The Cacao Disease Trilogy: Black Pod, Monilia Pod Rot, and Witches'-Broom

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For decades, cacao plantations in the Caribbean basin and Latin America have flourished, declined, then flourished again. These drastic production swings have been triggered by world bean prices, political turmoils, disastrous disease outbreaks, and the sociological nature of growing what was once considered a "peasant crop." As the world population has increased, so has the demand for the cocoa bean. Currently, one-third of the world's supply of cocoa is produced in the Americas, and monetary support for basic and field research on breeding, epidemiologic aspects, pollination, etc., is steadily increasing. The world's chocolate manufacturers are sponsoring this research via the American Cocoa Research Institute and the International Office of Cocoa and Chocolate. Cocoa organizations such as Centro Agronomico Tropical de Investigacion y Ensenanza (CATIE) in Turrialba, Costa Rica, and Comissao Executiva do Plano da Lavoura Cacaueira (CEPLAC) in Itabuna, Brazil, are endowed by the manufacturers as well as by their governments.

The Crop

Cacao (*Theobroma cacao* L.) originated and is grown commercially in the Americas in the moist, tropical "cocoa bean belt," 20° above and below the equator. In this habitat, the trees form a closed, integrated foliar canopy within 2 yr, depending on planting density. The canopy area, initiated from the spreading scaffold limbs, is 2–3 m above the ground. Taller trees (*Erythrina* sp.) are planted at intervals to provide a light overhead shade to the dense cacao canopy, which supplies the energy necessary for vegetative growth and bean production (17). The environment is confining, shaded, and cooler, with soft air currents, than ambient field temperatures. During rains, the shade trees and the cacao foliar canopy act like giant sponges, producing rivulets of water over the scaffold branches and down the trunks, while releasing congregated large (2–4 mm in diameter) rain droplets from the undersurface of the canopy. These drops fall vertically for roughly 2 m onto the soil and leaf-littered surfaces and produce an impressive number of ballistic droplets that rebound at least 0.5 m up the tree trunk. Other, more aerosol droplets move high into the cacao understory of branches and foliage (8).

The flowering phenomenon of cacao is unusual. Tiny flowers are produced on dense, cushionlike structures growing directly from the bark of the trunk, scaffold limbs, and older branches. The flower primordia arise from leaf axils, and their overall orientation on the bark surface follows the original leaf placement patterns. The cushions arise linearly on branches and spirally on "chupons" (vertical shoots). The number of flowers is immense, commonly 3,000–5,000 per tree. Usually, pod set is relatively low, the number of maturing pods per tree varying from 10 to 120. This can be offset, however, by scattering banana or plantain pseudostem pieces over the planting floor. These serve as nesting sites for the midge pollinator (18). A pod takes 6 mo to mature from pollination to harvest. Because of rhythmic flower flushes during the rainy season, pods in all stages of maturation are present on the tree. Inside these pods are some 30–40 cocoa beans, the economic units for chocolate manufacture.

The Challenge

Cacao is a suitable crop for small farms as well as large plantations, especially since the advent of hybrids with their increased productivity, but it is not without problems. Cacao is subjected at repeated intervals to a trilogy of crippling fungal diseases: black pod (*Phytophthora palmivora* (Butler) Butler), Monilia pod rot (*Moniliophthora roreri* (Ciferri) Evans et al), and witches'-broom (*Crinipellis perniciosa* (Stahel) Singer). The management of these diseases under tropical conditions challenges the aspiring and experienced pathologist alike. On the one hand are the extremes in rainfall, humidity, heterogenicity in soil types, and genetic stock with continued rhythmic flushes of new, unprotected growth while the maturing pod is at risk for months. On the other hand is the tortoise-slow pace of quantified chemical control schemes. The decades of spraying fungicides have proved three major shortcomings: 1) the practice is costly, 2) the results are poor, and 3) the available products are not fitted or formulated for the actual targets (4,7,9,15).

A review of all facets of each disease is not within the scope of this article. Rather, I will focus on a series of disease management hypotheses to generate changes, ideas, and hopefully advances by the chocolate, chemical, and equipment industries acting as a team.

Black Pod

The incidence of black pod peaks at harvest. In drought years, when infection levels are low, growers and spray masters become lax with their programs. Then when climatic conditions are conducive and disease levels skyrocket, they apply excessive amounts of fungicides at short intervals. The solution to such management is to complement the spray program with a "program package," in which cultural practices such as pruning, drainage, weed control, frequent removal of infected pods, and general tree sanitation are followed at intervals throughout the year and continued on an annual basis. These steps change the microclimate, improve spray coverage, and help to lower inoculum potential, making chemical management more feasible.

Some of the factors influencing disease development could be better handled. The infection gradient concept for "originating" sources of pod infection delimited the soil and infected flower cushions as the prime candidates (8). After the rainy season starts, sporangia of *Phytophthora* are produced on the surfaces of infected rootlets. These liberate motile zoospores that swim upward and accumulate at the soil surface (20). These in turn are splash-dispersed upward onto the host. Early studies with soil chemicals and/or protectant fungicides applied directly to this target area around the tree had mixed results (20). Also, copper fungicides have been applied for years and have accumulated in the soil surface. Further, *P. capsici* Leonian, rather than *P. palmivora*, is now the species to be dealt with in the Americas, and *P. megakarya* (Brasier & Griffin) is waiting in the wings (9,15,17). Their individual ED_{50} levels based on copper fungicide classes need to be identified. Also, in view of the potential copper concentrations on and in some of the cacao plantation floors, sensitivity ranges among the *Phytophthora* spp. could differ.

On the basis of today's soil strategy and in tune with the philosophy of the Environmental Protection Agency, there are two possibilities for a chemical mulch: the octylphenoxy ethanols (OPEs) and the isothiazolone compounds (11). Treatment of zoospores of

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Phytophthora spp. verified that nonionic OPEs caused zoospore lysis within 2–4 min of treatment (10). The biological sensitivity profile of isothiazolone includes the Oomycetes as well as *Corticium* spp. and *Ceratocystis* spp., other cacao pathogens. The foam and oil-in-water formulations of these products do not bounce when applied, resist evaporation, have good penetration, and remain active over a long period and should be compared with the standard water carrier system.

Flower cushions, the other "originating" source of pod infections, are dispersed up the trunk, over the scaffold branches, and partially into the canopy. I propose the use of a tree sanitizer, i.e., application of a single spray of isothiazolone biocide to the flower cushion zones at the end of the dry season and after the wilted, blackened "cherelles" (small, immature pods) and old, infected pods on the tree have been cleaned up. Isothiazolone is the only nonphytotoxic eradicant currently available, but an industrial eradicant-sanitizer exploratory screen for cacao (and also for apple, grape, and peach, to name a few) is in the offing.

As the season advances, the prime spray targets are the pods, which when fully developed are green and look like small footballs. After pollination, the immature pod lengthens and expands rapidly. The pod is susceptible to infection by *Phytophthora* for 5 mo. The pod surface is waxy, with microscopic rigid, obelisklike hairs and with raised stomata that increase in density with distal orientation (*unpublished*). The pod presents an interesting thermodynamic characteristic. It heats up during the day and cools at night, and by predawn its mass is in balance with the ambient temperature. A temperature rise at this time triggers water condensation over the pod surface (3), which becomes an ideal microincubator for spores of *Phytophthora*. Because spores of *Phytophthora* are hydrophilic, they are "within" the water droplet rivulet flow over the pod surface and aggregate where the flow finally comes to rest—the distal end of the pod (6,9).

The cultural goal is to have major pod production on the trunk and large scaffold branches, with maturing pods in the 0.5- to 2.0-m zone of each tree. This facilitates spray application to the pod targets and also simplifies harvest (9,17). This is the module in young plantations, but as time passes, lichens make their inroads, starting on the trunk and advancing up the tree. The typical shade environment required for cacao allows this ecosystem to occur. The lichens pose two distinct threats to pod production: 1) Their crustose, closely appressed growth on the bark covers flower cushion sites, and production areas are consigned higher and higher into the tree's framework. The grower, in turn, stops pruning the tree to allow for continued production. 2) They produce a series of "lichenic acid" compounds known to mineralize copper. As the hydrogen ion concentration increases, copper fungicides are solubilized, with associated decreasing biological activity and residual tenacity. Copper fungicides should clean up lichens effectively, since they are efficient algacides and since a lichen is an alga in association with a fungus (13). This is not the case in the Americas, however, where a copper treatment schedule may not be started until the planting is 4–6 yr old and lichen development is already under way. Nonetheless, this threat must be reckoned with, as it definitely curtails production. Field taxonomic studies on the lichens are needed to gain knowledge about their physiology and probable effects on fungicide activity.

In regard to pod protection, perhaps Pereira (15) said it best: ". . . in the absence of chemical control, other forms of inputs applied . . . would not give a positive cost/benefit return." Again, the "program package" is called for. Pereira pointed out the problems associated with use of field equipment; the tremendous range in copper dosages (0.3–14.0 kg/ha of metallic copper) used by growers, who vary the quantity of fungicide applied per hectare with the volume of water; and the tendency of growers to ignore spray forecasting and make their own decisions about when to spray, often on the basis of local folklore. Field studies were done on reducing the number of sprays per season by increasing the amount of copper per tree per spray, e.g., six 4-g sprays per tree per year could, under normal circumstances, be replaced by three 8-g sprays per tree per year. The theory worked experimentally, the key being to familiarize growers with precise dosage applications (14). The deposit serves as a reservoir for continued release over time, at a more or less constant rate of 1.5–2.2 mg/L. The higher the metallic copper content in the spray deposit, the longer the period of release.

Lichens give off acids that solubilize and erode the copper deposits. The pods have stomata that give off water vapors and excrete organic compounds. If one of the organic compounds is an amine, the compounds could form copper complexes and further reduce the fungitoxicity of copper. To improve the odds, the available copper in solution could be increased. If copper tolerance does exist, the problem could be bypassed by adding mancozeb to suspensions of fixed copper, at a tank-mix ratio of 1:3; this would increase soluble copper threefold to eightfold (14).

Another possibility to evaluate is the use of flowable copper formulations rather than the usual wettable powders. The flowables are more stable in suspension than the wettable powders, an important feature in view of the poor agitation common to portable field equipment (1). Flowables are also very adaptable to low-volume usage, with residual persistence increasing as volume applied decreases (*unpublished*).

Monilia Pod Rot

To an experienced epidemiologist, the field management of Monilia pod rot would appear to be "a piece of cake," since the pathogen's infectivity is limited to the conidia produced on the pod surface (4). Field management has not been attained, however. Control has fluctuated between cliff-hanging and outright calamity. Problems common to older plantations include little care, trees too tall for sanitation, and poor spray practices. Sporadic efforts to install basic chemical programs have met with little enthusiasm from governments and industry.

Pods are at high risk of infection for the first 90 days of their development. The incubation period is long—about 40 days on pods 20–60 days old and 60 days on pods 90 days old. The first notable symptoms are conspicuous swellings or areas of premature ripening on pod surfaces. These signal the need for follow-up sanitation before sporulation begins on the discolored areas of the affected pods. For new plantings where trees are pruned to manageable size (maximum height 3.5 m), sanitation survey teams could keep a stride ahead of potential inoculum pressures by operating at 7- to 14-day intervals, well within the expected surface-sporulation period.

Sporulation spreads rapidly over the entire pod surface, and this single locus can attain densities of 44 million conidia per square centimeter (4). Clouds of spores are released into the air by wind or by water droplets impacting on the hydrophobic spore bloom over the pod surface. Because the hydrophobic conidia are carried on the water surface, they move rapidly within the tree framework, leaving trails of spore tracks, especially over the young pods. This is corroborated by a significant positive correlation of high pod losses to heavy rainfall (4).

The key to effective control of Monilia pod rot is to stall the first wave of pod infections for 2–3 mo, since cacao pods are at risk their first 90 days. The only valid cost-effective way to do this is to eliminate the primary inoculum sources—the mummified hanging pods. The first step is a good sanitation sweep during the intercrop of the dry season; the suggested prototype tree framework of less height would facilitate cleanup. Step two—based on the premise that regardless of labor skill and supervision, some intercrop inoculum will remain in the trees—is tree sanitation, as for black pod. A single spray would be applied to the trunk and framework branches at the onset of the rains. Along with the the spray schedule would be surveys to identify and remove distorted pods before sporulation begins (distorted pods are usually removed later in the season, around harvest time). An integrated spray schedule would follow the sanitizer spray. The first two or three applications of flowable copper and mancozeb would be at 15- to 21-day intervals, depending on labor, equipment, and the weather. The third or fourth spray would include mineral oil in the formulation and would be applied in accord with the early warning survey. Oil has been used sporadically in formulations for cacao since the late 1950s, with the overall findings that pod sporulation is delayed and lesion size is greatly reduced (12; *unpublished*). Also noted are negligible bouncing of spray droplets after impaction on the waxy pod surface, good droplet spread, and residual persistence (1,2,6; *unpublished*). The oil formulation would be used for no more than two sprays per season, for a total of 7 L of oil per hectare.

Witches'-broom

Witches-broom is endemic to the area where cacao thrives and can cause pod losses of 50%, with losses escalating in direct proportion to the age of the plantings (5,16). The disease cycle, like that of *M. roreri*, is rudimentary. Approximately 8–12 wk into the rainy season, basidiocarps form on dead brooms (former season infections) in the tree framework, and the gravitational disposal of basidiospores begins. This is the primary source of inoculum and the only spore source for any given season; there is no secondary spore stage. The problem is that basidiocarps continue to form on these brooms as the season progresses, so that the inoculum becomes massive (5). Thus, the final leaf flushes at season's end have the highest number of new developing brooms—gearing up for next season's attack. At the microlevel, spore dispersal is prominent from midnight to 4 a.m. The spores can impact or flow on water to the target sites, i.e., actively growing (meristematic) tissue such as foliar flushes, flower cushions, and young pods. Spores germinate and penetrate these growing points within 6 hr, so the opportunity for chemical protection is slim. Also, vegetative and flower cushion infections are so spectacular that pod infections tend to be downgraded. The reverse is true, however, for witches'-broom is a major pod pathogen. Pods may be distorted if infected early, but generally they show premature yellowing followed by necrosis, destruction of internal tissues, and loss of beans (5,16).

Several key facts must be considered in planning management: 1) The necrotic broom sites are for the most part in the upper tree canopy, 2) the susceptible leaf flushes begin from buds as tiny flat leaves that are pubescent and hydrophobic, 3) the necrotic brooms require alternate wetting and drying for basidiocarp production (which explains the continued buildup to massive proportions as the rainy season progresses), 4) pods are basically susceptible from fertilization to 12 wk of age, 5) the whole infection process occurs on films of water during the nocturnal hours, and 6) pruned brooms left on the plantation floors produce basidiocarps for a season or longer.

Obviously, there are no quick-fix recommendations for this situation. As the planting ages, the brooms continue to build up in the dense upper canopy—the most difficult for fungicide droplets to penetrate. There is need for collaboration with engineers to improve droplet delivery and also for agronomy trials of star-wedge techniques for pruning the canopy (19). In the heat of the battle over the last several years, mineral oil has come to the forefront again. Treatment of necrotic brooms with mineral oil has delayed or eliminated basidiocarp production (12). Does the oil penetrate the dry necrotic brooms to affect fungal physiology, or does the oil change the physical characteristics of the broom surface from hydrophilic to hydrophobic? If the latter, then little water is absorbed into the broom for basidiocarp production. Oil in the formulations also aids droplet coverage of the young hairy, hydrophobic flushes (1,2,6). Bordeaux mixture works well in the cacao canopy because it carries a kinetic charge that allows it to adhere well to such tissues (1).

At this stage, many proposals need to be considered. As Evans (5) pointed out about witches'-broom, "It is only through . . . a multidisciplinary and international approach that significant progress will ever be achieved."

Several themes have been woven into the fabric of this article—some to highlight areas of progress, others to present causes for concern. Today's major change is the constant interaction and melding of the diverse sciences, for without cooperation, successes will be limited. The future is exciting, and the means are at hand to manage the cacao disease trilogy.

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