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Ecological Mechanisms for Pest and Disease Control in Coffee and Cacao Agroecosystems of the Neotropics

Jacques Avelino, G. Martijn ten Hoopen and Fabrice A. J. DeClerck

Introduction

Pests and diseases can have impacts upon most ecosystem services (ES), including food production and yield (Cheatham et al, 2009). Food production, according to the Millennium Ecosystem Assessment (MEA, 2005) is one of the most important ES. In severe cases, pest and disease damage results in plantation abandonment, famine and emigration. The Irish potato famine, caused by potato blight (*Phytophthora infestans*) in Ireland between 1846 and 1851, is one of the best-known cases. In the tropics, examples of disasters caused by pests include the coffee leaf rust (*Hemileia vastatrix*) in Ceylon (now Sri Lanka) during the 1870s, the coffee wilt disease (*Gibberella xylarioides*) in Central Africa during the 1940s and 1950s, and *Fusarium oxysporum*, the causal agent of Panama disease on bananas in Latin America during the 1960s. More recently, two closely related cacao pathogens, *Moniliophthora perniciosa* (previously *Crinipellis perniciosa*), the causal agent of witches' broom, and *Moniliophthora roreri*, the causal agent of frosty pod rot, have wreaked havoc among cocoa producers in the Neotropics. After the arrival of witches' broom

in Bahia in 1989, Brazil moved from being the second largest cocoa producer in the world (374,000 tonnes in 1988) to the fifth rank in 2000, with a 47 per cent decrease in production despite a 6 per cent increase of the planted area during the same period (Meinhardt et al, 2008; FAO, 2010). Similarly, frosty pod rot led to the almost total disappearance of cacao cultivation in Costa Rica during the 1970s.

After World War II, industrialized countries, while intensifying crop production, have avoided such disasters through increased use of pesticides. However, intensive pesticide use includes major negative externalities, such as human health problems, pollution, reductions in the populations of beneficial organisms, and the emergence of secondary diseases or pathogen resistance to pesticides (Wilson and Tisdell, 2001; Jackson, 2002; Tilman et al, 2002; Leach and Mumford, 2008; Geiger et al, 2010). Therefore, in order to reduce pesticide use and limit these negative externalities, the question of how to stimulate ecological mechanisms of pest and disease control seems very relevant in industrialized countries.

In less-developed tropical countries, the situation is somewhat different. In general, tropical agriculture does not consume the quantities of pesticides of industrialized countries (Abhilash and Singh, 2009). In the Neotropics, we often find low-input and low-yield (partly due to plant pest and disease impacts) smallholder systems with minimal or no use of pesticides. This is the case for almost all cacao producers and many coffee producers in Central America. Therefore, in the Neotropics ecological mechanisms of pest and disease control must be better used not only in order to reduce pesticide use, but also to increase yields of the very common low-input systems by reducing pest and disease impact.

The high vulnerability of agroecosystems to pests and diseases, compared to natural ecosystems, has been related to the loss of biodiversity and simplification of agroecosystems. As a consequence, increasing biodiversity has been proposed to decrease pest and disease risks (Andow, 1991; Altieri, 1999; Tilman et al, 2002; Bianchi et al, 2006; Cheatham et al, 2009; Malezieux et al, 2009). In Neotropical agroecosystems, particularly in agroforestry systems, plants, birds, insects, fungi and bacteria contribute to pest and disease control and consequently supply important environmental services (Cheatham et al, 2009). However, the myriad of interactions between plants, birds, insects, fungi and bacteria, the environment in which they live, and the way in which these interactions influence diseases and pests cycles in natural systems are extremely complicated and poorly understood. Future research should focus on elucidating these interactions to capitalize on biological control services (BCS) (Coll, 2009).

In this chapter we review examples of control effects, emphasizing the different pathways involved. We do not intend to describe all existing ecological mechanisms of pest and disease control, but highlight those present in coffee and cacao agroecosystems: two important crops of the Neotropics. It is important to note that although increasing biodiversity generally leads to

better control of pests and diseases, some negative effects also exist and will be discussed. Finally, the question of quantification of pest and disease regulation services provided by these tropical agroecosystems will be examined.

Genetic Diversity, Disease and Pest Resistance: The Need for *In-Situ* Conservation

Plants and co-evolved pathogens in their centre of origin have a high genetic diversity because of continuous mutual adaptation. Therefore, centres of origin for specific crops provide an important source of dynamically evolving resistance genes that are exploitable for plant breeding (Cheatham et al, 2009). In the Neotropics, this is especially true for cacao (*Theobroma cacao*), which is native to central and western Amazonia and has its centre of diversity in the upper Amazon Basin in Peru and Ecuador (Motamayor et al, 2008), although its centre of domestication is Mexico and Central America (Evans et al, 1998). The importance of *in-situ* conservation is particularly apparent when considering the current phytosanitary situation of cacao in Brazil. Since the outbreak of witches' broom in Bahia in 1989, approximately 150,000ha of susceptible varieties have been replaced with resistant descendants of Scavina clones as an emergency measure. Some of these descendants have shown a decreased resistance, probably the result of an increase in frequency of strains of witches' broom capable of overcoming Scavina's resistance (Gramacho and Pires, 2009). An additional problem of increasing importance in Bahia is *Ceratocystis* wilt caused by the fungus *Ceratocystis cacaofunesta* (Baker Engelbrecht and Harrington, 2005), which, similar to witches' broom and frosty pod rot, probably originated in northern South America, after which it spread to other cacao-growing regions (Engelbrecht et al, 2007). Because much of the germplasm that has been selected for resistance to witches' broom and other diseases is susceptible to *Ceratocystis* wilt, the impact of the wilt will increase as these materials are put in place. Since frosty pod rot, witches' broom and probably *Ceratocystis* wilt originated on cacao in the Americas, resistant sources should be present within cacao's centre of origin.

Plant Species Diversity and Pest and Disease Control Services

Modification of host plant densities and physical barriers for pests and pathogens

The first probable effect of introducing plant diversity in agroecosystems is modification of host plant densities. It is well known that agriculture has favoured monocultures where crops are more perceptible to pests and available to diseases (Burdon and Chilvers, 1982; Altieri, 1999; Malezieux et al, 2009). Tropical crops are not exempt. Several relationships between high densities and greater pest and disease attack intensities have been mentioned for coffee. For

instance, short distances between rows of coffee trees have been reported to facilitate American leaf spot disease (*Mycena citricolor*) spread, whose dispersal distance is very short (Avelino et al, 2007). This probably explains why this disease is considered to be severe almost only in Costa Rica, a country where coffee plantation densities are among the highest in the world. A similar relationship, again in Costa Rica, has been found in nematodes (*Meloidogyne exigua* and *Pratylenchus coffeae sensu lato*), organisms known for their very limited mobility. Increased contact between roots in high-density systems probably facilitates nematode spread (Avelino et al, 2009). Another disease favoured by high densities is *Rosellinia* root rot in coffee and cacao. *Rosellinia* dispersal is through root contact and is characterized by circular pattern patches caused by the infection process.

Introducing non-host vegetation in agroecosystems at plot and landscape scales can help to intercept pests and diseases when dispersing or spreading. Windbreaks, hedges and woody borders particularly influence insect dispersal (Pasek, 1988; Bhar and Fahrig, 1998; Schroth et al, 2000; Sciarretta and Trematerra, 2006). Barrier effects have also been reported for wind-borne, splash-borne or soil-borne pathogens in intercrop systems (Michel et al, 1997; Bannon and Cooke, 1998; Gomez-Rodriguez et al, 2003; Schoeny et al, 2010). According to Schroth et al (2000), shade trees in tropical agroforestry systems can potentially serve as barriers to pest and pathogen spread. Shade trees reduce wind speed in coffee and cacao plantations (Beer et al, 1998), and probably affect different wind-borne pathogens such as coffee leaf rust, frosty pod rot or witches' broom on cacao. Evans (1981), for example, noted that cacao grown in unshaded blocks without windbreaks demonstrated increased turbulence, especially at plantation edges, and that these currents favoured inoculum movement of *Moniliophthora perniciosa*, with a resulting increase in both pod and flower infections.

Similar effects can be found at landscape scales. Some landscape elements constitute dispersal-limiting barriers or, on the contrary, can serve as dispersal-favouring corridors (Altieri, 1999; Plantegenest et al, 2007). This is the connectivity paradox: connectivity for desirable organisms may also favour the spread of noxious organisms and make their control more difficult (Zadoks, 1999). The effect of connectivity on pest and pathogen dispersal has been suggested in only a few studies, mostly in temperate forests (Perkins and Matlack, 2002; Condeso and Meentemeyer, 2007). In those cases, landscape fragmentation with non-host plots was proposed to create barriers to pest and pathogen movement. There is no evidence of such effects on tropical crop pests and pathogens. However, the potential of fragmenting agricultural landscapes with forest corridors that serve as barriers for agricultural pests seems promising for less mobile pathogens or pests, particularly host-specific species such as the coffee berry borer. For noxious organisms with high dispersal abilities, such as coffee leaf rust, witches' broom and frosty pod rot of cacao, isolating susceptible plots may be insufficient to avoid infection.

Modifications of microclimate

Introduction of plant diversity into agroecosystems can deeply modify the microclimate, particularly that of understorey vegetation. Air and soil temperatures are generally buffered; wind speed and solar radiation are reduced, whereas relative humidity, plant organ wetness and soil humidity are increased (Ong et al, 1991; Olasantan et al, 1996; Beer et al, 1998; Staver et al, 2001; Avelino et al, 2004; DaMatta, 2007; Lott et al, 2009). These changes can directly affect different processes of the pest and pathogen life cycles and create adverse conditions for their development (Schroth et al, 2000; Gomez-Rodriguez et al, 2003; Schoeny et al, 2010). In Cameroon, shade trees have been suggested to reduce coffee berry disease (*Colletotrichum kahawae*) incidence by intercepting rainfall and reducing raindrop impact intensity upon coffee trees, consequently limiting the splash dispersal of propagules (Mouen Bedimo et al, 2008). In the Neotropics, coffee blight (*Phoma costarricencis*) can be reduced by establishing windbreaks and shade trees in the plantation (Muller et al, 2004). Trees buffer coffee plants from winds, which has a dual effect. First, the trees provide a degree of insulation from cold winds. Second, the trees protect the coffee plants from mechanical damage by reducing wind speed. Cold temperatures and infection entry points caused by wounded leaves and stems are two of the conditions that favour infection by the coffee blight. Shade also lessens coffee's brown eye spot disease (*Cercospora coffeicola*) (Echandi, 1969; Staver et al, 2001). According to Echandi (1969), *C. coffeicola* has a high temperature requirement for germination (30°C) and plant tissue colonization is favoured when soil moisture is low, two conditions frequently encountered at full sun exposure that can be corrected by intercropping coffee with shade trees.

Microclimate modifications due to shade may also indirectly affect pests and diseases through host physiology changes. That is the case with coffee leaf rust, whose epidemics are more intense when coffee yield is high (Avelino et al, 2004, 2006), probably because of the translocation of phenolic compounds from leaves to fruits. This condition is often reached at full sun exposure (see Figure 4.1). As a consequence, a high degree of shade may negatively affect the development of this disease through the effects of shade on yield (Avelino et al, 2004, 2006), which largely depends on light availability. Similarly, the overbearing disease (*Colletotrichum* spp.), which affects overproducing plants and causes branch dieback, can be almost completely eliminated by implementing an appropriate shade to regulate yield (Muller et al, 2004). A similar effect has been shown in the case of witches' broom. Since cacao grows more vigorously and produces more flowers and pods when grown under full sun, it becomes particularly vulnerable to witches' broom because this pathogen affects actively growing tissue (Evans, 1998). It has been demonstrated in Costa Rica that Neotropical mirids (*Monalonion* spp.) caused more damage on full sun-grown cacao compared with shaded cacao (Villacorta, 1977). A possible explanation, similar to the case of witches' broom, is that full sun-grown
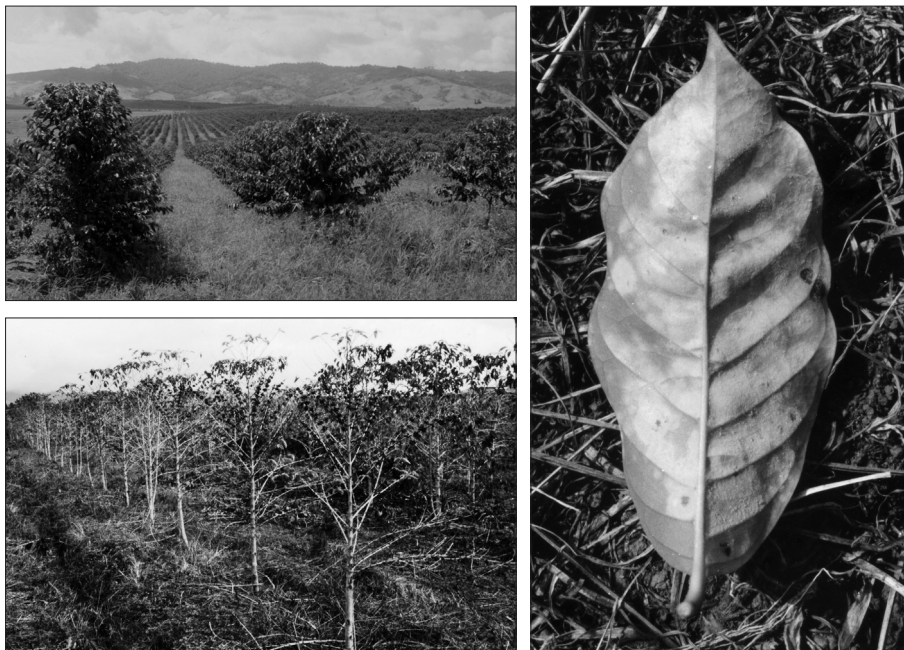
Figure 4.1 *High yields reached in a full-sun plantation predisposed coffee leaves to severe attacks by rust (*Hemileia vastatrix*) despite copper-based fungicide applications (left); a great proportion of the leaf area was infected (right)*

Source: J. Avelino

cacao is more vigorous and provides more food sources for cacao mirids than shade-grown cacao (Babin et al, 2010). Based on these results, it was suggested that homogeneous shade provided by large forest trees should reduce mirid damage more effectively.

Improvement of soil physical and chemical characteristics

Plant diversity can improve physical and chemical soil characteristics, which can have an indirect impact upon pest and disease control. In coffee-based agroforestry systems, di-nitrogen (N_2)-fixing leguminous trees are frequently used for coffee shading. Litter fall and pruned branches can contain up to 340kg of nitrogen ha^{-1} y^{-1} (Beer et al, 1998). As a consequence, total soil nitrogen (N) for the superficial soil layer was found to be higher in coffee intercropped with leguminous trees, compared to coffee monocultures (Hergoualc'h et al, 2008). In general, plants with good nutritional status and good growth are better able to replace diseased leaves or roots. This effect has been suggested for coffee leaf rust and American leaf spot disease on coffee, where disease intensities and the annual number of fertilizer applications were negatively associated (Avelino et al, 2006, 2007). Plant nutrition can also

Figure 4.2 *The appearance of cocoa pod rot, caused by Phytophthora, is delayed by the presence of a litter layer (left) when compared with a situation where no litter layer is present (right)*

Note: Only the young cocoa pods (cherelles) closest to the soil have been affected. Both pictures were taken on 25 May 2010.
Source: G. M. ten Hoopen

increase resistance of plants to pathogens. Disease severity of facultative parasites, which prefer senescent tissues and kill host plant cells in order to feed, normally decreases with nitrogen applications (Dordas, 2008). This has been found for brown eye spot disease (Pozza et al, 2001) and branch dieback associated with *Colletotrichum* spp. infections on coffee (Muller et al, 2004). Other elements such as potassium (K), phosphorus (P), manganese (Mn), boron (B), chlorine (Cl), sulphur (S) and silicon (Si) have also been cited to increase plant resistance to diseases (Walters and Bingham, 2007; Dordas, 2008). Moreover, the litter layer which forms from natural leaf fall and pruning residues can affect diseases. Experimentations in Cameroon showed that leaf litter acts as a physical barrier for the soil-borne primary inoculum of cacao *Phytophthora* pod rot (*P. megakarya*) and delays the first appearance of diseased pods by three to four weeks compared with the situation of no leaf litter present (see Figure 4.2) (ten Hoopen et al, 2009). Although a delay of three to four weeks may not seem very long, it reduces the number of fungicide applications by one or two compared to the official spray recommendation.

Biological Control Services (BCS)

Bird communities and pest control services

Possibly one of the most interesting advances in community ecology in relation to pest control as an ecosystem function explores the relationship between avian communities and arthropod removal. Although literature on this function is still scarce, there is increasing evidence that avian communities play an important role in pest control. In the Neotropics, the majority of this evidence is limited to coffee agroforests. The data from these studies overwhelmingly support three primary conclusions. First, they show that increasing tree density and diversity has a concomitant increase in bird community richness and abundance (Harvey et al, 2008). Second, the subset of these studies that test the effects of bird communities on arthropod removal find strong results, indicating that birds can contribute upwards of 80 per cent arthropod removal in coffee agroforests (Van Bael et al, 2008) and that this removal is strongly correlated with bird species richness. And, third, studies of arthropod removal in coffee systems all implicate Neotropical migratory species as the main drivers of this function (Komar, 2006). Two meta-analyses of enclosure studies in various agroforests likewise show that the species and functional richness of bird communities is strongly correlated to arthropod removal (Van Bael et al, 2008; Philpott et al, 2009); however, no distinction is made as to whether these are beneficial insects or crop pests. Several studies indirectly test the effects of bird predation by counting the number of damaged leaves inside and outside of enclosures. Greenberg et al (2000) and Johnson et al (2009) reported up to 50 per cent increase in coffee leaf damage inside bird-proof exclosures. Similarly, a study in shade-grown cacao showed that insectivorous birds slightly reduced herbivore damage to cacao foliage (Van Bael et al, 2007). In a study of Jamaican Blue Mountain coffee, Kellermann et al (2008), focusing on the impacts of bird communities upon the coffee berry borer, found infestations up to 14 per cent lower in coffee plants exposed to foraging birds compared to plants excluded from them. More importantly, their analysis of the stomach content of the three most important predators, black-throated blue warbler (*Dendroica caerulescens*), American redstart (*Setophaga ruticilla*) and prairie warbler (*D. discolour*), showed that the coffee borer comprised 53, 56 and 44 per cent of the stomach content, respectively. Although many studies indicate that bird abundance is strongly tied to shade in coffee agroforests, there is some debate as to whether this effect is carried over to pest control. Perfecto et al (2004) found that lepidopteran removal was twice as high in a coffee farm with diverse shade as in a coffee farm with simple shade, although there is no significant difference in bird diversity between the two systems. However, the total abundance of birds was twice as high, with three times as many insectivores in the diverse shade system. DeClerck and Martínez Salinas (see Chapter 3 in this book) likewise found no significant difference in migratory bird richness between simple shade and diverse shade systems, although abundance values are slightly greater in the diverse shade.

Additional foraging resources in multi-strata systems provided in the canopy may explain the difference (Van Bael et al, 2008). Many other studies, however, found no effect of farm tree cover on arthropod removal (Greenberg et al, 2000; Johnson et al, 2009; Philpott et al, 2009), with equal proportions of arthropods removed in sun coffee systems as well as shaded coffee systems. This may be partially explained by the high dispersal ability of birds, permitting them to seek forest cover for roosting, yet move into sun coffee systems for foraging.

Arthropods and pest control services

Pests are known to be especially severe in crops that do not originate in the region in which they are cultivated because they lack predators and parasitoids. Contrary to Africa and Asia where cacao mirids (*Sahlbergella singularis* and *Distantiella theobroma*) and cacao pod borer (*Conopomorpha cramerella*) are very serious new encounter pests of cacao, in the Neotropics cacao pests are of lesser importance than diseases (Vargas et al, 2005; Delabie et al, 2007). A reason could be that in cacao plantations in Africa and Asia, natural control mechanisms do not suffice to reduce the impact of these pests to economically supportable levels due to the exogenous nature of the cacao tree. According to Delabie et al (2007), the scarcity of insect pests in Bahian cacao systems (Brazil) is probably due to a predatory function exercised by ants and to the limited use of insecticides that most likely contributes to an insect equilibrium between pests and predators. Similarly, coffee berry borer is especially severe in Latin America and almost negligible in Africa (Wegbe et al, 2003), where coffee and the coffee berry borer originate and where numerous parasitoids of the borer can be found (Vega et al, 1999). Three of them, *Prorops nasuta*, *Cephalonomia stephanoderis* and *Phymastichus coffea*, were introduced from Africa to Latin America to help regulate coffee berry borer populations (Barrera et al, 1990; Espinoza et al, 2009).

In the Neotropics the most well-known cacao insect pests are mirids of the genus *Monalonion* and thrips. Mirids of the genus *Termatophylidae* are known predators of thrips (McCallan, 1975) and ants control thrips as well as mirids (Philpott and Armbrecht, 2006; Delabie et al, 2007). Ants are an important component of tropical biodiversity. They comprise a large fraction of the animal biomass and are among the major pest predators in tropical agroforestry systems (Philpott and Armbrecht, 2006). In Bahia, Brazil, two ant species (*Azteca chartifex spiriti* and *Ectatomma tuberculatum*) are recognized for their role as bio-control agents of cacao thrips and mirids (Delabie et al, 2007). In Mesoamerican coffee agroecosystems, ant species *A. instabilis* (Perfecto and Vandermeer, 2006) and *Solenopsis* cf. *picea* (Armbrecht and Gallego, 2007) have been reported to prey on coffee berry borer. Perfecto and Vandermeer (2006) showed that the presence of coccids (*Coccus viridis*) was important for coffee berry borer control through a complex mutual relationship between ants and the coccids. Predation of the Mediterranean fruit fly

(*Ceratitis capitata*) by the ants *Solenopsis* sp. and *Pheidole geminata* has also been reported in coffee plantations (Armbrecht and Perfecto, 2003). In addition, coffee leaf damage by leaf miners (*Leucoptera coffeella*) was significantly lower where abundance of twig-nesting ants was higher (De la Mora et al, 2008). Shaded coffee and cacao agroforests provide a refuge for biodiversity and enhance natural pest control. For instance, in Brazil, a high diversity of shade trees in cacao agroforests has been reported to favour parasitoid populations, which are potential natural enemies of cacao pests, due to increased resources (Sperber et al, 2004). On the contrary, reduction of plant diversity in coffee and cacao agroecosystems has led to losses of ant diversity due to microclimatic changes and nest site limitation (Philpott and Armbrecht, 2006). Ants appear to be important predators mainly in shaded plantations, as reported by Armbrecht and Gallego (2007) in the case of coffee berry borer predation. Ant species richness of ground-foraging ants in coffee plantations has also been shown to decrease with distance from forest fragments (Perfecto and Vandermeer, 2002). Similarly, Armbrecht and Perfecto (2003) found a reduction of twig-nesting ant species richness as the distance from forest fragments increased in coffee plantations shaded by *Inga*. However, in both cases, the reduction in ant species richness was limited or even reversed in coffee plantations with diversified and dense shade. These results provide evidence of the need to consider a broader scale (beyond farm boundaries) in order to foster biological control in agroecosystems (Coll, 2009).

Microorganisms and pest and disease control services

Many fungi and bacteria contribute to natural bio-control of pests and diseases. Four key mechanisms are sometimes involved together: parasitism, antibiosis, competition for resources and induced resistance. Beneficial microorganisms often cited are *Beauveria bassiana*, *Metarhizium anisopliae*, *Lecanicillium* spp., *Trichoderma* spp., *Bacillus* spp. and *Pseudomonas* spp. (Jacques et al, 1993; Verma et al, 2007; Lugtenberg and Kamilova, 2009; Vega et al, 2009). These organisms are either found as epiphytes, endophytes or sometimes both. Endophytes are especially interesting as they colonize host tissues without causing harm and can even establish mutualistic associations with plants. Mycorrhizal fungi, which form symbiotic associations with plant roots, may help plants to better tolerate stresses, especially biotic stresses, mostly by providing the plant with more nutrients, which leaves the trees in better general health (as discussed earlier) (Harrier and Watson, 2004).

A large variety of fungal and bacterial epiphytes are present on the aerial parts of cacao and coffee. Some of these epiphytes are pathogen antagonists. For instance, epiphytic fungal parasites of the genera *Clonostachys* and *Fusarium*, potential agents for bio-control of black pod (*Phytophthora palmivora*) and frosty pod rot, were detected on cacao flowers and pods in Costa Rica (ten Hoopen et al, 2003). Additionally, a study by Melnick et al (2008) showed that bacteria of the genus *Bacillus* were capable of colonizing

cacao leaves, primarily as epiphytes but also as endophytes. Their presence led to a significant decrease in disease severity when the leaves were challenged with *P. capsici*. Moreover, it seemed that one *Bacillus* isolate brought about a disease suppression mechanism of induced systemic resistance in cacao. Natural bio-control of pathogens by beneficial microorganisms can be established through complex ecological webs. Bio-control of *Hemileia vastatrix* appears to be enhanced by ant-coccid mutualism favouring the presence of abundant scale insects in coffee trees infected by *Lecanicillium lecanii*, which is, additionally, a hyper-parasite of the coffee rust fungus (Vandermeer et al, 2009).

Similar to the leaf surface (phyllosphere), the root surface (rhizosphere) contains many soil-borne disease antagonists. Castro (1995) and Mendoza García et al (2003) showed that fungal antagonists could help to control *Rosellinia* spp., causal agents of soil-borne diseases of coffee and cacao. In addition, Castro-Toro and Rivillas-Osorio (2002) showed the usefulness of mycorrhiza in controlling *Rosellinia* root rot. Similarly, Vaast et al (1998) demonstrated that mycorrhizal coffee plants exhibited enhanced tolerance to the root lesion nematode *Pratylenchus coffeae*. Lesions were fewer and more localized in mycorrhizal coffee plants than in non-mycorrhizal controls. Soil is also an important reservoir for entomopathogenic fungi. For instance, coffee berry borer is susceptible to *Beauveria bassiana*, which has been found to infect the pest naturally throughout America, with levels of infection reaching 44 per cent in some cases (Carrion and Bonet, 2004; Vera-Montoya et al, 2007; Monzon et al, 2008). This fungus has been used as an inundative biological control agent of coffee berry borer, particularly in Colombia (Benavides-Machado et al, 2003; Posada-Florez, 2008). The main challenge of biological control with *B. bassiana* is to find strains with a high ability to infect insects in diverse habitats. First, the fungus is considered a facultative insect pathogen and some strains have a limited effect on coffee berry borer. Moreover, *B. bassiana* genotypes are highly associated with their habitat, which indicates that habitat is an important selection factor (Bidochka et al, 2002). The preceding may explain some failures in control when using elite clonal strains in habitats very different from those in which they originated. A new strategy for improving the biological control of coffee berry borer is the use of strain mixtures adapted to different environmental conditions (Cruz et al, 2006).

Increasing evidence suggest that fungal endophytes of cacao, particularly the genera *Trichoderma* and *Clonostachys*, may be of interest in protecting cacao against pests and diseases (Arnold et al, 2003; Bailey et al, 2008; Mejia et al, 2008). Several new species of endophytic *Trichoderma*, cacao pathogen antagonists, have been described recently (Samuels et al, 2006; Hanada et al, 2008). One such endophytic *Trichoderma* species, *T. stromaticum* (Samuels et al, 2000), probably a co-evolved antagonist of *Moniliophthora perniciosa*, is now available as a commercial product with promising results for the management of witches' broom in Brazil (Loguercio et al, 2009a). This interesting

application also shows why conservation of the biodiversity of host plants and their associated fungi in their natural habitat (*in-situ* conservation, discussed above) is of such great importance.

Bio-control by fungi of pests and diseases affecting plant aerial organs seems to be improved by shade, which intercepts solar radiation and promotes wetness in the plantation, which in turn favours propagule viability and infection. In particular, Staver et al (2001) suggested that *Beauveria bassiana* and *Lecanicillium lecanii* found better microclimatic conditions for their development and bio-control in coffee plantations under managed shade compared to full sun exposure. Similarly, although mixed bio-control inocula (*Clonostachys rosea* and *Trichoderma* spp.) were able to reduce incidences of frosty pod rot, witches' broom and black pod rot (*Phytophthora palmivora*) in shaded and non-shaded cacao in Peru, the reduced disease loss attributed to the control only resulted in a net economic return in shaded plantations (Krauss and Soberanis, 2001). Different isolates of *Trichoderma stromaticum*, antagonist of *Moniliophthora perniciosa*, have also been reported to respond differently to microclimate variation in terms of sporulation and antagonism at different cacao canopy levels (Loguercio et al, 2009b). Litter and pruning residues of shade trees may also play an important role in soil pest and disease control through the improvement of soil microbial activity levels, particularly that of antagonists (Wardle et al, 1995; Altieri, 1999). This effect has been suggested in Costa Rica to explain the negative relationship between soil organic matter content and population densities of *Meloidogyne exigua* in coffee roots (Avelino et al, 2009). In Papua New Guinea, leaf litter mulch has been reported to reduce the survival of *P. palmivora* under cacao trees by accelerating substrate decomposition and by stimulating the activity of antagonistic and hyper-parasitic microbes (Konam and Guest, 2002).

Undesirable effects of biodiversity

Even though the overall balance of biodiversity at plot and landscape scales seems to favour noxious organism control, especially pest control (Andow, 1991; Altieri, 1999; Bianchi et al, 2006), some undesirable effects exist. Most negative effects of biodiversity are related to support plants serving as alternative hosts for pathogens or altering microclimate conditions in favour of pests and diseases (see Figure 4.3).

Some plant species may constitute alternative hosts or reservoirs for pests and pathogens at plot and landscapes scales (Schroth et al, 2000; Plantegenest et al, 2007). Actually, several pests and diseases of coffee and cacao are not specific to these two crops. For instance, *Phytophthora palmivora*, *P. citrophthora* and *P. capsici*, which cause cacao black pod rot in the Neotropics, can affect numerous hosts that are often found in or near cacao plantations, such as citrus species, squash crops, chillies or papaya. Similarly, *Moniliophthora roreri* is able to infect different plants of the *Theobroma* and *Herrania* genera, including *T. bicolor* (Evans et al, 2003), which is often intercropped with cacao trees,
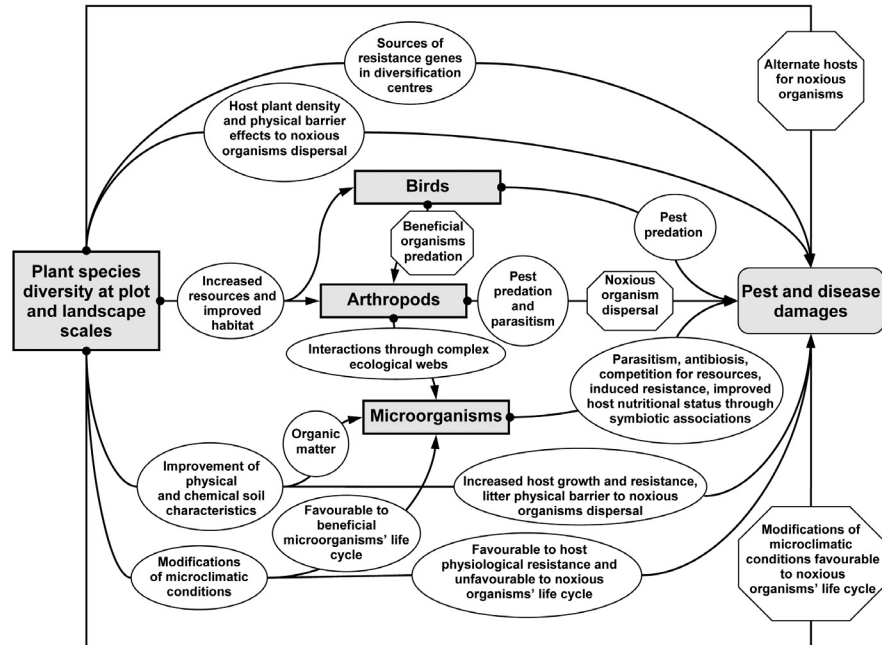
Figure 4.3 *A schematic overview of pathways and effects of biodiversity (rectangles) on pests and diseases of coffee and cacao agroforests: Despite some undesirable effects of biodiversity (octagons), the overall balance of biodiversity at plot and landscape scales seems to favour control of noxious organisms (ovals)*

Source: chapter authors

especially in Mexico. Other examples are the pathogens *Corticium salmonicolor* (now *Erythricium salmonicolor*), causal agent of pink disease, *Corticium koleroga*, responsible for the white thread blight, and *Rosellinia* spp. that affect a great number of plant species. Some of them are forestry species that could be used as shade trees in rustic systems (Benchimol et al, 2001; Roux and Coetzee, 2005; ten Hoopen and Krauss, 2006). Similarly, *Mycena citricolor* is able to attack at least 150 plant species belonging to 45 families, including legume trees of the genus *Inga* (Sequeira, 1958), which is commonly used as shade tree in Mesoamerica. However, Sequeira (1958) did not observe formation of pathogen propagules on most of these susceptible plants. Coffee berry borer, despite being considered specific to coffee, is able to find refuge and reproduce in other fruits (Damon, 2000; Gumier-Costa, 2009). *Xylella fastidiosa*, causal agent of the leaf scorch disease on coffee, also has a wide range of hosts and insect vectors. On citrus, *X. fastidiosa* causes the citrus variegated chlorosis (CVC). Li et al (2001) demonstrated that a strain of *X. fastidiosa* isolated from citrus plants was pathogenic for coffee plants, indicating that citrus, which is frequently planted adjacent to or intercropped with coffee, can be a source of inoculum for coffee.

Some pests and pathogens may be favoured by the microclimatic conditions of shaded plantations. In coffee plantations, shade is known to favour *Mycena citricolor* (Avelino et al, 2007), *Corticium koleroga* and *Corticium salmonicolor* (Schroth et al, 2000), probably because shading promotes higher wetness. Black pod rot of cacao is also favoured by increased wetness in shaded plantations (Beer et al, 1998; Schroth et al, 2000). Likewise, coffee berry borer seems to be favoured by shade (Bosselmann et al, 2009), particularly by dense shade (Feliz Matos et al, 2004), possibly in relation to the higher relative humidity which increases insect longevity and fecundity (Baker et al, 1994). The effects of shade on pests and diseases are usually not clear, as shade may favour a given process of the life cycle of a noxious organism and hamper another process at the same time. The balance of these antagonistic effects is variable and often controversial, as is the case of shade effects on coffee rust. As mentioned before, a high shade percentage may reduce coffee rust attacks by moderating yields, which could partly explain results obtained by Soto-Pinto et al (2002) in Mexico. However, shade also buffers temperatures, intercepts light and increases moisture in the plantation, all factors favourable to the infection process (Avelino et al, 2004), which can probably explain the opposite results observed in Central America (Staver et al, 2001; Avelino et al, 2006). Antagonistic effects of shade on black pod rot also exist. Work by Monteith and Butler (1979) and Butler (1980) showed that wind speed plays an important role in the duration of condensed water on cocoa pods, and pod wetness duration affects black pod rot. Increasing wind speed in the cocoa canopy by reducing shade tree density and even by making occasional openings in the cacao canopy will reduce pod wetness duration, which in turn reduces the occurrence of black pod rot. Yet, balanced against this will be the changing pattern of rainfall. Without a shade canopy, direct rain hitting the pod surface and the soil may increase intensity and velocity of raindrop splash, which, when combined with increased wind velocity, could result in increased long-range spore dispersal (Evans, 1998).

Natural enemies of pests and pathogens may also affect other beneficial organisms. For instance, it is difficult to know whether bird predation on arthropod communities has a significant net positive, negative or neutral effect since arthropods fall within multiple trophic levels (herbivores, predators and parasites). Greenberg et al (2000) noted that bird predation was mostly affecting leaf chewers (Orthoptera). However, predatory arthropods such as spiders were also significantly affected. Moreover, beneficial organisms can contribute to pathogen dispersal. The ant *Ectatomma tuberculatum*, which protects cacao from mirids and thrips, also facilitates the dissemination of the economically important black pod rot (Delabie et al, 2007).

Quantifying and Valuing Pest and Disease Control Services

Managing plots, farms and landscapes for the provision of pest and disease control services is far from straightforward and simple. Traditional control mechanisms target oversimplification: identify the problem and apply a targeted solution (literally the case when using agrochemicals and even when implementing biological control). Tropical countries are well known globally for their hyper-diversity, with numerous and complex inter-specific interactions that are the crux of natural pest and disease control (see Figure 4.3). Gliessman (1998) suggests that, ultimately, understanding the ecological basis for how diversity operates and taking advantage of complexity, rather than striving to eliminate it, is the only strategy leading to sustainability. Pest control as an ecosystem service is based on embracing this complexity. The question remains as to how to quantify these services, and to what degree of understanding the specifics of this complexity is needed. One of the advantages of ecosystem service-based management strategies is that they are based on complex adaptive systems that target the overall health of the plantation, rather than targeting any single disease. Managing for biodiversity, in theory, should increase the resistance of the parcel to the arrival of new pest and disease outbreaks, and should maintain these below epidemic levels (Andow, 1991; Altieri, 1999; Tilman et al, 2002; Bianchi et al, 2006; Cheatham et al, 2009; Malezieux et al, 2009).

Pest and disease control services can be quantified in terms of avoided crop losses. When assessing crop losses, the absolute reference is the attainable yield – that is, the yield and quality obtained using the fully available technology without any losses due to pests and diseases (see Figure 4.4) (Chiarappa, 1971; Zadoks and Schein, 1979; Savary et al, 2006). The attainable yield is theoretically independent of economic factors. Each pest and pathogen considered separately causes specific crop losses according to its particular effect on plant organs. Crop losses due to certain pests and diseases are relatively easy to quantify at different scales (plantation, regional and national). This is especially true for those cases where the disease or pest affects the harvested part of the plant. It becomes more difficult in cases where diseases and pests have an indirect effect on production, as with coffee rust or mirids of cacao that cause a reduction in leaf area with concomitant reductions in photosynthetic ability. This difficulty is even greater when considering the impacts upon product quality, especially sensory quality, whose development at the field level is still incompletely understood. In addition, different pests and pathogens are normally found in combination. Crop losses caused by different injury profiles, such as combinations of different injury levels caused by pests and diseases (see Figure 4.4), are generally less than the sum of the losses caused by each pest and disease as interactions among injuries occur (Savary et al, 1997, 2006). Despite its importance, reliable information on crop losses caused by pests and
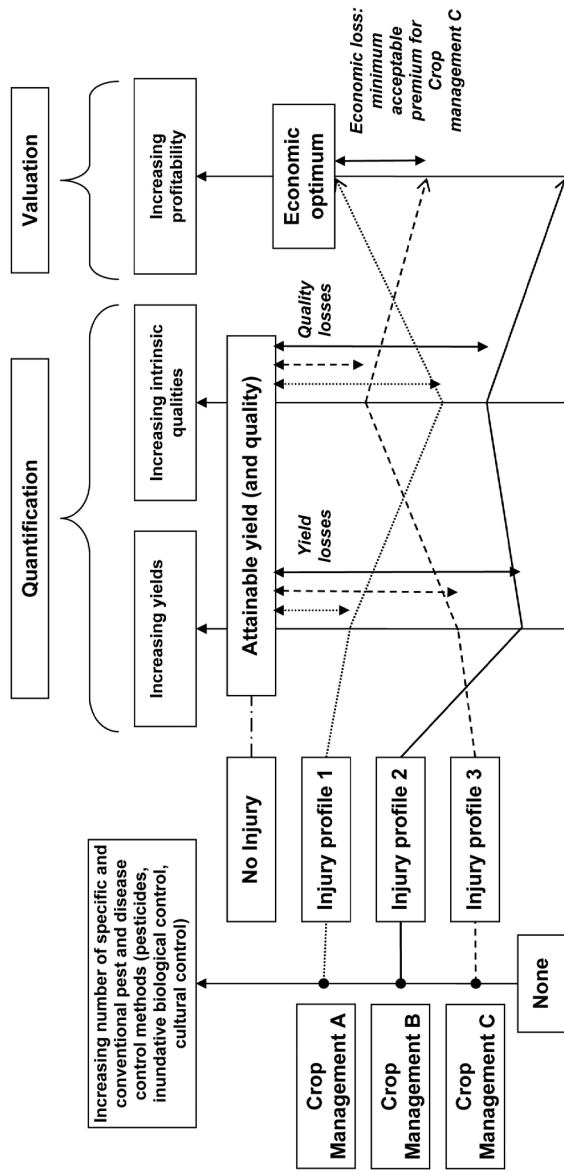
Figure 4.4 *Quantifying and valuing pest and disease control services as a function of crop losses and economic losses*

Notes: The figure represents the sequence of events leading to economic losses in a given physical context under different management scenarios. Crop management A is an intensified system whose yield is close to the economic yield (i.e. the yield obtained using only cost-effective practices). Most of the pest and disease attacks reach low to medium levels. Crop management B is an imperfectly managed plot. Its yield is low due to pest and disease attacks and low fertility management. Most of the pest and disease attacks reach medium to high levels. Pests and diseases are the same as in case A. In crop management C, an ecological strategy of pest and disease control is employed. Pests and diseases presented in cases A and B reach low levels and product quality is improved. However, other pests and diseases have emerged and yield is affected. Although pest and disease control services primarily affect injury levels caused by pests and diseases, services must be quantified in terms of avoided crop losses (yield and quality). In these hypothetical scenarios, the ecological crop management C enables avoidance of quality losses only. The minimum acceptable premium to ensure sustainability of crop management C is calculated utilizing the economic optimum as a reference.

Injury profile: a combination of injury levels caused by a range of pests and diseases (Savary et al, 2006).

Attainable yield: the yield and quality obtained using available technology (eventually non-economic production methods), which means without any losses, particularly without losses due to pests and diseases (Chiarappa, 1971; Zadoks and Schein, 1979; Savary et al, 2006). Quality may include sanitary attributes, as well as physical, chemical and sensory attributes of the product. Normally, high yields are not associated with high physical, chemical and sensory qualities.

Source: chapter authors

diseases is scarce (Savary et al, 2006). This lack of information is a handicap when quantifying and valuing pest and disease control services.

Managing trade-offs remains one of the biggest limitations to improving management of pest and disease control services. In this review, we highlighted several cases where management interventions that promote the control of one pest lead to the rise of a second pest. For example, increasing tree cover in coffee plantations provides habitat for beneficial insects and insectivorous birds, yet can alter the plantations' microclimatic conditions to favour fungal pathogens. Here, environmental management to reduce one impact, pest damage, could result in a different impact: disease losses. We might consider that there is a gain in pest and disease control services only if the new pathogen is less destructive than the one now under control.

Although yield differences between different management options are important, valuing pest and disease control services should also include the direct and indirect costs of the management intervention. Crop losses must be translated into economic terms, which should also include the financial cost of management, including labour and materials as well as the cost of maintaining the service through time. In that case, the reference for the calculation of economic losses is the economic optimum yield, such as the yield obtained using only cost-effective practices (see Figure 4.4) (Chiarappa 1971; Zadoks and Schein, 1979; Savary et al, 2006). In an interesting study, Bisseleua et al (2009) tried to establish a link between biodiversity and net income for cacao plantations in Cameroon. Their study showed that there was no simple trade-off between biodiversity and net income. Although simplification, reducing or eliminating shade is often recommended for increasing cacao yield, their study showed that the highest yield and income corresponded to 40 to 50 per cent shade cover. In part this is because reducing shade led to an increase in insect herbivory and a reduction in ant diversity.

As an illustration of how pest management as an ecosystem service can be quantified based on crop losses, consider three crop management (CM) patterns ranging from A to C according to the number of specific and conventional pest and disease control methods employed (see Figure 4.4). Crop management A (CM-A) is an intensified system whose yield is close to the economic optimum yield. It is characterized by a high number of pest and disease control methods, including pesticides, inundative biological control and/or cultural control. Most of the pest and disease attacks reach low to medium levels. Crop management B (CM-B) is an imperfectly managed plot. Its yield is low due to pests and diseases attacks and low fertility management. Most of the pest and disease attacks reach medium to high levels. Pests and diseases are the same as in case A. In contrast, in crop management C (CM-C), an ecological strategy of pest and disease control is employed. Pests and diseases present in cases A and B reach low levels. However, other pests and diseases may emerge and affect yield negatively.

The injury profiles of each of these management scenarios are distinct and are not equivalent in terms of crop losses. Each crop management, with its

corresponding injury profile, leads to a distinct proportion of the attainable yield. In these hypothetical scenarios, CM-A most closely reaches this yield, whereas CM-C offers a lower yield, but a greater yield than the imperfectly managed plot (CM-B). As a consequence, despite controlling some pests and diseases, the hypothetical CM-C case does not provide a sufficient pest and disease control service in terms of avoided yield losses. The service becomes obvious only when considering product quality, which is improved in CM-C with respect to CM-A and CM-B.

Unlike many other ecosystem services discussed in this book (e.g. carbon and hydrological services), farmers are the direct recipients in terms of reducing losses to pests and pathogens. However, maximizing pest and disease control services can have important indirect benefits received off farm or in neighbouring communities through improved product quality, environmental health or increased water quality due to a reduced reliance on agrochemicals (Wilson and Tisdell, 2001; Abhilash and Singh, 2009). Other possible impacts are the improved health of farm labourers, the increased pollinator populations, or even the additional carbon sequestered when agroforestry systems add to the qualities of the system. These indirect services can be considered as intrinsic qualities of the system. By intrinsic value we mean the additional ecosystem services and benefits that are provided by the ecologically based pest and disease control services. This intrinsic quality does not necessarily contribute to the attainable yield. However, this quality has value that must be taken into account in potential decreased economic value associated with ecologically based pest and disease control services. When the intrinsic quality includes services received off farm, then additional payment schemes such as certification or direct payments should be considered.

In order to ensure the sustainability of CM-C and its benefits for the farm and society, a premium has to be paid. The minimum acceptable premium can be calculated based on the differential between the economic optimum, the highest profitability (CM-A) and the profitability of CM-C. This differential is the economic loss accepted by CM-C to provide services to the farm and society and that have to be at least compensated by the premium. However, this minimum premium can be reduced substantially when the highest profitability is low – for instance, in case of low international prices of the product, indicating that additional payments for other services provided might be necessary.

Conclusions

There is still insufficient knowledge of the ecological mechanisms of pest and disease control. Understanding the complexity of these mechanisms and of their interrelationships is a necessary step still missing in order to apply them to the management of agroecosystems. This is certainly one of the greatest challenges for sustainable agriculture in the coming decades. As long as we fail to understand how this complexity works in its entirety, it is likely that

agroecosystems will remain highly simplified compared to natural ecosystems. These simplified systems will continue to yield ecological imbalances or pest and disease outbreaks that will lead to yield losses if not corrected by specific interventions such as pesticide applications, with all its negative externalities.

Agriculture must increase its production if it is to feed, clothe and fuel the growing global population while simultaneously reducing its environmental impact. We think this goal cannot be reached if we only consider intensified agriculture, which despite its high yields, is overly reliant on pesticides. We suggest that a two-pronged approach is needed. First, pesticide use in intensified systems must obviously be reduced, while retaining as high a yield as possible. This can be achieved by optimizing chemical control, but also by accompanying this optimization with ecologically based pest and disease control interventions. We must, however, be prepared for possible and/or temporary yield reductions. Second, yields of rustic or low technology systems must be increased while maintaining ecological functions of pest and disease control at high levels. Better management of biodiversity associated with the agroecosystem could probably help to attain these levels. Payments for services have an important role to play in promoting the development of systems that are less dependent on pesticides, while maintaining or even improving yield and quality.

Acknowledgements

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