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Control Strategies for Whitefly as a Vector for Cassava Viral Diseases

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Section I: Overview & Summary

Cassava is an important crop, particularly in food-insecure regions. It ranks 10th by quantity (19th most important by value) of crops worldwide, with 252,203,769 tonnes produced in 2011 (FAOStat). Cassava yields are compromised by pests such as whiteflies, mites, and weevils, which cause significant crop losses through the spread of viral disease and direct damage to plants. Whiteflies are vectors for viral diseases such as cassava mosaic disease (CMD) and cassava brown streak disease (CBSD), which can reduce yields by up to 40% (Legg & Fauquet, 2004). The flies can also cause direct damage by feeding on the crop and causing root yield reductions. Direct damage is more common on disease-resistant cassava varieties than on local cultivars due to higher whitefly populations on disease-resistant plants, illustrating the uniquely problematic vector-host relationship between cassava and this pest.

This report provides background on whitefly damage to cassava as well as summaries of the evidence on the efficacy of four control strategies:

- Breeding for host plant resistance
- Intercropping and other planting strategies
- Insecticides and Insecticide Resistance Management (IRM)
- Biological control through parasitoids, fungus, and predators

Though we group information by strategy, most researchers report that controlling whiteflies and the viruses for which it is a vector requires a multifaceted approach. As Thresh & Cooter (2005) suggest, the measures to control CMD should be "simple, inexpensive, and within the limited capacity of the farmers' concerns." The four whitefly control strategies are summarized below and discussed in further detail in **Section IV**.

Summary of Control Strategies

Breeding for host plant resistance:
While breeding resistance has received attention among researchers, whiteflies species adapt quickly, which renders plant resistance temporary. Researchers have identified genotypes that show resistance to whiteflies. These genotypes could provide the parental genotypes required for future breeding programs (Omongo, 2012). However, whitefly-resistant varieties are likely to be CMD-susceptible, so when whitefly-resistant varieties are identified, further breeding may be necessary to develop varieties that are resistant to both whiteflies and viruses (Thresh & Cooper, 2005). Centro Internacional de Agricultura Tropical (CIAT) is currently working on identifying genes that confer resistance to whitefly.

Intercropping and other planting strategies:
Intercropping is an environmentally benign method to control whiteflies. It is associated with lower whitefly populations, CMD incidence, and severity (Night, 2011). This planting strategy has the potential to decrease the need for insecticide use and is already commonly practiced by many smallholder farmers. Evidence shows that higher density intercropping is most

effective in controlling whitefly populations (Fargette & Fauquet, 1990). However, the precise planting densities at research stations may differ from what smallholder farmers practice, so results may vary when replicated in the field.

Insecticides and Insecticide Resistance Management (IRM):
Widespread insecticide use has historically been viewed as an ineffective and environmentally damaging strategy to control whitefly populations due to heightened whitefly resistance (Horowitz et al., 2011). However, more recent research shows that new, targeted insect growth regulators (IRGs), in combination with insecticide resistance management (IRM) efforts such as refuge strategies, can increase the effectiveness of these control strategies and delay the resistance of susceptible pests (Carriere et al., 2012). Much of the insecticide and insecticide resistance research has focused on commercial crops such as cotton and ornamental plants rather than cassava.

Biological control through parasitoids, fungus, and predators:
While natural enemies alone do not typically solve whitefly problems (Horowitz et al., 2011), introducing enemies and biological control as part of an integrated pest management system (IPM) may prove more effective. Biological control mechanisms shown to be successful against whiteflies include parasitoids, predators, and fungal control. Exotic parasitoids or predators have been used successfully against whitefly in other crops (Gerling et al., 2001) and may be effective for cassava in some cases after careful suitability studies (Aiisime et al., 2007). Other control methods (breeding for resistance, insecticide) can negatively impact natural enemies, making whitefly control more challenging over the long-term.

This report provides several appendices for reference. *Appendix 1* lists confirmed and proposed viral species spread by whitefly; *Appendix 2* lists natural enemies of whitefly on cassava, which may be important for biological control; and *Appendix 3* lists notable researchers and their affiliated institutions. To provide context for current research and interventions, *Appendix 4* provides a summary table of empirical studies by control mechanism, and *Appendix 5* provides a summary table of intervention programs with a whitefly component.

Section II: Methodology and Research Context

We searched for peer-reviewed journal articles and gray literature using Google, Google Scholar, and the University of Washington Library system using combinations of the words: whitefly, *Bemisia tabaci,* cassava, disease control, strategies, pest management, intercrop, breeding, resistance, and insecticide, among others. We generally limited literature searches to 1990 or later. While we primarily include literature specifically related to cassava, we also include results of research and interventions on other host crops. We have mostly excluded research on whitefly control studies in greenhouses.

Much of the literature on whitefly control mechanisms focuses on commercial crops, and the cassava-specific literature focuses primarily on whitefly as a vector for viral diseases. However, recent publications acknowledge the increasing threat of direct damage from whiteflies and increased risks of new virus types in areas with superabundant[1] whitefly populations.

Research on whitefly control strategies has been concentrated in two research centers: Centro Internacional de Agricultura Tropical (CIAT) in Colombia has focused on *A. socialis* species of whitefly common in the Americas and International Institute of Tropical Agriculture (IITA) in Nigeria has done research on *B. tabaci* common in Africa.

Section III: Background on Whitefly and Cassava Viral Diseases

Whiteflies

Entomologists have identified approximately 1,500 species of whitefly; *Bemisia tabaci (B. tabaci)* is the most common species to which crop losses are attributed in tropical regions (Legg et al., 2003). Whiteflies are difficult to control because they breed multiple times in a year (multivoltine), evolve rapidly, and have a broad range of plant hosts (extreme polyphagy) (Asiimwe et al., 2007).

In the Americas, several species of whitefly (*Aleurotrachelus socialis* and *Trialeurodes variabilis*) are considered to be among the major cassava pests, while in Africa and South Asia *Bemisia tabaci* (*B. tabaci*) is the most prominently cited

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[1] Superabundant whitefly populations are typically 100-times greater than populations outside the CMD pandemic zone (Legg, 2009).

species (Bellotti 2012). *Aleurodicus disperses* may be causing yield loss in Asia, though research on this species and the damage it causes is limited (Bellotti et al., 2012b). Table 1 from Bellotti et al., (2012b) shows the distribution of major whitefly species causing damage to cassava.

Table 1: Major Whitefly Species

Major Species	Americas	Africa	Asia
*Aleurotrachelus socialis**	x		
Aleurothrixus aepim	x		
Aleurodicus dispersus	x	x	x
Aleurodicus flavus	x		
Aleuronudus sp.	x		
Bemisia afer		x	x
Bemisia tuberculata	x		
Bemisia tabaci	x	x	x
Paraleyrodes sp.	x		
Tetraleurodes sp.	x		
Trialeurodes vaporariorum	x		
*Trialeurodes variabilis**	x		

Source: Bellotti *et al*., 2012b; *South America only (communication with Whitefly scientists)

Bemisia tabaci (B. tabaci)

B. tabaci is the most common whitefly species to which cassava crop damage and disease are attributed in tropical regions. Over 900 host plant species are associated with B. tabaci, and they transmit 111 virus species (Global Invasive Species Database). According to Carabalí (2010), scientists generally agree that B. tabaci is a "complex of morphologically indistinguishable populations with different biological biotypes." Both B and Q Biotypes of B. tabaci have been identified, and while the B-Biotype is particularly prevalent on crops in Africa, the Q-Biotype has been more recently identified as a pest to cotton and ornamental plants in the United States (Patil & Fauquet, 2009). Some researchers consider the B type a separate species (B. argentifoloo) (Bellotti et al., 2012b). Insecticide resistance, damage to plants, and virus transmission ability varies between biotypes. The inability of the B-Biotype to colonize cassava in the Americas is postulated as the reason CMD has not spread to this region (Carabali, et al., 2005). A study in Africa found that different types of B. tabaci found on cassava in different geographic areas breed readily, but sweet potato whiteflies do not breed with cassava whiteflies (Maruthi et al., 2001 in Legg et al., 2006).

Whitefly-caused damage

Whiteflies damage cassava directly and are a vector for disease. Whiteflies are vectors for five broad categories of viruses: *Begomovirus*, *Ipomovirus*, *Crinivirus*, *Carlavirus*, and *Torradovirus* but most of the virus species are in the *Begomovirus* genus (*Geminiviridae family,* also referred to as geminiviruses (Legg, 2009; Navas-Castillo et al., 2011). *Appendix 1* provides a list of all accepted and proposed virus species transmitted by the flies as of 2011. Cassava mosaic disease (CMD) (caused by *Begomovirus)* and cassava brown streak disease (CMSD) (caused by *Ipovirus*) cause the most damage in cassava (Legg, 2009). The flies can also cause direct damage by feeding on the crop and causing root yield reductions. Whiteflies also cause disease and damage on tomatoes, pepper, cucurbits, beans, sweet potatoes and other crop species and are a problem for both commercial and small-scale farmers (Morales, 2006).

Cassava Mosaic Disease:

CMD causes a yellowing and distortion of leaves and results in stunted growth. Losses from CMD spread by whiteflies and infected cuttings resulted in production losses up to 47% in East and Central Africa from the early 1990's to 2006 (IITA, n.d.). Despite widespread cassava cultivation in Latin America and several Southeast Asian countries, CMD has only been reported in the African continent and Indian subcontinent (Patil & Fauquet, 2009). CMD is not caused by a single virus, but a collection of several related begomoviruses (Navas-Castillo et al., 2011). Among cassava-infecting viruses, these include:

- African cassava mosaic virus
- East African cassava mosaic virus
- East African cassava mosaic Cameroon virus
- East African cassava mosaic Kenya virus
- East African cassava mosaic Malawi virus
- East African cassava mosaic Zanzibar virus
- South African cassava mosaic virus
- Indian cassava mosaic virus
- Sri Lankan cassava mosaic virus

Though CMD-resistant cassava varieties have been successfully introduced in many of the affected areas, the new CMD-resistant varieties appear to be particularly susceptible to whitefly infestation (ADD CITATION).

Cassava Brown Streak Disease:

Though cassava brown streak disease (CBSD) is less widespread and has received less attention than CMD, it causes major losses due to root necrosis and is now the most significant threat to cassava in East Africa (Hillocks, 2003; Mbanzibwa et al., 2011). Like CMD, CBSD is not caused by a single virus. Two species in the *Ipomovirus* genus, cassava brown streak virus, and the more recently described Ugandan cassava brown streak virus, are associated with CBSD (Mbanzibwa et al., 2011). Maruthi et al. (2005) established whiteflies are a vector for CBSD, but transmission is low and infected plant cuttings are likely a more significant cause of infection. Whiteflies are a vector only over distances of less than 50m, and the virus is transmitted during a short time period of infectivity (RCI- Mid-Term Review, 2012). However new infections of CBSD are associated with peaks in whitefly populations, and Maruthi et al. (2005) suggest experimental conditions may minimize transmission of CBSD by whiteflies relative to natural conditions. Mbanzibwa et al. (2011) report that recombination is a mechanism for both virus species and evolution could be accelerated as the viruses spread to new geographic areas.

Emerging Viruses

According to Navas-Castillo et al. (2011), in addition to the major cassava-affecting viral diseases, "it is not very risky to assert that a new virus will emerge when given the opportunity." The underlying causes of the emergence of new whitefly-transmitted viral plant diseases are multifactorial and result from a combination of changes in virus, vector, host, and environment. Factors that may contribute to emergence include recombination and synergism between virus species, new vector biotypes, genome integration of the virus and host adaptation (Fargette et al., 2006). Other factors that increase whitefly-transmitted diseases emerging include host range expansion, long-distance traffic of plant materials or insects, agro-ecological changes, agricultural intensification, and climate change.

Appendix 1 provides a comprehensive list of whitefly-hosted virus species, including the 111 that B. tabaci specifically host. The vast majority of viruses are begomoviruses (there are nine that cause cassava mosiac disease), though two ipomoviruses are important to cassava as well (these cause cassava brownstreak disease). In recent years, the numbers of new begomovirus species as well as new hosts and geographical distributions for known begomoviruses have increased substantially in Latin America, particularly in Brazil and in the Caribbean. The two more recent cases of emerging recombinant begomoviruses that have been well documented include tomato yellow leaf curl disease (TYLCD) in Southern Spain and a Ugandan strain of East African cassava mosaic virus. Other important emerging diseases affecting vegetable crops include diseases caused by bipartite begomoviruses in Latin America, ipomovirus diseases of cucurbits, tomato chlorosis caused by criniviruses, and the torrado-like diseases of tomato.

While Fauquet et al. (1998) argue that evolutionary changes in geminiviruses such as the recombination between ACMV and EACMV to produce UgV/EACMV-UG (the virus responsible for the CMD epidemic in Uganda from 1989-1991) may be relatively common, Legg & Thresh (2000) assert that the frequency with which these recombinations between two distinct cassava mosaic geminiviruses become epidemiologically significant is relatively low, which they say is encouraging for CMD management in the 21st century.

Controlling emerging whitefly-transmitted diseases is expected to require regional solutions (Navas-Castillo et al., 2011). In the case of a tomato mottle virus emergence in Florida, Navas-Castillo et al. describe the state's establishment of a synchronized tomato-free period and facilitated growers' use of transplants imported from distant, infection-free areas.

Direct damage from whiteflies

Direct crop damage occurs when whiteflies feed on plant phloem, removing plant sap and reducing overall plant vitality. Whiteflies also excrete honeydew, which promotes sooty mold on leaves that interferes with photosynthesis and damages harvest quality (Navas-Castillo et al., 2011). *A. socialis, A. aepim,* and *T. variabilis* cause yield loss through direct feeding in the Americas.

B. tabaci on CMD-resistant cultivars:

Until recently, whiteflies in Africa primarily harmed cassava as a viral vector, but beginning in the 1990's, superabundant whiteflies have also caused damage to cassava through direct feeding on plant leaves. Superabundant whitefly populations may be caused by a particular *B. tabaci* biotype or as a result of interaction between *B. tababci* and CMD-infected cassava. However, for unknown reasons, the superabundant populations are found on CMD-resistant varieties (Legg, 2009). Local cultivars in East Africa are highly susceptible to CMD but relatively unaffected by direct whitefly feeding, while improved, resistant varieties have yield losses from direct damage ranging from 12.5-44.6%, in part because CMD-resistant plants host larger populations of *B. tabaci* (Stansly & McKenzie, 2008). High populations of *B. tabaci* in Uganda are due in part to adoption of CMD-resistant cultivars (Omongo et al., 2012). The large populations of whiteflies feed on both the CMD resistant varieties and susceptible varieties planted nearby. This reduces the effectiveness of interventions aimed at breeding or dissemination of clean, virus-resistant cuttings and increases the risk of new virulent virus strains (Asiimwe et al., 2007). The cassava geminiviruses can recombine; recombination is more likely when whiteflies are superabundant (Legg et al., 2003).

Farmer awareness of whitefly as a disease vector

Many farmers have low awareness of whiteflies as vectors of CMD, as shown by surveys conducted with the ESCaPP program in the mid-90's in various countries in SSA. For example in Benin, whiteflies were present at all 60 research sites with an average of 0.5-3.2 flies per plant. However, the survey showed that 60% of farmers did not know that whiteflies caused damage to cassava. Those farmers did not have a specific word for whiteflies in the local language. They identified whiteflies with the general word "insect", implying a need to increase biological awareness. This may suggest that farmers' perception of the incidence of CMD was much lower than field data show (Anderson, 2005). Among farmers in various districts in western Kenya, several other species ranked as more important cassava pests, including mealy bugs, moles, green cassava mites, scales, and termites (IITA, 1999). We did not find more recent information on farmer perceptions of whitefly as a disease vector.

Section IV: Whitefly Control Strategies in the Literature

The following section provides an overview of recent, available literature on each of the whitefly intervention strategies, as summarized in **Section I**.

Breeding for Host Plant Resistance (HPR)

While breeding resistance has received attention among researchers, whitefly species adapt quickly, which renders plant resistance temporary. Whitefly "resistant" cassava varieties means that they can depress whitefly populations by reducing whitefly oviposition, lengthening the development period, and causing high nymphal mortality. If whitefly populations are depressed, then other methods of biological control (discussed below) can be more effective (Bellotti, 2012a).

Researchers have mapped the cassava genome (Prochnik et al., 2012) and identified genes conferring resistance to CMD (Akano, 2001; Okogbenin et al, 2012). Transgenic varieties have been developed with resistance to CMD and CBSD (Zhang, 2005; Vanderschuren, 2012; Patil, 2011). Whitefly resistant varieties are likely to be CMD susceptible, so when whitefly resistant varieties are identified, further breeding will likely be needed to develop varieties that are resistant to both whitefly and viruses (Thresh & Cooper, 2005). Since whiteflies also cause direct damage to cassava plants, Legg et al. (2006) suggest researchers should also consider selectively breeding to reduce direct damage.

Researchers at CIAT have used Simple Sequences Repeat (SSR) to identify markers associated with genes causing whitefly (*A. socialis*) resistance in MEcu 72. Preliminary framework maps were presented by Bellotti *et al* (2003). Bellotti *et al.*, (2012b) indicates the whitefly resistance gene tagging project is ongoing. CIAT scientists report that initial results suggest whitefly resistance may involve multiple genetic regions (Bohorquez *et al*, 2011).

Researchers have identified genotypes that show resistance to whiteflies, and transgenic breeding can be precise in introducing whitefly resistant genes (Legg et al., 2006).These genotypes could provide the parental genotypes required for future breeding programs (Omongo, 2012). CIAT research has demonstrated that cassava genotype MEcu 72 shows high levels of *A. socialis* resistance (with 72.5% nymph morality) and MEcu64, MPer 334, MP415, and MP273 express moderate-to-high resistance (Bellotti, 2012a). MEcu 72 was introduced in Uganda in 2005 (Bellotti *et al.*, 2012b). Ugandan landraces have also been found to be resistant to whiteflies and include Ofumba Chai, Nabwire 1, and Mercury (Ugandan landraces) (Omongo, 2012a).

The promising *A. socialis* resistant variety of cassava called Nataima-31 was bred in Colombia using MEcu 72. It was selected from various progeny because of its high yield and good cooking quality attributes. Without any insecticide application, it has attained yields of 33 t/ha which exceeds regional farmer's output by 34%. It is now being grown commercially in Colombia, Ecuador and Brazil (Bellotti, 2012a; Arias, 2004; Vargas, 2002).

Results from a CIAT study show the potential of gene introgression for pest resistance. Akinbo (2012) confirmed introgression of resistance to *A. socialis* after evaluating 227 genotypes and finding 17.8% promising for future breeding because they had low whitefly damage ratings, indicating high resistance. CIAT is currently using advanced back cross (ABC) Quantitative Trait Locus (QTL) to introgress genes for whitefly resistance (CIAT, 2012). Using molecular markers ABC-QTL mapping can more efficiently use introgression of useful genes from wild relatives to cultivated varieties (Bellotti, 2012b).

Phylogenetically related hosts such as *Jatropha gossypiifolia* can act as intermediate hosts in which whiteflies increase their biotic potential and ability to adapt to cassava. CIAT tested the ability of *B. tabaci* type B to colonize different varieties of cassava (one commercial *M. esculenta* and two wild *M. flabellifolia*, *M. carthaginensis*) after coming from host sequences of other species based on survival and oviposition rates. Carabalí (2010) found that 60% of whiteflies could reproduce on the wild cassava species, 55% on *J. gossypiifolia,* and 27.5% on the commercial variety. Phylogenetic analysis shows that a new strain of Indian cassava mosaic virus (transmitted to jatropha through whitefly) causes jatropha curcas mosaic disease (Gao, 2010). Proposed plans for jatropha as a major biofuel crop in the Americas could increase the possibility that *B. tabaci* could adapt to cassava as a host in the Americas and raises the risk of *B. tabaci*-spread viruses in the region (Bellotti *et al*., 2012b).

Intercropping and Planting Strategies

Intercropping is an environmentally benign method to control whiteflies and is associated with lower whitefly populations, CMD incidence, and disease severity (Night, 2011). This planting strategy has the potential to decrease the need for insecticide use and is already commonly practiced by many smallholder farmers. Evidence shows that higher density intercropping is most effective in controlling whitefly populations (Fargette & Fauquet, 1990). High density planting on cassava plots is more important than height barriers of intercropped or edge crops such as maize to control whitefly populations (Fargette & Fauquet, 1988). However, the precise planting densities at research stations may differ from what smallholder farmers practice, so results may vary when replicated on farms.

Different crops intercropped with cassava produce varying results in reducing whitefly populations. Cowpeas were shown to be more effective than maize in reducing whitefly egg densities on cassava leaves (Gold, 1990). The type of intercropping also has an impact on whether intercropped cassava has greater or lesser yields when compared to monocropped plots. Intercropping with maize has been shown to reduce cassava yield (Olasantan et al., 1996) while intercropping with legumes has been shown to increase cassava yield (Islami et al., 2011; Njoku & Muoneke, 2008). Thus, cowpeas generally are beneficial for reducing whitefly populations and increasing cassava yields while maize may not have the same overall positive benefits. Some crops should not be planted near cassava. Bellotti (2012b) recommends not planting jatropha in proximity to cassava due to whiteflies' ability to adapt to previously resistant cassava via other plant hosts.

Plant architecture is also an important factor influencing whitefly populations. Intercropping with certain crops can reduce cassava plant and leaf size since whitefly egg densities can be less on smaller leaves (Gold, 1990). However, different studies find varying impacts of intercropping on cassava leaf size. Gold (1990) found that intercropping cassava can reduce leaf size due to competition from maize and cowpeas, and Olasantan (1996) found the Leaf Area Index (LAI)[2] to be lower in cassava intercropped with maize. However, Njoku & Muoneke (2008) found that the LAI was higher or similar in plots intercropped with cowpeas. While intercropping can influence the LAI (Njoku, 2008), it is also heavily influenced by genotype, plant age, and environment. (IITA, n.d.).

Intercropping may be effective at controlling whiteflies because it changes the microclimate or field ecosystem, altering their movement and behavior (Fondong, 2002) or because competition for nutrients in an intercropped setting alters cassava plants (Olasantan, 1996; Gold, 1990). Impacts of intercropping to reduce whitefly populations on cassava leaves varies at different times of the growing cycle with the greatest reductions occurring post-harvest of the intercropped crop (Fondong, 2002; Gold, 1990).

Most studies rely on counting eggs, nymphs or adult whiteflies on cassava plants to determine if intercropping is an effective method for controlling populations. However counting methods are not consistent. Since whiteflies have a restless behavior and the numbers seen on leaves depend on the time of day and weather conditions, the measured effectiveness of intercropping on those populations will vary depending on how they are counted (Sseruwago et al., 2004; Abisgold & Fishpool, 1990). While intercropping can reduce whitefly populations on cassava plants, it does not eliminate the flies completely. The linkage between whiteflies and CMD remains strong: among intercropped plots, those with higher populations of whiteflies also have greater incidence of CMD (Fondong, 2002).

Insecticides and Insecticide Resistance Management (IRM)

Widespread insecticide use has historically been viewed as an ineffective and environmentally damaging strategy to control whitefly populations (Horowitz et al., 2011). Insecticide application on cassava is particularly challenging due to the location of flies (under leaves), their highly polyphagous nature, and their easy dispersion by the wind (Horowitz et al.; Navas-Castillo et al., 2011). While applying insecticide can reduce whitefly populations, the CRS Great Lakes Cassava Initiative report found that insecticides did not stop the spread of CBSV, and plots treated with insecticide were more susceptible to CBSD (Catholic Relief Services, n.d.).

According to Castle et al. (2010), over-reaching insecticide use has resulted in heightened resistance among whiteflies, "tipping the balance between a manageable infestation and uncontrolled outbreak." The majority of the literature agrees with the limited efficacy of insecticide-based control strategies due to environmental concerns and resistance (Horowitz et al., 2011).

In addition to environmental and health consequences, Thresh & Cooter (2005) advocate against insecticide use to avoid harming natural predators. Evidence from cotton (Eveleens, 1983; Dittrich et al., 1985) suggests that insecticides are more effective against natural enemies than against whiteflies, which can lead to population resurgence after insecticide use. Bellotti further agrees that farmers using insecticides to control whiteflies will also reduce the effectiveness of biological control (Bellotti in Anderson, 2005).

Despite the general consensus that widespread insecticide use is an ineffective control strategy, more recent research indicates that newer, more targeted insecticides and insect growth regulators (IRGs) are preferable because of their ability to target specific pests, their effectiveness at low application rates, and their non-persistent characteristics in the environment. Further, their selectivity renders many of them suitable for IPM programs (Casida & Quistad, 1998).

Newer, more selective IGRs have not been mentioned for use on cassava specifically (Horowitz et al., 2011). Producers in the U.S. have had the greatest success with novel insecticide chemistries such as Nicotinoids, Imadacloprid soil treatments, second-generation nicotinoids, and non-neurotoxic IGRs such as buprofezin and pyriproxyfen (Palumbo, et al., 2001). Insecticide resistance management strategies based on the structured and restricted use of non-neurotoxic IGRs, coupled

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with the use of cultural and biological pest management tactics, are presently held to provide the best model for combating insecticide resistance in *B. tabaci* (Ellsworth et al., 2001).

In combination with IRGs, refuge strategies can be effective in preventing resistance to pyriproxyfen. Spring melon, alfalfa, and cotton not treated with insecticides provide refuge for *B. tabaci* and promote their survival. Results may be useful to predict the spatial determination of a refuge strategy. Cotton refuges delayed pest resistance while treated cotton fields accelerated it (Carriere et al., 2012). Insecticide resistance management (IRM) strategies are important in addition to insecticides to "incorporate newer chemistries into viable control programs that emphasize conservation of natural enemies and active ingredients" (Castle et al., 2010).

Biological Control

While natural enemies alone do not typically solve B. tabaci problems (Horowitz et al., 2011), introducing enemies and biological control as part of an integrated pest management system (IPM) may prove more effective. Biological control methods can be combined and used with other pest management techniques such as intercropping (Legg et al., 2003). Other whitefly control methods (breeding for resistance, insecticide) can negatively affect natural enemies, making whitefly control more challenging over the long-term. Various biological control methods may also be incompatible. For example, some fungi that suppress whitefly also affect whitefly predators and parasitoids. Biological control mechanisms shown to be successful against whitefly include parasitoids, predators, and fungal control. Exotic parasitoids or predators have been used successfully in other crops (Gerling et al, 2001) and may be effective for cassava in some cases after careful suitability studies (Aiisime et al, 2007).

Biological control was initially dismissed as a control mechanism on cassava because until the 1990's whitefly was not recognized as causing substantial direct damage. Interest was renewed when direct damage was noted in Uganda and elsewhere (Thresh & Cooter, 2005). Introducing exotic enemies poses risks, but may be more effective at controlling than local natural enemies. Natural enemies can be introduced, conserved, or augmented (Bellotti et al., 2012a). Conservation or augmentation of local natural enemies may be an effective strategy, particularly in areas where insecticide use has changed natural balances between pests and enemies (Legg et al., 2003).

Parasitoids/predators:
Research is ongoing to identify natural enemies of whitefly and design interventions to use them for controlling whiteflies (Legg et al., 2006). Gerling et al. (2001) and Arno et al. (2010) identify 38 spider species and 123 insect species that are predators of B. tabaci (Horowitx et al., 2011). Predators are used primarily in greenhouse conditions and several are available commercially (Horowitz et al., 2011). However, predators may be specific to the host plant (Horowitz et al., 2011), so results from studies of other plants may not be applicable to cassava. Bellotti et al. (2012a) identifies Delphastus pusillus, and Condylostylus as whitefly predators on cassava. Aiisime et al. (2007) recommends conserving and/or enhancing parasitism to control whiteflies by developing cassava varieties that resist B. tabaci, but encourage survival of parasitoid species. They also recommend introducing exotic parasitoids (after careful suitability studies).

While parasitoids have been used most commonly in greenhouses, exotic parasitoids have also been introduced to control whiteflies on outdoor crops and nurseries (Gerling et al., 2001), including *Eretmoccerus* in Australia (De Barro & Coombs, 2008) and in Arizona, USA (Gould et al., 2008). Bellotti et al. (2012), identifies six parasitoids of *B. taba*ci on cassava: *Ecarsia Sophia*, *E. lutea*, *E. Formosa*, *E. mineaoi*, *Encarsia sp.*, and *Eretmocerus mundus.* Appendix 2 provides Bellotti's table of enemies for all species of whitefly that feed on cassava. Introduction of an exotic parasitoid to Africa successfully and economically controlled cassava mealybug and green mite, suggesting biological control of whiteflies could be feasible (Bellotti et al., 2012a; Bellotti et al., 2012b).

Fungal products/control:
Products based on fungi, (*Verticillium lecanii, Paecilomyces fumosoroseus* and *Beauveria bassiana*) have the capacity to suppress whitefly (Faria & Wraight, 2001). Horowitz et al. (2011) also notes *Aschersonia* and *Metarhisum* as infectious to whitefly. *Beauveria bassiana* is sold as Eco-Bb by Plant Health Products[3] for the control of whiteflies in South Africa and

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[3] http://www.plant-health.co.za/products.html

Zambia on beans, tomatoes, cucumbers, and eggplant. Constraints to effective use of fungal whitefly control include “slow action, poor adulticidal activity, potentially negative interactions with commonly used fungicides, relatively high cost, limited shelf life, and dependence on favorable environmental conditions” (Faria & Wraight, 2001). Bellotti et al. (2012b) notes these products appear to only be successful when applied when whitefly populations are low. Fungal pathogens can be delivered by spraying the underside of the crop leaves, but Faria & Wraight (2001), note in a paper geared towards commercial agriculture that cost is prohibitive. This suggests fungal products are unlikely to be economically feasible for small-scale cassava farmers. While fungi with potential for whitefly control do not pose risks for vertebrates, some types infect whitefly predators and parasites, potentially limiting these other mechanisms of whitefly control (Faria & Wraight, 2001).

Please direct comments or questions about this research to Leigh Anderson and Mary Kay Gugerty, at eparx@u.washington.edu.

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Appendix 1: Confirmed and proposed viruses spread by whiteflies (from Navas-Castillo et al. (2011))

Family Geminiviridae	Abutilon mosaic virus AbMV
Genus Begomovirus	African cassava mosaic virus ACMV
	Ageratum enation virus AEV
	Ageratum leaf curl virus ALCuV
	Ageratum yellow vein Hualian virus AYVHuV
	Ageratum yellow vein Sri Lanka virus AYVSLV
	Ageratum yellow vein virus AYVV
	Alternanthera yellow vein virus AlYVV
	Bean calico mosaic virus BCaMV
	Bean dwarf mosaic virus BDMV
	Bean golden mosaic virus BGMV
	Bean golden yellow mosaic virus BGYMV
	Bhendi yellow vein mosaic virus BYVMV
	Bitter gourd yellow vein virus BGYVV
	Boerhavia yellow spot virus BoYSV
	Cabbage leaf curl Jamaica virus CabLCJV
	Cabbage leaf curl virus CabLCV
	Chayote yellow mosaic virus ChaYMV
	Chilli leaf curl virus ChiLCV
	Chino del tomate virus CdTV
	Clerodendron golden mosaic virus ClGMV
	Corchorus golden mosaic virus CoGMV
	Corchorus yellow spot virus CoYSV
	Corchorus yellow vein Vietnam virus CoYVV
	Cotton leaf crumple virus CLCrV
	Cotton leaf curl Alabad virus CLCuAlV
	Cotton leaf curl Bangalore virus CLCuBaV
	Cotton leaf curl Gezira virus CLCuGeV
	Cotton leaf curl Kokhran virus CLCuKoV
	Cotton leaf curl Multan virus CLCuMuV
	Cowpea golden mosaic virus CPGMV
	Croton yellow vein mosaic virus CYVMV
	Cucurbit leaf crumple virus CuLCrV
	Desmodium leaf distortion virus DesLDV
	Dicliptera yellow mottle Cuba virus DiYMoCUV
	Dicliptera yellow mottle virus DiYMoV
	Dolichos yellow mosaic virus DoYMV
	East African cassava mosaic Cameroon virus EACMCV
	East African cassava mosaic Kenya virus EACMKV
	East African cassava mosaic Malawi virus EACMMV
	East African cassava mosaic virus EACMV
	East African cassava mosaic Zanzibar virus EACMZV
	Erectites yellow mosaic virus ErYMV
	Eupatorium yellow vein mosaic virus EpYVMV
	Eupatorium yellow vein virus EpYVV
	Euphorbia leaf curl Guangxi virus EuLCGxV
	Euphorbia leaf curl virus EuLCuV
	Euphorbia mosaic virus EuMV
	Hollyhock leaf crumple virus HoLCrV
	Honeysuckle yellow vein Kagoshima virus HYVKgV
	Honeysuckle yellow vein mosaic virus HYVMV
	Honeysuckle yellow vein virus HYVV
	Horsegram yellow mosaic virus HgYMV
	Indian cassava mosaic virus ICMV
	Ipomoea yellow vein virus IYVV
	Kudzu mosaic virus KuMV

Lindernia anagallis yellow vein virus LaYVV
Ludwigia yellow vein Vietnam virus LuYVVNV
Ludwigia yellow vein virus LuYVV
Luffa yellow mosaic virus LYMV
Macroptilium mosaic Puerto Rico virus MacMPRV
Macroptilium yellow mosaic Florida virus MacYMFV
Macroptilium yellow mosaic virus MacYMV
Malvastrum leaf curl Guangdong virus MaLCGdV
Malvastrum leaf curl virus MaLCuV
Malvastrum yellow leaf curl virus MaYLCV
Malvastrum yellow mosaic virus MaYMV
Malvastrum yellow vein virus MaYVV
Malvastrum yellow vein Yunnan virus MaYVYnV
Melon chlorotic leaf curl virus MCLCuV
Merremia mosaic virus MerMV
Mesta yellow vein mosaic virus MeYVMV
Mimosa yellow leaf curl virus MiYLCV
Mungbean yellow mosaic India virus MYMIV
Mungbean yellow mosaic virus MYMV
Okra yellow crinkle virus OYCrV
Okra yellow mosaic Mexico virus OYMMV
Okra yellow mottle Iguala virus OYMoIgV
Okra yellow vein mosaic virus OYVMV
Papaya leaf curl China virus PaLCuCNV
Papaya leaf curl Guandong virus PaLCuGdV
Papaya leaf curl virus PaLCuV
Pedilenthus leaf curl virus PeLCuV
Pepper golden mosaic virus PepGMV
Pepper huasteco yellow vein virus PHYVV
Pepper leaf curl Bangladesh virus PepLCBV
Pepper leaf curl Lahore virus PepLCLaV
Pepper leaf curl virus PepLCV
Pepper yellow leaf curl Indonesia virus PepYLCIV
Pepper yellow vein Mali virus PepYVMLV
Potato yellow mosaic Panama virus PYMPV
Potato yellow mosaic virus PYMV
Pumpkin yellow mosaic virus PuYMV
Radish leaf curl virus RaLCuV
Rhynchosia golden mosaic Sinaloa virus RhGMSiV
Rhynchosia golden mosaic virus RhGMV
Senecio yellow mosaic virus SeYMV
Sida golden mosaic Costa Rica virus SiGMCRV
Sida golden mosaic Florida virus SiGMFlV
Sida golden mosaic Honduras virus SiGMHV
Sida golden mosaic virus SiGMV
Sida golden yellow vein virus SiGYVV
Sida leaf curl virus SiLCuV
Sida micrantha mosaic virus SiMMV
Sida mottle virus SiMoV
Sida yellow mosaic China virus SiYMCNV
Sida yellow mosaic virus SiYMV
Sida yellow mosaic Yucatan virus SiYMYuV
Sida yellow vein Madurai virus SiYVMaV
Sida yellow vein Vietnam virus SiYVVV
Sida yellow vein virus SiYVV
Siegesbeckia yellow vein Guangxi virus SgYVGxV
Siegesbeckia yellow vein virus SgYVV
South African cassava mosaic virus SACMV

Soybean blistering mosaic virus SbBMV
Soybean crinkle leaf virus SbCrLV
Spilanthes yellow vein virus SpYVV
Squash leaf curl China virus SLCCNV
Squash leaf curl Philippines virus SLCuPV
Squash leaf curl virus SLCuV
Squash leaf curl Yunnan virus SLCuYnV
Squash mild leaf curl virus SMLCuV
Sri Lankan cassava mosaic virus SLCMV
Stachytarpheta leaf curl virus StaLCuV
Sweet potato leaf curl Canary virus SPLCCaV
Sweet potato leaf curl China virus SPLCCNV
Sweet potato leaf curl Georgia virus SPLCGoV
Sweet potato leaf curl Lanzarote virus SPLCLaV
Sweet potato leaf curl Spain virus SPLCESV
Sweet potato leaf curl virus SPLCV
Tobacco curly shoot virus TbCSV
Tobacco leaf curl Cuba virus TbLCuCV
Tobacco leaf curl Japan virus TbLCJV
Tobacco leaf curl Yunnan virus TbLCYnV
Tobacco leaf curl Zimbabwe virus TbLCZV
Tomato chino La Paz virus ToChLPV
Tomato chlorotic mottle virus ToCMoV
Tomato curly stunt virus ToCSV
Tomato golden mosaic virus TGMV
Tomato golden mottle virus ToGMoV
Tomato leaf curl Arusha virus ToLCArV
Tomato leaf curl Bangalore virus ToLCBaV
Tomato leaf curl Bangladesh virus ToLCBV
Tomato leaf curl China virus ToLCCNV
Tomato leaf curl Comoros virus ToLCKMV
Tomato leaf curl Guangdong virus ToLCGdV
Tomato leaf curl Guangxi virus ToLCGxV
Tomato leaf curl Gujarat virus ToLCGuV
Tomato leaf curl Hsinchu virus ToLCHsV
Tomato leaf curl Java virus ToLCJaV
Tomato leaf curl Joydebpur virus ToLCJoV
Tomato leaf curl Karnataka virus ToLCKaV
Tomato leaf curl Kerala virus ToLCKeV
Tomato leaf curl Laos virus ToLCLV
Tomato leaf curl Madagascar virus ToLCMGV
Tomato leaf curl Malaysia virus ToLCMYV
Tomato leaf curl Mali virus ToLCMLV
Tomato leaf curl Mayotte virus ToLCYTV
Tomato leaf curl New Delhi virus ToLCNDV
Tomato leaf curl Philippines virus ToLCPV
Tomato leaf curl Pune virus ToLCPuV
Tomato leaf curl Seychelles virus ToLCSCV
Tomato leaf curl Sinaloa virus ToLCSiV
Tomato leaf curl Sri Lanka virus ToLCLKV
Tomato leaf curl Sudan virus ToLCSDV
Tomato leaf curl Taiwan virus ToLCTV
Tomato leaf curl Uganda virus ToLCUV
Tomato leaf curl Vietnam virus ToLCVV
Tomato leaf curl virus ToLCV
Tomato mild yellow leaf curl Aragua virus ToMYLCAV
Tomato mosaic Havana virus ToMHaV
Tomato mottle Taino virus ToMoTaV

	Tomato mottle virus ToMoV
	Tomato rugose mosaic virus ToRMV
	Tomato severe leaf curl virus ToSLCV
	Tomato severe rugose virus ToSRV
	Tomato yellow leaf curl Axarquia virus TYLCAxV
	Tomato yellow leaf curl China virus TYLCCNV
	Tomato yellow leaf curl Guangdong virus TYLCGdV
	Tomato yellow leaf curl Indonesia virus TYLCIDV
	Tomato yellow leaf curl Kanchanaburi virus TYLCKaV
	Tomato yellow leaf curl Malaga virus TYLCMaV
	Tomato yellow leaf curl Mali virus TYLCMLV
	Tomato yellow leaf curl Sardinia virus TYLCSV
	Tomato yellow leaf curl Thailand virus TYLCTHV
	Tomato yellow leaf curl Vietnam virus TYLCVV
	Tomato yellow leaf curl virus TYLCV
	Tomato yellow margin leaf curl virus TYMLCV
	Tomato yellow spot virus ToYSV
	Tomato yellow vein streak virus ToYVSV
	Vernonia yellow vein virus VeYVV
	Watermelon chlorotic stunt virus WmCSV
Proposed species:	Ageratum yellow vein China virus AYVCNV
	Allamanda leaf curl virus AYVCNV
	Bean leaf curl Madagascar virus AllLCV
	Bhendi yellow vein Bhubhaneswar virus BLCMGV
	Bhendi yellow vein Delhi virus BYVDeV
	Bhendi yellow vein Haryana virus BYVHaV
	Bhendi yellow vein Maharashtra virus BYVMaV
	Bhendi yellow vein virus BYVV
	Blainvillea yellow spot virus BlYSV
	Cherry tomato leaf curl virus CtoLCV
	Chilli leaf curl Pakistan virus ChiLCPKV
	Clerodendron golden mosaic China virus ClGMCNV
	Clerodendron golden mosaic Jiangsu virus ClGMJgV
	Clerodendron yellow mosaic virus ClYMV
	Cotton leaf curl Burewala virus CLCuBuV
	Cotton leaf curl Rajasthan virus CLCuRaV
	Crassocephalum yellow vein virus CraYVV
	Cucumber leaf curl virus CuLCuV
	Emilia yellow vein virus EmYVV
	Euphorbia mosaic Peru virus EuMPV
	Euphorbia yellow mosaic virus EuYMV
	Gossypium punctatum mild leaf curl virus GPMLCuV
	Ipomoea yellow vein Malaga virus IYVMaV
	Jatropha leaf curl virus JLCuV
	Jatropha yellow mosaic virus JYMV
	Kenaf leaf curl virus KLCuV
	Macroptilium golden mosaic virus MacGMV
	Malvastrum leaf curl Fujian virus MaLCFjV
	Malvastrum yellow mosaic Helshire virus MaYMHeV
	Malvastrum yellow mosaic Jamaica virus MaYMJV
	Malvastrum yellow vein Baoshan virus MaYVBsV
	Malvastrum yellow vein Honghe virus MaYVHhV
	Merremia leaf curl virus MerLCuV
	Mesta yellow vein mosaic Bahraich virus MeYVMBaV
	Okra leaf curl virus OLCuV
	Okra mottle virus OMoV
	Papaya leaf curl New Delhi virus PaLCuNDV
	Passionfruit severe leaf distortion virus PSLDV

	Pepper leaf curl Yunnan virus PepLCYnV
	Potato yellow mosaic Trinidad virus PYMTTV
	Rhynchosia golden mosaic Havana virus RhGMHaV
	Rhynchosia golden mosaic Yucatan virus RhGMYuV
	Rhynchosia rugose golden mosaic virus RhRGMV
	Rhynchosia yellow mosaic virus RhYMV
	Sida common mosaic virus SiCMV
	Sida mosaic Sinaloa virus SiMSiV
	Sida yellow leaf curl virus SiYLCV
	Sun hemp leaf distortion virus SHLDV
	Sweet potato leaf curl Bengal virus SPLCBeV
	Sweet potato leaf curl Italy virus SPLCITV
	Sweet potato leaf curl Japan virus SPLCJV
	Sweet potato leaf curl Shangai virus SPLCShV
	Tobacco curly shoot India virus TbCSIV
	Tobacco leaf curl Comoros virus TbLCKMV
	Tobacco leaf curl Thailand virus TbLCTHV
	Tobacco leaf rugose virus TbLRV
	Tobacco mottle leaf curl virus TbMoLCV
	Tobacco yellow crinkle virus TbYCV
	Tomato common mosaic virus ToCMV
	Tomato leaf curl Antsiranana virus ToLCAnV
	Tomato leaf curl Cameroon virus ToLCCMV
	Tomato leaf curl Cebu virus ToLCCeV
	Tomato leaf curl Cotabato virus ToLCCoV
	Tomato leaf curl Diana virus ToLCDiV
	Tomato leaf curl Ghana virus ToLCGV
	Tomato leaf curl Hainan virus ToLCHnV
	Tomato leaf curl Ilocos virus ToLCIlV
	Tomato leaf curl Laguna virus ToLCLaV
	Tomato leaf curl Mindanao virus ToLCMiV
	Tomato leaf curl Mohely virus ToLCMoV
	Tomato leaf curl Namakely virus ToLCNaV
	Tomato leaf curl Nigeria virus ToLCNGV
	Tomato leaf curl Ouani virus ToLCOuV
	Tomato leaf curl Palampur virus ToLCPalV
	Tomato leaf curl Patna virus ToLCPaV
	Tomato leaf curl Rajasthan virus ToLCRaV
	Tomato leaf curl Sulawesi virus ToLCSuV
	Tomato leaf curl Togo virus ToLCTOV
	Tomato leaf curl Toliara virus ToLCToV
	Tomato leaf deformation virus ToLDeV
	Tomato leaf distortion virus ToLDV
	Tomato mild mosaic virus ToMMV
	Tomato yellow leaf distortion virus ToYLDV
	Tomato yellow leaf curl Chuxiong virus TYLCChuV
	Tomato yellow leaf curl Dan Xa virus TYLCDXV
	Tomato yellow leaf curl Iran virus TYLCIRV
	Velvet bean severe mosaic virus VBSMV
	Wissadula golden mosaic virus WGMV
Family Closteroviridae *Genus Crinivirus*	Abutilon yellows virus AbYV
	Bean yellow disorder virus BYDV
	Beet pseudoyellows virus BPYV
	Blackberry yellow vein-associated virus BYVaV
	Cucurbit yellow stunting disorder virus CYSDV
	Lettuce chlorosis virus LCV
	Lettuce infectious yellows virus LIYV
	Potato yellow vein virus PYVV

	Strawberry pallidosis-associated vius SPaV Sweet potato chlorotic stunt virus SPCSV Tomato chlorosis virus ToCV Tomato infectious chlorosis virus TICV
Proposed species:	Diodia vein chlorosis virus DVCV Cucurbit chlorotic yellows virus CCYV
Family Betaflexiviridae *Genus Carlavirus*	Cowpea mild mottle virus CPMMV Melon yellowing-associated virus MYaV
*Family Potyviridae** *Genus Ipomovirus*	Cassava brown streak virus CBSV Cucumber vein yellowing virus CVYV Squash vein yellowing virus SqVYV Sweet potato mild mottle virus SPMMV
Family Secoviridae *Genus Torradovirus*	Tomato torrado virus ToTV Tomato marchitez virus ToMarV
Proposed species:	Tomato chocolàte virus ToChV Tomato chocolate spot virus ToChSV

*Ugandan cassava brown streak virus (UCBSV) was also identified (Mbanzibwa *et al., 2011)*

Appendix 2: Natural enemies of whitefly on cassava (from Bellottii *et al.*, 2012b)

Principal Species	Parasitoids	Predators	Entomopathogens (fungus)
Aleurotrachelus sociales	Amitus macgowni E. americana E. bellotti E. cubensis Encarsia hispida E. luteola E. sophia Encarsia sp. nr. variegata Encarsia sp. E. tabacivora Euderomphale sp. Eretmocerus spp. Metaphycus sp. Signiphora aleyrodis	Delphastus sp D. quinculus D. pusillus Chrysopa sp. nr. cincta Condylostylus sp.	Beauveria bassiana lecanicillium lecani Aschersonia aleyrodes
Aleurothrixus aepim	Encarsia porteri E. aleurothrixi E. hispida Eretmocerus sp.		Cladosporium sp.
Aleurodicus dispersus	Aleurotonus vittatus E. haitiensis Encarsia sp. Eretmocerus sp. Euderomphale sp.		
Aleuroglandulus similis	Encarsia guadeloupae Encarsia desantisi	Nephaspis namolica	
Aonidomytilus albus	Aspidoiphagus citrinus Signiphora sp.	Chilocorus distigma	Septobasidium sp.
Bemisia tuberculata	E. hispida E. pergandiella E. sophia Encarsia sp.prob. variegata E. tabacivora Eretmocerus sp. Euderomphale sp. Metaphycus sp.	Condylostylus sp.	
Bemisia tabaci	Encarsia sophia E. lutea E. Formosa E. mineoi Encarsia sp. Eretmocerus mundus	Delphastus pusillus Condylostylus sp.	
Trialeurodes variabilis	E. bellotti E. hispida E. luteola E. nigricephala E. pergandiella Encarsia sp. E. sophia E. strenua E. tabacivora Eretmocerus spp.	Chrysopa sp. nr. cincta Condylostylus sp.	Aschersonia aleyrodes Beauveria bassiana Lecanicillium lecani
Trialeurodes vaporariorum	Encarsia tabacivora		

Appendix 3: Notable Researchers

- James Legg (j.legg@cgiar.org)
    - IITA plant virologist, Tanzania, 1386 citations, Great Lakes Cassava Initiative (BMGF funded)
    - Biography: http://www.iita.org/legg-james
- Anthony Bellotti
    - CIAT Cassava Program entomologist, Colombia
    - Information: http://www.ciatnews.cgiar.org/2013/03/06/the-passing-of-tony-bellotti/
- Pamela Anderson
    - International Potato Center (CIP) Director General, Peru
    - Biography: http://cipotato.org/about-cip/board/pamela-anderson

Appendix 4: Whitefly Control Studies by Control Mechanism

Citation	Year	Region(s)	Main Findings	Organization(s)
Breeding for Host Plant Resistance				
Akinbo, O., Labuschagne, M., & Fregene, M. (2012). Introgression of whitefly (*Aleurotrachelus socialis*) resistance gene from F1 inter-specific hybrids into commercial cassava. Euphytica, 183(1), 19-26.	2012	Colombia- with relevance for Latin America and Africa	Confirmed introgression of resistance to *A. socialis* after evaluating 227 cassava genotypes for leaf damage and found 17.8% of genotypes highly resistant and promising for future breeding.	CIAT, Colombia; Department of Plant Sciences, University of the Free State, South Africa; Donald Danforth Plant Science Center, St. Louis, USA.
Omongo, C. A., Kawuki, R., Bellotti, A. C., Alicai, T., Baguma, Y., Maruthi, M. N., ... & Colvin, J. (2012). African Cassava Whitefly, *Bemisia tabaci*, Resistance in African and South American Cassava Genotypes. Journal of Integrative Agriculture, 11(2), 327-336.	2012	Colombia- with relevance for Latin America and Africa	All improved, high yielding CMD resistant varieties were highly susceptible to *B. tabaci*; several Ugandan landraces and South American genotype MEcu 72 showed greatest resistance.	National Crops Resources Research Institute, Uganda; Natural Resources Institute, UK; CIAT, Colombia
Intercropping and Planting Techniques				
Night, G., Asiimwe, P., Gashaka, G., Nkezabahizi, D., Legg, J. P., Okao-Okuja, G., ... & Mutumwinka, M. (2011). Occurrence and distribution of cassava pests and diseases in Rwanda. Agriculture, Ecosystems & Environment, 140(3), 492-497.	2011	Rwanda	In an observational survey, whitefly populations were higher on improved variety cassava, though CMD was lower; intercropping was associated with lower pest populations (whitefly and green mite) and lower disease incidence and severity.	Institut des Sciences Agronomiques du Rwanda, Rwanda; University of Arizona, USA; IITA, Uganda and Tanzania
Ewusie, E. A., Parajulee, M. N., Adabie-Gomez, D. A., & Wester, D. (2010). Strip cropping: a potential IPM tool for reducing whitefly, *Bemisia tabaci* Gennadius (Homoptera: Aleyrodidae) infestations in cassava. West African Journal of Applied Ecology, 17(1).	2010	Ghana	Significantly lower numbers of immature and adult *B. tabaci* were found on cassava plots surrounded by five rows of cotton and jatropha.	Biotechnology and Nuclear Agriculture Research Center, Ghana; Texas Tech University, USA
Fondong, V. N., Thresh, J. M., & Zok, S. (2002). Spatial and temporal spread of cassava mosaic virus disease in cassava grown alone and when intercropped with maize and/or cowpea. Journal of Phytopathology, 150(7), 365-374.	2002	Cameroon	Intercropping with maize or cowpea reduced whitefly population by 50% and incidence of CMD by 20% in unimproved or semi-improved varieties of cassava, but not in the improved variety on experimental plots.	Department of Plant Pathology, Cornell University, USA; Natural Resources Institute, University of Greenwich, UK; Edona Research Centre, Cameroon
Fargette, D., Fauquet, C., Grenier, E., & Thresh, J. M. (1990). The spread of African cassava mosaic virus into and within cassava fields. Journal of Phytopathology, 130(4), 289-302.	1990	Cote d'Ivoire	Lower incidence of ACMD (directly related to whitefly populations) was found on high density plots.	Scottish Crop Research Institute, UK; Washington University, USA; Laboratoire de Biomere, Franc; Overseas Development Natural Resources Institute
Gold, C. S., Altieri, M. A., & Bellotti, A. C. (1990). Direct and residual effects of short duration intercrops on the cassava whiteflies *Aleurotrachelus socialis* and *Trialeurodes variabilis* (Homoptera: Aleyrodidae) in Colombia. Agriculture, Ecosystems & Environment, 32(1), 57-67.	1990	Colombia	Cassava intercropped with maize or with cowpeas had significantly lower densities of whitefly eggs on leaves than monocropped experimental plots.	Division of Biological Control, University of California Berkeley, USA; CIAT, Colombia

Fargette, D., & Fauquet, C. (1988). A preliminary study on the influence of intercropping maize and cassava on the spread of African cassava mosaic virus by whiteflies. Aspects of Applied Biology, 17, 195-202.	1988	Cote d'Ivoire	On experimental plots whitefly populations were lower on cassava plants intercropped with maize at high density than low density, but not significantly different from monocropped cassava plots.	Laboratoire de Vriologie, Institut Francais de Recherche pour le Devloppment en Cooperation (ORSTROM) Cote d'Ivoire.

Citation	Year	Region(s)	Main Findings	Organization(s)
Insecticide				
Dennehy, T. J., & Williams, L. (1997). Management of resistance in Bemisia in Arizona cotton. *Pesticide science*, *51*(3), 398-406.	1997	Arizona, USA	This study incorporated two new integrated resistance elements: once-per-year use of the insect growth regulators (IGRs) pyriproxyfen and buprofezin, and measures to delay use of pyrethroids for as long into the growing season as possible. Through regimented timing of application and sampling plans, results indicated improvement in *B. tabaci* control and reduced insecticide use.	University of Arizona, Department of Entomology; Arizona Cotton Growers Association; Cotton Incorporated; USDA-ARS Western Cotton Research Laboratory; University of Arizona College of Agriculture
Denholm, I., Cahill, M., Dennehy, T. J., & Horowitz, A. R. (1998). Challenges with managing insecticide resistance in agricultural pests, exemplified by the whitefly Bemisia tabaci. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, *353*(1376), 1757-1767.	1998	North America, Israel	Studies in Israel and the SW United States have succeeded in arresting the resistance treadmill in *B. tabaci* through a combination of increased chemical diversity, voluntary or mandatory restrictions on the use of key insecticides, and careful integration of chemical control with other pest–management options, increasing the prospect of sustained use of existing and future insecticides.	Dept. of Biological and Ecological Chemistry, IACR-Rothamsted; Dept. of Entomology, University of Arizona; Dept. of Entomology, Institute of Plant Protection, Volcani Center, Israel
Ellsworth, P. C., & Martinez-Carrillo, J. L. (2001). IPM for *Bemisia tabaci*: a case study from North America. Crop Protection, 20(9), 853-869.	2001	North America	Insecticide resistance management strategies based on the structured and restricted use of non-neurotoxic IGRs, coupled with the use of cultural and biological pest management tactics, presently provides the best model for combating insecticide resistance in *B. tabaci*.	Maricopa Agricultural Center, University of Arizona
Palumbo, J. C., Horowitz, A. R., & Prabhaker, N. (2001). Insecticidal control and resistance management for *Bemisia tabaci*. Crop Protection, 20(9), 739-765.	2001	North America, Israel	Producers in the U.S. have had the greatest success with novel insecticide chemistries such as Nicotinoids, Imadaclोprid soil treatments, second-generation nicotinoids, and non-neurotoxic insect growth regulators (IGRs) such as buprofezin and pyriproxyfen (Palumbo, et al., 2001).	University of Arizona, Yuma
Horowitz, A. R., Gorman, K., Ross, G., & Denholm, I. (2003). Inheritance of pyriproxyfen resistance in the whitefly, Bemisia tabaci (Q biotype). *Archives of insect biochemistry and physiology*, *54*(4), 177-186.	2003	UK	Two parental strains of B. tabaci belonging to the Q biotype were assayed with pyriproxyfen, and the resistance ratio and statistical modeling indicated that reistance was incompletely or partially dominant. Resistants to pyriproxyfen is conferred primarily by a mutant allele at a single locus.	Organizations: Gilat Research Center, Israel; Rothamsted Research, UK

Carrière, Y., Ellers-Kirk, C., Hartfield, K., Larocque, G., Degain, B., Dutilleul, P., ... & Tabashnik, B. E. (2012). Large-scale, spatially-explicit test of the refuge strategy for delaying insecticide resistance. Proceedings of the National Academy of Sciences, 109(3), 775-780.	2012	Arizona, USA	Refuge strategy effective in preventing resistance to pyriproxyfen when nearby spring melon, alfalfa, and cotton not treated with insecticides provide refuge for *B. tabaci* and promote survival or susceptible pests. Cotton refuges delayed resistance while treated cotton fields accelerated it.	National Academy of Sciences, U of Arizona, McGill, Arizona Cotton Research and Protection Council
Citation	**Year**	**Region(s)**	**Main Findings**	**Organization(s)**
Biological Control (Parasitoids)				
Venkatesan, S., & Palanisamy, V. (2010). Eco-friendly management of cassava whitefly, *Bemisia tabaci* gennadius. Madras Agricultural Journal, 97(1/3), 78-80.	2010	India	Application of sweetflag rhizome *Acorus calamus* 10D and neem seed kernal extract (NSKE) significantly reduced whitefly populations	Tapioca and Caster Research Station
Otim, M., Kyalo, G., Kyamanywa, S., Asiimwe, P., Legg, J. P., Guershon, M., & Gerling, D. (2008). Parasitism of *Bemisia tabaci* (Homoptera: Aleyrodidae) by *Eretmocerus mundus* (Hymenoptera: Aphelinidae) on cassava. International Journal of Tropical Insect Science, 28(3), 158.	2008	Uganda	Experiement comparing parisitoid activity of *Eretmocerus mundus* on glabrous leaf and hirsute leaf cassava varieties found that leaf hairiness was not a factor in parasitoid activity, though there were some behavior changes.	National Crops Resources Research Institute, Uganda; Crop Science Department, Uganda; University of Arizona, USA; IITA, Tanzania;National Resources Institute, UK; Tel Aviv University , Israel
Asiimwe, P., Ecaat, J. S., Otim, M., Gerling, D., Kyamanywa, S., & Legg, J. P. (2007). Life-table analysis of mortality factors affecting populations of *Bemisia tabaci* on cassava in Uganda. Entomologia experimentalis et applicata, 122(1), 37-44.	2006	Uganda	Observational study of sources and rates of B. tabaci mortality on cassava in Uganda (post CMD epidemic) found parasitism to be highest cause of mortality across all stages, followed by dislodgement, predation, inviable eggs, and unknown causes.	IITA, Uganda; University of Greenwich, UK
De Barro, P. J., & Coombs, M. T. (2009). Post-release evaluation of Eretmocerus hayati Zolnerowich and Rose in Australia. *Bulletin of entomological research*, *99*(2), 193.	2009	Australia	Evaluation of the 2004 release of *Eretmocerus hayati* showed increased parasitism, with *Er. hayati* contributing 85% of parasitism	CSIRO Ecosystem Sciences
Biological Control (Fungal)				
Al-Deghairi, M. A. (2008). Bioassay evaluation of the entomopathogenic fungi, *Beuveria bassiana* Vuellemin against eggs and nymphs of Bemisia tabaci Gennadius (Homoptera: Aleyrodidae). Pakistan J. Biol. Sci, 11(12), 1551-1560.	2008	Saudi Arabia	Fungal control study of *Beauveria bassiana* (squash) on *B. tabaci* eggs, and young and old nymphs: found nymphs more susceptible than eggs.	Qassim university, Saudi Arabia
Wraight, S. P., Carruthers, R. I., Jaronski, S. T., Bradley, C. A., Garza, C. J., & Galaini-Wraight, S. (2000). Evaluation of the Entomopathogenic Fungi *Beauveria bassiana* and *Paecilomyces fumosoroseus* for Microbial Control of the Silverleaf Whitefly, *Bemisia argentifolii*. Biological Control, 17(3), 203-217.	2000	Texas, USA	Fungal control study of *Beauveria bassiana* and *Paecilomyces fumososeus* against *Bemisi argentifolii* found high efficacy against nymphs, but minimal effectiveness against adults. Suggests the pathogens have strong potential for controlling whiteflies in cucurbit crops (melons and cucumbers).	USDA, USA; Mycotech Corporation, USA

Appendix 5: Whitefly Control Intervention Programs (1990-present)

Project	Organizations	Years	Region(s)	Project Overview	Whitefly Component
Ecologically sustainable cassava plant protection (ESCaPP)	IITA's Plant Health Management Division (PHMD), UNDP-funded	1993-1997	Benin, Cameroon, Ghana, Nigeria	The Ecologically Sustainable Cassava Plant Protection (ESCaPP) project which began in 1993 in West Africa provides such a working model. Researchers and extension agents training farmers in principles and practices of sustainable crop production and protection.	Tested and adapted sustainable cassava plant protection technologies for the most important arthropod, pathogen and weed pests in West Africa.
Tropical Whitefly IPM Project	IITA, CIAT, NRI, NARO (Uganda), USAID, DFID, NZAid, others	Phase 1: 1997-2000 Phase 2: 2001-2004 Phase 3: 2005-2008	Worldwide	Five subprojects: (1) *Bemisia tabaci* as a vector of viruses affecting cassava and sweet potato in sub-Saharan Africa (IITA, NRI, CIP, CIAT); (2) *B. tabaci* as a vector of viruses in mixed cropping systems of Mexico, Central America, and the Caribbean (CIAT); (3) *B. tabaci* as a vector of viruses in mixed cropping systems of eastern and southern Africa (ICIPE, AVRDC); (4) *B. tabaci* as a vector of viruses in mixed cropping systems of Southeast Asia (AVRDC); (5) *Trialeurodes vaporariorum* as a pest in mixed cropping systems of the Andean highlands (CIAT); and (6) whiteflies as pests of cassava in South America (CIAT).	Provided crisis mitigation for CMD pandemic in Tanzania and Uganada; validated IPM components; and developing training materials characterized and targeted "hot spots" surrounding Lake Victoria in Uganda and Tanzania. Developed integrated pest management (IPM) components and packages that are safe and affordable for small-scale farmers. Also strengthened the tropical whitefly research network and provided advanced training (technical, M.Sc., Ph.D.) and IPM information for plant protection specialists from other institutions. Integration of different IARCs and IRS scientists. Project showed that "genetic improvement is the most sustainable component of an IPM Programme."
Sustainable Integrated Management of Whiteflies as Pests and Vectors of Plant Viruses in the Tropics	CGIAR Systemwide Programme on IPM. CIAT-led, in partnership with IARCs, Advanced Research Intstitute and local NARS.	2001-2004	Colombia, Ecuador, El Salvador, Guatemala, Uganda, United Republic of Tanzania	Promote IPM packages and training materials to address whiteflies as pests in tropical highlands, vectors in mixed cropping systems, and as virus vectors and pests in cassava.	This subproject of the Tropical Whitefly IPM Project intends to scale out by gathering, generating, and analyzing baseline data relevant to the diagnosis and characterization of whitefly and WTV problems in the tropics in order to propose a sound research agenda for improved understanding of pest and disease dynamics, IPM development and IPM implementation. Results of various projects summarized in Anderson (2005).
Integrated Protection of Cassava from Emerging Pests and Diseases that Threaten Rural Livelihoods	IITA	2007-2010	Benin, Cameroon, DR, Congo, Guinea, Tanzania	Aimed to test and implement sustainable IPM technologies to mitigate losses to major cassava pests and diseases in five countries, including DRC and Tanzania, including evaluating pest and disease resistant varieties and their multiplication and dissemination to farmers. It looked at the use of natural enemies to control pests and diseases, the spread of diseases and their insect vectors, and attempted to put together pest /disease management options and test them at farmer level.	Introduced into eastern Africa (first to Tanzania) parasitoids that were shown to be effective in controlling spiralling whitefly in West Africa. Efforts to bring parasitoids of spiralling whitefly succeed in establishing in East Africa aimed to bring pest under control at least in the coastal areas of Tanzania.

Project	Organizations	Years	Region	Project Overview	Whitefly Component
Great Lakes Cassava Initiative (GLCI)	Catholic Relief Services	2007-2012	SSA:Burundi, Democratic Republic of Congo, Kenya, Rwanda, Tanzania and Uganda	Overall goal of distributing clean planting material of disease tolerant or resistant varieties to 1.15 million farmers to six countries. Multi-phase project also included research, farmer training, and capacity building in CBSVs diagnostics and response amongst GLCI countries. Follow-up project to C3P, focusing on both research and development activities.	Research to increase knowledge in CBSV transmission by whitefly. Results of CBSD field trials in Tanzania and Uganda suggests treating whiteflies with insecticides is effective in reducing whitefly populations and CMD incidence, but does not stop whitefly adults from entering treated plots and feeding on plants in those treated plots, which suggests contrasting transmission characters by whiteflies. This study also showed that the improved variety was much more resistant to CMD infection (near immune) than the local variety.
Enabling Research Tools for Cassava Virologists and Breeders	University of Greenwich Natural Resources Institute, partnered with Mikocheni Agricultural Research Institute, Tanzania (BMGF Funded)	2013-ongoing	East Africa	Training for East African researchers in molecular biology techniques.	Expected to deliver diagnostic markers identifying gene sequences in superabundant whitefly populations.
Integrated Cassava Disease Interventions with Little or No Whitefly-Specific Component					
Emergency Programme to Combat the Cassava Mosaic Disease Pandemic in East Africa	USAID, IITA	1998-2001	East Africa	Emergency program to multiply and disseminate mosaic resistant cassava in Uganda, Kenya and Tanzania through clean cutting multiplication sites, germplasm diversification, and farmer training in partnership with local organizations.	No specific whitefly component, but CMD incidence data from leaf samples included both cutting- and whitefly-borne infection data.
C3P ON-FARM VOUCHERS:	CRS	2006-2008	Eastern Africa	Pilot Use of On-Farm Vouchers to Disseminate Cassava Planting Material in Western Kenya. Multiplication and dissemination of clean planting materials through on-farm vouchers in all six participating countries and was notable for developing Quality Management Protocol.	
Cassava Mega Project	ASARECA, with funding from USAID	2008-2012	Eastern and Central Africa	Project to improve cassava productivity and utilization throughout the region with interventions at research, development, and policy levels. Activities include putting in place systems for generating quality cassava planting materials of improved cassava varieties and scaling up technologies for cassava production, processing and marketing. Policy activities aimed to put in place supportive policies to promote cassava production and processing and to develop appropriate quality standards.	

Regional Cassava Initiative (RCI)	FAO, Humanitarian Aid dept of the European Commission (ECHO)	2006-present	Central and Eastern Africa	Emergency project funded by ECHO to address cassava diseases in Eastern and Central Africa through increasing access to improved cassava varieties, strengthening surveillance information to government authorities, NGOs, and donors, and promoting operational cassava commissions in each country to better regulate movement of cassava vegetative material throughout countries. Works in collaboration with GLCI and Cassava Mega Project.	