Current Status of **Moko Disease and Black Sigatoka** in Latin America and the Caribbean, and Options for Managing Them

Elizabeth Álvarez, Alberto Pantoja,
Lederson Gañán, and Germán Ceballos

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Contents

Significance of Plantains and Bananas to Latin America and the Caribbean

The banana and plantain industry is particularly important to most countries in Latin America and the Caribbean (LAC), both for generating foreign currency and for contributing to the region's food security population. According to CIRAD (2008), more than 33 million tons of plantain and banana are produced yearly in LAC. Likewise, this region exports the largest volume of fruit, reaching a value of more than US$3000 million per year. Ecuador is the world's leading exporter, with Costa Rica ranking third. The banana and plantain industry also generates tens of thousands of direct and indirect jobs all year round in the tropical and subtropical production areas of the Americas (Pocasangre et al. 2009).

Asia, as the Musaceae's center of origin, has the largest number of *Musa* species. It is also the largest producer, followed by Africa and Latin America (Figure 1).

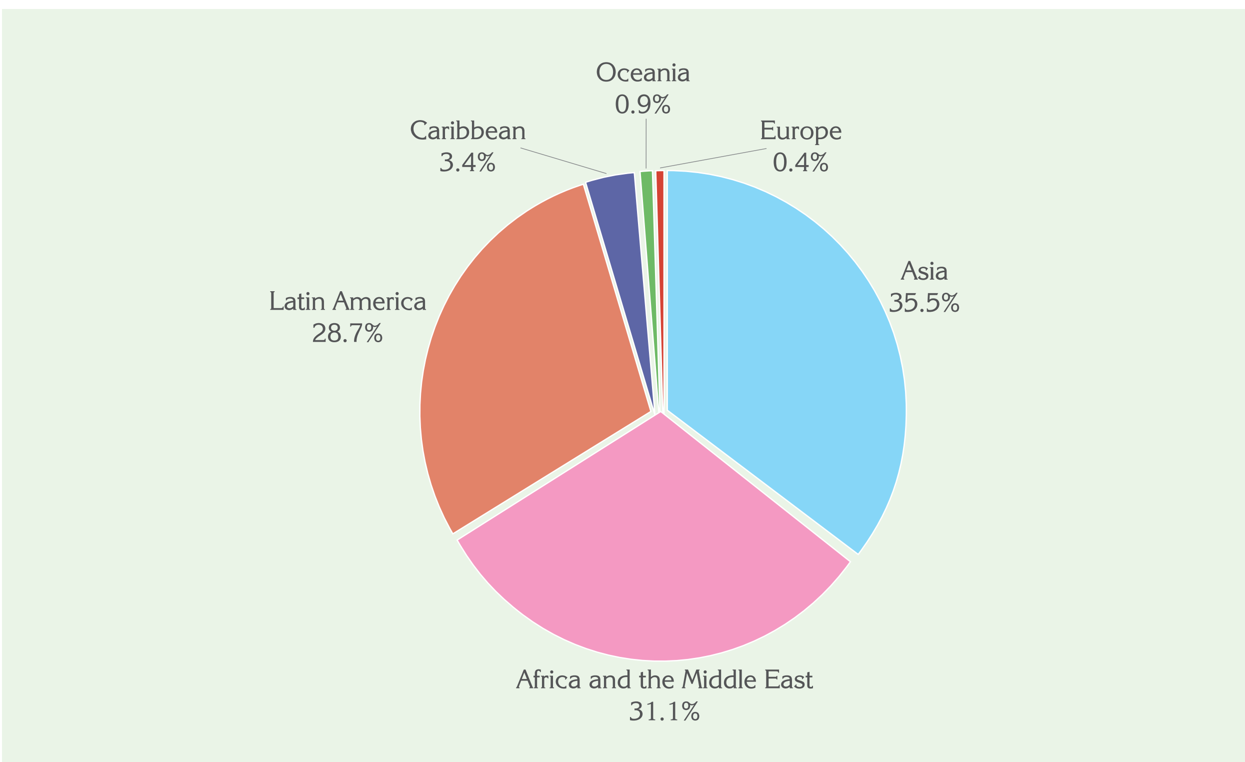


Figure 1. Total production of Musaceae by region (CIRAD 2008).

Despite important changes in the number of countries belonging to the European Union (EU) (currently 27) and their import regulations, Latin America continues to grow as the EU's main supplier of Cavendish bananas, exporting 3.8 million tons in 2007 (73%). In contrast, supplies from the African, Caribbean, and Pacific Group of States (ACP; at 0.8 million tons, i.e., 16%) and the European Community (EC; at 0.5 million tons, i.e., 11%) have continued their downward trends (Figure 2).

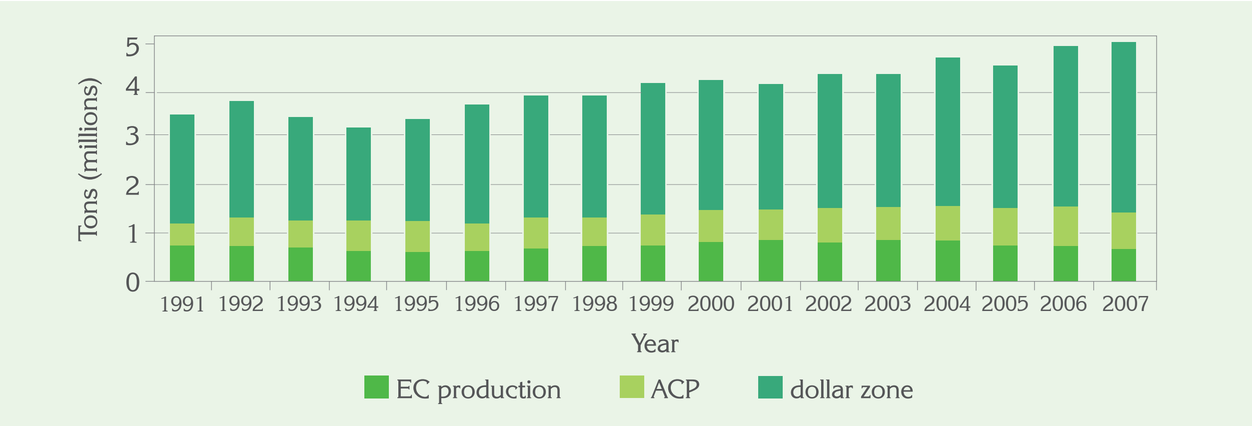


Figure 2. Supplies of Cavendish bananas to the European Union by origin, 1991–2007. SOURCE: Lescot, 2009.

In 2007, LAC had a 32.1% share of world production of bananas and plantains, after Asia at 35.5%. Much of LAC's participation corresponded to Cavendish bananas (23.8%), compared with Asia at 55.9%.

World production of plantains was around 35.1% in LAC, compared with Africa at 56.7% (Lescot 2008).

The supply of plantains to the EU has increased significantly in a linear fashion since 1995, mainly because of consumption by growing populations of ethnic groups (Africans and Latinos) in EU (Figure 3).

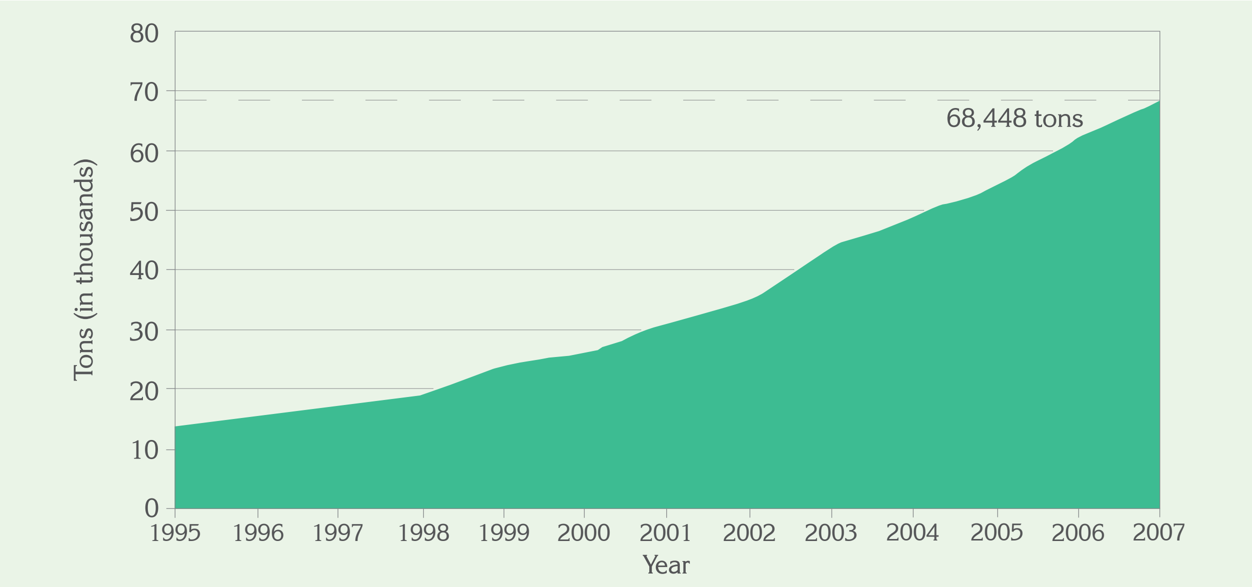


Figure 3. Plantain imports by the European Union, 1995–2007. SOURCE: Lescot (2008).

In 2007, 97% of the plantains imported by the EU were supplied by LAC countries, including Ecuador (49.7%), Colombia (37.4%), and Costa Rica (9.9%) (Figure 4) (Lescot 2008).

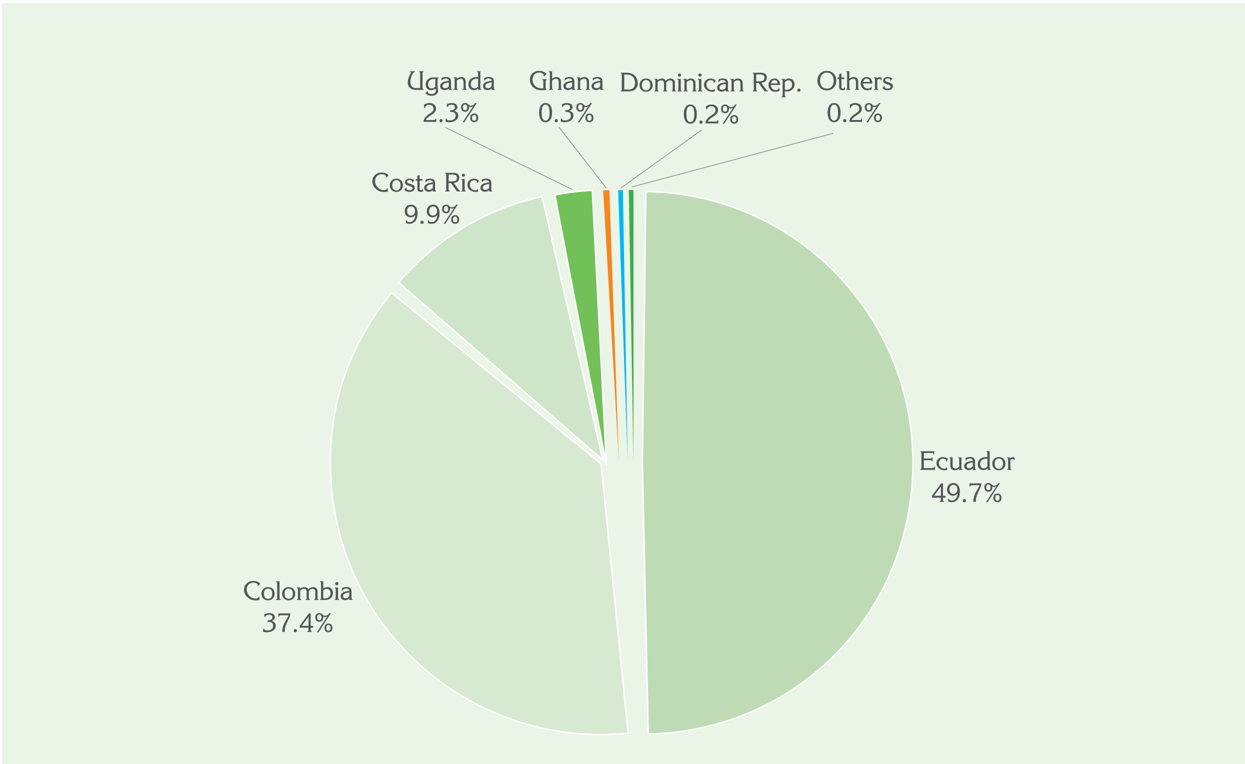


Figure 4. Distribution of plantain suppliers to the European Union in 2007. SOURCE: Lescot (2008).

Moko Disease
(Bacterial Wilt, Vascular Wilt, *Maduraviche, Ereke*)

Vascular wilt caused by *Ralstonia solanacearum* is a major disease affecting crop plants. This phytopathogen, a natural inhabitant of soil, is present on all continents and on many islands between the Tropics of Cancer and Capricorn (Elphinstone 2005). Recent evaluations of pathogenicity and genetic studies have shown that many strains of the bacterium can survive for more than 25 years, evolving in very different places. They can inhabit native flora, organic matter in soils, and a variety of hosts (Buddenhagen 1986). Because of this phytopathogen's genetic diversity, this group of microorganisms is also known as the *R. solanacearum* species complex (RSSC) (Fegan and Prior 2005).

Strains belonging to the RSSC can be classified into biovars on the basis of acid production from disaccharides (cellobiose, lactose, and maltose) and oxidation of hexose alcohols (sorbitol, dulcitol, and mannitol) in a base medium (Hayward 1964; Denny and Hayward 2001).

Ralstonia solanacearum biovars differ in the range of hosts that they attack, their geographic distribution, pathogenicity, epidemiological relationships, and physiological properties. For this reason, for the last three decades, races and biovars have been used as an informal classification at the infra-subspecific level. For example, race 1 includes biovars 1, 3, and 4, infecting many plants, including sweet potato, tomato, and the Solanaceae in general; race 2 (biovars 1 and 3) infects plantains, bananas, and heliconias; race 3 (biovar 2) is specific to sweet potato and is associated with other Solanaceae; race 4 (biovar 4) affects ginger; and race 5, blackberry (Hayward 1991).

According to Fegan and Prior (2005), the RSSC is divided into four phylotypes, corresponding to four genetic groups identified according to sequence analyses. A phylotype is therefore defined as a monophyletic cluster of strains as determined by phylogenetic analysis of sequence data; in this case, through ITS regions, the *hrpB* gene, and the endoglucanase gene egl (Genin and Denny 2012). The four phylotypes are:

Phylotype I: Equivalent to division 1 as defined by Cook and Sequeira (1994). All the strains in this phylotype belong to biovar 3, 4, or 5, and are isolated primarily from Asia.

Phylotype II: Equivalent to division 2, with the strains belonging to biovar 1, 2, or 2T. They are isolated primarily from the Americas. This type also includes race 3 (a potato pathogen), which is distributed worldwide, and race 2, pathogenic to banana and plantain.

Phylotype III: Comprises strains that belong to biovar 1 or 2T, and which are primarily isolated from Africa and nearby islands.

Phylotype IV: Comprises strains belonging to biovar 1, 2, or 2T and isolated primarily from Indonesia, but also from Australia and Japan. This Phylotype also includes two close relatives of *R. solanacearum: R. syzygii* and the blood disease bacterium of banana (BDB).

Moko disease of plantain and banana, also known as bacterial wilt, vascular wilt, *maduraviche*, or *ereke*, is caused by *R. solanacearum* race 2 (Smith) (Yabuuchi et al. 1995) (see Phylotype II above). Production losses are high, as are eradication costs and plant quarantines. It is, therefore, a major phytosanitary constraint in LAC, second to black sigatoka.

Moko disease in Latin America and the Caribbean

According to Thurston (1989), this disease caused severe losses in 1840 in Guyana. Then, towards the end of the 19th century, it caused the destruction of almost the entire planting of the 'Moko' plantain cultivar (Bluggoe subgroup) in Trinidad, giving the disease its name. In the 1960s, a pathotype transmitted by insects devastated the plantain crop in Central America, as well as in Colombia and the Peruvian Amazon. The disease was estimated to have eliminated plantain and banana crops from thousands of square kilometers in Latin America (Buddenhagen 1986; Belalcázar et al. 2003b).

Moko disease is endemic to Central America and South America, and is officially recorded in Belize, Brazil, Colombia, Costa Rica, Ecuador, El Salvador, Granada, Guatemala, Guyana, Honduras, Mexico, Nicaragua, Panama, Peru, Suriname, Trinidad, and Venezuela. In 2004, the disease was confirmed in Saint James Parish, Jamaica (Eyres et al. 2005) (Figure 5).

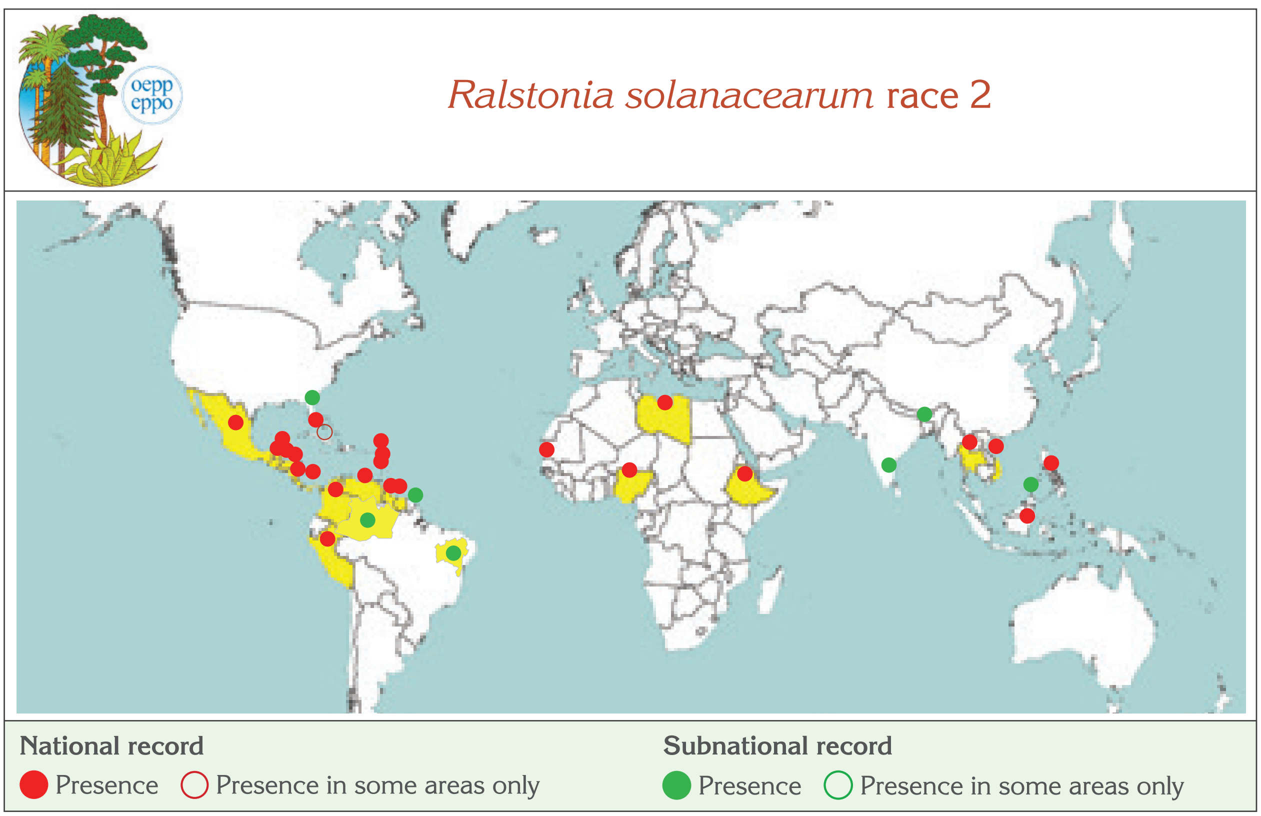


Figure 5. World distribution of *Ralstonia solanacearum*. SOURCE: EPPO (2010).

In Colombia, the disease was reported for the first time in 1954, as well as in Peru, Hawaii, and along the Amazon River (Quinón and Aragaki 1963; Stover 1972).

In Honduras, incidence of Moko disease was more frequent recently in the Comayagua Valley, the country's principal center of horticultural production. The disease is therefore considered as a serious threat to susceptible crops (FHIA 2011).

Moko disease in Colombia

After black sigatoka, Moko disease is, economically, the most important constraint to plantain and banana production, totally destroying some plantations. Its dissemination increases when measures for timely control are not taken (CORPOICA 2003).

According to Toomey (2004), Moko disease was seen in plantain for the first time in 1954, in the Department of Tolima. The worst affected areas included the Department of Meta where 20,000 ha of crops were wiped out between 1970 and 1980. In Urabá, Department of Antioquia, 87 ha of plantain were eradicated in 1993, coinciding with the disease's maximum incidence (Castañeda and Espinosa 2005; Londoño 2012). In Santa Marta, in 1996, over only 2.5 months, 4387 infected plants were eradicated from 18.3 ha planted to Cavendish banana (Mejía 1996); and, in Quindío, from 1999 to 2000, the disease caused losses worth about US$73,000 (Obregón 2007).

Although plantain cultivation in the Department of Quindío has attained a high level of technological development, it is seriously threatened by Moko disease, which has been present in the region since 1971 (ACORBAT 2002). This is despite the Colombian Agricultural Institute (ICA, its Spanish acronym) implementing a control campaign almost as soon as it appeared (Vargas-Sánchez et al. 2002). The problem in Quindío increased surprisingly in 1997, despite efforts to control it. ICA–Quindío, in search of solutions, designed a new campaign of intensive integrated management. With the support of the farmers themselves, a group called *Club de Afectados por Moko* (Club of Those Affected by Moko) was set up for disease control, achieving very positive results (Toomey 2004).

The problem of Moko disease in Colombia's Coffee Belt is aggravated by the planting of host crops near plantain crops. Fegan and Prior (2005) reported that Phylotype II of *R. solanacearum* not only infects plantain, but also tomato (*Lycopersicon esculentum*). *Ralstonia solanacearum* was isolated from samples collected from a tomato plantation growing in Montenegro (Quindío) and showing symptoms of bacterial wilt. Semi-selective medium South Africa (SMSA) was used. When the bacterium was inoculated into plantain plants under greenhouse conditions, symptoms of Moko disease were reproduced (CIAT 2005) (Figure 6).

In 2004, in Colombia, the incidence of Moko disease in plantain increased in area to the point where 95% of the country's plantain plantations had at least one plant with Moko disease, despite the publication of preventive measures and disease management (Galindo 2004, pers. commun., ICA–Bogotá).

Figure 6. A tomato plantation suffering from vascular wilt caused by *Ralstonia solanacearum.*

Moko disease has seriously reduced plantain production in the main growing areas of Colombia, causing losses of up to 100% and obliging many farmers to substitute this crop with fruit trees, in view of the lack of options for the disease's control and eradication. In affected areas, the disease has spread along the main rivers of the Departments of Tolima, Valle del Cauca, Huila, Caquetá, Amazonas, and Putumayo, as well as along the Atlantic Coast (Belalcázar et al. 2003b). Planting materials (i.e., seed) constitute the primary source of infection in disease-free zones.

Unlike other diseases infecting the plantain crop, Moko disease destroys the raceme (i.e., the bunch of fruit) and prevents the plant from completing its vegetative cycle (Martínez and García 2004). Despite presenting itself in focuses, the disease is devastating. Once a diseased plant is detected, it must be eradicated to prevent the bacterium from spreading to healthy plants and the soil.

The bacterium is transmitted through infested tools, vector insects, infested plant residues, contaminated soil, and root contact between diseased and healthy plants. The bacterium can spread through runoff water, rivers and streams, and seed from contaminated plantations.

Once the disease appears in a locality, it spreads into the depths of plantations through cultural tasks, that is, through tools that are not constantly disinfected, footwear carrying contaminated soil, insects and probably birds, and domestic animals and humans (Álvarez et al. 2007).

Previously, practices for managing this disease consisted of eradicating plants with symptoms and then changing to another crop. Research shows that the bacterium can survive between 2 and 10 years in fallow soil while, in other soils, populations decline rapidly, despite the presence of susceptible crops (Martins 2000).

Collaborative work between CIAT and ICA, and participatory research with leading farmers in the Department of Quindío, made possible the design and validation of a management protocol for areas affected by Moko disease, with excellent results. This protocol is known as *the traffic light system* (Álvarez and ICA 2007; Álvarez et al. 2013a).

Current management strategies for Moko disease in plantain and banana crops focus on preventing the introduction of the bacterium through any means of dissemination, and/or eradicating any infected plants, using chemical techniques.

Recognizing and diagnosing *Ralstonia solanacearum*

Macromorphology of *R. solanacearum*

Ralstonia solanacearum characteristically presents two types of colonies: one is fluid (mucoid because of abundant production of extracellular polysaccharide [EPS]), smooth, irregular, and round; and the other is dry, round, translucent, wrinkled, and not fluid.

If the medium contains tetrazolium, normal virulent colonies are smooth, fluid, and irregular, with white or slightly red centers, but avirulent mutants have the opposite characteristics (Kelman 1954).

Ralstonia solanacearum colonies grown in a semi-selective medium, South Africa (SMSA) are fluid, with irregular edges, and mucoid, forming a red swirl at the center. They are classified as virulent and are similar in appearance to colonies growing in triphenyl tetrazolium chloride (TTC) medium (Kelman 1954) (Figure 7).

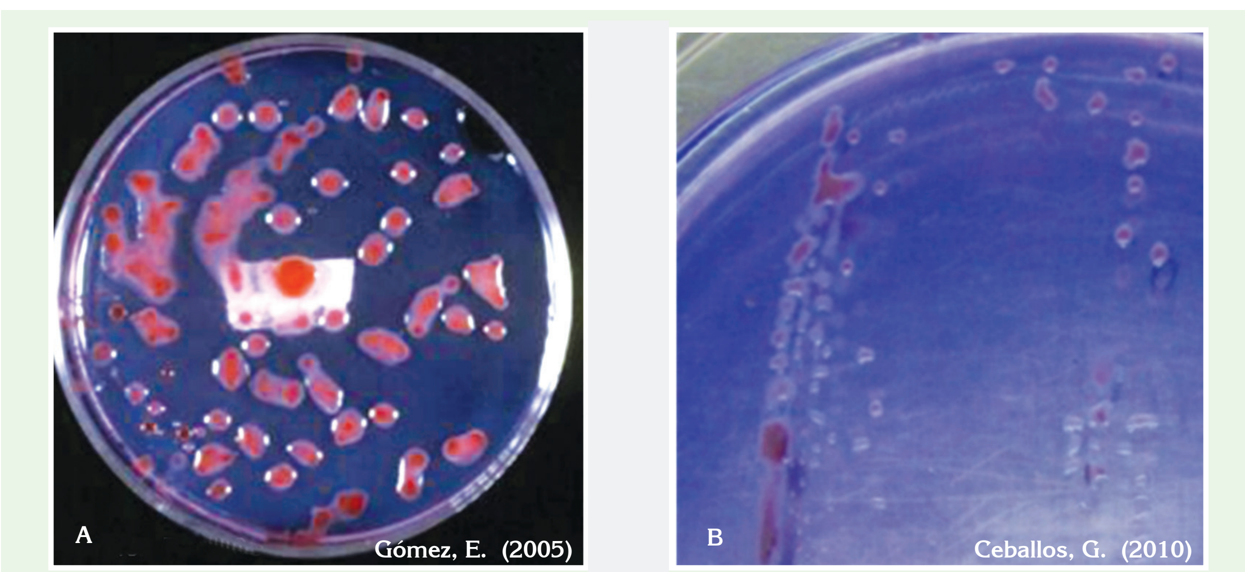


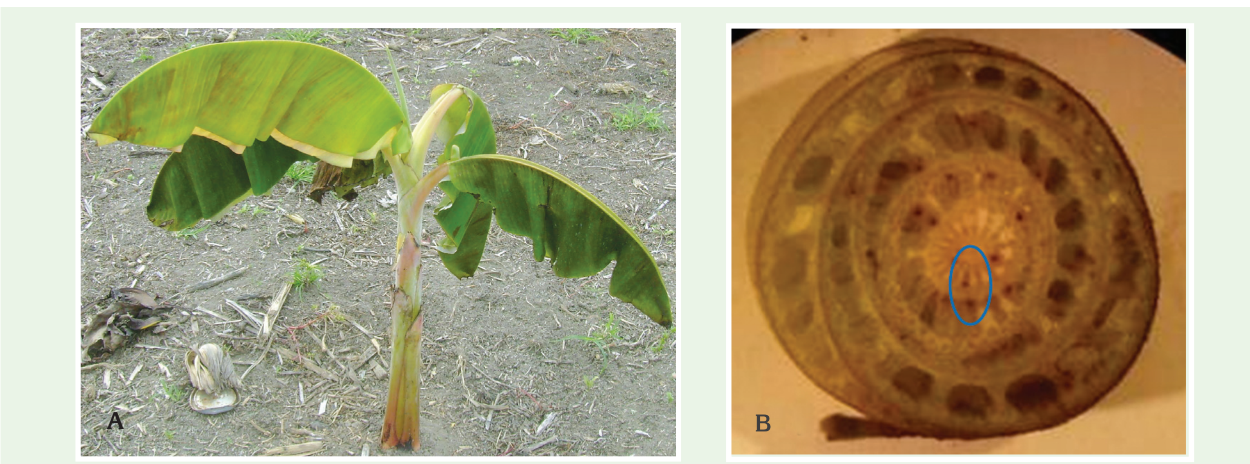
Figure 7. Typical colonies of *Ralstonia solanacearum* growing in **(A)** TTC medium and **(B)** SMSA medium.

Symptoms of Moko disease in plantain

Symptoms manifested by this disease are variable, taking several weeks to develop, and requiring a person trained to detect it in its early stages. These characteristics increase the risk of Moko disease disseminating because apparently healthy plants are deleafed, desuckered, harvested, and otherwise treated without precautions being taken (Vásquez 2008).

Moko disease induces wilting, which begins with the yellowing and collapse of the youngest leaves, and necrosis of the flag leaf (also known as "candle", "tobacco", or "cigar" leaf). These symptoms progress towards the oldest leaves and, internally, the vascular tissues become necrotic, especially those located in the central area of the pseudostem. Immature fruits of infected plants are yellow and hollow from dry rot of the pulp. When infections are early or occur before flowering, the fruiting bunch may show abnormal or no development (De Oliveira e Silva et al. 2000).

Being a systemic disease, that is, where the pathogen is translocated through the plant via vascular bundles, symptoms can appear in any of the crop's phenological stages. In newly planted seedlings, a widespread yellowing appears, with later necrosis (Figure 8A). When the pseudostem is cut, a few reddish spots or brown lines appear, corresponding to the vascular bundles where the pathogenic bacterium has degraded tissues (Figure 8B).



Figurae 8. Symptoms of Moko disease in plantain plants: **(A)** at two months after transplanting, and **(B)** necrosed vascular bundles seen in a cross-section of a pseudostem (observation with stereoscope).

In young plants, dry leaves appear in the middle of asymptomatic leaves, or the flag leaf appears completely necrosed (Figure 9).

When cutting the rachis, fruits, pseudostem, or corms, internal damage can be observed as lesions that are, at first, pale yellow, becoming reddish brown, and then black (Vásquez 2008) (Figure 10).

Figure 9. Necrosis in alternate leaves of plantain plants.

Figure 10. Necrosis of vascular bundles in a plantain pseudostem, cut diagonally.

When attack is late or transmission is by vector insects to the bunch, reddish or black coloration appears in the affected banana fingers. On cutting across the rachis, spots can be seen. These correspond to infected vascular bundles through which the bacterium has moved through the plant (Figure 11).

Figure 11. Symptoms of Moko disease: **(A)** a cross-section of a rachis shows infected vascular bundles, **(B)** internal necrosis of fruit pulp, and **(C)** cross-sections of fruits in a bunch of plantains

When cutting infected organs, or removing the bracts of a flower bud or pod, latex and bacterium are released, exuding as small white droplets (ICA 2000) (Figure 12).

Figura 12. Latex exudes onto a plantain male flower bud on removal of a bract.

Transmission and dissemination

Moko disease can also spread to new areas through infested soil, by contact with roots, or transmission by vector insects when the inflorescence is the site of primary infection. Such transmission gives rise to symptoms of wilt (Denny and Hayward 2001). Insects, particularly stingless bees (*Trigona* spp.), transmit the bacterium from inflorescences of diseased plants to those of healthy plants.

Moko disease can be transmitted by asexual seed, if suckers of infected plants are selected as planting materials. This is the principal form of dispersal among different plantain-producing regions in each country.

The movement of Moko disease to deep within a commercial plantation occurs mainly through the use of contaminated tools for routine tasks such as deleafing, desuckering, or trimming. Tools such as spades, machetes, or deleafers that have been in contact with the latex of diseased plants can easily transmit the disease to nearby healthy plants.

Infection of fruits is practically non-existent in commercial plantations, as these are covered with translucent plastic bags to protect them from insects. Moreover, male flowers are removed, further reducing the possibility of inoculation (Molina 1999).

Transmission also occurs through water sources such as irrigation, runoff, groundwater, and streams because of the farmers' unsuitable practice of throwing diseased plants into rivers and streams (Martínez-Garnica 2006).

These means of dissemination and transmission, associated with a lack of resistant cultivars and low-technology production, make Moko disease a highly serious problem for plantain and banana cultivation (Molina 1999; De Oliveira e Silva et al. 2000).

Strategies for managing Moko disease and mitigating damage

Control of Moko disease has been limited because of the lack of effective management technologies and of resistant plantain varieties. The only control mechanisms available to farmers are using clean seed, disinfecting footwear and tools at deleafing, eradicating plants showing symptoms, and marking out infected sites. These are all recommended by institutions such as the Colombian Agricultural Institute (ICA), the Colombian Corporation of Agricultural Research (CORPOICA), and CIAT (Mesa and Triviño 2007).

Preventive management

The principal strategy for controlling Moko disease is exclusion, that is, preventing the disease from entering a plantation through the various means of transmission.

Healthy planting materials

This measure has traditionally been the most effective one, as it guarantees the health of the materials produced. This practice involves using a system of thermotherapy—implemented by CIAT and the Colombian National Federation of Plantain Producers (FEDEPLÁTANO)—to produce multiple shoots. Thermotherapy stimulates the rapid growth of clean seed (Figure 13), producing about 90 shoots/m^2 per month and involving a total greenhouse time of 3 months. The system also permits automated and constant control of climatic variables such as temperature and relative humidity.

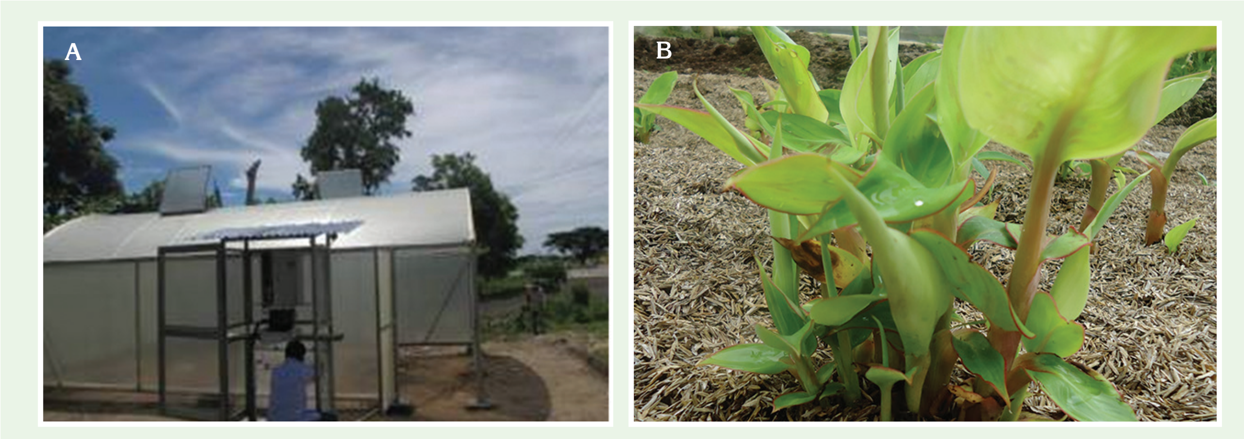


Figure 13. Mass propagation system for clean *Musa* seed, using thermotherapy: **(A)** thermal chamber built at CIAT; and **(B)** profuse shoot production in the chamber.

The use of the materials produced can benefit small- and medium-scale farmers and farmers associations by providing access to high-quality and low-cost seed (Álvarez et al. 2013c).

Disinfecting tools, footwear, and vehicle tires

Tools such as deleafers, spades, and machetes should be disinfected with a bactericide (2.5% sodium hypochlorite), spraying the tools after completing tasks for each plant. Foot baths, containing sodium hypochlorite solution, should also be placed at farm entrances and at different plots. Farm workers can therefore disinfect their footwear as they enter and leave. Likewise, for vehicle tires, wheel baths, containing sodium hypochlorite solution at the same concentration, are also constructed at farm entrances.

Note: After evaluating more than 100 products for disinfecting tools, CIAT determined that 2.5% sodium hypochlorite was the most effective and economic means of preventing the dissemination of *R. solanacearum* on tools. Formol (formaldehyde) was traditionally used to disinfect or sterilize tools and planting substrates, but it has serious implications for high impact on the environment: it reduces soil fertility, and constitutes a risk of poisoning workers. Sodium hypochlorite at the recommended concentration is an effective option for disinfecting tools, and, unlike formol, is an alternative preventive management practice. The sodium hypochlorite solution should be renewed every 3 hours to minimize degradation by solar radiation.

Eradicating diseased plants

If the disease is present in the plantation, the following measures should be taken: (1) fence off the diseased plants and those nearest to them at a radius of 5 m; (2) eradicate these plants by injecting herbicide (recommended and authorized by competent authorities) at three different positions on the pseudostem.

Note: These plants constitute a disease focus, and tasks conducted in such sites must be done by only one person. This person wears garments (footwear and clothes) and uses tools specifically for such focuses and not for the rest of the plantation.

Alternative management

Álvarez et al. (2002) suggested that a promising alternative is to use compost lixiviate. This liquid is obtained by decomposing organic residues into beneficial products. It enriches beneficial microorganisms and prevents plant diseases. Lixiviates can also enhance soil fertility and improve plant nutrition (SP-IPM 2008).

Plantain lixiviate (Figure 14) is a mixture of non-humic and humic substances. Non-humic substances include sugar, amino acids, polysaccharides, and proteins, while humic substances include mixtures of different macromolecular complexes. The use of lixiviate involves microorganisms responsible for carrying out microbial decomposition (Arenas et al. 2004), inhibiting phytopathogens such as *Mycosphaerella fijiensis*, *R. solanacearum*, and *Sphaerotheca pannosa*. This effect is attributed to the combined actions of biochemical compounds with antimicrobial effects—mainly phenolic acids, saponins, essential oils, naphthoquinones, and terpenoids (Mainer 2009). Incorporating plantain rachis lixiviate into the soil can therefore result in a 31.6% control of plant diseases.

Figure 14. Production of plantain rachis lixivate.

Likewise, significant reductions of the *R. solanacearum* in the soil can also be achieved by applying other inputs, for example:

- Incorporating French marigold *(Tagetes patula)* into the soil will reduce *R. solanacearum* populations by 84.7% (Arenas et al. 2004).
- Using liquid fertilizer that comprises 2.7% total nitrogen, 1.7% phosphorus, 5% potassium, 12% fulvic acids, and 5% humic acids can achieve a 58.2% reduction.
- Incorporating Calfos, a phosphoric fertilizer containing calcium and other elements, will reduce populations by 50.8%.

The four alternative biocontrols just described—lixiviates, marigold, liquid fertilizer, and Calfos—were developed because chemical control can create problems for both the environment and human health; practices such as crop rotation are not entirely successful in managing Moko disease; and the bacterium is able to survive for years on organic matter, soil, or alternative hosts. These alternative products have now replaced formol (formaldehyde), a highly toxic product that was previously used by farmers on their plantations.

Biological diversification of soil

Applications of organic fertilizer, use of lixiviates, and fewer herbicide applications for weed control have had positive effects on soil biodiversity, as shown by increased populations of native mycorrhizae, worms, and beneficial nematodes (Chagüezá 2011). Such factors are significant indicators of soil health.

Moreover, this biodiversity also improves soil chemical properties (especially organic matter and nutrient availability) and soil physical properties (particularly structure, porosity, and moisture retention). The result is improved crop nutrition (Fernández-Larrea 2001; Álvarez et al. 2011).

Use of varieties that tolerate Moko disease

At CIAT, infection tests were conducted for Moko disease, using pathogenic strains that represent the genetic diversity of *R. solanacearum* in Colombia (Gómez et al. 2006). These were inoculated into 34 varieties of plantains and bananas under greenhouse conditions. On the basis of their resistance response to Moko disease and their potential for the fresh market, six plantain varieties were selected—Pelipita, Saba, Fougamou, Maritú, Pisang Ceylon, and FHIA-21—together with four banana varieties—FHIA-17, FHIA-01, Sedita, and Yangambi Km5) (CIAT, unpublished data).

Two plantain varieties were then selected for a pilot trial, which is currently being evaluated on three farms in the principal plantain-growing region of Colombia (central Coffee Belt, Quindío). The varieties are being assessed in focuses where Moko disease has devastated the highly susceptible 'Dominico Hartón' (*Musa* AAB). To date, results are promising for managing the disease in that tolerance levels are excellent and typical symptoms are notably lacking. Fruiting bunches, with optimal characteristics in terms of yield and quality, have been harvested. At the same time, one variety also showed tolerance of black sigatoka.

These findings bear out the discoveries of Cuéllar et al. (2011), made during greenhouse evaluations, and reports from the Honduras Foundation for Agricultural Research (FHIA 2008) on the adaptability and response of hybrid FHIA-21 to black sigatoka in the Dominican Republic.

Advantages: By showing tolerance of Moko disease and an evident response to black sigatoka, hybrid FHIA-21 becomes a management option for reducing applications of agrochemicals for both diseases. This translates into reduced contamination of water sources, less exposure of workers to chemical products, and lower production costs.

General recommendations

Status of Moko disease	Preventive management	Intervention	Eradication
Absent from the farm	1. Use certified seed. Do not exchange corms with other farms or use if of doubtful quality. Disinfect seed. 2. Apply fertilizers according to recommendations of extension workers or on national technology packages. 3. Install disinfection stations at farm entrances. 4. Undertake regular training to understand the disease and how to prevent it. 5. Cover the bunches with bags in a timely fashion. 6. Apply lixiviates from healthy plantain rachis (Álvarez et al. 2013b). 7. Monitor the disease.		
Present on nearby farms	1. Use healthy seed obtained by thermotherapy. Do not exchange corms with other farms or use if of doubtful quality. 2. Install disinfection stations at farm entrances. 3. Apply suitable fertilizers to the crop in a timely fashion. 4. Undertake regular training to understand the disease and how to prevent it. 5. Cover the bunches with bags in a timely fashion. 6. Apply lixiviates from healthy plantain rachis. 7. Fence off the plantation to prevent entry of animals from neighboring farms.	1. Inform phytosanitary authorities of the existence of disease focuses. 2. Advise farmers to apply intervention measures.	Request the intervention of phytosanitary authorities in these areas

(continues)

Status of Moko disease	Preventive management	Intervention	Eradication
Present on the farm	1. Do not use seed from the farm itself. Use healthy seed obtained by thermotherapy. 2. Plant resistant varieties. 3. Constantly disinfect workers' tools, footwear, and clothing. 4. Train administrators and workers on preventive management. 5. Cover the bunches with bags in a timely fashion. 6. Fence off or isolate affected areas to prevent the entry of animals and workers.	1. With help from competent authorities, use the eradication protocol to tackle disease focuses. 2. Protect soil from erosion and runoff. 3. Incorporate phosphoric rock, French marigold, and rachis lixiviate into the soil. 4. Use duly composted organic matter and antagonistic microorganisms.	Inject diseased plants and their five nearest neighbors according to the management protocol known as "circle" or "traffic light system" (Álvarez and ICA 2007; updated by Álvarez et al. 2013a).

Black Sigatoka
(Black Leaf Streak Disease, BLSD)

Black sigatoka or black leaf streak disease (BLSD), caused by the fungus *Mycosphaerella fijiensis*, is the most limiting leaf disease in Musaceae production worldwide. By reducing the healthy leaf area, this disease considerably reduces the plant's ability to conduct photosynthesis (Figure 15). Consequently, the bunches and fruit fingers weigh less than those of healthy plants (Ramsey et al. 1990). Severe infections of black sigatoka also markedly affect fruit physiology, causing premature ripening (Meredith 1970; Stover 1972; Wardlaw 1972). Severity of this disease increases in a system like Musaceae cultivation, in which a genetically uniform clone is cropped over large extensions. Such a system becomes highly vulnerable to epidemic attacks from the pathogen (Manzo-Sánchez et al. 2005).

Figure 15. A crop of the plantain 'Dominico Hartón' (*Musa* AAB) affected by black sigatoka.

Black sigatoka was first recorded in 1963 on the islands of Fiji from where it quickly spread, displacing yellow sigatoka (*M. musicola*). Such displacement was observed as being similar in most banana- and plantain-growing regions around the world (Belalcázar 1991; Martínez-Bolaños 2012), being mainly attributed to the aggressive nature of *M. fijiensis*, particularly when favored by environmental conditions (especially temperatures). It also requires fewer days to complete its pathological cycle, compared with *M. musicola*. Currently, black sigatoka is reported from most tropical and subtropical regions where Musaceae are cultivated. The economically most important and/or extensively cultivated plantain and banana varieties are susceptible to this disease, which, under favorable conditions, can reduce yields by 35% to 50% (Riveros 2000; Bennett and Arneson 2003).

Symptomatology

Symptoms of black sigatoka vary according to plant development, host variety, and severity of attack. In susceptible varieties, the disease is recognized mainly by the presence of numerous streaks and blotches, most noticeably on lower leaf surfaces. The blotches accelerate the drying and death of the leaf area, which then affects the plant's photosynthetic capacity. The disease starts as small red or brown dots found mainly on lower leaf surfaces. These spots grow and lengthen to produce darker and larger blotches that then begin to dry out (Marín et al. 2003).

The disease usually evolves through stages, of which six are recognized according to the Fouré scale (1982) (Figure 16):

Stage 1. Small lesions or spots, yellowish-white to brown in color, and 1 mm long. Known as *pizcas* (specks) in Spanish, they are barely visible on the lower surfaces of leaves.

Stage 2. Chlorotic lines or streaks, 3–4 mm long x 1 mm wide, initially greenish yellow, becoming brown.

Stage 3. The lines or streaks lengthen and widen, giving the impression of having been painted on. Without well-defined edges, they are brown, and can be up to 2 cm long.

Stage 4. Oval-shaped blotches, coffee-colored on the lower surfaces and black on the upper surfaces of leaves.

Stage 5. Black blotches, surrounded by black rings and sometimes yellowish halos, with dry semi-sunken centers.

Stage 6. Light brown blotches, with grayish-white sunken centers showing collapsed tissue, surrounded by chlorotic tissue.

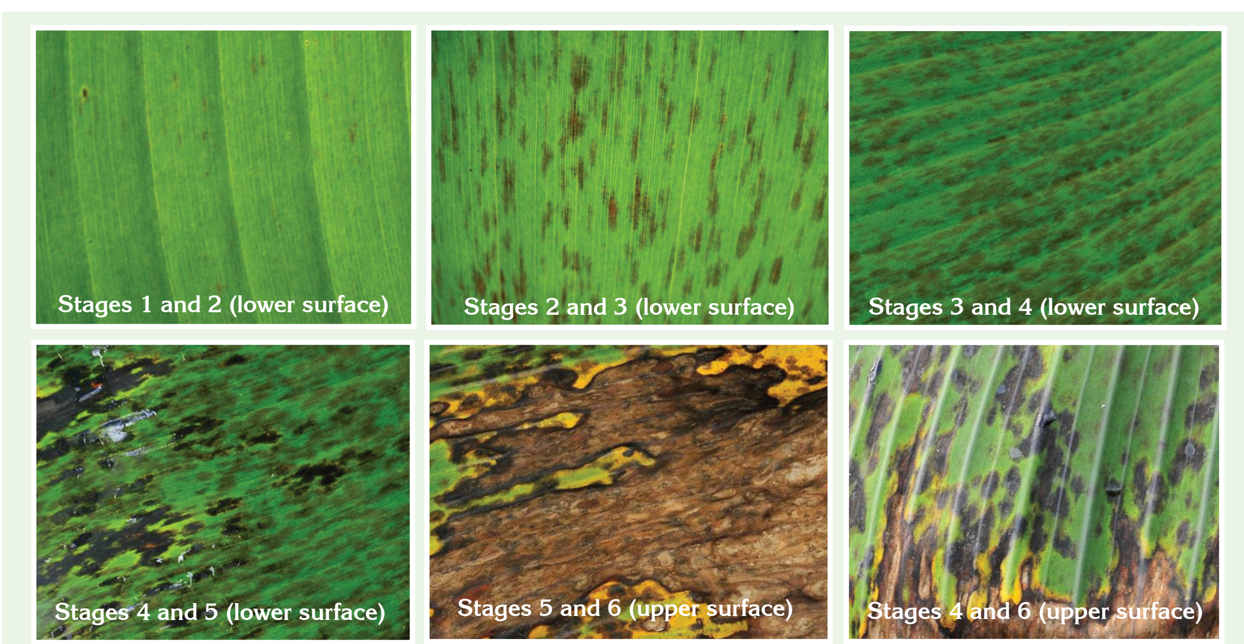


Figure 16. Symptoms of black sigatoka on leaf surfaces at different stages of disease progress.

Pathological cycle and epidemiology

The disease cycle is directly influenced by climatic conditions, the variety cultivated, and agronomic crop management.

The pathogen's aggressiveness is directly related to climatic conditions. Areas worst affected by black sigatoka are those that have rainfall of more than 1400 mm per year, relative humidity of more than 80%, and an average temperature of 23° to 28°C (Fouré 1994; Gauhl 1994; Mobambo 1995; Martínez et al. 2002;Torrado and Castaño-Zapata 2008).

The fungus causing black sigatoka in Musaceae can reproduce in two ways: (i) during the sexual phase, called *Mycosphaerella fijiensis*, spores (ascospores) are produced during advanced stages (5 and 6) of the disease; and (ii) during the asexual phase, called *Pseudocercospora fijiensis*, when spores (conidia) are produced in early stages (2 to 5) of the disease, in larger quantities, and on the lower surfaces of affected leaves (Merchán Vargas 2000).

Both conidia and ascospores play important roles in the dispersal of the disease (Marín et al. 2003). Both are infective, producing the same type of blotching and later development of the disease (Ploetz 2001; Agrios 2005). The ascospores are regarded as the main means of long-distance dispersal between plantations and between new areas (Ploetz 2001; Pineda-Rubio and Castaño-Zapata 2005). Conidia are associated mainly with local dissemination by wind, rain, and rain splash (Marín et al. 2003; Agrios 2005; Torrado and Castaño-Zapata 2008).

The ascospores are deposited mainly on the lower surfaces of new leaves as they unfold, producing a band pattern of infections on the first side exposed. The pattern reflects the growing deposits of spores in the cylinder of the cigar leaf while it is unfolding (Marín et al. 2003). Infection is favored by prolonged periods of high humidity and the presence of free water on leaves (Marín et al. 2003; Agrios 2005).

The spores (ascospores and/or conidia) germinate and germ tubes enter leaves through stomatal openings. The fungus then grows inside the leaf, consuming the internal contents of cells, killing them. However, depending on environmental conditions, initial symptoms are observed only 10 to 30 days after infection, that is, at leaf 3 or later. Diseased leaves then become a source of new inocula to give rise to new infections in the field (Figure 17). Thus, if environmental conditions are favorable, the disease can produce devastating effects.

Managing black sigatoka

Black sigatoka is best controlled from an integrated disease management (IDM) approach, which offers farmers effective, safe, and sustainable solutions. Its success depends on the farmer's or technician's skill in combining different tactics or compatible practices and which are applicable to the agroecosystem according to ecological, economic, and technical principles. The technician must clearly understand the disease—its symptoms, pathological cycle, and epidemiology—and the options for preventing or reducing the pathogen's populations (control methods, genetic resistance, disease prediction systems, and costs). Principal methods for managing the disease are described below.

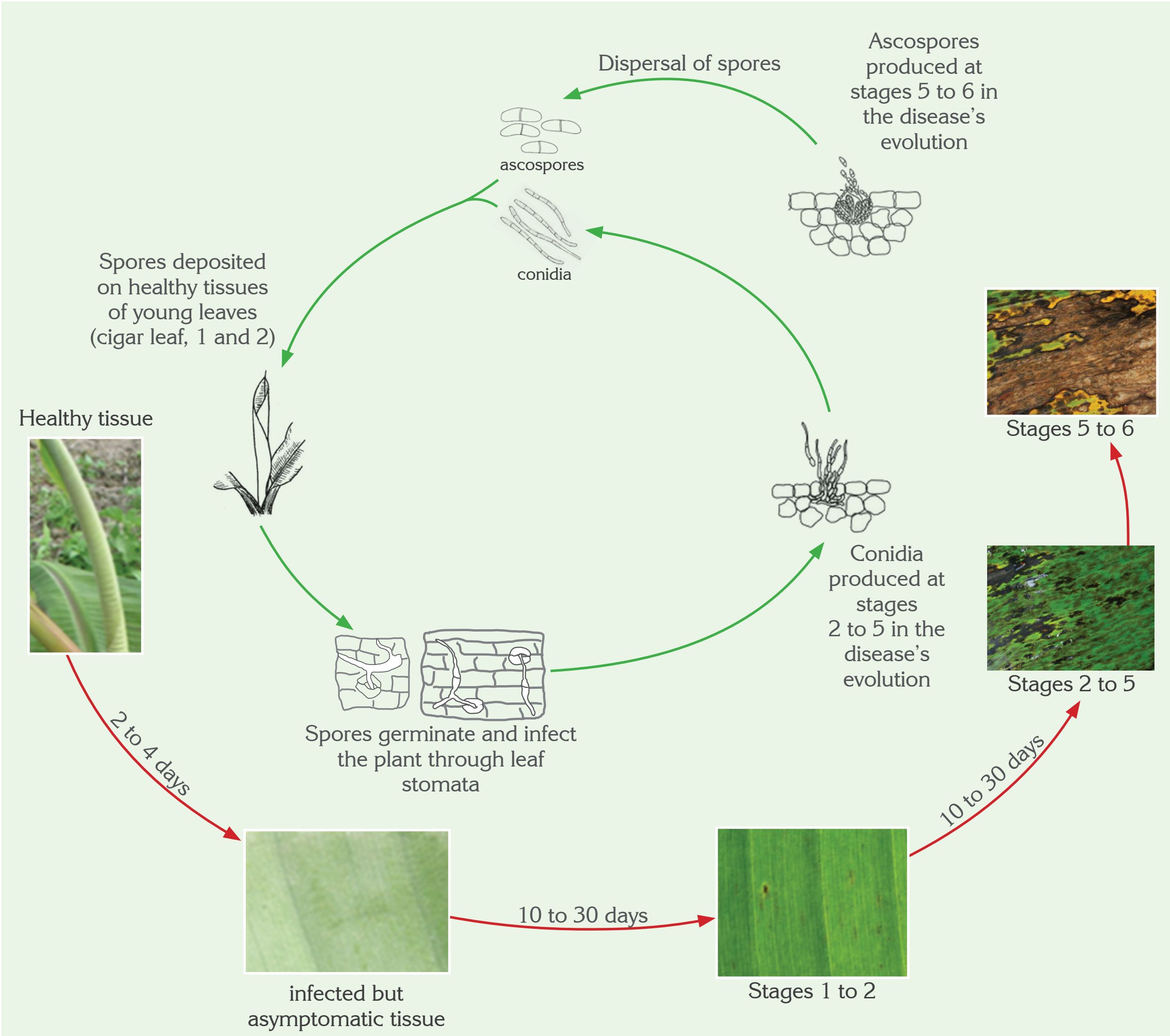


Figure 17. Pathological cycle of black sigatoka in Musaceae.
SOURCES: Adapted from Bennett and Arneson (2003) and Ganry et al. (2012).

Cultural control

This practice aims to reduce sources of pathogen inoculum and improve host-plant conditions to minimize impact from disease. For black sigatoka, cultural control includes the following practices:

Phytosanitary deleafing
This consists of partial (trimming) or total (deleafing) removal of leaves that are wasted and spotted or necrotic (Figure 18) and, together with these, the fungal propagules (Orozco-Santos et al. 2008). Leaves infected with stages 3 to 6 represent the only source of inoculum of the disease. The best management measure therefore is to prevent the pathogen from sporulating and so causing new infections (Marín and Romero 1992; Orozco-Santos et al. 2002; Marín et al. 2003; Orozco-Santos et al. 2008). The frequency and extent of elimination of spotted leaf areas depend particularly on the stage of the crop's development, climatic conditions, and the degree of severity of sigatoka.

Phytosanitary trimming and deleafing, accompanied by applications of chemical products, under a biological early-warning system has proved an effective management practice, resulting in good quality bunches with fewer applications of chemical products (Gañán et al. 2007).

Figure 18. Trimming and deleafing a crop of the plantain 'Dominico Hartón'.

In dry seasons, the practice of deleafing does not need to be so strict, as conditions are unfavorable for disease development. In contrast, strict measures should be taken during rainy seasons to eliminate the inoculum (Orozco-Santos et al. 2002) and so reduce epidemic effects. For example, research conducted in Colombia resulted in a phytosanitary program for crops of Hartón plantains, based on regular deleafing every 4 weeks in dry seasons and every 2 weeks in rainy seasons (Merchán Vargas and Chavarriaga 1994). Nevertheless, regularity of deleafing depends not only on environmental conditions, but also on crop variety and stage of crop development.

If diseased leaves are left on the plant, the production and dispersal of *M. fijiensis* ascospores can last for as long as 20 weeks (Gauhl 1994). However, if leaves are cut and deposited on the ground, where they decompose, the pathogen can survive only 3 to 6 weeks (Guzmán and Romero 1995; Villalta and Guzmán 2005). Thus, fewer spores survive and are released (Gauhl 1994), thereby reducing inoculum sources.

The total or partial cutting of leaves depends on the severity of disease. If infection covers less than 50% of leaf area, then trimming off the affected tissue only (i.e., performing surgery) is sufficient. If, however, infection is severe, the whole leaf should be removed (deleafing) and left on the ground.

Most sporulation occurs during the first 15 days after necrosis of leaf tissue. However, black sigatoka lesions continue to produce inoculum for up to 30 days after the leaf has been cut and deposited on the ground (Villalta and Guzmán 2005). Even so, the period of inoculum production can be reduced by chopping up leaves to speed tissue decomposition through activities of soil microorganisms. Decomposed leaves on the ground will also contribute nutrients and organic matter.

Only by practising phytosanitary deleafing and trimming can the severity of black sigatoka be kept at a level that will guarantee adequate bunch production (Gañán et al. 2007). Results can be enhanced by combining with other management practices. Note that phytosanitary deleafing also helps make applications of chemical, biological, or organic products more effective.

Pruning or suckering

This activity involves the removal of surplus offshoots (or suckers, Figure 19A) from the plants' rhizomes. A suitable plant population is thus maintained, and mother plants are not exhausted by competition for light, nutrients, and water (Figure 19B). More energy is thus channeled into bunch production. Moreover, thinning improves and facilitates crop management, as well as fungicide application (Stover 1980; Marín et al. 2003; Orozco-Santos et al. 2008). One or two good-quality offshoots (daughter and granddaughter) (Figure 19B) should be selected to ensure the plant's productive return.

Figure 19. The value of thinning: **(A)** the mother plant (largest plant) has too many offshoots for quality production; **(B)** offshoots have been culled to two good-quality individuals (on either side of the mother plant).

Plantain and banana production system

Plantain and banana production systems can be categorized according to cropping time—perennial, annual, or biennial—and to production scheme—monocropping or associated cropping.

Monocropping
Generally, large-scale cultivation is of the monocropping type, whether perennial, annual, or biennial. Black sigatoka can be devastating in commercial monocultures because of the uniformity of clones, which are usually highly susceptible to the disease. Also favoring the severity and rapid movement of the disease is the presence of plants of different ages in the plantation, especially those that are flowering and close to harvest, when release of inoculum is highest.

Planting density is also a significant factor in monocropping. Although planting density as a practice for managing sigatoka is controversial, higher densities are known to increase production per unit area in certain banana and plantain cultivars. According to Belalcázar et al. (2003a), high planting densities (at 3000 plants/ha) of the plantain 'Dominico Hartón' (*Musa* AAB) in Colombia not only increased fruit yield, compared with the traditional system (at 1000 plants/ha), but they also reduced the incidence of black sigatoka. Similar results were obtained in Cuba with the banana 'FHIA-23' at 4000 plants/ha.

Associated cropping
The use of a diversified system of associated crops contributes significantly to family food security—it even contributes to a country's food security. Species diversity is important for regulating the ecosystem, allowing for the crop's sustainable production. It also minimizes dependence on external inputs such as pesticides or chemical fertilizers, mechanization of soil preparation, and on other technologies more appropriate for large-scale monocropping (Toledo et al. 1985; Altieri et al. 2012).

The use of associated cropping as such implies not only ecological benefits but also economic and social benefits. Family-scale or small-farm production is characterized mostly by the cultivation of plantain and banana in a perennial planting system in association with other crops typical of the region and culture. This cropping system also provides small farmers with alternative food crops (subsistence crops) and/or cash crops that generate income throughout the year. This system reduces the effects caused not only by black sigatoka, but also by other diseases or pests. It also efficiently uses soil nutrients (FAO 2000).

Examples of associated cropping include plantain traditionally planted in association with coffee, cacao, cassava, and fruit trees (Colombia; Rodríguez-Martínez and Rodríguez-Saavedra 2001); maize–plantain associations in Africa (Noupadja 1997); and maize–banana associations in Cuba (Espinosa et al. 2003). Such associations not only offer benefits in terms of food or economic security but they also contribute significantly to biomass, which benefits both Musaceae crops and the soil (Espinosa et al. 2003).

Other agronomic practices
Black sigatoka's progress in the plant, known as its development rate, can also be directly affected by the nutritional state and phenological stage of the host plant. Plants that receive good agronomic practices (e.g., fertilizer applications, suitable planting density, and irrigation) will develop better physiologically (e.g., in terms of foliar emission rates), and thus be able to tolerate disease attack (Gauhl 1994), compared with stressed plants or plants with delayed physiological development.

Soil conditions (physical, chemical, and biological) also affect the plantain's response to black sigatoka. Ready availability of minerals such as calcium, magnesium, and potassium, and an adequate nitrogen–potassium ratio means vigorous plants and reduced disease development

(Romero 1998). Recent research has shown that silicon, applied to the soil as silicic acid or potassium silicate, helps reduce the progress of black sigatoka in banana (Jiménez 2008; Kablan et al. 2012). However, excessive applications of nitrogenated fertilizers can cause the opposite effect, predisposing plants to attack by the disease.

Fertilizer applications should also include adequate contributions of organic matter to the soil, using the production system's own resources (e.g., leaves, stems, and rachis lixiviate) and biofertilizers such as bacteria that promote root growth and fungi that form arbuscular mycorrhizal associations. Applications of biofertilizers, accompanied by organic fertilizers, can improve soil conditions to the point where applications of chemical fertilizers can be reduced (Rivera-Cruz et al. 2008; Álvarez et al. 2011; Gañán et al. 2011).

Excess humidity favors the development of black sigatoka and other pathogens that may affect the crop (Gauhl 1994; Orozco-Santos and Orozco-Romero 2006). Adequate drainage in the plantation will quickly eliminate surplus water, reducing the humid conditions required by the pathogen. Poor drainage may slow down foliar emission rates, thus favoring severe attack by black sigatoka. It will also negatively affect soil nutrient availability (Orozco-Santos et al. 2008).

Equally important is managing pests such as nematodes, scale insects, and weevils to maintain root and corm health. Planting materials must be certified or be of known provenance and in good health. Contaminated seed is the principal means of disseminating nematodes and weevils. Procedures for seed disinfection are required, ranging from working the soil and conducting sanitary cleansing or "peeling" of corms to treatment with agrochemicals and beneficial organisms such as the fungus *Paecilomyces lilacinus* (Guzmán-Piedrahita et al. 2012).

Biological control

Biological control strategies have recently become more important as alternatives to chemical products in disease management and in response to increased market demand for foods obtained through organic and/or sustainable production systems. Reductions in chemical substances that contaminate the environment and lower production costs are advantages that encourage this practice.

Among other factors, biological control includes the use of antagonistic fungi or bacteria (e.g., *Bacillus subtilis*), organic products or natural extracts with biocide effects, and resistance inducers (Riveros and Arciniegas 2003). However, many studies showing encouraging results were trialed in laboratories only and are not available to farmers. A recent study indicated that using organic fungicides or biofungicides (e.g., essential oils, organic acids, potassium carbonates, and lixiviates of pseudostems and fruits) to manage disease in the field did not offer disease control under high inoculum pressure (Ganry et al. 2012). The mechanisms and interactions affecting the relationship between disease progress and biological controllers are as yet unknown, hampering the development of biological control tactics that are efficient in the field.

de Lapeyre de Bellaire et al. (2009) suggest that applications of mixtures of biocontrol agents such as *Bacillus subtilis* and *B. pumilis* and contact fungicides would reduce the number of fungicide applications.

Although biocontrollers are effective in plans of preventive disease management, they do not constitute a curative measure, but must be used alternately with chemical control (Riveros 2000).

Use of lixiviate from plantain harvest residues

Lixiviate is a liquid produced by decomposing plantain harvest residues (Figure 20). After the bunches are harvested, their rachis is cut up and stored in a *ramada* or roofed compost trough (Figure 20A), where it begins decomposing through physical (temperature and humidity) and biological processes. The resulting lixiviate contains partially decomposed organic matter, bacteria, and byproducts formed during decomposition (Grajales and Villegas 2002). Traditionally, lixiviate was regarded as a liquid organic fertilizer and, for several years, used empirically by some plantain farmers in Colombia as a biofertilizer and biofungicide. Several publications have since provided evidence of the level of protection achieved by this bioproduct, including for managing black sigatoka (Valeska and Apezteguia 2001; Riveros and Arciniegas 2003; Larco 2004; Escobar and Castaño-Zapata 2005; Mainer 2009; Ortiz 2009; Álvarez et al. 2010; Hernández et al. 2010).

According to the experiences of plantain farmers in Colombia, the number of applications of agrochemicals to control sigatoka can be reduced by spraying leaves with lixiviate. Álvarez and Gañán (2013) conclude that not all sources of lixiviate effectively manage black sigatoka, because of differences in chemical and organic properties (which are governed mainly by the raw materials' mineral and biological contents) and/or the time that elapsed since production. The authors also indicate that the best results were obtained by using lixiviates from rachis (as sole raw material) and with a production time of more than 6 months, with constant recirculation of the lixiviate in the composting system. The principal author and her work team are currently researching and validating the use of lixiviate as an option for managing sigatoka in plantain crops.

Figure 20. Producing lixiviate from plantain rachis: **(A)** plantain rachis piled into a *ramada* or roofed compost trough; **(B)** the dark liquid (lixiviate) resulting from decomposing harvest residues.

Genetic resistance

The widely cultivated commercial clones of Musaceae that are susceptible to *M. fijiensis* are hybrids of two wild species: *Musa acuminata* (A genome) and *M. balbisiana* (B genome). These genetic materials have evolved largely through asexual propagation, which generates limited genetic variation and higher susceptibility to pests and diseases (Janick 1998). Developing plants resistant to the disease from commercial cultivars, using traditional improvement methods, is difficult, as they are usually polyploid and sterile. However, over the last few decades, efforts have been made to develop new plantain and banana cultivars that are resistant to black sigatoka by introducing genes from wild diploid bananas.

The Honduras Foundation for Agricultural Research (FHIA, its Spanish acronym) has used conventional genetics to develop tetraploid hybrids of plantain and banana (named FHIA), with resistance to black sigatoka and other diseases and with higher yields than traditional cultivars. Several studies have confirmed the resistance shown by plantain genotypes FHIA-20 and FHIA-21 (Molina-Tirado and Castaño-Zapata 2003; Hernández et al. 2006; Cuéllar et al. 2011) and banana genotypes FHIA-01, FHIA-02, FHIA-03, FHIA-17, and FHIA-23 (Molina-Tirado and Castaño-Zapata 2003; Hoyos and Castaño-Zapata 2007; Cuéllar et al. 2011). The FHIA hybrids differ from the traditional varieties mainly in their appearance, size, flavor, texture, and shelf life. These characteristics, and the lack of appropriate diffusion and transfer programs, have meant that, in most producing areas, these materials have not been well received or multiplied by farmers and traders (Merchán Vargas 2002).

One exception is the FHIA-21 hybrid, which has been accepted for consumption, either boiled or as fried plantain chips. The hybrid's yield is two to three times higher than those of the traditional plantain under similar conditions. It is cultivated commercially by small farmers and cooperatives in Honduras, Nicaragua, Ecuador, and the Dominican Republic (FHIA 2013). In Colombia, FHIA-21 is also being cultivated commercially by a small group of farmers.

Recent research at CIAT headquarters indicates a higher response of partial resistance to *M. fijiensis* in materials such as Topocho and Maqueño (plantain), and Sedita (banana), where resistance was expressed as a slow and less severe progress of the disease. This contrasted with the disease's rapid evolution in the susceptible plantain genotypes Guayabo, Hartón, Cubano Blanco, and Africa; and susceptible banana genotypes Gros Michel, Gros Michel Coco, Giant, Gran Enano, and Valery Cavendish (Cuéllar et al. 2011) (Figure 21).

Other cultivars are also considered as partially resistant to black sigatoka: Pisang Mas, Pisang Ceylon, Saba, and Fougamou (Mourichon et al. 1997; Cruz-Cruz et al. 2011). Although the plantain 'Africa' is susceptible to black sigatoka, it is more precocious than the commercial 'Dominico Hartón', meaning that it can tolerate the disease, reaching harvest with more leaves (Hoyos and Castaño-Zapata 2007).

Because of the pathogen's genetic variability, resistant cultivars of plantain and banana can become susceptible to *M. fijiensis* isolates, especially in large-scale crops, where clone uniformity would encourage the appearance of new and more virulent pathogen populations.

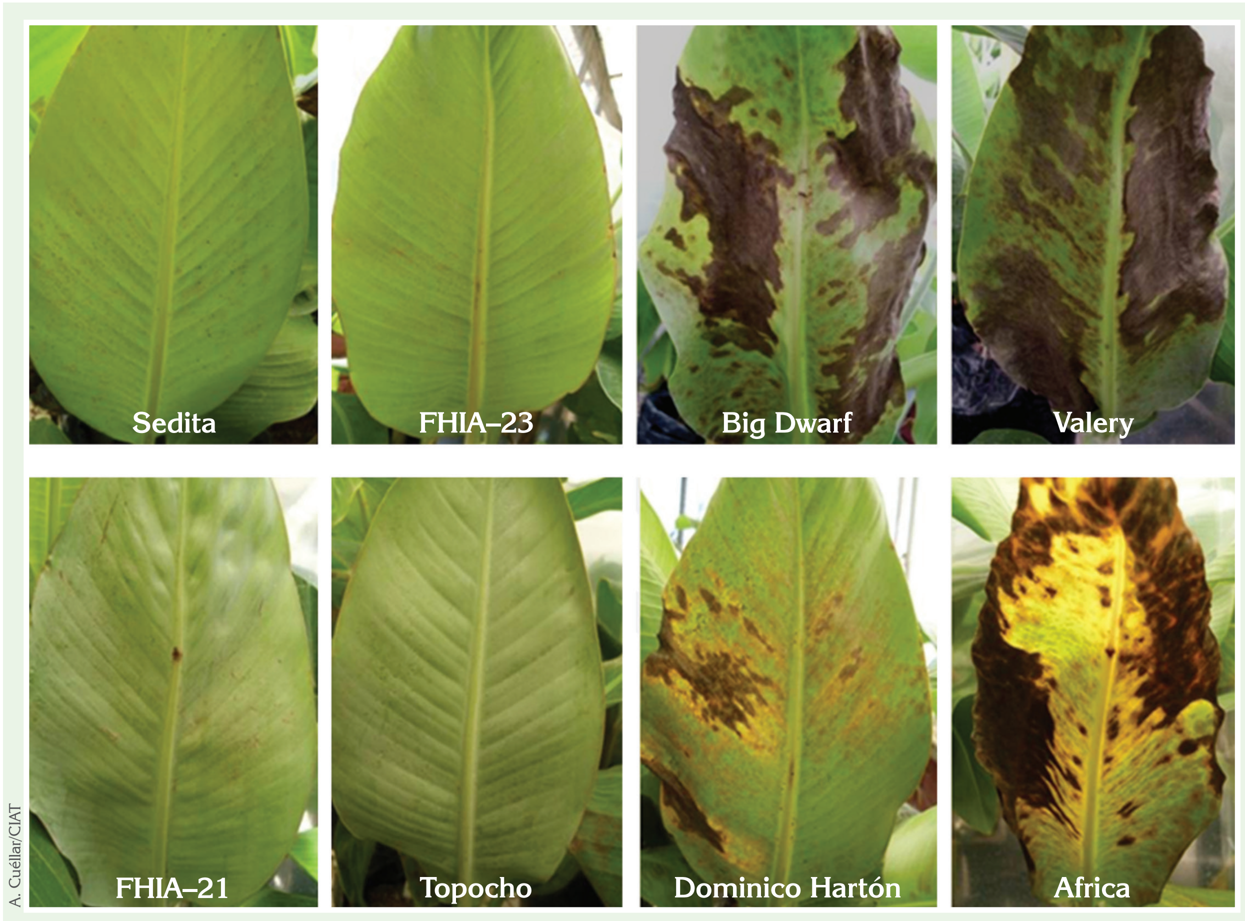


Figure 21. Response of some banana (top) and plantain (bottom) material to the development of the black Sigatoka disease.

Chemical control

Commercial products require regular applications of fungicides to successfully control black sigatoka because of the disease's polycyclic nature, high inoculum pressure (especially in large-scale monocropping), and tropical climatic conditions, which favor disease development. Strategies of fungicide use include alternating systemic-action products with protectants to reduce the appearance of resistance. Chemical control with fungicides such as benzimidazoles, triazoles, and strobilurins can effectively suppress the development of black sigatoka, especially when aerial applications and prediction strategies are used (Fouré and Ganry 2008; Ganry et al. 2008).

Agricultural spray adjuvants, because they are fungistatic mineral oils, can be used either alone or in combination with fungicides to improve the latter's curative effect of controlling the disease (Ganry et al. 2012).

However, repetitive use of agrochemicals has led to the appearance of *M. fijiensis* strains that are resistant to, or tolerant of, different fungicides (Chica et al. 2004; Brent and Hollomon 2007; FRAC 2010). These resistant strains have led to increasingly frequent applications of fungicides (up to 60 applications per year), thereby increasing production costs by 30% (Bennett and Arneson 2003).

Although applications of chemical products may reduce the damage caused by the disease, the resulting economic and environmental costs are not justifiable for most small-scale farmers, who are then more prone to suffer losses from this disease. Programs designed to guarantee food for subsistence farmers are therefore seriously concerned, as 90% of the world's production of plantain and banana comes from small-scale farmers and is destined for local consumption.

Recommendations for managing black sigatoka in family agriculture

The table below provides recommendations for treating black sigatoka attacking Musaceae crops grown on small farms. These recommendations take into account each of the five stages of crop development—planting and emergence, seedling, vegetative growth and preflowering, flowering and fruit maturation, and harvest—and are designed to help ensure the sustainable productivity of Musaceae crops.

Recommendations for managing black sigatoka in family agriculture

Planting and emergence	Seedling	Vegetative growth and preflowering	Flowering and physiological maturation of fruit	Harvest
CULTURAL PRACTICES				
Use certified or healthy planting materials. Install drainage to prevent saturation of water in the soil. Plant associated crops such as maize and coffee.				
Apply mineral fertilizers that contribute, in particular, phosphorus (P), potassium (K), and calcium (Ca). Supplement with applications of organic matter, plantain rachis lixiviate, and biofertilizers				
Manage weeds, pests, nematodes, and crop diseases				
	Deleafing: To be carried out when leaves are totally or more than 50% affected. Otherwise perform surgery, that is, remove those areas of leaves with stages 3 to 6 of the disease. **Frequency of deleafing:** Every 15 days in rainy seasons and 20 to 30 days in dry seasons. Leaves should be chopped up to speed their degradation into the soil. **Pruning or suckering**			
			Debudding, dehanding, and covering the bunches with bags.	
				Chop up the leaves
GENETIC RESISTANCE				
Choose the variety according to objective. Not all varieties are commercial. They also differ in characteristics such as appearance, size, flavor, texture, and postharvest maturation. **Varieties with partial resistance:** Plantain: FHIA-21, FHIA-20, Topocho, Maqueño. Banana: Foumagou, Sedita, Pisang Mas, Pisang Ceylon, FHIA-02, FHIA-03, FHIA-17, FHIA-23. **Precocious variety:** Africa				
		CHEMICAL CONTROL		
		Consult an agronomist for recommendations on chemical control. Before applying, deleaf or perform surgery. Apply fungicides under conditions of high inoculum pressure (susceptible variety, rainy season, and temperatures of >23 °C). Alternate the mode of action of fungicides (i.e., systemic-contact-systemic-contact) and use dispersant additives and coadjutants to improve the applications' effectiveness. Carry out applications in the morning or afternoon and use protective equipment.		

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