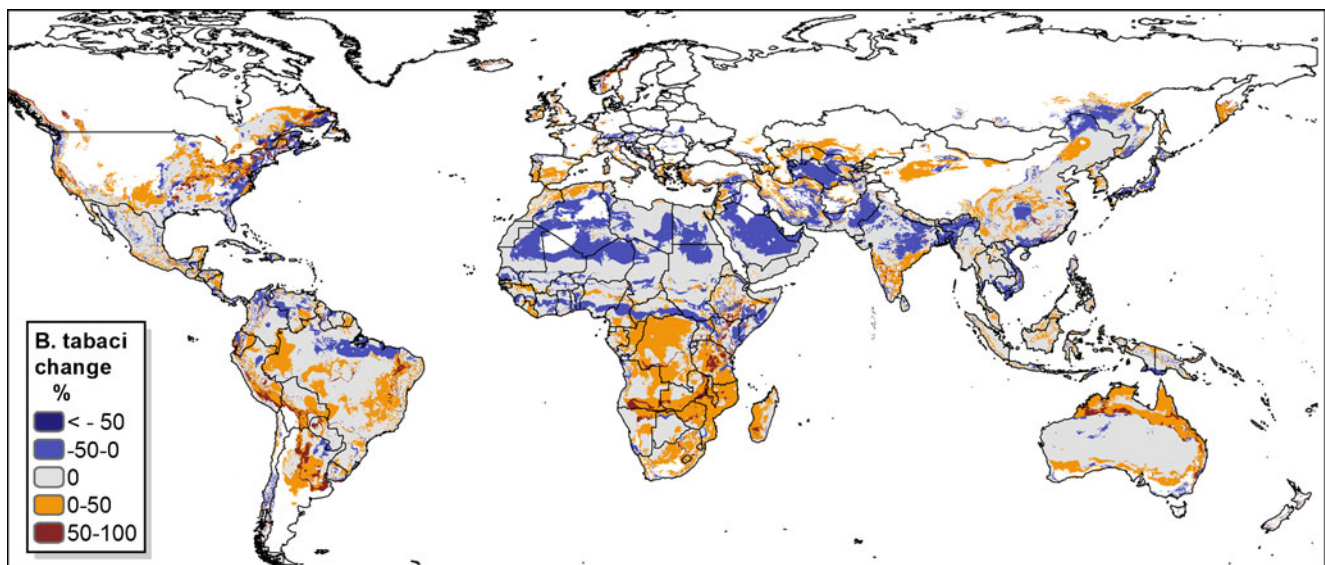


**Fig. 8** Suitability of whitefly (*Bemisia tabaci*) for projected climate (2050). Values of suitability show 1- No suitability, 2- Restricted, 3- Low, 4- Moderate, 5- Optimum

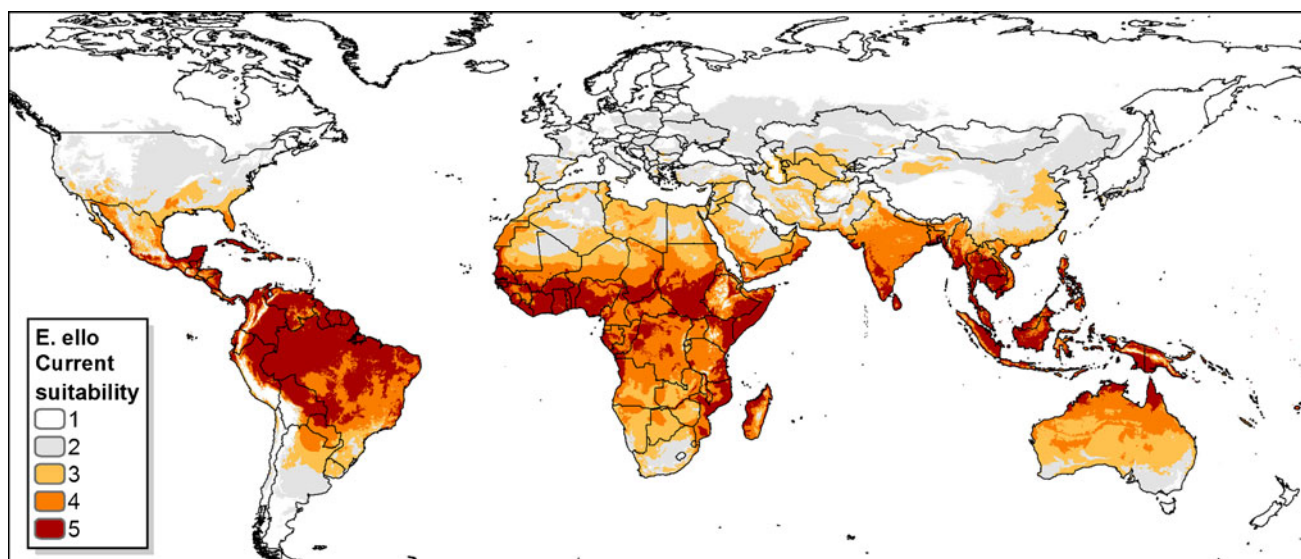
thereby able to increase their populations rapidly when environmental conditions are favorable. Natural enemy populations may not respond rapidly enough to suppress the increasing pest populations, and outbreaks can occur.

This scenario seems to be occurring in south-central Brazil (States of Paraná, Sao Paulo, Mato Grosso Sul), where in recent years pest populations have shown dramatic increases on large scale (over 50 ha) cassava plantations. Crop damage resulting in root yield losses due to whiteflies, mealybugs, lacebugs and hornworm have been observed in this region. These increases in pest populations and crop damage may be the consequence of climate changes and subsequent alterations in

crop management practices (Herrera Campo et al. 2011; Bellotti et al. 2010). South-central Brazil is sub-tropical and in recent years, according to cassava producers in the region, temperatures during the “winter” months (June to August) have been warmer, with less probability of frost. This has had an effect on crop management practices and pest populations. Farmers no longer prune all stems back to ground level (to save and insure planting material for the subsequent crop cycle), leaving growing stems and foliage. This practice, combined with the absence of frost, results in higher populations of pests surviving the “winter” period (Bellotti per observ. 2006–2010). Therefore there is an active pest population



**Fig. 9** Suitability change of whitefly (*Bemisia tabaci*). Blue tones represent less suitability and red tones increased suitability

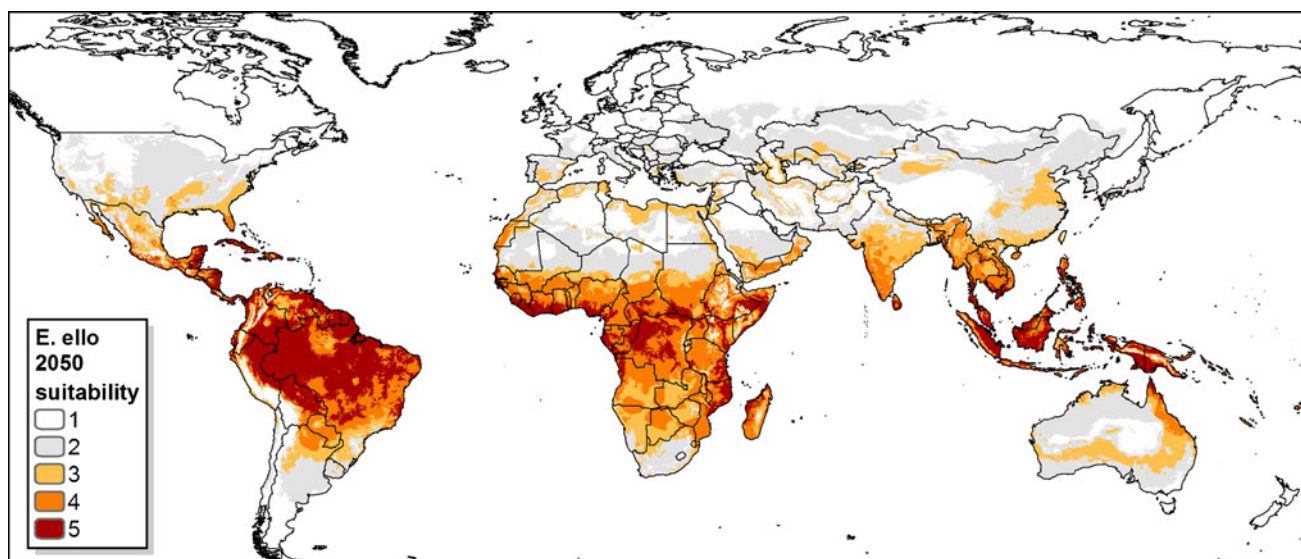


**Fig. 10** Suitability of hornworm (*E. ello*) for current conditions. Values of suitability show 1- No suitability, 2- Restricted, 3- Low, 4- Moderate, 5- Optimum

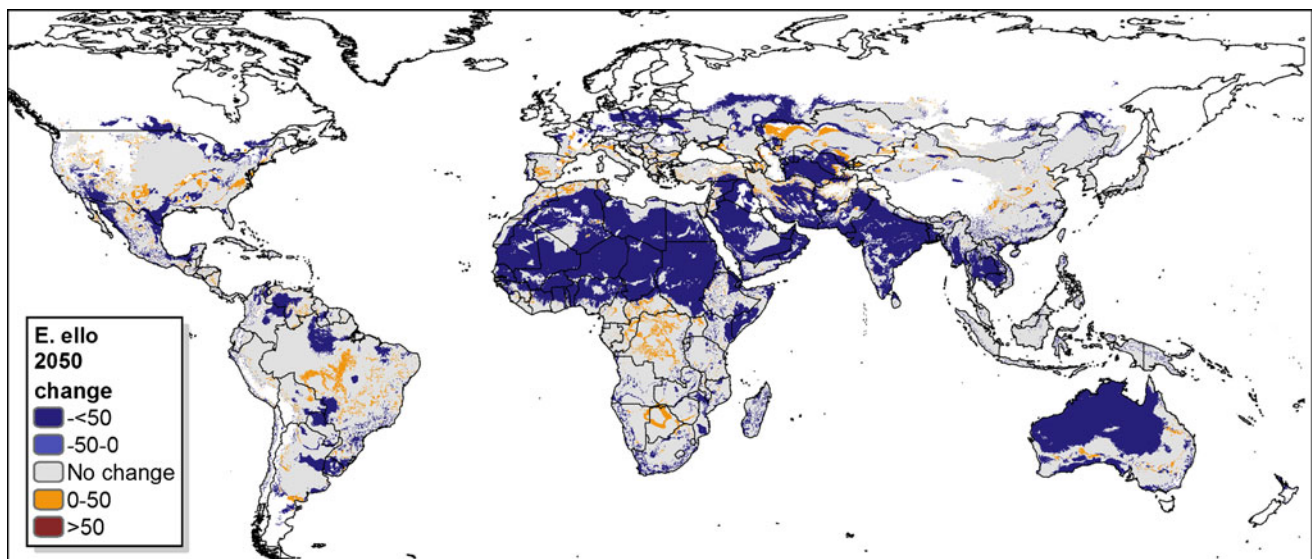
present when re-growth occurs in September and when stem cuttings of the subsequent crop cycle emerge, establishing young tender plants. In addition, warmer temperatures and more frequent rainfall have encouraged more frequent or staggered plantings, resulting in having the presence of cassava at varying ages in the same field or plantation. This provides ideal conditions for increases in cassava pests, such as whiteflies, mealybugs and lacebugs. This system of continual planting, growth and harvest is driven by the demands of the starch processing industries.

Modifications in crop management and effects of climate change, especially warmer temperatures and altered rainfall patterns, also affect the occurrence and dynamics of arthropod pests in cassava fields. This may be manifested in several ways:

1. The emergence of secondary pests in higher populations, able to cause crop damage.
2. Changes in pest distribution and extension of geographic ranges of pests.



**Fig. 11** Suitability of cassava hornworm (*E. ello*) for projected climate (2050). Values of suitability show 1- No suitability, 2- Restricted, 3- Low, 4- Moderate, 5- Optimum



**Fig. 12** Suitability change of cassava hornworm (*E. ello*). Blue tones represent less suitability and red tones increased suitability

3. Shifts in species abundance and intensification of pest management problems.
4. Changes in population growth rate and the intrinsic rate of increase of pests.
5. Increased number of pest generations during a cropping cycle, which can be especially important on a long season crop like cassava.
6. Extension of the pest development season.
7. Changes in crop-pest-natural enemy synchrony.
8. Increased risk of invasion of exotic or migrant pests.

It is considered that the increase in pest problems being experienced on cassava in Asia and South America, especially in Brazil, can be attributed to one or more of the above conditions.

### Future Trends

Important criteria and future trends that will influence the management of arthropod pests of cassava include:

1. Industrialization, increased area under production, greater yield losses due to pests on larger plantations and spatial and temporal continuum of cassava cultivation will require alternative and innovative management strategies.
2. Changing climatic patterns, warmer temperatures and prolonged dry seasons will influence pest occurrence and population dynamics.
3. Increased pesticide use on larger, commercial production units for industrial processing of cassava may disrupt natural biological control, causing outbreaks of key and secondary pests.
4. Continual or overlapping production cycles and other changes in crop management may increase pest incidence and severity and lead to increased pesticide use.
5. An increased potential for introduction of exotic pest species may result from pest movement and dissemination, introduction of exotic and invasive species and the industrialization and increased movement of modified or improved germplasm and varieties.
6. Host plant resistance could be the most practical and cost efficient pest management option for both the small and large cassava farmer. The use of wild *Manihot* species as a source of pest resistance genes should be encouraged.
7. The use of entomopathogens (fungi, bacteria, baculoviruses, nematodes, etc.) could be an effective IPM strategy.
8. The use of ecological niche models and other analysis methods and variables should be used to predict potential distribution of cassava pests and “hotspots” for potential pest outbreaks.
9. Quarantine regulations need to be reinforced to prevent introduction of exotic species and movement of cassava stems between regions, countries or continents. Tissue culture should be promoted as a strategy for the safe movement of cassava germplasm.
10. Global information and communications systems should be developed to monitor pest incidence and movement.

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