Plant Pathology (2004) **53**, 541–547 Doi: 10.1111/j.1365-3059.2004.01067.x

LETTER TO THE EDITOR

Effects of crop management patterns on coffee rust epidemics

J. Avelino[a]*†, L. Willocquet[b] and S. Savary[b]

[a]*Centre de Coopération Internationale en Recherche Agronomique pour le Développement – UMR CBGP (Centre de Biologie et Gestion des Populations), IICA-PROMECAFE, AP 55, 2200 Coronado, San José, Costa Rica; and* [b]*UMR INRA-ENSAR BiO3P (Biologie des Organismes et des Populations appliquée à la Protection des Plantes), BP 35327, 35653 Le Rheu cedex, France*

The effects of crop management patterns on coffee rust epidemics, caused by *Hemileia vastatrix*, are not well documented despite large amounts of data acquired in the field on epidemics, and much modelling work done on this disease. One main reason for this gap between epidemiological knowledge and understanding for management resides in the lack of links between many studies and actual production situations in the field. Coffee rust epidemics are based on a seemingly simple infection cycle, but develop polycyclic epidemics in a season and polyetic epidemics over successive seasons. These higher-level processes involve a very large number of environmental variables and, as in any system involving a perennial crop, the physiology of the coffee crop and how it affects crop yield. Crop management is therefore expected to have large effects on coffee rust epidemics because of its immediate effect on the infection cycle, but also because of its cumulative effect on ongoing and successive epidemics. Quantitative examples taken from a survey conducted in Honduras illustrate how crop management, different combinations of shade, coffee tree density, fertilization and pruning may strongly influence coffee rust epidemics through effects on microclimate and plant physiology which, in turn, influence the life cycle of the fungus. We suggest there is a need for novel coffee rust management systems which fully integrate crop management patterns in order to manage the disease in a sustainable way.

Keywords: cropping practices, epidemic risk, *Hemileia vastatrix*, monocyclic process, polycyclic epidemic, polyetic epidemic

Introduction

The ways by which crop management patterns affect coffee rust, one of the most important diseases of the Arabica coffee tree, caused by *Hemileia vastatrix*, are not well documented and remain controversial. For instance, intensification of coffee production, which has been possible with the use of dwarf varieties, high inputs and the reduction or suppression of shade trees in coffee plantations, has been reported in some cases as a factor reducing the risk of a serious coffee rust epidemics (Machado & Matiello, 1983; Avelino *et al*., 1991) and in other cases as a factor increasing that risk (Seivert *et al*., 1984). Shade is at the centre of the controversy. Some authors have reported high coffee rust intensities on shaded coffee trees (Machado & Matiello, 1983; Staver *et al*., 2001) and others, in contrast, report low incidences (Soto-Pinto *et al*., 2002). This lack of consolidated information explains why crop management patterns are not currently taken into account in current coffee rust control systems. Our hypothesis is that the current management of this disease does not sufficiently take into account the relationships between production situations and epidemiological processes. A production situation is the combination of biological, technical, economic and social factors that determines agricultural production (De Wit, 1982). Several studies on annual crops (Savary, 1987; Savary *et al*., 2000) have shown that production situations, and especially the crop management component of production situations, are key to explaining and managing diseases in an integrated way.

Here we attempt to explain why crop management patterns may strongly influence coffee rust epidemics; how these effects influence the risk of an epidemic occurring;

*To whom correspondence should be addressed.

†E-mail: jacques.avelino@cirad.fr

Accepted 22 May 2004

and how knowledge of these effects may be integrated into rational disease management systems.

Effects of microclimate and host on the life cycle of *H. vastatrix*

Minute changes in microclimate and host plant physiology influence the different components of the coffee rust infection cycle. Figure 1 summarizes the large amount of information available on these relationships. The main factors known to affect the life cycle of the fungus are wind, rainfall, leaf area, leaf wetness, light, temperature, fruit load, soil moisture and stomatal density. Wind contributes to urediniospore liberation and transport (Rayner, 1961a, 1961b; Bowden *et al*., 1971; Becker *et al*., 1975). Rainfall may also play the same role, with water droplets releasing urediniospores by contact or impact on leaves and splash dispersal (Rayner, 1961a, 1961b; Bock, 1962a; Nutman & Roberts, 1963). Spore deposition on a coffee tree leaf depends on the foliar area deployed that may intercept them (Kushalappa *et al*., 1983). Urediniospore germination depends on temperature, with an optimum of 22°C (Nutman & Roberts, 1963); darkness favours it (Rayner, 1961a; Nutman & Roberts, 1963); and the presence of liquid water is a requirement (Rayner, 1961a; Nutman & Roberts, 1963; Kushalappa *et al*., 1983). Under near-optimal conditions germination can be achieved within less than 5 h (Rayner, 1961a; Nutman & Roberts, 1963). Subprocesses of the infection cycle have also been documented, such as appressorium formation, which is water-dependent (derived from Eskes, 1982) and stimulated by cool temperature in the range 13–16°C (De Jong *et al*., 1987). Alternating high (22–28°C, favouring spore germination) and low temperatures (13–16°C, favouring appressorium formation) thus enable infection to take place in only 4–6 h (De Jong *et al*., 1987). Penetration requires well formed leaf stoma (McCain & Hennen, 1984); high stomatal densities thus probably increase the penetration frequency. High soil moisture (Hoogstraten *et al*., 1983), and thus absence of water stress, or a large fruit load (Eskes & De Souza, 1981) increases infection efficiency and reduces the latency period duration. Latency period depends on temperature (17·6 days at 25°C, 21·6 days at 21°C; Leguizamón, 1983), with lethal levels above 40°C (Ribeiro *et al*., 1978). Various equations to describe the temperature–latency period relationship have been developed (Rayner, 1961a; De Moraes *et al*., 1976). Emergence of sporogenous cells also occurs via stoma. Sporulation intensity thus partly depends on stomatal density (and the maximum number, five to 10, of sporogenous cells depends on the diameter of the stomatal pore; McCain & Hennen, 1984).

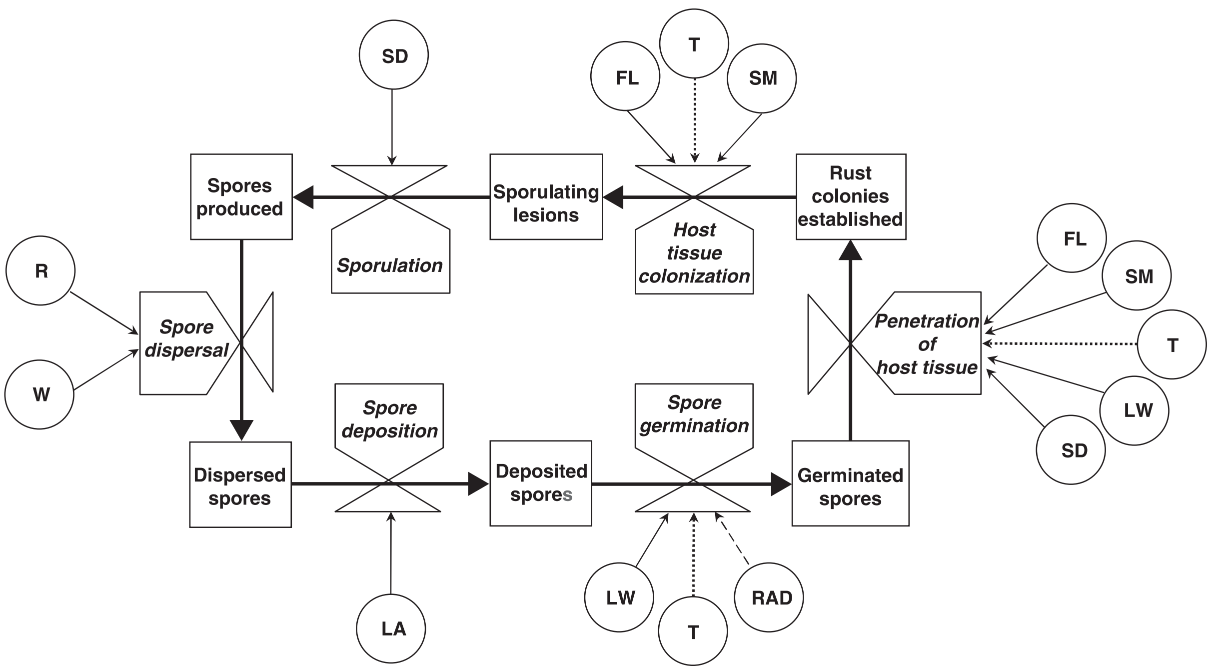

Figure 1 Simplified flow chart representing the coffee rust infection cycle and some of its main factors as reported in the literature. Boxes, state variables; valves, processes (rates); bold arrows, flows of individuals; circles, parameters (factors); thin arrows, effects of factors on processes. Nine factors are indicated on the flow chart: fruit load, FL; leaf area developed by the coffee tree canopy, LA; radiation intercepted by the coffee tree canopy, RAD; rainfall, R; soil moisture, SM; leaf wetness duration, LW; stomatal density, SD; air temperature, T; wind speed in the coffee tree canopy, W. Three categories of effects are distinguished: positive (solid lines); negative (dashed lines); or with an optimum (dotted lines). For example temperature, radiation and leaf wetness have an optimum-shaped, negative and positive effect, respectively, on the process of spore germination; whereas stomatal density (and diameter of stomata) have a positive effect on the spore-production process. See text for details.

Table 1 Effects of cropping practices on processes of the coffee rust infection cycle

Stage of monocyclic process	Factors[a] affecting infection cycle	Cropping practice[b]			
		Shading	High planting density	Fertilization	Pruning
Spore dispersal	R	±			
	W	–			
Spore deposition	LA	+	+	+	±
Spore germination	LW	+	+		
	T	+	+		
	RAD	+	+		–
Penetration	FL	±	–	+	+
	SM	+	+		
	T	+	+		
	LW	+	+		
	SD	–			
Tissue colonization	FL	±	–	+	+
	T	+	+		
	SM	+	+		
Sporulation	SD	–			

[a]Rainfall (R), wind (W), leaf area of canopy (LA), leaf wetness (LW), temperature (T), radiation (RAD), fruit load (FL), soil moisture (SM), stomatal density (SD) (see Fig. 1).
[b]Symbols indicate positive (+), negative (–), or variable effects (±) of cropping practices via host or environmental factors on monocyclic processes of coffee rust (derived from the literature).

Effects of cropping practices on coffee crop microclimate, tree physiology and the coffee rust infection cycle

Some cropping practices may affect the development of the disease through their influence on the microclimate and the host which, in turn, act on the life cycle of the fungus. These relationships can be illustrated using four cropping practices as examples, selected as key attributes of the diversity of crop management patterns: crop shading practices, planting density, fertilization and pruning (Table 1).

The effects of these cropping practices on the pathosystem and its factors are complex. Some practices influence a given microclimate or host characteristic in a variable way by favouring or hampering a given process of the infection cycle, as illustrated in the three cases developed below (± in Table 1).

Shade trees intercept rainfall (Imbach *et al.*, 1989; Jaramillo-Robledo & Chaves-Córdoba, 1998, 1999). In shaded plantations, at low rainfall intensity and duration, many water droplets do not reach the coffee trees and so spore liberation and dispersal are reduced. In this respect shading is detrimental to the spread of coffee rust. At high rainfall intensity and duration, however, shade trees form gutters, with large drops produced and falling onto the coffee tree canopy. The number of impacts on the coffee trees is thereby reduced, but the kinetic energy of impacts is stronger; fewer drops fall on diseased coffee leaves, but they release more spores.

Shading limits berry production during a given year (fruit load, Table 1) but stabilizes yield levels over successive years (Boyer, 1968; Cannell, 1975; Soto-Pinto *et al.*, 2000). On the other hand, absence of shade, and thus high radiation interception by the coffee canopy, enables coffee trees to achieve very high yields in some years. High production by a tree in a season suppresses productivity in the next, so high yields in one year are typically followed by low yields in the next. The positive relationship between fruit load and infection processes (Fig. 1) partially explains why, in unshaded coffee plantations, high-yield years are conducive to serious epidemics whereas low-yield years are less so. In shaded plantations, however, shading generally allows for intermediate yields that are always sufficient to render coffee leaves susceptible enough to infection.

The main purpose of pruning is to stimulate new vegetative growth, and thus increase yield, by removing nonproductive old stems and branches. This results in a large leaf area index which favours spore interception. The immediate effect of pruning, however, is a reduction of the foliage area that may intercept spores, and the elimination of infectious lesions. Pruning thus simultaneously reduces the amount of inoculum available for dispersal and the probability of spore interception until new regrowth occurs.

Some cropping practices have opposite effects on coffee rust because they act on different characteristics of the microclimate or of the host, some favouring a given process of the infection cycle (+ in Table 1) and others, hampering the same or another process (– in Table 1).

Shading practices can again be used as one type of cropping practice, with at least six additional, and sometimes opposite, effects on processes involved in the disease infection cycle. First, shading buffers temperatures and probably increases leaf wetness because it decreases vapour pressure deficit and evaporation (Barradas & Fanjul, 1986; Jaramillo-Robledo & Gómez-Gómez, 1989;

Caramori *et al*., 1996), factors that are favourable to urediniospore germination and fungal penetration. Second, shading decreases the amount of light that reaches the coffee canopy (Jaramillo-Robledo & Gómez-Gómez, 1989), and reduced irradiation favours urediniospore germination. Third, shading, when not excessive, increases coffee leaf area (Boyer, 1968; Maestri & Barros, 1977; Fahl *et al*., 1994) and so favours urediniospore interception by individual leaves. Shading also increases the lifespan of leaves (Staver *et al*., 2001), and thereby the lifespan of sporulating lesions, thus maintaining stocks of inoculum in the canopy, and also increases soil moisture conservation (Jaramillo-Robledo & Chaves-Córdoba, 1999) rendering leaves more susceptible to infection and reducing the latency period duration. Finally, shading reduces wind speed (Jaramillo-Robledo & Gómez-Gómez, 1989) thus reducing dry urediniospore dispersal, and reduces stomatal density (Boyer, 1968) thus hindering penetration and sporulation.

The practice of planting at high density, which increases the self-shading of coffee trees, has similar effects to growing shade trees in terms of coffee leaf area (Arcila-Pulgarín & Chaves-Córdoba, 1995), leaf surface temperature (Akunda *et al*., 1979), light levels (Akunda *et al*., 1979; Gathaara & Kiara, 1984), water stress and thus probably leaf wetness (Fisher & Browning, 1979), soil moisture (Akunda *et al*., 1979), and individual coffee tree yields (Fisher & Browning, 1979; Gathaara & Kiara, 1984), and therefore shares some of the effects on coffee rust associated with (interspecific) shading practices. But the practice of planting coffee trees at high density is also associated with effects of its own, such as interplant competition for soil nutrients which limits individual tree yields and so decreases leaf susceptibility. Moreover, the high number of trees in closely spaced plantations increases the leaf area index (Cannel, 1975; Arcila-Pulgarín & Chaves-Córdoba, 1995), which favours urediniospore interception.

Pruning enables better light penetration in the plantation, which is detrimental to urediniospore germination. However, pruning also leads to higher fruit load, which increases leaf susceptibility.

No effects of fertilization practices on the microclimate have been specifically reported in the literature. Overall, increased fertilization favours coffee rust (Table 1). Fertilized plants have a greater leaf area (Cannell, 1975; Maestri & Barros, 1977; Fahl *et al*., 1994) which favours urediniospore interception, and have higher yields which increases leaf susceptibility and reduces the latency period duration.

Effects of crop management patterns on coffee rust epidemics

These complex effects of cropping practices on coffee rust explain why it is difficult to understand, at first glance, how crop management patterns (combinations of cropping practices) affect the development of epidemics. Below we define, in broad terms, two prototype production situations which are used to analyse the importance of coffee rust, and explore entry points for better disease management.

(i) An intensive plantation: no shade, high planting density, large fertilizer inputs, systematic and severe pruning (e.g. stumping), along rows or in blocks, a marked 2-year production rhythm (high yields per unit area in one year, followed by low yields the next).

(ii) An extensive plantation: diversified shade tree species and dense shading, low planting density, little or no fertilization, little or no pruning, low and stable yields per unit area over the years.

In an intensive plantation, the absence of (interspecific) shading is partly detrimental to spore deposition, germination, and fungal penetration and colonization. Other environmental factors, driven by cropping practices in this pattern of management, simultaneously favour both spore deposition and infection (Table 1). In an extensive plantation the opposite seems true. The overall outcomes of crop management patterns on coffee rust epidemics in both crop management cases, despite opposite individual effects on specific processes, is difficult to establish. This is because the rust–coffee–crop management systems involve several levels of integration: (i) individual monocyclic processes; (ii) infection cycle; (iii) epidemic; (iv) polyetic (Zwankhuizen & Zadoks, 2002) epidemics, where too many factors are acting, which are related to host physiology, environmental physics and cropping practices. While a given process is very strongly influenced by a particular factor at one integration level, the effect of this factor may become marginal at the next, higher level, because other processes are taking place and additional factors are to be accounted for. Field experience and numerous reports indicate that it is a fair assumption that cropping practices have a very large driving effect on such a system (De Wit, 1982). Complex systems such as these need to be addressed step by step, for example with the objective of explaining the epidemic level of integration using one, albeit multifaceted, set of factors, such as cropping practices.

It is possible to highlight the overall effect of crop management patterns influencing coffee rust epidemics. In Fig. 2, maximum annual disease incidences (percentage diseased leaves) and yields were recorded in six plots with very different crop management patterns. These plots were monitored between 1994 and 1997 as part of an intensive survey conducted in Honduras (Avelino, 1999). The six plots were located at three sites (two plots per site): Lake Yojoa, El Paraíso and Santa Bárbara. The paired plots at each site were geographically very close and therefore under the influence of the same macroclimate. The substantial heterogeneity in incidence of coffee rust in each site (Fig. 2) can therefore be attributed to specific characteristics of each plot, including crop management patterns. The effect of crop management patterns on coffee rust was closely linked to its effect on tree yields (fruiting nodes per tree; Fig. 2). These effects were especially strong in plots Y1 and P1, which were fairly close to the intensive management pattern. The substantial direct sunlight received by coffee trees, and fertilization

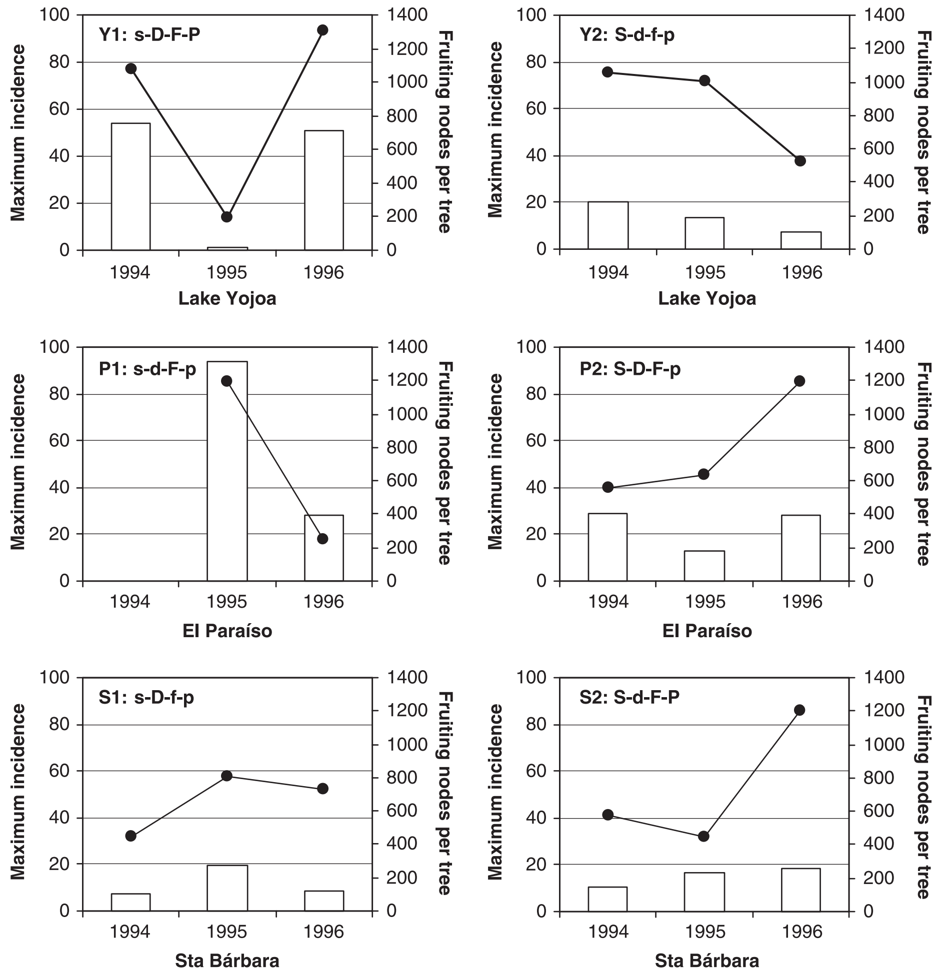

Figure 2 Trends in maximum annual incidences of coffee rust (●) and number of fruiting nodes per coffee tree (histograms) in six plantations without chemical control from regions of Lake Yojoa (Y1, Y2), El Paraíso (P1, P2) and Santa Bárbara (S1, S2), Honduras. Average annual rainfalls for plots of Lake Yojoa, El Paraíso and Santa Bárbara over the observation period are 2823, 1186 and 1995 mm, respectively. Average elevations above sea level for plots at Lake Yojoa, El Paraíso and Santa Bárbara are 650, 905 and 668 m, respectively. S, >50% shading; s, <50% shading; D, density over 4200 coffee trees per hectare; d, density under 4200 coffee trees per hectare; F, plot fertilized at least once a year over the observation period; f, plot fertilized less than once a year over the observation period; P, coffee tree pruning at least once over the observation period; p, no coffee tree pruning over the observation period.

practices, led to high yields accompanied by very high disease incidences (>75%). A subsequent drop in yield was observed the following year, accompanied by very low disease incidence. The effect of crop management patterns on infection through variation in fruit load appears relevant in this case. In plots Y2, S2 and P2, with dense shading (Fig. 2), which were therefore fairly close to the extensive management pattern, yields did not reach very high levels (Fig. 2). In these plots, however, disease incidence remained moderately high (≥30%). Coffee rust incidence could even be fairly high when trees had a fruit load >200 fruiting nodes, a very moderate yield that possibly did not justify the implementation of expensive control methods. Favourable effects of shading on urediniospore germination were probably decisive in that case. This example suggests that fruit load and shade combine to influence rust epidemics. Plot S1 was an intermediate case, which is quite a common occurrence worldwide: a plot with little shading and dense planting, neither fertilized nor pruned. Yield was low, and coffee rust incidence was moderate over the years, even when the number of fruiting nodes exceeded 200. In this case there was probably an accumulation of unfavourable crop management effects on the infection phase.

Epidemic risks are dependent on production situations

The risk of a serious coffee rust epidemic occurring is linked to the climate, especially rainfall distribution and amount. Height above sea level, which governs temperatures, is also important (Bock, 1962b; Avelino *et al*., 1991; Brown *et al*., 1995). Epidemiological risk also appears to depend on soil factors, especially moderate soil acidity which seems to favour coffee rust (Lamouroux *et al*., 1995; Avelino, 1999). Our analysis shows that the risk of a serious coffee rust epidemic also very strongly depends on crop management patterns, because of their important effects on the microclimate and on plant physiology. The risk of a serious coffee rust epidemic is therefore a reflection of site-specific factors on which farmers' influence is small, slow or nil (soil and climate), and of local, direct and strong man-made factors (crop management pattern), a reflection of production situations (De Wit, 1982).

Developing a coffee rust management system

Disease management that focuses heavily on the risk due to site, primarily the risk due to macroclimatic conditions, does not appear to be sufficient or adequate. The implementation of a rational and optimized disease management system, which is increasingly influenced by decreasing coffee prices and increasing environmental awareness on the use of fungicides, requires in-depth knowledge of the technical and agrophysiological characteristics and yield performances of coffee plantations. The scope of recommendations should not be solely site-dependent (geographical–topographical). Different recommendations are needed depending on technical and biological criteria specific to each site – which may vary over time with changes in farmers' practices. This series of recommendations would be easier to implement than a disease management system (Kushalappa *et al*., 1983, 1986) that requires frequent and systematic observations from producers (disease assessment at least, and microclimate monitoring in the most complex systems).

Disease management should be seen as an integral part of crop management itself (Zadoks & Schein, 1979), and many cropping practices, while reflections of a farmer's adaptive response to the production environment (biophysical as well as economic; De Wit, 1982), can reduce disease epidemics (Palti, 1981). This perspective leads to the realization that farmers have concerns other than diseases; conversely, the context where production takes place may provide opportunities to improve disease management in a framework that producers are accustomed to.

A practical objective is to develop a tool that can be used to assess, at the beginning of the rainy season and hence only once a year, the exposure of a coffee crop stand to a specified epidemic risk level depending on site, crop management patterns and biological criteria. Definition of recommendation domains first requires the determination of a typology of production situations and their corresponding epidemic risk (Savary, 1987; Savary *et al*., 2000). Management methods that tally with the anticipated risk levels should then be outlined, and these be adapted to actual patterns of crop management.

References

Akunda EMW, Imbamba SK, Kumar D, 1979. High density plantings of coffee. I. Microclimatic and related changes. *East African Agricultural and Forestry Journal* **45**, 130–2.

Arcila-Pulgarín J, Chaves-Córdoba B, 1995. Desarrollo foliar del cafeto en tres densidades de siembra. *Cenicafé* **46**, 5–20.

Avelino J, 1999. Contribution à la gestion du pathosystème *Hemileia vastatrix* et *Coffea arabica* au Honduras. Influence des principaux facteurs physiques, phytotechniques et biologiques. PhD thesis. Orsay, France: Université de Paris XI.

Avelino J, Muller RA, Cilas C, Velasco H, 1991. Développement de la rouille orangée dans des plantations en cours de modernisation plantées de variétés naines dans le Sud-Est du Mexique. *Café Cacao Thé* **35**, 21–42.

Barradas VL, Fanjul L, 1986. Microclimatic characterization of shaded and open-grown coffee (*Coffea arabica* L.) plantations in Mexico. *Agricultural and Forest Meteorology* **38**, 101–12.

Becker SM, Mulinge SK, Kranz J, 1975. Evidence that uredospores of *Hemileia vastatrix* Berk. & Br. are wind-borne. *Phytopathologische Zeitschrift* **82**, 359–60.

Bock KR, 1962a. Dispersal of uredospores of *Hemileia vastatrix* under field conditions. *Transactions of the British Mycological Society* **45**, 63–74.

Bock KR, 1962b. Seasonal periodicity of coffee leaf rust and factors affecting the severity of outbreaks in Kenya colony. *Transactions of the British Mycological Society* **45**, 289–300.

Bowden J, Gregory PH, Johnson CG, 1971. Possible wind transport of coffee leaf rust across the Atlantic ocean. *Nature* **229**, 500–1.

Boyer J, 1968. Influence de l'ombrage artificiel sur la croissance végétative, la floraison et la fructification des caféiers Robusta. *Café Cacao Thé* **12**, 302–20.

Brown JS, Whan JH, Kenny JH, Merriman PR, 1995. The effect of temperature on the development of epidemics of coffee leaf rust in Papua New Guinea. *Crop Protection* **14**, 671–6.

Cannell MGR, 1975. Crop physiological aspects of coffee bean yields: a review. *Journal of Coffee Research* **5**, 7–20.

Caramori PH, Androcioli A, Leal AC, 1996. Coffee shade with *Mimosa scabrella* Benth. for frost protection in southern Brazil. *Agroforestry Systems* **33**, 205–14.

De Jong EJ, Eskes AB, Hoogstraten JGJ, Zadoks JC, 1987. Temperature requirements for germination, germ tube growth, and appressorium formation of urediospores of *Hemileia vastatrix*. *Netherlands Journal of Plant Pathology* **93**, 61–71.

De Moraes SA, Sugimori MH, Ribeiro IJA, Ortolani AA, Pedro MJ Jr, 1976. Periodo de incubaçao de *Hemileia vastatrix* Berk. et Br. em tres regioes do estado de Sao Paulo. *Summa Phytopathologica* **2**, 32–8.

De Wit CT, 1982. La productivité des pâturages sahéliens. In: Penning de Vries FWT, Djiteye MA, eds. *La Productivité des Pâturages Sahéliens. une Étude des Sols, des Végétations et de L'exploitation de Cette Ressource Naturelle*. Wageningen, the Netherlands: Pudoc, 22–35.

Eskes AB, 1982. The use of leaf disk inoculations in assessing resistance to coffee leaf rust (*Hemileia vastatrix*). *Netherlands Journal of Plant Pathology* **88**, 127–41.

Eskes AB, De Souza EZ, 1981. Ataque da ferrugem em ramos com e sem produçao, de plantas do cultivar catuaí. In: *9th Congresso Brasileiro de Pesquisas Cafeeiras, Sao Lourenzo, Minas Gerais, Brasil, 27–30 Agosto 1981*. Brazil: IBC, 186–8.

Fahl JI, Carelli MLC, Vega J, Magalhaes AC, 1994. Nitrogen and irradiance levels affecting net photosynthesis and growth of young coffee plants (*Coffea arabica* L.). *Journal of Horticultural Science* **69**, 161–9.

Fisher NM, Browning G, 1979. Some effects of irrigation and plant density on the water relations of high density coffee (*Coffea arabica* L.) in Kenya. *Journal of Horticultural Science* **54**, 13–22.

Gathaara MPH, Kiara JM, 1984. Factors that influence yield in close-spaced coffee. 1. Light, dry matter production and plant water status. *Kenya Coffee* **49**, 159–67.

Hoogstraten JGJ, Toma-Braghini M, Eskes AB, 1983. Influencia da umidade do solo e umidade relativa do ar sobre a resistencia do cafeeiro a *Hemileia vastatrix*. In: *10th Congresso Brasileiro de Pesquisas Cafeeiras, Poços de Caldas, Minas Gerais, Brasil, 29 agosto–1 septiembre 1983*. Brazil: IBC/GERCA, 110–1.

Imbach AC, Fassbender HW, Beer J, Borel R, Bonnemann A, 1989. Sistemas agroforestales de café (*Coffea arabica*) con laurel (*Cordia alliodora*) y café con poró (*Erythrina poeppigiana*) en Turrialba, Costa Rica. 6. Balances hídricos e ingreso con lluvias y lixiviación de elementos nutritivos. *Turrialba* **39**, 400–14.

Jaramillo-Robledo A, Chaves-Córdoba B, 1998. Interceptación de la lluvia en un bosque y en plantaciones de *Coffea arabica* L. *Cenicafé* **49**, 129–34.

Jaramillo-Robledo A, Chaves-Córdoba B, 1999. Aspectos hidrológicos en un bosque y en plantaciones de café (*Coffea arabica* L.) al sol y bajo sombra. *Cenicafé* **50**, 97–105.

Jaramillo-Robledo A, Gómez-Gómez L, 1989. Microclima en plantaciones a libre exposición solar y bajo sombrío. *Cenicafé* **15**, 65–79.

Kushalappa AC, Akutsu M, Ludwig A, 1983. Application of survival ratio for monocyclic process of *Hemileia vastatrix* in predicting coffee rust infection rates. *Phytopathology* **73**, 96–103.

Kushalappa AC, Hernandez TA, Lemos HG, 1986. Evaluation of simple and complex coffee rust forecasts to time fungicide application. *Fitopatologia Brasileira* **11**, 515–26.

Lamouroux N, Pellegrin F, Nandris D, Kohler F, 1995. The *Coffea arabica* fungal pathosystem in New Caledonia: interactions at two different spatial scales. *Journal of Phytopathology* **143**, 403–13.

Leguizamón J, 1983. Contribution à la connaissance de la résistance incomplète du caféier à *Hemileia vastatrix* Berk. et Br. PhD thesis. Montpellier, France: ENSA.

Machado JRM, Matiello JB, 1983. Curva epidemiologica da ferrugem (*Hemileia vastatrix* Berk. et Br.) em cafeeiros sombreados e a pleno sol, na Ibiapaba, noroeste do Ceara. In: *Simposio sobre Ferrugens do Cafeeiro, Oeiras, Portugal, 17–20 Outubro 1983*. Oeiras, Portugal: CIFC, 282–6.

Maestri M, Barros RS, 1977. Coffee. In: Alvim PT, Koslowski TT, eds. *Ecophysiology of Tropical Crops*. New York, NY: Academic Press, 249–78.

McCain JW, Hennen F, 1984. Development of uredinial thallus and sorus in the orange coffee rust fungus *Hemileia vastatrix*. *Phytopathology* **74**, 714–21.

Nutman FJ, Roberts FM, 1963. Studies on the biology of *Hemileia vastatrix* Berk. & Br. *Transactions of the British Mycological Society* **46**, 27–48.

Palti J, 1981. *Cultural Practices and Infectious Crop Diseases*. Berlin, Germany: Springer-Verlag.

Rayner RW, 1961a. Germination and penetration studies on coffee rust (*Hemileia vastatrix* B. & Br.). *Annals of Applied Biology* **49**, 497–505.

Rayner RW, 1961b. Spore liberation and dispersal of coffee rust *Hemileia vastatrix* Berk. & Br. *Nature* **191**, 725.

Ribeiro IJA, Monaco LC, Tisseli Filho O, Sugimori MH, 1978. Efeito de alta temperatura no desenvolvimento de *Hemileia vastatrix* em cafeeiro suscetivel. *Bragantia* **37**, 11–6.

Savary S, 1987. Enquête sur les maladies fongiques de l'arachide (*Arachis hypogaea*) en Côte d'Ivoire. II. Epidémiologie de la rouille de l'arachide (*Puccinia arachidis*). *Netherlands Journal of Plant Pathology* **93**, 215–31.

Savary S, Willocquet L, Elazegui FA, Du Teng PSPV, Zhu D, Tang Q, Huang S, Lin X, Singh HM, Srivastava RK, 2000. Rice pest constraints in tropical Asia: characterization of injury profiles in relation to production situations. *Plant Disease* **84**, 341–56.

Seivert B, Boccas B, Pellegrin F, Kohler F, 1984. La rouille orangée du caféier Arabica en Nouvelle-Calédonie. 3. Comparaison de l'épiphytie dans les plantations traditionnelles et dans les plantations nouvelles. *Café Cacao Thé* **35**, 209–14.

Soto-Pinto L, Perfecto I, Castillo-Hernández J, Caballero-Nieto J, 2000. Shade effect on coffee production at the northern Tzeltal zone of the state of Chiapas. *Mexico. Agriculture, Ecosystems and Environment* **80**, 61–9.

Soto-Pinto L, Perfecto I, Caballero-Nieto J, 2002. Shade over coffee: its effects on coffee berry borer, leaf rust and spontaneous herbs in Chiapas, Mexico. *Agroforestry Systems* **55**, 37–45.

Staver C, Guharay F, Monterroso D, Muschler RG, 2001. Designing pest-suppressive multistrata perennial crop systems: shade-grown coffee in Central America. *Agroforestry Systems* **53**, 151–70.

Zadoks JC, Schein RD, 1979. *Epidemiology and Plant Disease Management*. New York, USA: Oxford University Press.

Zwankhuizen MJ, Zadoks JC, 2002. *Phytophthora infestans*'s 10-year truce with Holland: a long-term analysis of potato late-blight epidemics in the Netherlands. *Plant Pathology* **51**, 413–23.