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INTEGRATED MANAGEMENT OF THE INVASIVE COCOA PATHOGEN *MONILIOPHTHORA RORERI*, CAUSAL AGENT OF FROSTY POD ROT

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ABSTRACT. The basidiomycete *Moniliophthora roreri* causes the devastating frosty pod rot (FPR) disease of cocoa (*Theobroma cacao*), a disease that commonly reduces yields by over 80% within a few years of pathogen establishment. The invasive pathogen originated in Western Colombia/Ecuador. In recent years it has expanded its range in South America (Peru and Venezuela) and rampaged throughout Mesoamerica as far as Mexico. Africa, Asia, and insular Caribbean are still free of this pathogen. Thus, the full management cascade recommended for invasive plant pathogens is applicable at certain locations: prevention, early detection and rapid response, and impact mitigation using various control approaches. This paper presents key issues and prioritizes actions that need to be taken to manage this pathogen cost-effectively at the applicable intervention point(s):

(1) Prevention

- Public awareness and education
- More efficient enforcement of existing regulations
- Extreme alertness and regional cooperation in the insular Caribbean, Eastern Venezuela, French Guiana, the Co-operative Republic of Guyana, Brazil, and Bolivia
- Strategic measures for intercontinental germplasm transfer, transport and trade

(2) Early Detection and Rapid Response

- Training of quarantine and survey personnel in early detection of latent infections
- Anticipatory emergency plan, based on pathway risk analysis
- Effective mechanism for prompt host elimination and compensation scheme

(3) Impact Mitigation

- Integrated approach, supplementing cultural control with chemical and biological agents
- Design of disease-resilient agroforestry systems (both short term)
- Classical biocontrol where introduced, e.g., with endophytes (medium term)
- Genetic and induced resistance (long term)
- Regular review of cost-effectiveness of measures, e.g., modelling for decision-making

KEY WORDS: Cocoa, invasive species management, *Moniliophthora roreri, Theobroma cacao*

RESUMEN: El basidiomicete *Moniliophthora roreri* causa la moniliasis, una pudrición devastadora de mazorcas del cacao (*Theobroma cacao*), la cual comúnmente reduce los rendimientos por más de 80% dentro de pocos años de su establecimiento. El patógeno invasivo originó en el Oeste de Colombia y/o Ecuador. Durante años recientes expandió su alcance en Sudamérica (Perú y Venezuela) y arrasó cacaotales a través de Mesoamérica hasta México.

Hasta el momento, África, Asia y el Caribe insular quedan libres del patógeno. Por lo tanto, toda la cadena de intervenciones recomendadas contra fitopatógenos invasivos aplica en ciertos ámbitos: prevención; detección temprana y respuesta rápida; así como mitigación del impacto empleando una gama de métodos de control. Este artículo presenta asuntos claves y prioriza acciones necesarias para el manejo rentable del patógeno en los varios puntos aplicables de intervención:

(1) Prevención

- Concienciación y educación pública
- Ejecución más efectiva de reglamentos existentes
- Vigilancia alta y cooperación regional en el Caribe insular, Venezuela oriental, las Guayanas, Brasil y Bolivia
- Mediadas estratégicas para la transferencia internacional de germoplasma, transporte y comercio

(2) Detección Temprana y Respuesta Rápida

- Capacitación de inspectores fitosanitarios y personal cuarentenario en la identificación de síntomas tempranos de la infección
- Plan previsor de emergencia, basado en análisis de riesgo de vías
- Mecanismo eficiente para la eliminación del hospedante y compensación de productores

(3) Mitigación del Impacto

- Sistema integrado con agentes químicos y biológicos complementando medidas culturales
- Diseño de sistemas agroforestales resistentes a plagas y enfermedades (ambos disponibles a corto plazo)
- Control biológico clásico, por ejemplo con endófitos, donde el patógeno es exótico (a mediano plazo)
- Resistencia genética e inducida (a largo plazo)
- Revisión frecuente de la rentabilidad de la medidas de control, por ejemplo por modelaje para toma de decisiones

PALABRAS CLAVES: Cacao, manejo de especies invasivas, *Moniliophthora roreri, Theobroma cacao*

INVASIVE TRACK RECORD OF MONILIOPHTHORA RORERI

Frosty pod rot (FPR) of cocoa (*Theobroma cacao*) is caused by the basidiomycete *Moniliophthora roreri*. The correct name for FPR in Spanish is *moniliasis*; the term “monilia” is inaccurate in either language. *M. roreri* is believed to have evolved in the forests of western Colombia and/or Ecuador on *Theobroma gileri*. The geographic spread started relatively recently, mediated by humans transporting cryptically infected cocoa germplasm (Evans et al. 2003). The pathogen expanded its range in South America (Peru, Ecuador, Venezuela, and Colombia) and was first recorded in Panama in 1956; from there it progressed through Central America (Costa Rica, Nicaragua, and Honduras) during the late 1900s. In recent years, FPR established itself in Guatemala (2002), Belize (2004), and Mexico (2005) (Phillips-Mora et al. 2007; Figure 1). In 2009, outbreaks in the Democratic Republic of São Tomé and Príncipe, Gulf of Guinea, off the western equatorial coast of Central Africa (Island Biodiversity Race 2009) and

Brazil (Anonymous 2009) were feared, but later appeared to have been false alarms, Reports that *M. roreri* has been detected in Cuba and Trinidad (CABI & EPPO 2010) are also erroneous and have been flagged for rectification.

Figure 1. Invasive Spread of *Moniliophthora roreri* throughout Mesoamerica (from Phillips-Mora et al. 2007).

FPR constitutes the greatest potential threat to cocoa production in insular Caribbean, which remained FPR-free in 2010. However, few plant pathologists doubt that the spread of FPR to insular Caribbean is only a question of time. FPR causes yield losses of around 70–80% in most areas within a few years of pathogen establishment and can lead to complete crop failure (Krauss et al. 2003). This frequently renders the production of this environmentally sound understory crop in highly diverse agroforestry systems unattractive, leading to the abandonment and conversion of the affected agroforests. This, in turn, results in habitat loss for wildlife through the felling of trees and fragmentation of landscapes by triggering unsustainable trends in livelihoods due to conversion of forest into cattle pasture and moving towards monocultures of annual crops or urbanization with the concomitant real estate development. It is therefore imperative that the introduction of the pathogen to additional cocoa-producing regions is prevented. These include insular Caribbean, Bolivia, and Brazil in the Americas, as well as the bulk-cocoa producing continents of Africa and Asia.

MANAGEMENT CASCADE FOR INVASIVE ALIEN SPECIES (IAS)

The generally recognized management cascade for IAS has three principal approaches that are described below: (1) prevention, (2) early detection and rapid response, and (3) impact mitigation. These follow each other both in terms of importance and chronological order of deployment. The Convention on Biological Diversity (CBD) is the only global, binding legal instrument on IAS management. Article 8(h) requires parties "to prevent the introduction of, control or eradicate those alien species which threaten ecosystems, habitats or species."

Prevention

Public Awareness and Education

Prevention is the most cost effective measure for managing IAS and is a key component of the CBD guiding principles. However, prioritizing exotic and still absent species to be kept out of a country is a nearly insurmountable task, as it requires a rare combination of knowledge to assess risks and arrive at a list of priority species for preventative measures and capacity building:

- Risk of arrival or introduction
- Local condition that may favour invasiveness
- Potential for invasiveness under conducive conditions

This information tends to be unavailable in most countries. External sourcing of information requires a good idea of where to start (i.e., a pre-prioritization of organisms), leading to a circular task that can only partly be completed by a combination of good intuition with careful and scientific iteration. In reality, the prioritization of mainstream preventative measures tends to focus on pathway management rather than particular species, which are targeted only when a known high risk of introduction exists and/or severe impact would be associated with their arrival, as is the case for *M. roreri* and Caribbean cocoa-producing nations.

Efficient Enforcement of Existing Regulations

Since IAS is international in character, the prevention of IAS introduction requires an international legislative framework through global, regional, or bilateral agreements. Trade is one major pathway (Waugh 2009). The World Trade Organization's (WTO) Agreement on the Application of Sanitary and Phytosanitary Measures (SPS Agreement) is the major international instrument related to global trade that provides binding rules. These are enforced by a compulsory dispute settlement mechanism. The key objective of sanitary and phytosanitary (quarantine) measures is to protect humans, animals, and plants (wild and cultivated) from damage due to pests and diseases. This is often achieved through the use of import and export control measures. The SPS Agreement also provides a set of basic rules as to how WTO members can apply measures to manage invasive alien pests and pathogens.

The International Plant Protection Convention (IPPC) under the umbrella of the Food and Agriculture Organization (FAO) of the United Nations is an international framework to prevent the spread of plant pests; it also promotes appropriate measures for their control. Parties are required to adopt standards and procedures to identify organisms that threaten plant health. Parties may prohibit the introduction of certain plants and restrict the import of plant products, execute inspections and detain consignments. Parties are also required to share information regarding plant pests as well as means of prevention and control. Each party is required to establish a National Plant Protection Organization (NPPO); some NPPOs are cooperating via Regional Plant Protection Organizations (RPPOs). One of the key components of many national phytosanitary systems is the three-stage pest risk analysis (PRA).

The IPPC Secretariat facilitates the development of International Standards for Phytosanitary Measures (ISPMs). These are designed to prevent the introduction or spread of plant pests of potential economic importance while encouraging the international harmonization of phytosanitary measures to facilitate safe trade and avoid unjustified barriers. The most important ones in the invasive alien pathogen species context are:

- ISPM No. 01 (2010), Phytosanitary Principles for the Protection of Plants and the Application of Phytosanitary Measures in International Trade
- ISPM No. 3 (2005), The Code of Conduct for the Import and Release of Exotic Biological Control Agents
- ISPM No. 07 (1997), Export Certification System
- ISPM No. 11 (2004), Pest Risk Analysis for Quarantine Pests, including Analysis of Environmental Risks and Living Modified Organisms
- ISPM No. 12 (2001), Guidelines for Phytosanitary Certificates
- ISPM No. 15 (2009), Guidelines for Regulating Wood Packaging Material in International Trade
- ISPM No. 20 (2004), Guidelines for a Phytosanitary Import Regulatory System
- ISPM No. 25 (2006), Consignments in Transit

Early Detection and Rapid Response

Early detection and rapid response have a number of prerequisites for success. For early detection quarantine and survey, personnel need to know (i) what to look for and (ii) to whom they should report suspicious sightings for confirmation, and (iii) if indicated, how to accomplish destruction of the harmful invasive species. This requires staff training which, for logistic reasons, cannot possibly address all threats, but instead tends to focus on interception along high risk pathways (i.e., the infamous "four Ts": Trade, Tourism, Transport, and Travel).

For rapid response, it is essential that an emergency response plan (ERP) already exists <u>at the time of detection</u> of a specific IAS. Thus, the ERP needs to be prepared with anticipation, which is not a natural strength of our Caribbean mentality, and is further complicated by the notorious understaffing of relevant posts in Small Island Developing States (SIDS). The latter forces staff to fire-fight and react to problems, leaving little scope for planning ahead (i.e., exactly what would be required to develop an ERP).

A practical ERP requires an effective mechanism for prompt eradication of the newly detected IAS (i.e., before it establishes, reproduces, and spreads). This may entail host elimination, in which case a compensation scheme is also required. Thus any realistic ERP must contemplate funding of the required interventions and be accompanied by the establishment of a contingency fund that can be accessed without undue bureaucracy should certain circumstances (which are defined in the ERP) present themselves.

Impact Mitigation

If the above-mentioned two approaches fail and the IAS becomes established, the only option left is damage limitation and mitigation. Generally, integrated options that resort to several IAS control tools are preferred. Their case-specific selection should be based on assessment of cost-effectiveness in the medium to long term.

MANAGEMENT OPTIONS FOR FROSTY POD ROT

Prevention of *Moniliophthora roreri* entry

As with any IAS, prevention of entry is the first choice also for *M. roreri*. The pathogen has an average latency period of seven weeks. This deceives many into believing that they are transporting healthy pods. By the time external symptoms appear, the cocoa beans inside are largely destroyed. One week after the infected pods have been discarded, the fungus sporulates on the pod surface, releasing billions of microscopic, wind-dispersed spores into the air at the slightest agitation. On the other hand, *M. roreri* only infects the fruit and only of two closely related genera: *Theobroma* and *Herrania*. Thus prevention can focus on categorically prohibiting the transport of the pods (e.g., transporting the recalcitrant seeds) of these two species whether they appear healthy or not and enforcing this regulation effectively.

To-date, the pathogen is present in most mainland Caribbean countries that produce cocoa, while still being absent from the insular Caribbean, the Co-operative Republic of Guyana, and French Guiana. Two island nations are at particular risk: the Dominican Republic and Trinidad & Tobago. As a Spanish-speaking country, the Dominican Republic has close cultural and economic ties with infested mainland neighbors. For example, the Dominican Republic–Central America Free Trade Agreement (DR–CAFTA) encompasses the Central American countries of Costa Rica, El Salvador, Guatemala, Honduras, and Nicaragua, as well as the United States and, since 2004, the Dominican Republic. El Salvador, the Dominican Republic, and the United States are the only signatories that were still FPR-free in 2010. El Salvador does not border the Caribbean Sea and the United States is not a commercial cocoa producer, although some field cocoa research is carried out in Hawaii, Florida, and Puerto Rico. In the latter two locations, germplasm collections are also maintained. The Dominican Republic, on the other hand, is the world's largest producer of organic cocoa, with a lot at stake. In response to this and other threats, the Dominican Republic recently embarked upon the establishment of a nation-wide diagnostic network, which is linked also with the incipient Caribbean Pest Diagnostic Network (Reyes Valentin et al. 2009).

Trinidad is separated from Venezuela by the narrow Columbus Channel, which is traversed by both official and unofficial trade. FPR is already present in western Venezuela. At least until now, the Andean mountain chain has provided an effective physical barrier. However, mechanisms to prevent the internal transport of infected cocoa pods within Venezuela are rather weak. Thus, there is a high risk of *M. roreri* spreading to eastern Venezuela, and from there across to the shores of Trinidad. Trinidad is a traditional producer of fine-flavored cocoa and hosts an international cocoa germplasm bank, with the concomitant exchange of experts and plant material.

Both nations are members of the Caribbean Plant Protection Commission (CPPC), a RPPO under the IPPC. However, the CPPC is designated to be phased out in favor of the Caribbean Agricultural, Health, and Food Safety Agency (CAHFSA) under the umbrella of the Caribbean Community (CARICOM). The Dominican Republic is also a member of the *Organismo Internacional Regional de Sanidad Agropecuaria* (OIRSA), which is dominated by Mesoamerican membership.

Both the Dominican Republic and Trinidad & Tobago are among the five participating countries in the regional project "*Mitigating the Threats of Invasive Alien Species in the Insular Caribbean*", which is funded by the Global Environment Facility (GEF). This pilot project, developed to strengthen the preventative capacity of Trinidad & Tobago, uses FPR as its model IAS. Public awareness is being raised (Figure 2a), and surveillance, quarantine, and early detection mechanisms are been strengthened. Lessons are being exchanged with other project countries as well as in the Wider Caribbean Region.

Extreme alertness and regional cooperation is needed throughout insular Caribbean, Eastern Venezuela, Guyana, French Guiana, Brazil, and Bolivia if FPR introduction is to be prevented or at least delayed. On a global scale, strategic measures for intercontinental germplasm transfer, transport, and trade are required to prevent the transatlantic spread of *M. roreri* to the bulk cocoa producers of West Africa. Since fungal dissemination in an eastward direction, against the Trade Winds, is only conceivable if vectored by man, interventions should focus again on the "four Ts" (Figure 2b).

from V. Ferguson-Dewsbury

Figure 2a. Pest Alert Poster in Trinidadian ports of entry

Meissner et al. (2009)

Figure 2b. Inspections focus on high risk pathways of trade, tourism, transport, and travel (four Ts)

Figure 2. Frosty Pod Rot prevention in insular Caribbean Prevention needs to focus on public awareness, with alertness of inspectors along prioritized pathways of high risk.

Early Detection of Frosty Pod Rot and Rapid Response

Early detection and rapid response have never been applied successfully against FPR! There are good reasons for that, and we need to learn from past failures. *M. roreri* has a latent infection phase of approximately seven weeks, followed by prolific sporulation within one week of diagnostic symptom development. This leaves an extremely narrow window of opportunity for early detection. Thus, farmers as well as field officers should be trained in the recognition of <u>early</u> symptoms of FPR. Practical tools for training and diagnostics have been developed (Krauss et al. 2006; Figure 3).

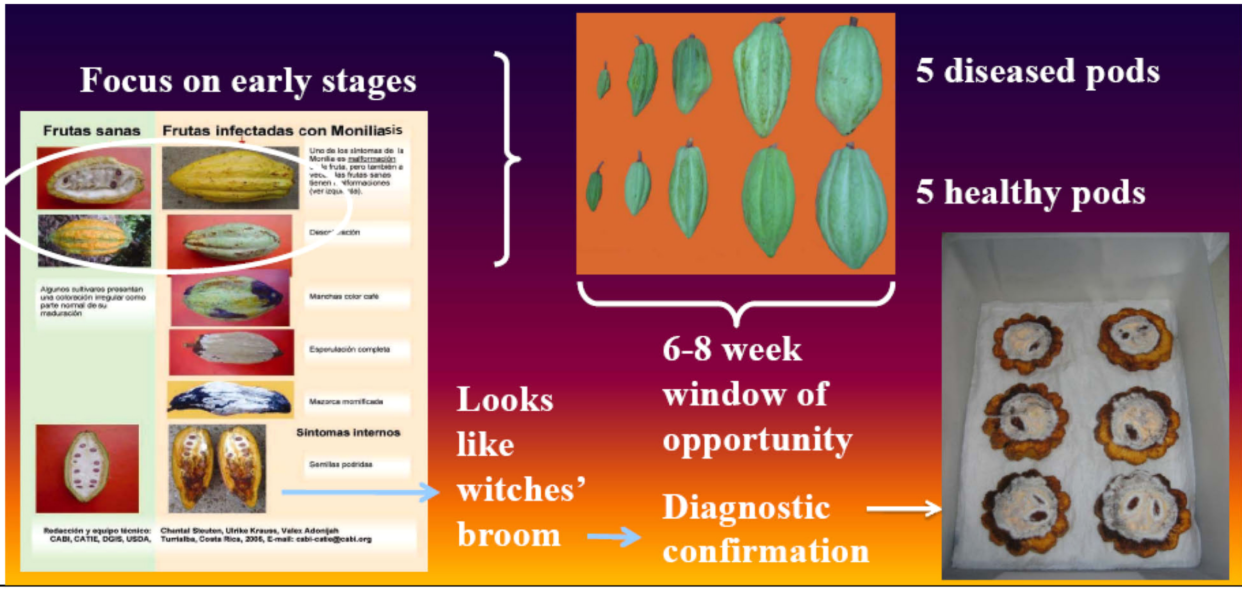

Figure 3. Visual aids for identifying IAS infestation of cocoa beans. Visual aids help trainees to hone in on the early phase of infections, during which symptoms are very subtle. A robust diagnostic test gives clarification within days (Krauss et al. 2006).

An innovative approach has been devised in Brazil: classical spore trapping is combined with an enzyme-linked immunosorbent assay (ELISA; Pomella et al. 2005) to detect the inconspicuous spores of *M. roreri* and distinguish them from other fungal taxa. Sentinel stations near the borders with Colombia and Peru, where the disease is rife — far away from the cocoa-producing regions of Eastern Brazil — are proposed (Figure 4), in the hope that distant rapid response could win enough time to save the Brazilian cocoa industry from an invasion by *M. roreri*.

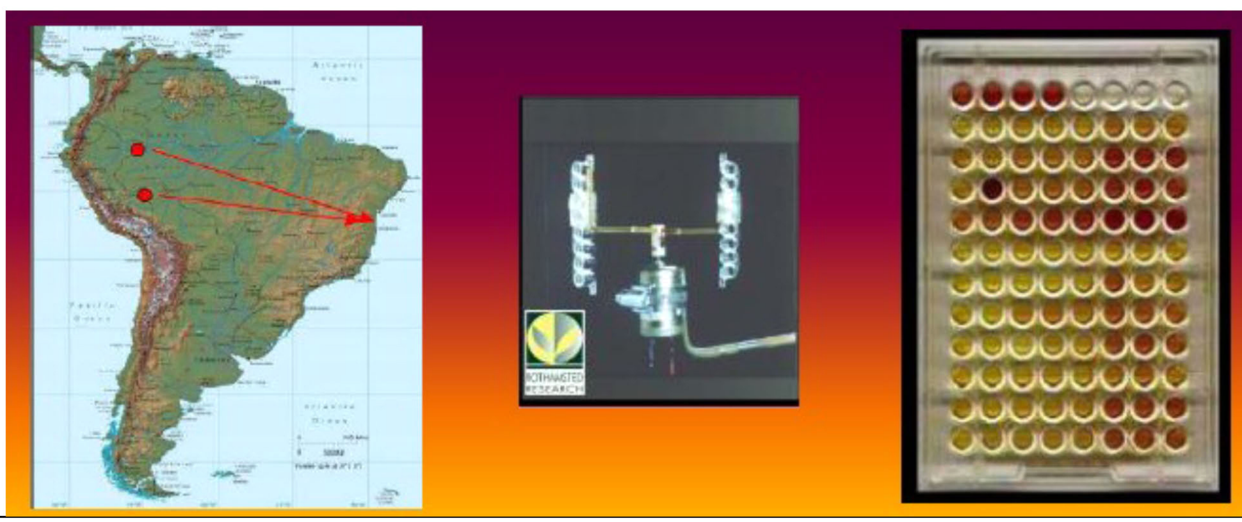

Figure 4. Sentinel stations for detecting *M. roreri*. Brazil is attempting to detect border crossings of *Moniliophthora roreri* using a combination of spore trapping and immunological assays (Pomella et al. 2005).

This approach focuses on border-crossing peoples in the Amazon basin as a high-risk pathway. Deliberate and illegal long-distance movement of cocoa tissue — as is believed to have been responsible for the introduction and spread of witches' broom (*Moniliophthora perniciosa*) in

Bahia (Andebrhan et al. 1999) — needs to be targeted separately, if early detection and rapid response are to become successful in FPR management.

Given the narrow host range of *M. roreri*, host destruction, or at least thorough stripping of developing pods, are feasible options for rapid response if thorough implementation can be achieved. This, however, will depend on the active collaboration of farmers, which can only be created via a fair loss compensation scheme. Thus, planning for rapid response must entail the establishment of access to a contingency fund, with a swift and unbureaucratic payout mechanism for both the mobilization of trained field technicians and to recompense of growers.

Integrated Control of Frosty Pod Rot

Cultural control has proven to be the central pillar of any integrated control strategy for FPR in afflicted countries. Diseased pods have to be removed from cocoa trees before the pathogen sporulates. The epidemiology of the pathogens dictates weekly phytosanitation, but this is not always cost-effective. Thus, economic analysis (e.g., using modelling) needs to go hand in hand with training of field staff to find an optimum frequency for each locality (Krauss et al. 2003, 2006; Leach et al. 2002). Cultural measures can be further enhanced by integrating cocoa into a disease-resistant agroforestry system (AFS). A diversified AFS is not only a good risk avoidance strategy, but also a tool to optimize shade cover, temperature, and aeration for a healthy cocoa crop. Furthermore, non-hosts can intercept water splash and aerosols carrying the pathogen propagules, thereby reducing inoculum pressure (Krauss 2004). These tools are already available.

Chemical and biological agents are being developed as supplementary management options (Bateman et al. 2005a, 2005b). Phytosanitation requires a manageable tree height. There is no short-cut to cultural measures, including formation and maintenance pruning. Copper fungicides are the most cost-effective to-date. Copper hydroxide is the least hazardous compound and thus best suited for smallholders. Modern systemic agents could substitute for copper during the early season, particularly if applied with a sticker (Krauss et al. 2010).

Inundative biocontrol uses local antagonists with supposedly good adaptation to prevailing agroecological conditions. Nevertheless, these agents have to be applied regularly, which is costly. Mixtures of local antagonists were highly successful in Peru, where they controlled three cocoa pod diseases (FPR, witches' broom, and black pod) simultaneously, leading to yield increases of up to 16.7% (Krauss and Soberanis 2001, 2002). However, this approach proved less promising in Costa Rica (Krauss et al. 2003). There, classical biocontrol may be more applicable, as both the crop and the pathogen are removed from their center of origin. Establishment can be the bottleneck with this approach but, if successful, the introduced agent becomes self-perpetuating. Evans et al. (2003) collected numerous candidates for FPR control from *T. gileri* in western Ecuador, including several endophytes (i.e., fungi that develop asymptomatic infections within healthy plants to form a mutualistic symbiosis). An endophytic and mycoparasitic isolate of *Trichoderma ovalisporum* yielded respectable results in both Ecuador and Costa Rica (Holmes et al. 2006; Krauss et al. 2010). Endophytic biocontrol agents have been implicated in induced systemic resistance (Bailey et al. 2006). They also create a much wider window of opportunity for antagonism through exclusion (competition), mycoparasitism, and/or antibiosis because spores of *M. roreri* germinate and penetrate the pod surface soon after landing there to establish a systemic pod infection, which can be latent for two months (Evans 1981). Coevolved endophytic antagonists may thus be a particularly suitable medium-term solution for the classical biocontrol of *Moniliophthora* spp. in cocoa planted outside their South American centre of origin (Krauss et al. 2010).

Breeding for FPR resistance focuses on horizontal resistance, which is less complete but more durable, an important consideration in a perennial crop. In Colombia, during field trials with artificial inoculation, clone ICS-95 showed consistent resistance against several isolates that belong to four genetic groups of the pathogen (Phillips-Mora et al. 2005). Schnell et al. (2007) have identified a quantitative trait marker(s) for each FPR, witches' broom, and black pod resistance, which are being used in accelerated breeding for resistance, as a longer-term perspective.

CONCLUSIONS

1. Prevention is the first choice management approach for IAS in general and *M. roreri* in particular
2. Early detection and rapid response, the typical second line of defense against IAS, has never been applied successfully against FPR. A more rigorous approach, particularly the anticipatory development of an ERP, would be needed to improve this poor track record
3. Impact mitigation for FPR must center on sound cultural management. There are no shortcuts!
4. Priority action points for the integrated management of *M. roreri* are:
    - Proactive operation of the management cascade
    - Awareness-raising among all stakeholders with respect to high risk pathways for FPR introduction, the cryptic nature of early infection, and the devastating impact pathogen invasion would have on livelihoods. Phytosanitary inspectors and customs/quarantine officers need to be targeted as a priority
    - Training in the detection of early FPR symptoms for farmers, extensionists, and field technicians
    - ERPs need to be developed prior to pathogen detection, including effective enforcement and funding mechanisms
    - Regional and international cooperation to prevent the long-distance dispersal of *M. roreri* by man

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