20 Pest Management in Organic Cacao

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Introduction

General information on cacao

Cacao, *Theobroma cacao*, is a small tree from the family *Malvaceae*, and originated in different forest areas of South and Central America (Wood, 1985). During the 20th century, the cacao-growing belt spread considerably over tropical areas of America, Africa and Asia, and is around 10 million ha today (FAOSTAT, 2014). Cocoa beans are produced for butter and powder that are used mainly in chocolate manufacture. In 2014, chocolate confectionery produced revenues of around US$120 bn, and these are expected to grow with the developing markets in countries with rising middle classes (Hawkins and Chen, 2014). At the same time, cocoa world production rose constantly for decades and reached 5 million t in 2012 (FAOSTAT, 2014). In 2012, Africa alone produced around 66% of total world production with four countries in the top five cocoa-producing nations, namely Ivory Coast (with 1.6 million t), Ghana, Nigeria and Cameroon. Asia produced around 19% of world production, with Indonesia being the world's second largest producer. The Americas produced around 14% of total world production of cocoa (FAOSTAT, 2014).

Cacao crop expansion in Africa and Asia came with the emergence of major pests and diseases, which have adapted to the crop from their local host plants. The most infamous examples are the cocoa mirids *Sahlbergella singularis* Hagl. and *Distantiella theobroma* Dist. (Hemiptera: Miridae), and the black pod disease due to *Phytophthora palmivora* Butler and *Phytophthora megakarya*, which became major threats for West African-producing countries in the 1960s and 1970s, respectively (Entwistle, 1985; Lass, 1985). In Latin America, witches' broom disease due to the basidiomycete fungus *Moniliophthora perniciosa* highly impacted production of cocoa in Brazil in the 1990s (Meinhardt *et al.*, 2008), while the frosty pod rot, due to *Moniliophthora roreri*, that is widely spread in Latin America, currently leads to low yield and crop abandonment (Phillips-Mora *et al.*, 2007). The cocoa pod borer *Conopomorpha cramerella* became a major pest of cacao in South-east Asia in the mid-1980s and is considered the main threat for cocoa production in most Asian-producing countries since the early 2000s (Posada *et al.*, 2011).

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Cacao pests and diseases are numerous and no part of the plant is spared. Some insects are disease vectors, such as mealybugs of the Pseudococcidae family, which transmit the cacao swollen shoot virus (CSSV), a plant pathogenic virus that infects cacao trees in West Africa, affecting yields and often killing the trees within a few years (Domfeh *et al.*, 2011). Global crop losses due to these pests and diseases are usually assessed at 30–40% of the world cocoa production (ICCO, 2013). But pest and disease pressure is also responsible for higher costs of production, health and environmental issues due to the use of pesticides and farmer despondency leading to lower investment in cacao farming. Indeed, pest and disease management is usually problematic for cacao farmers, especially in Africa and Asia, because of inadequate farmer knowledge and practices, as well as limited access to resistant varieties and agrochemicals (ICCO, 2013).

General considerations of organic cocoa production

It is important to consider that cacao is not an industrial crop like other crops in developed countries. Cacao (90%) is grown by smallholders. Their number has been estimated at around 5 million worldwide (Hawkins and Chen, 2014). Although cacao is the main income source for most of them, farming practices still suffer from insufficient knowledge and capital investment (Hawkins and Chen, 2014). Thus cacao is often grown with little or no use of synthetic inputs, which are usually too expensive for farmers. In Africa, this situation is due to cocoa sector evolution in the last five decades. From the 1960s, governments promoted cacao cultivation and invested a lot of money in supporting farmers, especially for pest and disease management. In Cameroon, for instance, government subsidized spraying campaigns for cocoa mirids and fungicide distribution for black pod disease. Because of the 1990s' economic crisis, the pesticide and cocoa sectors were liberalized and subsidies dropped in a few years, leaving cacao farmers unprepared for facing the threats (Sonwa *et al.*, 2008). The private sector was not able to offer support to the farmers, and so pest and disease pressure worsened in the next three decades, contributing to low yields and cocoa beans of poor quality.

However, certified organic cacao exists, in low but growing proportions worldwide. Latest statistics from the International Cocoa Organization (ICCO) estimate production of certified organic cocoa at 15,000 t, less than 0.5% of the world production (ICCO, 2014). A recent world survey conducted by the Research Institute of Organic Agriculture (FiBL) and the International Federation of Organic Agriculture Movements (IFOAM) gives a more optimistic report with the total area under organic cacao assessed at 220,000 ha in 2011, around 2.3% of the world cacao-growing area. This is more than twice the proportion of the world's organic agricultural land, estimated at 0.9% in 2011 (Willer and Lernoud, 2013). The same survey indicates that the area under organic cacao increased fivefold since 2004, which is much more than most other crops (Willer and Lernoud, 2013). The fact is that countries with the highest volumes of certified organic cocoa are the minor producers of Latin America such as Bolivia, Mexico, Honduras and Peru, or other minor cocoa-producing countries like the Dominican Republic, the United Republic of Tanzania, Madagascar and São Tomé and Príncipe. By contrast, the largest cocoa producers produce low levels of certified organic cocoa, with Ivory Coast producing 0.0%, Indonesia 0.1%, Ghana 0.5% and Nigeria 0.4% (Willer and Lernoud, 2013).

Cacao pest management, organic by default

While the proportion of certified organic cocoa production is globally low worldwide, pest management on cacao is conducted for a significant part through ecologically sound practices, for two main reasons: (i) some pests have proven to be totally immune to chemical spraying because of their biology or because they develop resistance to insecticides; and (ii) the difficulties in accessing chemical inputs for smallholder farmers has resulted in use of more economic practices including the evaluation of the farm natural environment. In fact, a significant part of recommended (or traditional) practices currently used by farmers for insect pest management are fully compatible with organic production standards. However, it has to be noted that, currently, there is no single organic solution for the control of the major pests of cacao. Farmers are usually told to employ several practices to keep pest infestations under economic thresholds, and organic pest management practices are sometimes associated with inappropriate chemical spraying.

The aim of this chapter is to collate the existing knowledge of the pest management practices and tactics that could be used in organic cacao farming. The main pests of cacao are reviewed followed by details on the strategies compatible with organic farming that have been developed for their management.

Pests of Cacao

Major pests

Cacao crop development in tropical Africa and Asia came with the emergence of major insect pests, which adapted to the crop from their local host plants. Currently, in Latin America, its native continent, the crop is relatively unaffected by insect pests compared with Africa and Asia, where some major pests are widely distributed causing extensive damage to the crop.

Cocoa mirids

Mirid bugs are the most widespread and harmful insect pests of cacao worldwide. However, among the 40 species of the family Miridae damaging cacao, only a few have major economic impact on the world cocoa production. All the mirids injurious to cacao belong to the subfamily Bryocorinae and to two different tribes, the Odoniellini and the Monaloniini. The two tribes have very different morphological traits: mirids from tribe Odoniellini are usually robust insects and brownish in colour, while tribe Monaloniini are gracile and brightly coloured insects. Synthetic publications were devoted to cocoa mirid systematics, biogeography, biology, ecology and management, in the 1970s (Entwistle, 1972; Lavabre, 1977).

Sahlbergella singularis Hagl. and *Distantiella theobroma* Distant, of the tribe Odoniellini, are two closely related species native to the forest area of West and Central Africa. They were described for the first time on cacao around the beginning of the 20th century, and since then, have considerably spread with the crop throughout the current cocoa-producing countries of the region. *S. singularis* and *D. theobroma* are 10 mm long in the adult stage, and brown in colour. Their overall appearance mimics the bark of trees where they usually rest during the day. On cacao, eggs are inserted into pods and green shoots. Mirid population density is usually low in cacao plantations with seasonal maximum density of 2500 individuals/ha (around two individuals per tree). However, damage to the crop is considerable, due to mirid feeding behaviour. Like most Hemiptera, the mouthparts (stylets) are inserted in fruits at different developmental stages, as well as buds and green shoots. A large supply of saliva with hydrolytic enzymes is injected, leading to the liquefaction of plant tissues, which are finally ingested by the bug. Mirid feeding lesions on cacao pods and shoots appear as a black plug of dead tissue. On young pods, this damage may cause distortion during growth, sometimes leading to yellowing and fruit abortion. But the main damage is on vegetative parts of trees with the death of the terminal part of branches as well as many lesions. Mirid-damaged cacao plants are susceptible to fungal infection, resulting in cankering or bark roughening, destruction of the flower cushions, severe dieback of twigs and branches, and degradation of cacao farms. Economic losses attributed to African cocoa mirids have been assessed at 25–30% of the cocoa production of four of the five most important producing countries of the world, namely Ivory Coast, Ghana, Nigeria and Cameroon (Lavabre, 1977).

In Asia, Monaloniini mirids from the genus *Helopeltis* are numerous and widely distributed. Unlike mirids from tribe Odoniellini, *Helopeltis* spp. are gracile and coloured, and sometimes called cocoa mosquito bugs. Several *Helopeltis* species are major pests of important cash crops in Asia, such as black pepper (*Piper nigrum*), cashew (*Anacardium occidentale*), cinchona (*Cinchona* spp.), cacao and tea (*Camellia sinensis*) (Stonedahl, 1991). *Helopeltis antonii* Sign. was first observed on cacao in 1863 in Ceylon (present-day Sri Lanka). Nowadays, *H. antonii* and *Helopeltis theivora* (with *Helopeltis theobromae* as a subspecies) are widely distributed on cacao, with damage similar to that of African cocoa mirids, although economic loss is mainly due to damage on pods. They make characteristic necrotic lesions that kill young pods and shoots. In Malaysia, maximum damage to pods has been estimated at 85% during the fruiting months and yield losses of around 50% have been reported (Tong-Kwee *et al.*, 1989).

Mirids are usually well controlled with insecticides. The spraying campaigns implemented by West African governments from the 1960s to the 1980s led to a quick and significant increase of cocoa production in West Africa.

Cocoa pod borer

The cocoa pod borer, *Conopomorpha cramerella* Snellen is a small moth in the family Gracillariidae, endemic to South-east Asia, where it is known to affect different native fruit trees, such as rambutan (*Nephelium lappaceum*), pulasan (*Nephelium mutabile*), nam-nam (*Cynometra cauliflora*), kasai (*Pometia pinnata*) and different *Cola* species (Lim, 1992). *C. cramerella* was first reported attacking cacao in the 1860s in Sulawesi (present-day Indonesia) (Yen *et al.*, 2010). At the end of the 1980s, it was considered as the main pest of cacao in South-east Asia being widely distributed in Indonesia, the Philippines and Malaysia (Keane, 1992; Posada *et al.*, 2011). Cocoa pod borer has more recently reached New Guinea where it is now considered a major pest of cacao (Yen *et al.*, 2010). The adult female lays eggs on the cacao pod surface and the newly hatched nymph bores into the pod epidermis to reach the placenta (pulp) on which it feeds, disturbing the development of beans (Lim, 1992). Cocoa yield can be reduced by 60–84% in the case of severe infestation, and dry bean quality is also affected, which led to economic losses assessed at US$500 million/year in Asia in the early 2000s (Posada *et al.*, 2011). There is no single management strategy able to control this pest. As the nymph lives inside the pod, it is out of reach of insecticide spraying (Day, 1989; Shapiro *et al.*, 2008).

Mealybugs as vectors of CSSV

Hemiptera like aphids, scale insects and mealybugs are numerous on cacao but are usually not considered as major pests of the crop. However, some mealybugs of the Pseudococcidae family, such as *Planococcoides njalensis* (Laing), *Planococcus citri* (Risso), *Ferrisia virgata* (Cock.) and *Phenacoccus hargreavesi* (Laing) are vectors of a devastating disease in West Africa, the cocoa swollen shoot virus disease (CSSVD) (Bigger, 1981; Nguyen-Ban, 1984). Trees infected by the virus show swelling of stems and roots, mosaics, distortion of pods, as well as dieback, which lead to low yield and often to the short-term death of the trees (Lot *et al.*, 1991). The disease was first reported in 1936 in Ghana and is now affecting most parts of this country, resulting in the cutting of millions of cacao trees (Domfeh *et al.*, 2011). Nowadays, CSSVD is considered a serious threat to most of the cocoa-producing countries of West Africa, including Nigeria, Togo, Ghana and Ivory Coast.

Secondary pests

Secondary pests include insects that feed and develop on cacao but with infestation usually kept under the economic threshold by environmental factors. However, pest outbreaks can be observed in particular cropping conditions or in geographically limited areas, where these pests are then considered as major pests. In spite of this, they rarely cause significant economic losses at the world scale.

Cocoa mirids of secondary importance

Bryocoropsis laticollis Schum. (Odoniellini) has morphology very similar to *S. singularis* and *D. theobroma* and shares the same habitat. However, *B. laticollis* only feeds on pods and does not cause damage to the cacao canopy (Kumar and Ansari, 1974). *Boxiopsis madagascariensis* Lavabre is an Odoniellini endemic to the coast of Madagascar, where it was initially found on *Urena lobata* (Malvaceae). On cacao, *B. madagascariensis* causes damage similar to that of *S. singularis* and *D. theobroma* and has been considered as a major pest of cacao in Madagascar (Decazy, 1977). The bee bug *Platyngomiriodes apiformis* Ghauri is considered as an important pest of cacao in Sabah, Malaysia (Lim *et al.*, 1992). *Pseudodoniella laensis* Miller, *Pseudodoniella pacifica* China & Carvalho and *Pseudodoniella typica* (China & Carvalho) are known as important pests of cacao in New Guinea (Entwistle, 1972).

From the dozen species of Monaloniini of the genus *Afropeltis* recorded on cacao in Africa, two are commonly found in plantations: *Afropeltis lalandei* Carayon in West Africa and *Afropeltis corbisieri* Schmitz in Central Africa. Outbreaks of these two species have been locally noted, leading to significant production losses (Collingwood, 1977a). The genus *Afropeltis* is closely related to the genus *Helopeltis* with similar morphological and life history traits, and sometimes *Afropeltis* species are included in the *Helopeltis* genus.

The genus *Monalonion* is represented on cacao by seven species, distributed in Latin America from Mexico to Bolivia (de Abreu, 1977). These species feed almost exclusively on cacao pods. Heavy damage can lead to young fruit abortion and lowering of bean quality. These insects are sometimes considered as minor pests of cacao but the species *Monalonion dissimulatum*, which is the most widely distributed on cacao, was the cause of considerable production losses in Venezuela and Peru in the first half of the 20th century. Nowadays, *M. dissimulatum* is considered as a major pest in several countries of Latin America such as Bolivia and Ecuador (Ferrari *et al.*, 2014). In Brazil, the seven *Monalonion* species are present in cacao plantations but *Monalonion bondari* is the most common (Entwistle, 1972).

The shield bug Bathycoelia thalassina

The shield bug *Bathycoelia thalassina* (Herrich-Schaeffer) (Hemiptera: Pentatomidae) is a pest of cacao in most of the producing countries of West and Central Africa. Nymphs and adults feed on developing beans that they reach through the pod cortex with their long stylets, leading to bean abortion, pod distortion and premature ripening. Outbreaks of this pest in some localities of Ghana and Nigeria are responsible for significant production losses that were estimated at 18% in Ghana in the late 1970s (Owusu-Manu, 1976, 1990).

The cocoa borer Steirastoma breve

In the Neotropics, the longicorn beetles *Steirastoma* spp. (Coleoptera: Cerambycidae) are widely distributed on various host plants. *S. breve* damages young cacao trees: adult females feed on the bark and nymphs bore into the cacao stems making galleries, which opens the door for pathogenic microorganisms to colonize the plants. The beetle is considered a major pest of cacao in Venezuela, and in some areas of Brazil and the Caribbean islands, such as Trinidad (Liendo-Barandiaran *et al.*, 2010).

The cocoa fruit borer Carmenta theobromae

The cocoa fruit borer, *Carmenta theobromae* (Busck) (Lepidoptera: Sesiidae), is a small moth newly considered as a major pest of cacao in some areas of Venezuela and Colombia. Another species, *Carmenta foraseminis* increasingly affects cocoa production in Colombia. Similar to the cocoa pod borer, *Carmenta* spp. females lay eggs on the cacao pods and the larvae bore galleries inside, causing the fruit to rot following infections with pathogenic fungi (Morillo *et al.*, 2009).

The cocoa weevil Pantorhytes *spp.*

Weevils from the genus *Pantorhytes* (Coleoptera: Curculionidae) are major pests of cacao in New Guinea. Of the 11 species injurious to cacao plants, six have been found to be of economic importance. They are robust apterous insects about 1–5 cm long. Larvae tunnel into the cacao stem between the bark and the wood leading to weakened trees, infection by microbes and often sudden death of trees. Totally destroyed plantations have been reported in some areas of Papua New Guinea and the weevil has contributed to cocoa industry collapse in some important producing regions of the country (Moxon, 1992).

The cocoa stem borer Eulophonotus myrmeleon

Eulophonotus myrmeleon Fldr. is a moth from the family Cossidae, whose larvae feed on cacao wood, boring galleries in the stem. Initially considered as a minor pest, reports of *E. myrmeleon* on cacao became more numerous in the 1990s and early 2000s in West Africa. The pest has been recently recorded as serious in some areas of Nigeria and Ivory Coast. Infestation levels reaching around 5% of trees damaged by the pest have been reported in plantations near Ibadan in Nigeria (Anikwe, 2010).

Minor pests of cacao

Large numbers of insects can feed or breed on the plant, or both, without affecting production significantly. They are usually considered as minor pests of cacao although some of them can be major pests of other crops.

The cocoa psyllid *Tyora tessmani* (Aulmann) (Hemiptera: Psyllidae) feeds on cacao shoots leading to interference in leaf development. In cacao nurseries, large populations of the psyllid affect seedling development and should be controlled by chemical spraying (Igboekwe, 1983). Several Scolytidae species have been reported to damage cacao worldwide. Species of the beetle genera *Xyleborus* and *Xylosandrus* attack twigs, damaging the cacao canopy (Navarro and Liendo, 2010). Other species feed on pods and could be involved in pod infection by pathogens causing serious cacao pod diseases such as black pod (*Phytophthora palmivora*) (Konam and Guest, 2004). Leaf-feeding moths and beetles are numerous on cacao although rarely associated with damage of economic importance. The cacao armyworm *Tiracola plagiata*, a noctuid moth, is a pest of cacao in Asia and has been shown to be more abundant in plantations shaded with *Leucaena leucocephala* (Room and Smith, 1975). The cacao plume moth, *Michaelophorus nubilus*, is a moth of the family Pterophoridae damaging young cacao leaves in Latin America (Matthews and Miller, 2010).

In sub-Saharan Africa, two moth species of the family Nolidae are found on cacao: (i) the cacao pod borer *Characoma stictigrapta* Hmps.; and (ii) the spiny bollworm *Earias biplaga* Walk. The former species feeds on cacao leaves and pods while the larvae of *E. biplaga* attack the buds and young leaves, leading to serious damage on seedlings especially (Entwistle, 1972; Akotoye and Kumar, 1976). Some leaf-feeding beetles are reported as pests of cacao, among which is the Scarabaeidae *Adoretus versutus* Har., an Asian polyphagous chafer beetle, outbreaks of which caused serious defoliations in cacao plantations in Vanuatu in the 1980s (Beaudoin *et al.*, 1995). Chafer beetles from the genera *Apogonia*, *Anomala* and *Chaetadoretus* include leaf-feeding pests of cacao as well (Entwistle, 1985). Longhorned beetles (Cerambycidae) include several species of cocoa stem borers damaging cacao branches and stems worldwide. Genera *Phosphorus* and *Tragocephala* are commonly found boring galleries in cacao wood in West Africa, where they also damage coffee (Entwistle, 1972). Longhorned beetles from the genus *Glenea* include many pests of trees, some of which are found on cacao in different countries, notably in Papua New Guinea (Entwistle, 1972).

Pest Management Practices Compatible with Organic Cocoa Production

As noted above, certified organic cocoa represents a very small part of the world cocoa production and a tiny fraction of the cocoa crop in the biggest producing countries of West Africa and South-east Asia. Yet most of these countries have to face major insect pests, and taking into account the increasing consumer demand for organic cocoa, stakes are high for the development of organic means to control these pests. Hence, all the pest management strategies are being considered today – those made available to farmers after decades of research for alternatives to chemical control, as well as those traditionally implemented by farmers to protect their farms. The following paragraphs will present these solutions, with for each of them, an assessment of the degree of implementation.

Preventive solutions

The term 'preventive' here means those solutions implemented at the initial time of cacao planting or during routine maintenance work, to prevent infestation by insect pests and their damage. A significant part of these practices is based on farmer traditional knowledge and others come from scientific knowledge of the biology and ecology of insect pests. In any case, these solutions are currently highlighted as the engine of agroecological concepts implementation.

Planting resistant cacao varieties

An important consideration is that a large part of smallholder cacao farmers still use their own seeds or seeds collected from nearby farms for planting. Seeds come from pods usually collected on trees selected for their vigour, productivity and tolerance to pests and diseases. This traditional selection process, as well as improved variety dissemination by governments, has resulted in a large genetic variability within farms, which is now used by cacao selection programmes, incorporating farmers' perception within a participative approach (Eskes, 2011).

From the researchers' point of view, selection of resistant cacao varieties for pest and disease management is probably the strategy that has generated the most work, especially in the last three decades. However, it should be noted that if varietal solutions have been found and implemented for some cacao diseases, such as the witches' broom disease caused by *M. perniciosa* in Brazil, no definitive solution has been found for any cacao insect pest. For African cocoa mirids, ongoing research shows how the mechanisms involved in the resistance are complex. Resistance has been assessed through records of cumulative damage in selection trials, notably in Ivory Coast (Sounigo *et al.*, 2003). Antixenosis, antibiosis and tolerance of different genotypes have been tested through choice tests with cacao twigs in the laboratory and by enclosing mirids in sleeves on trees in Cameroon, Ivory Coast and Nigeria (Dibog *et al.*, 2008; N'Guessan *et al.*, 2008; Anikwe *et al.*, 2009). These studies allowed the selection of promising clones for further use in breeding programmes, but sometimes with inconsistent results, and much work remains to be done before cacao farmers can actually plant improved cacao varieties for pest control (Eskes, 2011). Major challenges are the identification of varieties combining resistance to mirids, the black pod disease and the cacao swollen shoot virus disease, as well as improved seed production and dissemination to farmers.

To a lesser extent, similar work has been done for the cocoa pod borer, resulting in similar challenges. Pod-surface smoothness, timing of pod development and pod hardness are factors affecting the breeding success of the moth and are pointed out as potential levers for cacao resistance to cocoa pod borer (Teh *et al.*, 2006). But for now, no totally resistant genotype exists and the strategy could be the planting of a mix of various genotypes, including a few susceptible ones. Such genetic diversity may force the moth to make a choice of cacao pods for egg laying, leading to lower global infestation of the plantation (McMahon *et al.*, 2009).

Some work on resistance of cacao to secondary or minor pests, such as *Steirastoma breve* (Morillo *et al.*, 2008), has been conducted and has revealed the potential of some varieties.

Cacao maintenance

Among good agricultural practices for the maintenance of the cacao tree, some are specifically recommended for pest management. For African cocoa mirids, pruning practices aim to prevent chupons on trees. Chupons are vertical shoots growing on the trunk, usually near the ground or below the tree crown. Chupons are particularly attractive to mirids, which feed and lay eggs on them, contributing to maintaining mirid populations on farms even when trees do not bear fruits. Since isolated cacao trees have been found to shelter more mirids than others, another good practice for mirid control is to maintain (while pruning) a continuous cacao canopy with branches touching each other in a thin continuous layer (Padi *et al.*, 2002a).

Given the gravity of the cocoa pod borer threat in some areas of South-east Asia, a radical cultural practice has been used since the early 20th century. Known as 'rampassen', the practice consists of removing all the fruits from cacao in a plantation in order to break the pest life cycle (Lim, 1992). Assessments of the impact of the practice on cocoa pod borer populations yielded an uneven picture, among which were major constraints such as labour costs and economic losses for cacao farmers (Lim, 1992). A conservative practice is to harvest ripening pods as frequently as possible and to break them open immediately to collect the cacao beans (Lim, 1992). After bean extraction, the pod husks can be used as a mulch to destroy immature stages of the pest.

Plant association

Cacao is an understorey crop traditionally grown under shade trees within agroforestry systems. Where possible, smallholder farmers establish cacao in the forest after having cleared the ground of understorey vegetation. Where there are no forests, farmers often shade cacao with trees they grow for fruits, firewood, timber or traditional medicine. Some of the practices recommended for cacao–tree association are specific to pest control. They involve tree species to be planted in association with the crop, and tree canopy management for shade.

REMOVAL OF ALTERNATIVE HOST PLANTS OF CACAO PESTS. A common recommendation in pest control is to remove alternative host plants of cacao pests from the crop or from the surrounding environment. In West Africa, cocoa mirids have adapted to cacao from native forest trees of the family *Malvaceae*. The most famous of them is the kola tree (genus *Cola*), which is grown for its nuts, and which contains seeds rich in caffeine. Due to the lack of farmer knowledge, kola trees are often used to shade cacao and some authors have suggested that the quick expansion of mirid dispersion on cacao in West Africa might be linked to kola tree–cacao associations (Entwistle, 1972). Similar recommendations exist for cocoa pod borer in Asia (Lim, 1992).

SHADE MANAGEMENT. Shade has proven to be a determining factor of cocoa mirid infestation and damage in West Africa. Unshaded plantations are usually more damaged by mirids than shaded ones and in shaded plantations mirid populations are usually sheltered by cacao trees exposed to direct sunlight through gaps in the shade-tree canopy layer (Babin *et al.*, 2010). A common shade recommendation for mirid control in West Africa is to maintain a regular shade level in cacao plantations (Padi *et al.*, 2002a). High forest trees have been shown to be more suitable than fruit trees because they provide a lighter and more uniform shade (Babin *et al.*, 2010).

PLANTING TREES TO FAVOUR PEST NATURAL ENEMIES. Some tree species are recommended in cacao plantations because they provide habitats for pest natural enemies. For example, in Malaysia, associations between cacao and coconut palms are recommended to improve the control of cacao pests, such as the mirid

Helopeltis theobromae by the generalist predator ants *Dolichoderus thoracicus* and *Oecophylla smaragdina*, through providing ants with nesting sites (Way and Khoo, 1991).

Biological control

Parasitoids

Old studies on natural enemies of the cocoa mirids *S. singularis* and *D. theobroma* in Africa report that parasitoids are few and do not lead to sufficient parasitism rates to be good candidates for biological control. Only one species of nymphal parasitoid has been recorded, *Leiophron* (*Euphorus*) *sahlbergellae* Wlk. (Braconidae, Euphorinae), with parasitism rates of 15–40% and 6–20% assessed in Ghana and Nigeria, respectively (Collingwood, 1977b). A hyperparasitoid, *Mesochorus melanothorax* Wlk. (Ichneumonidae) attacks *L. sahlbergellae* while feeding (Entwistle, 1972). Three other parasitoids from the genera *Telenomus* (Scelionidae), *Pediobus* (Eulophidae) and family Signiphoridae have been collected from *S. singularis* eggs, with parasitism rates lower than 10% (Entwistle, 1972).

By contrast, an indigenous egg parasitoid, *Trichogrammatoidea bactrae fumata* Ngaraja (Hymenoptera: Trichogrammatidae) was found to be associated with cocoa pod borer in Malaysia in 1982, and is now considered a good biological control agent for the pest on cacao (Lim, 1992). Parasitism rates ranging from 10% to 56% were observed in the 1980s and strong density dependence between the parasitoid and the pest was demonstrated (Lim, 1992). However, to the best of the author's knowledge, the literature does not give clear evidence of the use of large-scale releases of this parasitoid for the biological control of cocoa pod borer.

Generalist predators

Entwistle (1972) listed arthropod predators of African cocoa mirids. An old study by Williams (1954) revealed levels of predation of mirid nymphs as high as 16%, 19% and 21% for praying mantises (Mantidae), Reduviidae and ants, respectively. However, because they are generalist feeders, they are usually not considered as good candidates for biological control.

By contrast, some species of ants with very large polydomus colonies have been considered for biological control on cacao. As for most tropical ecosystems, ants are a key component of cacao agrosystems (Philpott and Armbrecht, 2006). In West Africa notably, ant communities have been well described in the past especially the arboreal species (Williams, 1954; Bigger, 1981). A high level of species diversity as well as strong spatial structuration of communities led authors to characterize them as ant mosaics (Tadu *et al.*, 2014a). In cacao agrosystems, ant mosaics are usually structured by highly dominant species such as *Oecophylla longinoda*, *Tetramorium aculeatum* and *Crematogaster* spp., which prey on a large range of invertebrates, including insect pests such as mirids and shield bugs. However, their actual impact on damage by mirids is still controversial and, to the best of our knowledge, there are no specific recommendations for the use of ants as biological control agents for any pest of cacao in Africa.

In that regard, farmers have set positive examples worldwide. In southern Cameroon for instance, in the 1960s, cacao farmers successfully used the little fire ant, *Wasmannia auropunctata* Roger, to get rid of insect pests on their plantations, building colonies in their farms by trapping ants with sweet baits (Bruneau de Miré, 1969). Unfortunately, by doing this, farmers have probably contributed to the expansion of this invasive tramp species, accidentally introduced in this area and now widely considered as a threat for Congo basin forest biodiversity.

In Asia, farmers have used ants for several centuries now, especially to protect fruits from insect pests. On cacao, the Asian weaver ant *O. smaragdina* is known as a beneficial predator of many pests such as the mirids *Helopeltis theobromae* and *Pseudodoniella laensis*, and the cocoa weevils (*Pantorhytes* spp.) in Papua New Guinea (Way and Khoo, 1992). But this species is aggressive to people and may hinder agricultural operations, in such a way that it is not always welcome in plantations. By contrast, the black ant *D. thoracicus* is not aggressive and Indonesian cacao farmers have used it to protect pods from mirid damage since the early 1900s (Way and Khoo, 1992). Since then, research has confirmed that *D. thoracicus* is a valuable biological control agent for the major pests *Helopeltis antonii* and *H. theivora* in Indonesia and *H. theobromae* in Malaysia (Saripah and Azhar, 2012). Research on *D. thoracicus* has led to recommendations to favour colony establishment in plantations, among which the destruction of antagonist ant species, the improvement of nesting conditions by planting coconut palms or introducing artificial nests, and artificial infestation of cacao with mealybugs, which are tended by black ants for honeydew (Way and Khoo, 1992).

The crazy ant, *Anoplolepsis longipes*, has shown promise for the control of *Pantorhytes* spp. in Papua New Guinea and methods have been developed for establishing colonies in cacao plantations (Moxon, 1992). But the use of crazy ants as a biological control agent is questioned due to the difficulty of maintaining large colonies in plantations over time.

Pesticides

Bacterial and fungal preparations

Several *Bacillus thuringiensis* (*Bt*) toxins have been tested for the control of cocoa pod borer. Eight of the 12 Cry1 proteins tested through laboratory bioassays were able to kill 50% of cocoa pod borer larvae maintained on an artificial diet (Santoso *et al.*, 2004). Field trials of *Bt* insecticide formulations in Indonesia have shown significant reduction of cocoa pod borer infestation and yield increase (Senewe *et al.*, 2013). Commercialized and local strains of *Beauveria bassiana* have been tested with promising results for *Monalonion dissimulatum* through field investigation in Bolivia (Ferrari *et al.*, 2014) and for *Pantorhytes plutus* in Papua New Guinea. Moreover, *B. bassiana* has been established as an endophyte of the cacao tree by spraying seedlings or flowers. In the latter case, the entomopathogenic fungus was re-isolated from pods, suggesting that the method could be used for major pest management of cocoa pod borer and mirids (Posada *et al.*, 2010). Suspensions of local strains of entomopathogenic fungi from *Paecilomyces* and *Lecanicillium* genera were tested on *Carmenta foraseminis* with success (Figueroa Medina *et al.*, 2013). Although these results are promising, to the best of our knowledge, there is no report on the use of commercialized bacterial and fungal preparations by cacao farmers for the control of insect pests.

Botanical pesticides

A curative practice that can be implemented in organic farming is the use of approved insecticides of biological and mineral origin. These are defined by the IFOAM *Basic Standards for Organic Production and Processing* (IFOAM, 2005). Neem (*Azadirachta indica*) extracts are one of the commonly used natural insecticides as they have shown real efficiency on several pests worldwide. On cacao, neem crude extracts at different concentrations, as well as commercial formulations, were tested on mirids in Ivory Coast and Ghana, and gave high levels of mortality in the laboratory and in the field (Padi *et al.*, 2002b). The repellent or deterrent effects of neem on mirids were also shown through attractiveness tests in the laboratory (N'Guessan *et al.*, 2006). Also, neem gave promising results on mealybugs, vectors of the CSSV, and on other pests such as *Helopeltis* spp. and the psyllid *Tyora tessmanni*.

At the present time, no data on the actual use of neem-based insecticides by cacao farmers is available. By contrast, the use of natural pesticides developed by farmers themselves in response to problems of agrochemical supply is reported. For example, a study conducted in Cameroon reveals that various herbal preparations of hemp (*Cannabis sativa*) are used alone or mixed with extracts from tobacco leaves, indigenous trees or with chemicals for the control of pests and diseases (including cocoa mirids and black pod) (Coulibaly *et al.*, 2002).

Mechanical control

Physical barriers

In Indonesia, cacao smallholder farmers have developed a physical method for controlling the cocoa pod borer. They use plastic bags to sleeve pods and prevent the moth from laying eggs on them. The issue of plastic bag pollution has led researchers to test the method using biodegradable plastic bags. A recent study conducted in Indonesia shows that only 50% of the pods were preserved this way from cocoa pod borer and discusses the importance of good timing of the pod sleeving that seems to depend on cacao variety and season (Rosmana *et al.*, 2010). Sleeving pods at an earlier developmental stage can reduce cocoa pod borer infestation by 85–100% but this also increases the risk of production losses due to physiological death of pods (wilt) and *Phytophthora* pod rot.

A few studies report assessments of other methods to physically protect pods from insect attack, by spraying kaolin and silicon-based products, but results should be confirmed with more investigations of these products (Ferrari *et al.*, 2014).

Hand picking and physical destruction of pests

Another mechanical practice developed by cacao growers worldwide for the control of stem borers is the poking of holes tunnelled by the pest with a wooden stick or a wire to kill the larvae. This practice has proved inefficient in controlling increasing populations of *Eulophonotus myrmeleon* in Nigeria when implemented alone, but is recommended in combination with well-targeted chemical control (Anikwe, 2010).

Hand picking may be a good strategy for some cacao pests that are easily seen on trees. This is true for the cocoa weevils *Pantorhytes* spp., whose adults are easily detected in the trees and destroyed by farmers in Papua New Guinea (Moxon, 1992).

Semiochemical control

Traps containing synthetic sex pheromones of cocoa mirids have been tested in Ghana and Cameroon (Padi *et al.*, 2004; Mahob *et al.*, 2011). Sticky traps baited with different blends of two components of the *Sahlbergella singularis* female sex pheromone, namely hexyl (R)-3-((E)-2-butenoyloxy)-butyrate and hexyl (R)-3-hydroxybutyrate, gave promising results for this pest, suggesting that the trap could be used for pest monitoring at least (Mahob *et al.*, 2011). There is still much work to be done, however, to measure its efficiency in reducing infestation and improving yield, before this can be considered.

Similar work has been conducted for the cocoa pod borer in Indonesia and Malaysia (Zhang *et al.*, 2008). Different blends of synthetic female sex pheromone of *C. cramerella*, including (E,Z,Z)- and (E,E,Z)-4,6,10-hexadecatrienyl acetates and the corresponding alcohols showed satisfactory attractiveness. Here again, experimentation on a larger scale is needed before including pheromone traps within strategies for biological control of cocoa pod borer.

Some pest control methods based on evaluation of semiochemicals have been tested for cacao pests of secondary importance. For example, the use of cacao brushwood piles has been tested for the control of the cocoa beetle *Steirastoma breve* in Venezuela (Liendo-Barandiaran *et al.*, 2010).

The Future of Biological Control of Pests on Cacao

Collective management strategies to be thought of in time and space

Pest management strategies compatible with certified organic cacao are numerous. Farmers are already implementing some, others have proven to be efficient although not yet widely used and some need more work for their efficiency to be demonstrated. However, if implemented alone, none of these practices has proven to be a complete and definitive solution, either because they failed to keep pest damage under economic thresholds or they caused other problems that overshadowed the benefits. Control of major pests, especially, requires a combination of practices implemented from the beginning of cacao plantation establishment, and taking into account recommendations for other major production constraints. This should be the case for some areas of West Africa where cacao production is threatened by damage on trees from both mirids and CSSV, and pod loss due to black pod disease.

Moreover, as a tree crop, the cacao development period can extend for several decades. Routine maintenance of a cacao farm is crucial for good productivity, and decisions need to be made at the time of plantation establishment, notably in terms of cacao varieties and plant association, which are of primary importance, with long-term consequences.

In many countries worldwide, cacao is grown continuously over wide areas, but by a large number of farmers, each owning a few acres. For pests with good dispersion ability, such as mirids and cocoa pod borer, pest management has to be organized at a larger scale than at individual farm level. This shows the importance of farmer organization and how a socio-economic approach plays a crucial role in pest management on cacao. This also shows how a landscape approach is important, taking into account spatial arrangements of cacao farms as well as the different components of the agricultural landscape.

Plant diversification as the main lever of agroecology

One of the aims of agroecology is to value ecological mechanisms for the design and management of sustainable agrosystems. Many studies on many crops worldwide have shown that enhancement of plant diversity in agrosystems is a good strategy for pest and disease regulation (Ratnadass *et al.*, 2012). Plant diversification helps to return the natural balance through re-establishment of trophic webs.

Since cacao is still grown in highly diversified agroforestry systems in various environments worldwide, cacao agrosystems offer excellent models for the study of ecological mechanisms involved in pest regulation. Recent studies showed how tree associations should be viewed in terms of composition and spatial structure for the regulation of cocoa mirids, through shade management and natural enemies' promotion (Gidoin *et al.*, 2014; Tadu *et al.*, 2014b).

Farmer knowledge as a cornerstone of agroecology

Because they suffered in the past and still suffer in some areas from financial constraints, smallholder farmers have developed their own management strategies for pest control worldwide. Most of these strategies are based on a better use of what is present on their farm or surrounding farms, as well as what the surrounding natural environment offers. The most persuasive evidence, already mentioned above, is the use of their own cacao varieties, the development of pesticides from local plants and enhancement of pest natural enemies. Farmers' technologies usually need improvement but accumulated knowledge is always of great interest and should contribute to an agroecological approach to pest control.

Cacao certification: a solution for organic pest management?

Due to the limited production of organic cacao worldwide, few studies have measured the impact of organic practices on cocoa production and environment. A study conducted in Bolivia showed that a certified organic cacao environment had greater plant diversity compared with a traditional agrosystem as well as providing better yields, leading to higher family income. This is explained by better organic farmer knowledge and practices, linked to self-organization and affiliation to farmers' organizations (Jacobi *et al.*, 2013).

By contrast, other certifications are exploding in growth, involving thousands of farmers, especially in the major producing countries of West Africa. As a matter of fact, the main cocoa industry companies, with the aim of improving their image, have set an ambitious target of 100% certified cacao for 2020. Certifications based on environmental and ethical standards as well as good farming practices are promoted by international non-governmental organizations (NGOs) such as The Rainforest Alliance and UTZ Certified. However, mass certification as practised currently in West Africa is not producing the desired results in terms of yield growth, farmer welfare and environmental protection (Ruf *et al.*, 2013). Regarding pest and disease control, a recent study conducted in Ivory Coast showed that certified farmers do not usually follow the chemical spraying recommendations (Ruf *et al.*, 2013).

This analysis, among others, clearly underlines that cacao certification should be carefully considered and planned from the beginning, when starting a cacao plantation and on a long-term basis, by incorporating farmers' expectations and constraints, as well as the knowledge and innovations that they have developed (Ayenor *et al.*, 2004, 2007).

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