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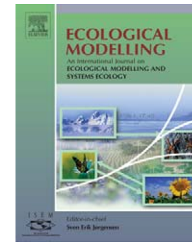

The intensity of a coffee rust epidemic is dependent on production situations

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ABSTRACT

To gain a clearer understanding of conditions conducive to the development of coffee rust and improve disease control, we monitored the development of rust epidemics in 73 plots in Honduras, over 1–3 years depending on the case, focusing on coffee tree characteristics, crop management patterns, and the environment. A simple correspondence analysis was used to show that a link could be found between certain production situations and the intensity of coffee rust epidemics. Local characteristics specific to each plantation were particularly well linked to the intensity of coffee rust epidemics, whereas regional factors such as rainfall appeared to be of secondary importance. The yield and the number of leaves of the coffee trees were positively linked to epidemic development. Soil pH and fertilisation were negatively associated with epidemic development. Shade, when it did not limit yield, probably affected the microclimate in such a way that coffee rust incidence increased. Altitude was a serious constraint in disease development. These links were illustrated by a segmentation tree, which helped to define risk domains and rationalise coffee rust control. It also provided an understanding of how intensifying Arabica cultivation, through its effects on yield and soil acidification, increased the risk of a serious coffee rust epidemic occurring.

1. Introduction

Coffee rust, caused by *Hemileia vastatrix*, is one of the main diseases of Arabica coffee trees in Latin America. It is effectively controlled by particularly using copper fungicides, applied as a preventive measure following stereotyped treatment timetables (Avelino and Savary, 2002). However, it is becoming increasingly necessary to implement rational and optimised control of this disease, due to low coffee prices and pollution problems. Kushalappa and co-workers in Brazil have developed the only tool for managing this disease that is currently available (Kushalappa et al., 1983, 1984, 1986). It can be used to predict the risk of an epidemic, based on a systematic assessment of the amount of inoculum and of certain characteristics

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of the host, or even of the microclimate in the most complex system. Fungicide spraying is recommended as soon as the risk is considered to be serious. However, in practice this useful tool does not appear to be used, probably because it is difficult to manage.

We feel that the risk of an epidemic could be assessed simply, by considering that an epidemic is the outcome of a risk associated with the characteristics of the region, primarily with the climate, but also with the soil that seems to affect coffee rust (Lamouroux et al., 1995; Avelino, 1999), and of a risk attributable to local conditions, i.e. a risk primarily linked to the characteristics of the plant, but also to crop management patterns, and especially shade management, which are known to act on coffee tree plantations microclimate (Avelino et al., 2004; DaMatta, 2004). In other words, the risk of an epidemic would depend on production situations (De Wit, 1982). This hypothesis (Avelino et al., 2004) is based on results of studies carried out on groundnut in West Africa (Savary, 1987a, 1987b) and on rice in tropical Asia (Savary et al., 2000).

In our study, we demonstrated first of all that links could be found between production situations, characterised through a survey conducted in Honduras, and coffee rust intensities. We then defined simplified risk domains, based on certain characteristics of coffee plantations and coffee trees, which were easy to measure, and which appeared to be important through their links with the disease.

2. Materials and methods

2.1. *Agrobiological context of the survey*

For this investigation, some characteristics of coffee growing in Honduras were especially favourable.

In Honduras, *Coffea arabica* is the only cultivated species. It is assumed that almost 100% of coffee varieties are Typica or Bourbon types, and their dwarf derivatives Caturra and Catuai (Avelino, 1999). Those varieties are thus genetically very similar. They only have one resistance factor, S_H5, and are vulnerable to most of the known coffee rust races (Rodrigues et al., 1975). Therefore, genetic resistance could not be a source of variation of the attack levels.

In Central America, and especially in Honduras, coffee rust genetic variability is very low. Until 1997, all coffee rust samples from Central America, studied in the Centro de Investigaçao das Ferrugens do Cafeeiro (CIFC, Portugal), which held a complete collection of differential hosts, were identified as samples of race II (Rodrigues Jr., pers. commun.). Race II holds only one virulence factor, v_5 (Rodrigues et al., 1975). In our study, we collected 27 coffee rust samples in various sites of the survey. Twenty-one samples belonged to race II. Only six samples, from the lake Yojoa region (Fig. 1), were found to contain race I, probably mixed with race II (Avelino, 1999). Although race I holds virulence factors v_2 and v_5 (Rodrigues et al., 1975), it seems less aggressive than race II (Gil, 1988). So, the physiological race factor should not be a source of variation of the attack levels either.

Honduran coffee is still partially produced from old plantations established with tall varieties, with a low productivity and a low level of maintenance. This type of plantation was not considered in this work, because we assumed that coffee rust was not a limiting factor, as was the crop management. On the other hand, a growing part of the coffee area is being planted with dwarf varieties. These varieties allow using high planting densities and usually represent the first step towards intensification. Generally, and mainly for economical reasons, the producers put into practice only part of the available recommendations. This is why one can find varied crop management patterns (Avelino, 1999). The nature and density of shade trees

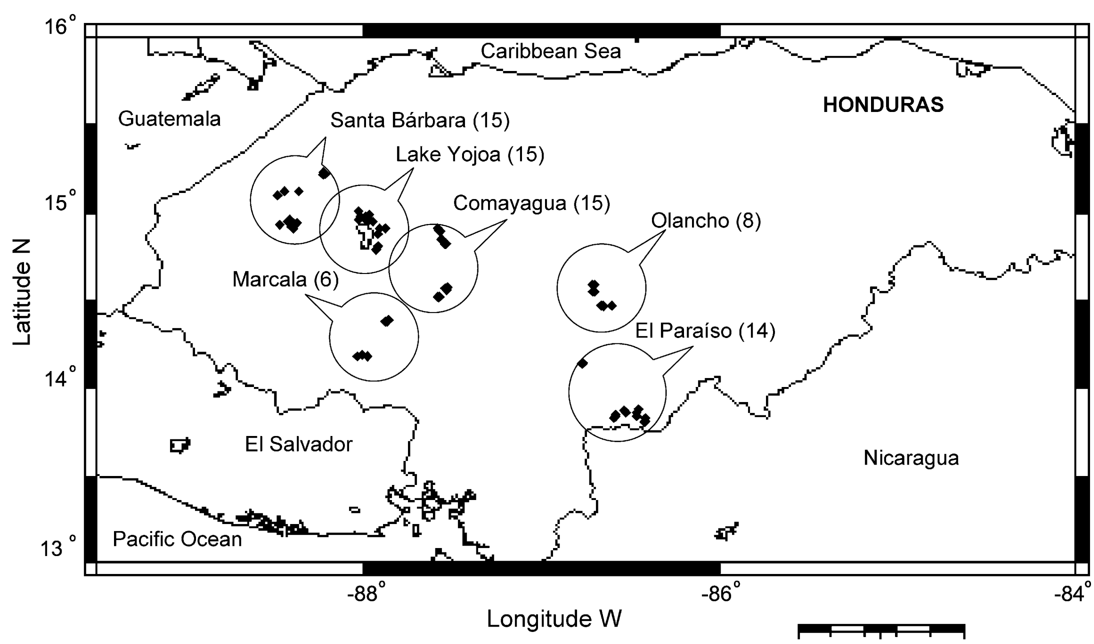


Fig. 1 – Geographical location of the 73 sampled plots (black diamonds) during the coffee rust survey conducted in Honduras, and their number per region (in parentheses).

are a notably large source of heterogeneity. One can find tree legumes, mostly *Inga*, as well as banana trees, other fruit trees, and quite often remaining forest trees. Therefore, we chose to conduct this survey on dwarf varieties plots only.

Arabica coffee is cultivated in Honduras in a fairly large range of altitudes (mainly from 600 to 1700 m). The annual rainfall and its pattern are very diverse as a consequence of different oceanic influences. A substantial Pacific influence is felt in South East, marked by a long dry season. A clear Caribbean influence marks the North West along with a short dry season (Zúñiga Andrade, 1990). Consequently, Honduras has a large diversity of production situations (De Wit, 1982). Honduran coffee growing was thus a good sphere for our survey.

This diversity leads to very diverse productivities. The average productivity was really poor in 1994, at the start of this study; however some fields planted with dwarf varieties under high input levels did reach a high productivity level, close to 2 metric tonnes green coffee ha. This study could therefore provide useful information on the effects of intensification on the coffee rust epidemics.

2.2. *Sampling methods*

The purpose of this sampling was to encompass a large range of production situations. Thus, most of the Honduran coffee regions were sampled, as they were very different from an environmental point of view. In each region, we selected several localities, mostly for their altitude. Then, in each locality, we selected plots (usually three) whose crop managements were different.

The survey was conducted over three rainy seasons, from July 1994 to March 1997. The geographical location of the surveyed regions and plots is given in Fig. 1. Twenty-five plots in three regions of Honduras (lake Yojoa, Santa Bárbara, El Paraíso) were surveyed in 1994–1995. Those same plots and ten other plantations, including nine in a new region (Comayagua), were observed in 1995–1996. Over the 1996–1997 period, a further six individuals per region were sampled and two new regions were added to the study, Olancho and Marcala, where eight and six plots were surveyed respectively. The survey thus involved 73 plots. The plots were observed over several years and considered as different individuals. Consequently, there were 133 plot-year individuals.

The study plots contained 170 coffee trees on average (between 120 and 580 m^2 depending on density). Five coffee trees were marked in a zigzag inside the plot. On each of the five coffee trees, three branches were identified in three different storeys. A large number of measured variables were assessed on those trees and branches.

2.3. *Coffee plots characterisation*

The different variables directly assessed or documented during interviews with farmers are shown in Table 1.

Climate was characterised by the annual rainfall and altitude. Records from 29 raingauges located near the study plots were used (one raingauge for three plantations in general).

For each plot, we analysed a composite soil sample taken just before the rainy season began, near the five marked coffee trees. Analyses focused on soil elements or characteristics essential for coffee growing (Miranda Arauz, 1989).

The number of fruiting nodes was counted on the marked coffee trees just before the harvest. This variable largely explains yield (Upreti et al., 1992). We also assessed the fruit load, the number of fruits in relation to the number of young leaves counted at the start of the rainy season. Fruits and young leaves counting was carried out on the marked branches. The criterion used to define leaf age was a very short internode arising during the dry season. Old leaves were located between the base of the branch and the short internode. Young leaves, from the current year, were located between the short internode and the tip of the stem (Avelino et al., 1991). The number of young leaves counted at the beginning of the rainy season was a measurement of foliage density.

The height of the coffee trees and the circumference of the main stem at ground level were also measured. The ratio of these two variables was considered as a measurement of coffee tree vigour. The higher the value, the less vigorous coffee trees were.

Some data concerning crop management patterns were supplied by the farmers: the variety and age of the coffee trees, the number of weeding rounds (chemical, physical), number of fertiliser applications (on soil, on foliage), number of soil improvement operations, number of shade tree and coffee tree pruning operations, number of pickings, number of insecticide or fungicide spraying rounds. In spite of the fact that the growers were not supposed to spray the surveyed plots, some of them did use fungicides. This is why we documented this variable.

Others, such as the distance between coffee trees along the planting row and the distance between rows, were measured on the marked coffee trees. The shade percentage was also evaluated on each marked coffee tree using a spherical densiometer used to measure forest overstory density (Lemmon, 1957). It was determined once in 1994 (just before harvesting) and twice in 1995 and 1996 (at the beginning of the rainy season and during the harvest). Annual means were used for the analyses. The shade trees in the plot were also identified. Lastly, the number of coffee trees per hole and the existence of coffee trees that had been cut down were recorded.

Coffee rust epidemics were monitored on the marked branches. Three inspections were made in 1994–1995 (just before the harvest, during the harvest, at the end of the harvest) and four in 1995–1996 and 1996–1997 (an additional inspection at the beginning of the rainy season). The maximum percentage of young affected leaves for each year, i.e. the maximum incidence for the year, was the variable used in the analyses. This variable (referred to as R hereafter) was a good indicator of epidemic severity (Kushalappa and Chaves, 1980; Silva-Acuña et al., 1999).

2.4. *Analytical methods*

2.4.1. *Relationships between production situations and R*

A survey is by essence a descriptive method, where most variables are often linked together. This is frequently the case of variables characterising the soil. For example, pH is associated

Table 1 – List of variables describing coffee plots

Kind of variable	Variable	Code	Unit
Coffee rust	Maximum annual incidence of coffee rust (maximal percentage of young leaves infected in the year)	R	–
Climate	Altitude	Alt	m
	Annual rainfall	Rain	mm
Soil	pH	–	–
	K	–	C mol$^{(+)}$/kg
	Ca	–	C mol$^{(+)}$/kg
	Mg	–	C mol$^{(+)}$/kg
	Al	–	C mol$^{(+)}$/kg
	P	–	mg/kg
	Fe	–	mg/kg
	Cu	–	mg/kg
	Mn	–	mg/kg
	Zn	–	mg/kg
	Organic matter	OM	% dry weight
	Sand	–	% dry weight
	Silt	–	% dry weight
	Clay	–	% dry weight
Cropping practices	Variety[a]	Var	–
	Distance between rows	Dro	m
	Distance between plants on the row	Dpl	m
	Density of coffee trees per hectare	De/ha	Plants ha^{-1}
	Number of coffee trees per hole[a]	Pl/Ho	–
	Presence of cut down coffee trees[a]	Cut	–
	Shade percentage	Shp	–
	Shade type[a]	Sht	–
	Annual number of shade pruning operations[a]	Psh	–
	Annual number of coffee trees pruning operations[a]	Pcof	–
	Annual number of foliar fertilisations only[a]	Ffert	–
	Annual number of soil fertilisations[a]	Sfert	–
	Annual number of soil improvement activities[a]	Simp	–
	Annual number of fertilisations[a]	Fert	–
	Annual number of physical weeding rounds[a]	Pwee	–
	Annual number of chemical weeding rounds[a]	Cwee	–
	Annual number of weeding rounds[a]	Wee	–
	Annual number of fungicide sprays[a]	Fsp	–
	Annual number of insecticide sprays[a]	Isp	–
	Annual number of pickings[a]	Pic	–
Coffee tree productive characteristics	Coffee tree age	Age	Year
	Circumference of the trunk at ground level	Cir	m
	Height of the coffee tree	Hei	m
	Height of the coffee tree/circumference of the trunk at ground level	Hei/Cir	–
	Number of fruiting nodes per plant	Fnod	–
	Foliage density (number of young leaves per branch at the beginning of the rainy season)	Fdens	–
	Fruit load (number of cherries related to the number of young leaves counted at the beginning of the rainy season)	Fload	–

[a] The initial nature of the variable is qualitative. Others variables are quantitative.

to base contents. This is also the case of variables describing coffee crop management. The level of fertilisation required often depends on shade density. The same is true for variables that characterise the climate or the coffee tree. When analysing survey data, such associations are unavoidable, and instead, should be considered as a reflection of systems' properties. An analytical method based on the creation of typologies was chosen, which is derived from several analyses where large survey data sets were addressed (Savary et al., 1994, 1995, 2000). The approach we used has two main stages:

(1) The first stage consisted in creating typologies of soils, climates, crop management patterns, and of coffee tree productive characteristics. We did this by proceeding in three phases: the first phase consisted in categorising variables and in simplifying information by reducing their

number, second phase allowed more a simplification of information by attaching less importance to non-standard plots, and a third phase in which a cluster analysis was carried out to build typologies. (i) The variables measured were of a heterogeneous nature, some were quantitative, others were qualitative. The quantitative variables were therefore converted into classes to enable joint analysis of the information. This method facilitated avoiding problems of extreme values, standardising distributions, and homogenising data. The latter is especially useful when all variables are not assessed with the same precision (Savary et al., 1994, 1995). The number of classes and their limits could be fixed in line with critical thresholds known beforehand (Savary et al., 1995). Here, as we did not know any critical thresholds, we chose to construct classes in such a way as to minimise the loss of information linked to coffee rust. To do this, *R* was converted into three classes with the same number of individuals. The other quantitative variables to be coded were then divided into three classes, such that χ^2, calculated in a contingency table in which the newly coded variable and *R* modalities were cross-referenced, was maximum. The small number of classes made possible to keep a sufficient filling in each class, in order to respect the condition for the validity of χ^2 test: when defining the boundaries of the classes, we verified that none of the theoretical classes contained fewer than five individuals. On the rare occasions where constructing three classes did not seem wise, four classes were formed, by dividing one class into two. The variables for which the χ^2 value was low ($p \geq 0.10$) were eliminated in the following phase. Thus, information was simplified by eliminating variables that were unnecessary due to their absence of links to *R*. (ii) In the second phase, for each category of variables we carried out a multiple correspondence analysis (MCA). This technique is well adapted to qualitative variables. The data were binary codes expressing the absence (0) or presence (1) of each modality. The MCA was used to calculate the factorial coordinates of the plots on the first axes, those that grouped the most representative information. The selection of axes was conducted by verifying the quality of their relationship with *R* displayed as supplementary variable. This procedure allowed us to keep maximum information linked to *R* and, at the same time, to give less weight to non-standard individuals, those that were well explained by last MCA axes. Otherwise, those individuals would have been singled out at the time of typologies construction. (iii) Then, the coordinates of the individuals on the selected axes were used in a cluster analysis (aggregation criterion: second order moment) which led to the creation of typologies. The number of groups was chosen in order to respect the condition of validity of the χ^2 test (see above) performed on contingency tables in which the typologies and *R* modalities were cross-referenced. The combination of a MCA and a cluster analysis is a common way to create typologies (Kristensen, 2003).

(2) In the second stage, we compared these typologies with the *R* modalities in a simple correspondence analysis (SCA) using a contingency table in which the *R* modalities were in columns and the typologies in rows.

2.4.2. *Definition of simplified risk domains*

The previous analytical approach was used to place the typologies, most of which were complex, in relation with coffee rust attack levels. The purpose of this approach was to construct a simplified tool for explaining *R* using certain characteristics of coffee plantations and coffee trees, which were obviously chosen because they came out in the previous analysis, but also because they were easy to measure. In other words, it was a matter of determining simplified risk domains, from which control recommendations were then deduced.

We did this using a segmentation technique that was adapted to qualitative explanatory variables (Morgan and Sonquist, 1963). Segmentation is useful in agronomy where this situation is frequently encountered (Perrier and Delvaux, 1991; Rosso and Hansen, 2003; Colbach et al., 2004). It operates by dichotomies. It consists in dividing a set of observations into two groups, obtained by grouping the modalities of an explanatory variable into two modalities, such that the two resulting groups are the most different with respect to the variable to be explained. The indicator of that difference, which is also an indicator of the explanatory power of the explanatory variable, is the total within group sum of squares calculated from the variable to be explained. This indicator is described in the automatic interaction detection (AID) method of Morgan and Sonquist (1963). The most explanatory variable is therefore the one that separates the initial first population into two sub-populations, which themselves can be subsequently divided according to the same principle by the same variable or other explanatory variables. Consequently, segmentation orders variables according to their discriminatory power. The quality of each division is assessed by the Student t test on the means of the explained variable of the two groups formed in that way. The succession of dichotomies leads to the formation of a segmentation tree. Each branch of the tree is processed independently. The explanatory variables adopted are therefore not necessarily the same in the different branches of the tree.

In our case, we placed *R*, a quantitative variable to be explained, in relation with several qualitative, often ordered, explanatory variables from those shown in Table 2. A 5% probability threshold was fixed for the Student's *t*-test. We imposed an additional condition when forming the dichotomies: no group with fewer than nine individuals was allowed.

3. Results

3.1. *Categorisation and elimination of variables with little or no link to coffee rust*

The results of quantitative variable categorisation are shown in Tables 2 and 3. The variables that were discarded due to an absence of any link with coffee rust (low χ^2 values, $p \geq 0.10$) are shown in Table 3, whereas Table 2 shows the variables that were kept for the rest of the analysis. It can be seen that various soil characteristics were kept, notably those associated with its acidity, such as pH, aluminium, magnesium, or with its texture, such as the silt and clay percentages. Altitude and annual rainfall were also chosen. All the variables characterising foliage and yield were clearly associated with the disease

Table 2 – Categorisation of the selected variables (including coffee rust) and results of the χ^2 tests performed on contingency tables of the form (coded variable × coffee rust classes)

Kind of variable	Variable[a]	Unit	Classes				χ^2 test	
			1	2	3	4	χ^2 value	p
Coffee rust	R	–	[8.2, 32.0]	[32.0, 53.4]	[53.4, 93.3]	–	–	–
Climate	Alt	m	[595, 655]	[655, 995]	[995, 1100]	[1100, 1300]	20.0	<0.01
	Rain	mm	[1050, 2053]	[2053, 2902]	[2902, 4145]	–	11.6	0.02
Soil	pH	–	[4.0, 5.2]	[5.2, 6.0]	[6.0, 7.7]	–	13.5	0.01
	Mg	C mol$^{(+)}$/kg	[0.2, 1.3]	[1.3, 1.7]	[1.7, 12.1]	–	11.4	0.02
	Al	C mol$^{(+)}$/kg	[0.01, 0.02]	[0.02, 0.30]	[0.30, 7.44]	–	11.2	0.02
	Mn	mg/kg	[4, 22]	[22, 31]	[31, 170]	–	11.0	0.03
	Fe	mg/kg	[3, 15]	[15, 23]	[23, 190]	–	10.9	0.03
	Zn	mg/kg	[0.5, 3.0]	[3.0, 8.0]	[8.0, 16.0]	–	9.8	0.04
	P	mg/kg	[0.2, 15.5]	[15.5, 31.6]	[31.6, 167.9]	–	8.7	0.07
	Silt	% dry weight	[10.6, 29.6]	[29.6, 34.8]	[34.8, 53.0]	–	11.9	0.02
	Clay	% dry weight	[4.8, 23.8]	[23.8, 27.8]	[27.8, 49.8]	–	11.3	0.02
Cropping Practices	Shp	–	[5, 56]	[56, 61]	[61, 83]	–	13.3	0.01
	Pic[b]	–	2 or 3	4 or 5	6–13	–	11.3	0.02
	Sht[b]	–	Only legumes	With banana trees, fruit trees or forest trees	–	–	6.9	0.03
	Fert[b]	–	None	1–8	–	–	5.7	0.06
	Ffert[b]	–	None	1–5	–	–	4.8	0.09
Coffee tree productive characteristics	Fdens	–	[4.6, 7.0]	[7.0, 7.6]	[7.6, 20.4]	–	17.9	<0.01
	Fnod	–	[10, 229]	[229, 495]	[495, 1577]	–	12.0	0.02
	Fload	–	[0.0, 1.0]	[1.0, 1.6]	[1.6, 10.9]	–	10.7	0.03
	Age	year	[2, 4]	[4, 11]	[11, 24]	–	9.3	0.05
	Cir	m	[0.08, 0.16]	[0.16, 0.19]	[0.19, 0.31]	–	8.1	0.09

[a] See Table 1 for the signification of codes.
[b] The initial nature of the variable is qualitative. Others variables are quantitative.

and were kept. In terms of crop management patterns, good links were found with fertilisation, shade and the annual number of pickings.

3.2. *Typologies of soils, climates, crop management patterns, and of coffee tree productive characteristics*

Tables 4–7 describe typologies of soils, climates, crop management patterns and of coffee tree productive characteristics, along with the contribution made by the initial variables to the construction of the groups. It would take too long and would probably not be worth describing all the typologies in detail. We shall merely describe the extreme cases. Among the six soils obtained, S1 and S3 differed most from each other (Table 4). S1 was the most acid, the one with the highest Al and Fe contents and the one with the lowest Mg, Zn, Mn, and P contents. It also had large proportions of clay and small proportions of silt. On the other hand, S3 was the least acid soil, the one with the lowest Al contents and among the lowest Fe contents, the highest P contents, and among the highest Mg, Zn, and Mn contents. It also had large proportions of silts and intermediate clay contents. In terms of climates, C1 and C2 were very clear cut (Table 5). C1 included the plots located at a very high altitude, with moderate annual rainfall. In this group, only the Lake Yojoa region, out of the regions we sampled, was not represented. On the other hand, C2 included low altitude plots with a high annual rainfall. This group only contained plots in the Lake Yojoa and Santa Bárbara regions. Table 6 shows the categories of crop management patterns obtained. For the qualitative variables, the annual number of fertilisations (Fert), annual number of foliar fertilisations (Ffert) and annual number of pickings (Pic), the conditions for validating the χ^2 test were not met. However, the high χ^2 values reflected a strong contribution towards the construction of the groups. CM5 and CM6 were particularly clear cut groups. CM5 comprised plots with little fertilisation, with moderately dense shade, and generally consisting of legumes only. CM6 included some fertilised plots, with moderately dense shade and generally heterogeneous. For the groups of coffee tree productive characteristics, P1 and P5 particularly differed from each other (Table 7). P1 consisted of moderately aged coffee trees, reflected in an average trunk circumference, of coffee trees with a low number of leaves, low production and low fruit load. P5 also had moderately aged coffee trees, but with a larger trunk circumference. These coffee trees had moderate foliage. They had the highest yields and fruit loads out of the coffee trees we characterised.

3.3. *Relations between production situations and R*

It can be seen from Table 8 that the categories of soils, climates, crop management patterns, and coffee tree productive characteristics were closely linked to the coffee rust modalities we

Table 3 – Categorisation of the non-selected variables and results of the χ^2 tests performed on contingency tables of the form (coded variable x coffee rust classes)

Kind of variable	Variable[a]	Unit	Classes 1	Classes 2	Classes 3	χ^2 value	p
Soil	K	C mol$^{(+)}$/kg	[0.1, 0.3]	[0.3, 0.4]	[0.4, 2.3]	6.1	0.19
	Ca	C mol$^{(+)}$/kg	[1.0, 7.8]	[7.8, 12.3]	[12.3, 28.8]	6.0	0.20
	OM	% dry weight	[0.5, 2.7]	[2.7, 3.9]	[3.9, 16.0]	4.1	0.39
	Cu	mg/kg	0.5	1.0	[1.0, 9.0]	2.3	0.69
	Sand	% dry weight	[16.8, 37.4]	[37.4, 45.2]	[45.2, 83.2]	7.3	0.12
Coffee tree productive characteristics	Hei/Cir	–	[5.9, 14.3]	[14.3, 16.7]	[16.7, 22.6]	7.2	0.12
	Hei	m	[1.2, 1.8]	[1.8, 2.1]	[2.1, 4.0]	5.7	0.22
Cropping Practices	Isp[b]	–	None	1–4	–	4.2	0.12
	Sfert[b]	–	None	1–4	–	4.0	0.13
	Pcof[b]	–	None	1–3	–	3.9	0.14
	Wee[b]	–	None or 1	2–7	–	3.8	0.15
	Dro	m	[0.9, 1.7]	[1.7, 1.8]	[1.8, 2.5]	5.7	0.22
	Simp[b]	–	None	1 or 2	–	2.1	0.35
	Fsp[b]	–	None	1 to 4	–	2.0	0.38
	Dpl	m	[0.8, 1.0]	[1.0, 1.1]	[1.1, 1.8]	4.1	0.40
	Var[b]	–	Catuaï	Caturra type	–	1.8	0.41
	De/ha	Plant ha^{-1}	[2910, 4120]	[4120, 4330]	[4330, 14360]	3.8	0.44
	Cut[b]	–	Yes	No	–	1.7	0.44
	Pwee[b]	–	None or 1	2–6	–	1.6	0.46
	Pl/Ho[b]	–	1	At least one hole with more than one plant	–	1.1	0.58
	Psh[b]	–	None	1–4	–	0.7	0.72
	Cwee[b]	–	None	1–5	–	0.4	0.83

[a] See Table 1 for the signification of codes.
[b] The initial nature of the variable is qualitative. Others variables are quantitative.

constructed (Table 2). The χ^2 test was highly significant in all cases ($p < 0.01$). The proximity of the different categories and of the coffee rust modalities on the only possible graphic representation of the SCA (for three column variables there are only two axes) could therefore be interpreted as being indicative of an association (Fig. 2). In this figure, the modalities best represented on axis 1 of the SCA ($\cos 2 > 0.6$) are shown in a rectangle. The modalities best represented on axis 2 are shown in an oval. Axis 1 is an axe of decreasing coffee rust intensity from medium (R2, between 32.0% and 53.4%) to low incidences (R1, between 8.2% and 32.0%). The contributions of R1 and R2 to axis 1 are respectively 59.9% and 37.0%. Axis 2 is an axe of increasing coffee rust intensity from medium (R2) to high incidences (R3, between 53.4% and 93.3%). The contributions of R2 and R3 to axis 2 are respectively 29.9% and 63.9%. It can be seen that R1 is associated to S3, C1, C3, P1, CM2 and CM6. R2 is close to S2, S4, C5, P4, P6, CM1, CM5. R3 is linked to S1, S6, C2, C4, P5 and CM3. Some of these categories were described in the previous section. The detailed description can be found in Tables 4–7. There were therefore common

Table 4 – Description of the soil categories[a] (means)

Soils	pH	Al (C mol$^{(+)}$/kg)	Mg (C mol$^{(+)}$/kg)	Fe (mg/kg)	Zn (mg/kg)	Mn (mg/kg)	P (mg/kg)	Clay (% dry weight)	Silt (% dry weight)	N
S1	4.5 d	3.0 a	0.6 b	61.2 a	1.6 b	16.3 b	5.5 c	25.2 a	21.7 c	17
S2	5.6 b	0.1 c	3.5 a	24.5 b	8.1 a	27.4 b	27.4 b	22.8 a	30.8 b	24
S3	6.4 a	0.0 c	2.7 a,b	17.9 b	7.7 a	50.3 a,b	55.2 a	22.2 a	30.2 b	15
S4	5.1 c	1.5 b	2.8 a,b	48.4 a	3.6 b	39.5 a,b	7.4 c	27.0 a	37.0 a	18
S5	5.0 c	0.9 b,c	1.5 b	9.1 b	3.3 b	38.4 a,b	7.4 c	10.7 b	19.8 c	16
S6	5.4 b,c	0.3 c	2.9 a	49.1 a	3.3 b	50.5 a	13.0 c	21.9 a	29.0 b	43
Overall	5.3	0.8	2.5	37.8	4.5	39.0	18.0	21.8	28.5	133
F value	29.9**	20.6**	7.8**	9.0**	12.7**	4.8**	8.9**	8.0**	12.1**	

Values in the same column followed by the same letter are not significantly different according to the Newman–Keuls test at $p < 0.05$. N: number of plots.
[a] The soil categories were obtained by cluster analysis of the six leading factorial coordinates calculated by the multiple correspondence analysis of pH, Al, Mg, Fe, Zn, Mn, P, clay and silt (Tables 1 and 2). The first six dimensions on a total of 18 explained 59% of the variation.
** Significant at $p < 0.01$.

Table 5 – Description of the climate categories[a] (means)

Climates	Alt (m)	Rain (mm)	Regions[b]	N
C1	1161 a	1958 c	El Paraíso: 33.3%, Marcala: 22.2%, Sta Bárbara: 16.7%, Comayagua: 16.7%	18
C2	754 d	2595 b	Lake Yojoa: 68.8%, Sta Bárbara:31.2%	16
C3	758 d	3533 a	Lake Yojoa: 100%	11
C4	864 c	1555 d	Comayagua: 46.1%, Sta Bárbara: 28.2%, El Paraíso: 18.0%, Olancho: 7.7%	39
C5	1040 b	1950 c	El Paraíso: 42.3%, Sta Bárbara: 30.8%, Olancho: 11.5%, Comayagua: 7.7%, Marcala: 7.7%	26
C6	633 e	2347 b	Lake Yojoa: 47.8%, Sta Bárbara: 26.1%, El Paraíso: 26.1%	23
Overall	877	2112	Lake Yojoa: 24.8%, Sta Bárbara: 24.8%, Comayagua: 21.8%, El Paraíso: 18.0%, Olancho: 6.0%, Marcala: 4.6%	133
F value	151.8**	25.5**		

Values in the same column followed by the same letter are not significantly different according to the Newman–Keuls test at $p < 0.05$. *N*: number of plots.

[a] The climate categories were obtained by cluster analysis of the three leading factorial coordinates calculated by the multiple correspondence analysis of altitude (Alt) and annual rainfall (Rain) (Tables 1 and 2). The first three dimensions on a total of five explained 68% of the variation.

[b] Variable not used in the cluster analysis.

** Significant at $p < 0.01$.

attributes at different plantations, including crop management pattern attributes, linked to the intensity of coffee rust epidemics. The different combinations of soils, climates, crop management patterns and coffee tree productive characteristics constituted diverse production situations. The intensity of the coffee rust epidemics was therefore linked to the production situations.

3.3.1. *Relations between soil and R*

It is easier to see the relations between soil and coffee rust in Fig. 2a. The low values of *R* (R1) were mostly found on moderately acid soils, rich in Mg, Zn, Mn and P, with low Al and Fe levels (S3). An increase in soil acidity, Al and Fe content, and a drop in P content, and to a lesser degree in the Mg, Zn and Mn contents (S4, S2, S6, S1), were associated with increasing *R* values (R2 and R3). There did not appear to be any marked tendency for soil texture, except that heavy soils (S4) were not associated with the highest *R* values.

3.3.2. *Relations between climate and R*

The relations between climate and *R* can be seen in Fig. 2b. Low *R* values (R1) were found at very high altitudes, or in places with low rainfall (C1, C3). A decrease in altitude and an increase in rainfall (C5, C4, C2) were linked to increasing *R* values (R2 and R3). It should be noted that very low altitudes (C6) were not associated with the highest *R* values.

Table 6 – Description of the crop management patterns[a] (means for quantitative variables or percentage of plots for qualitative variables)

Crop management patterns	Shp	Sht	Fert	Ffert	Pic	N
CM1	58.0 b	Sht 2: 88.9%	Fert 2: 77.8%	Ffert 1: 83.3%	Pic 1: 27.8%, Pic 2: 50.0%, Pic 3: 22.2%	18
CM2	36.5 d	Sht 2: 65.6%	Fert 2: 93.8%	Ffert 1: 71.9%	Pic 3: 100%	32
CM3	67.0 a	Sht 2: 90.0%	Fert 2: 55.0%	Ffert 1: 85.0%	Pic 1: 20.0%, Pic 2: 55.0%, Pic 3: 25.0%	20
CM4	43.5 c	Sht 2: 58.3%	Fert 2: 80.6%	Ffert 1: 100%	Pic 2: 100%	36
CM5	48.5 c	Sht 1: 54.6%	Fert 1: 72.7%	Ffert 1: 100%	Pic 1: 100%	11
CM6	42.0 cd	Sht 2: 75.0%	Fert 2: 100%	Ffert 2: 100%	Pic 1: 43.7%, Pic 2: 56.3%	16
Overall	47.5	Sht 1: 30.1%, Sht 2: 69.9%	Fert 1: 22.6%, Fert 2: 77.4%	Ffert 1: 76.7%, Ffert 2: 23.3%	Pic 1: 20.3%, Pic 2: 48.9%, Pic 3: 30.8%	133
F value	24.6**					
χ^2 value (d.f.)		12.8* (5)	31.5[b] (5)	68.6[b] (5)	163.4[b] (10)	

Values in the same column followed by the same letter are not significantly different according to the Newman–Keuls test at $p < 0.05$. *N*: number of plots.

[a] The crop management patterns were obtained by cluster analysis of the five leading factorial coordinates calculated by the multiple correspondence analysis of Shp, Sht, Fert, Ffert, Pic. Shp: shade percentage. Sht: shade type. Fert: annual number of fertilisations. Ffert: annual number of foliar fertilisations. Pic: annual number of pickings (Tables 1 and 2). The first five dimensions on a total of seven explained 83% of the variation.

[b] Not tested (expected values under 5).

* Significant at $p < 0.05$.

** Significant at $p < 0.01$

Table 7 – Description of the coffee tree productive characteristics categories[a] (means)

Coffee tree productive characteristics categories	Fdens	Fnod	Fload	Age (year)	Cir (cm)	N
P1	7.7 b	291 b,c	1.7 c	7.2 b	15 c	24
P2	8.1 b	344 b,c	1.7 c	13.9 a	22 a	25
P3	10.1 a	346 b,c	2.8 b	3.6 c	13 d	19
P4	10.1 a	213 c	0.7 d	6.1 b	16 c	20
P5	8.3 b	794 a	3.8 a	8.2 b	19 b	15
P6	6.9 b	384 b	2.5 b	7.3 b	16 c	30
Overall	8.4	375	2.1	7.9	16	133
F value	9.2**	19.0**	12.2**	26.6**	27.6**	

Values in the same column followed by the same letter are not significantly different according to the Newman–Keuls test at $p < 0.05$. *N*: number of plots.

[a] The coffee tree productive characteristics categories were obtained by cluster analysis of the five leading factorial coordinates calculated by the multiple correspondence analysis of Fdens, Fnod, Fload, Age, Cir. Fdens: foliage density. Fnod: number of fruiting nodes per plant. Fload: fruit load. Age: coffee tree age. Cir: trunk circumference at ground level (Tables 1 and 2). The first five dimensions on a total of 10 explained 69% of the variation.

** Significant at $p < 0.01$.

Table 8 – Relationships between coffee rust classes and soil, climate, crop management, and coffee tree productive characteristics categories[a]

Category	χ^2 value	d.f.	*p*
Soil	28.4	10	<0.01
Climate	28.6	10	<0.01
Coffee tree productive characteristics	32.6	10	<0.01
Crop management	31.2	10	<0.01

[a] The relationships are indicated by a χ^2 test performed on a contingency tables of the form (category × coffee rust classes).

3.3.3. *Relations between crop management pattern and R*

Fig. 2c shows the relations between the crop management pattern and *R*. Low *R* values (R1) were associated with CM2 and CM6, groups containing generally fertilised plots (with substantial foliar fertilisation for CM6) displaying low shade percentages. An increase in the percentage of shade and a reduction in fertilisation (CM5, CM1, CM3) were associated with the highest *R* values (R2 or even R3).

3.3.4. *Relations between coffee tree productive characteristics and R*

Fig. 2d shows the relations between coffee tree production characteristics and *R*. Low *R* values (R1) were associated with low fruit loads (P1). High *R* values (R3) were associated with high fruit loads and a large number of fruiting nodes, i.e. high yields (P5). Intermediate fruit loads and yields (P6) were associated with average *R* values (R2). Moreover, it was surprising to see that P4, which included low productivity plots, was associated with average *R* values (R2) and not low values. This relation, which was found to a lesser degree in the case of P3, was no doubt due to the considerable number of leaves recorded at the beginning of the rainy season in those plots.

3.4. *Definition of simplified risk domains*

The previous analysis brought out several variables whose links with the disease were close and seemed to be quite easy to measure: pH of the soil (pH), its Mg (Mg) and Al (Al) levels, the altitude (Alt), annual rainfall (Rain), the shade percentage (Shp), the annual number of fertilisations (Fert), the annual number of foliar fertilisations (Ffert), the number of fruiting nodes per plant (Fnod), the foliage density (Fdens), the fruit load (Fload) (Table 2). Only these variables were used in the rest of the analysis.

Fig. 3 shows the segmentation tree obtained. A histogram is shown for illustration purposes, for each group formed, representing the frequencies of individuals in the three categories of *R*, R1 (between 8.2% and 32.0%), R2 (between 32.0% and 53.4%), and R3 (between 53.4% and 93.3%) described in Table 2.

The variable that best explained the disease was the number of fruiting nodes per plant (Fnod). Modality 1, which characterised low-yielding plots (between 10 and 229 fruiting nodes per coffee tree) led to the formation of an indivisible group A, for which *R* values were low: the average was 36.2% and the largest proportion of individuals was in R1. It was the annual number of fertilisations (Fert) that was involved in the second level of segmentation. Productive, unfertilised coffee trees had high *R* values: the average was 60.0% and the largest proportion of individuals was in R3. Shade percentage (Shp) was the variable that could be used to divide the latter sub-population into two indivisible groups, C and D. In these two groups, the largest proportion of individuals was classed in R3. However, the highest average for *R* was found in group D (67.8%), which only contained individuals for which the shade percentage was between 56% and 83%. For productive and fertilised coffee trees, the *R* values varied substantially. The standard deviation (21.1) was the highest of all the standard deviations calculated in the segmentation. Altitude (Alt) was the variable that led to the creation of the following dichotomy. Productive, fertilised coffee plots that were located between 1100 and 1300 m above sea level had low *R* values (32.2% on average). These were indivisible group B. The majority of individuals were in R1. The other branch of the dichotomy was divided by the soil pH. Productive, fertilised plots located between 595 m and 1100 m above sea level, where the soil had a pH between 6.0 and 7.7, formed indivisible group E. They had low *R* values

(32.6% on average). Most of the individuals were classed in R1. Group F was created following the dichotomy performed on the foliage density (Fdens). Productive, fertilised plots located between 595 and 1100 m above sea level, where the soil pH was between 4.0 and 6.0, and where the foliage was sparse (between 4.6 and 7.6 young leaves per branch) had average *R* values (42.6% on average). Most of the individuals in this group were in R2. Lastly, the fruit load (Fload) was responsible for a final dichotomy on the branch that combined individuals with between 7.6 and 20.4 young leaves per branch. It culminated in the creation of groups G and H. Group G contained plots where the fruit load was low (fewer than 1.6 fruits per young leaf). Average *R* values were found (46.3% on average). Most of the individuals were classed in R2 and R3. Group H combined plots with a high fruit load (between 1.6 and 10.9 fruits per young leaf). The *R* values were high (64.5% on average). Most of the individuals making up this group were in R3.

The different groups formed by segmentation therefore contained plots that were similar for certain environmental characteristics, for the crop management pattern or the coffee tree. Moreover, in each group, the plots suffered from similar coffee rust attacks. The groups could therefore be considered as different risk domains with regard to this disease.

4. Discussion

4.1. *The risk of an epidemic depends on the production situation*

Our results indicated that coffee rust epidemics depend on the soil, climate, crop management patterns and certain coffee tree characteristics. The risk of an epidemic therefore results from a risk attributable to the region and a risk attributable to local conditions. In agreement with our hypothesis, the risk of an epidemic depends on the production situation.

It is because our study integrated all the factors affecting coffee rust that this result was obtained. In reality, most of the relations we revealed have already been reported in numerous publications, but in a dispersed manner, which is why our study provides a clearer understanding of the pathosystem.

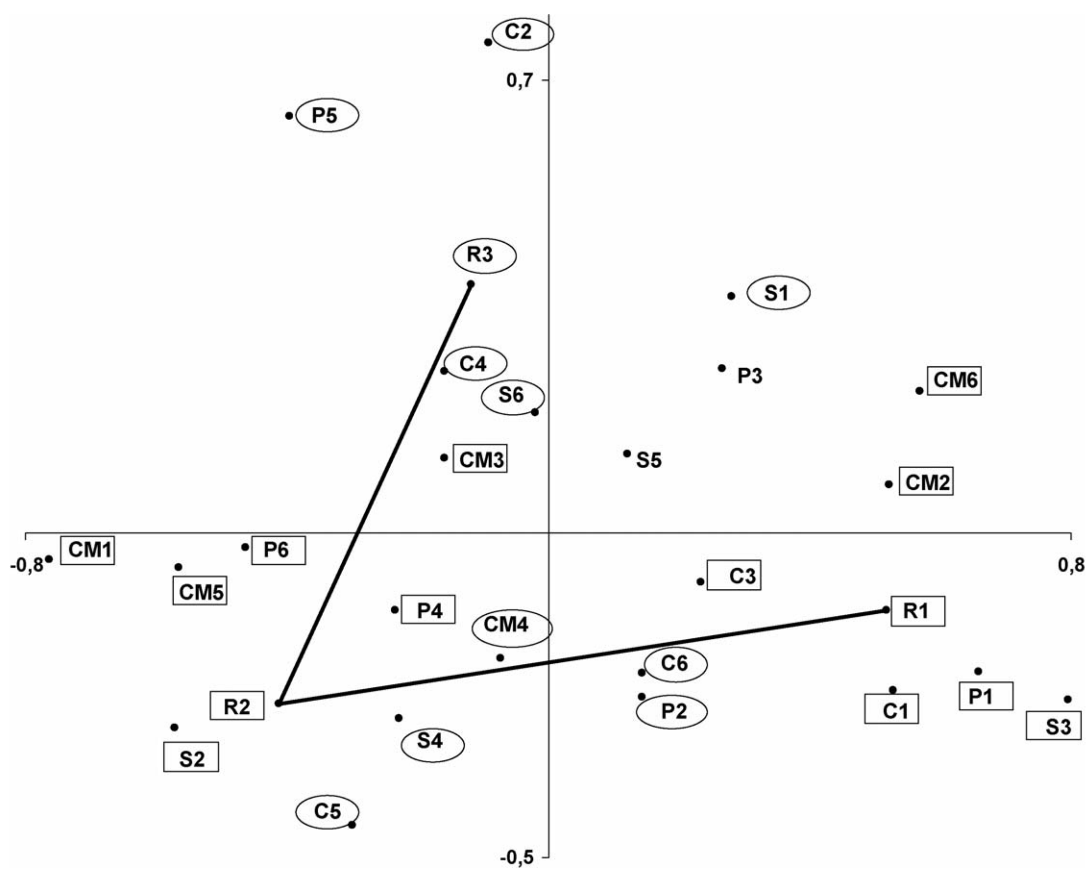


Fig. 2 – Graph of the simple correspondence analysis (SCA) based on a contingency table where the soils (S, Table 4), climates (C, Table 5), crop management patterns (CM, Table 6), and categories of coffee tree productive characteristics (P, Table 7) are in rows and the modalities of annual maximum coffee rust incidences (*R*, Table 1) are in columns. R1: low incidences (between 8.2% and 32.0%); R2: medium incidences (between 32.0% and 53.4%); R3: high incidences (between 53.4% and 93.3%). The best represented modalities on axis 1 of the SCA (cos 2 > 0.6) are shown in a rectangle. The modalities best represented on axis 2 are shown in an oval. Partial representations of the SCA: (a) soils, (b) climates, (c) crop management patterns and (d) categories of productive characteristics.

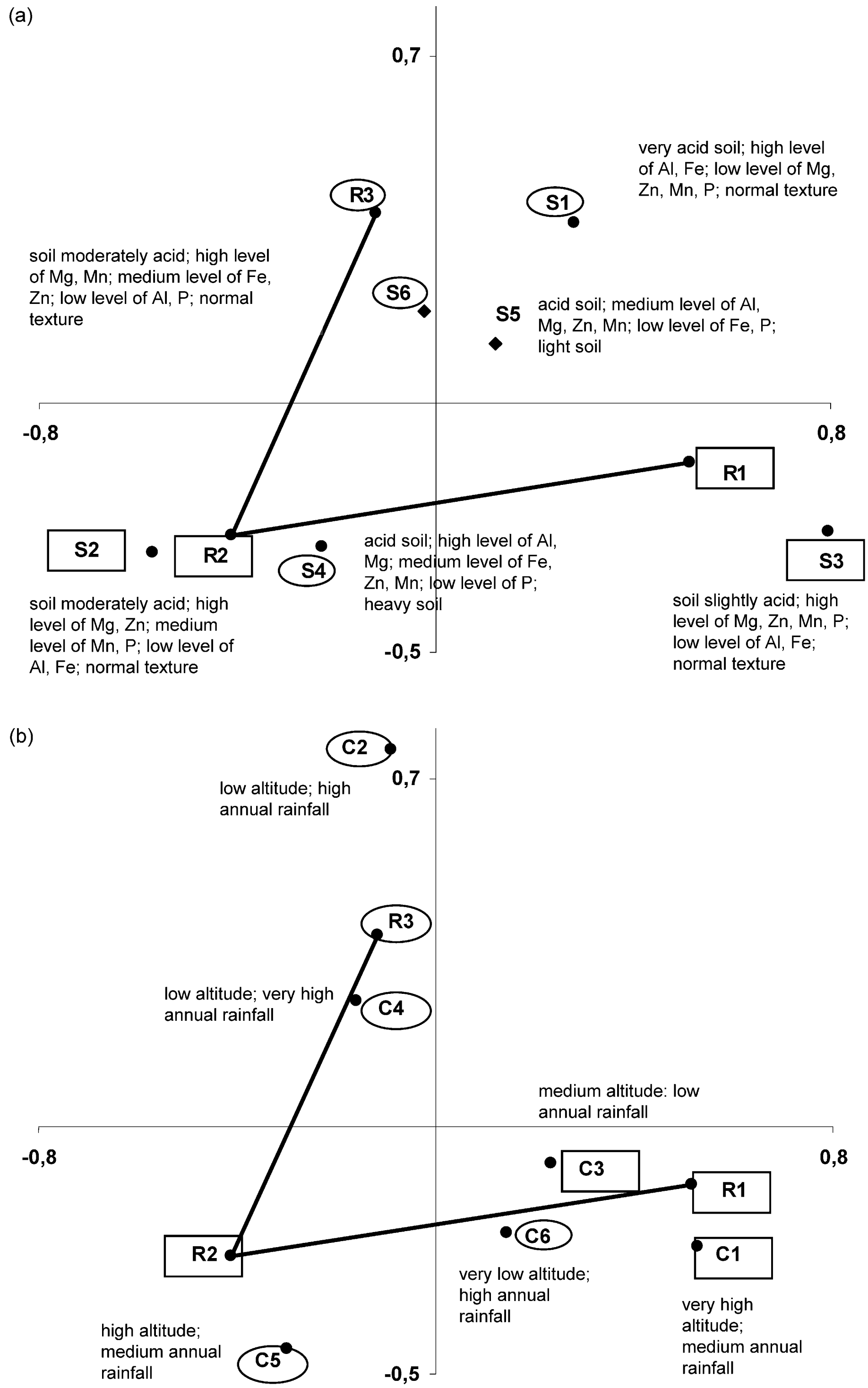


Fig. 2 – (*Continued*)

4.1.1. *Relations between soil, climate, crop management patterns, coffee tree productive characteristics and R*

The association we found between soil acidity and coffee rust attacks was reported in New Caledonia (Lamouroux et al., 1995) under profoundly different growing conditions from those found in Honduras. It suggests that as yet poorly explained nutritional factors are involved in the coffee tree–rust relation. Although the coffee tree grows on acid soil, extreme acidity conditions can lead to an impoverishment in exchangeable bases such as magnesium, which is important for the coffee tree, and its replacement by aluminium, whose toxicity is known. Moreover, these acidity conditions lead to problems with the uptake of certain nutrients, such as calcium, magnesium and copper, through a reduction in the permeability of root membranes (Fassbender and Bornemisza, 1994). The mechanisms by which these nutrients act in field

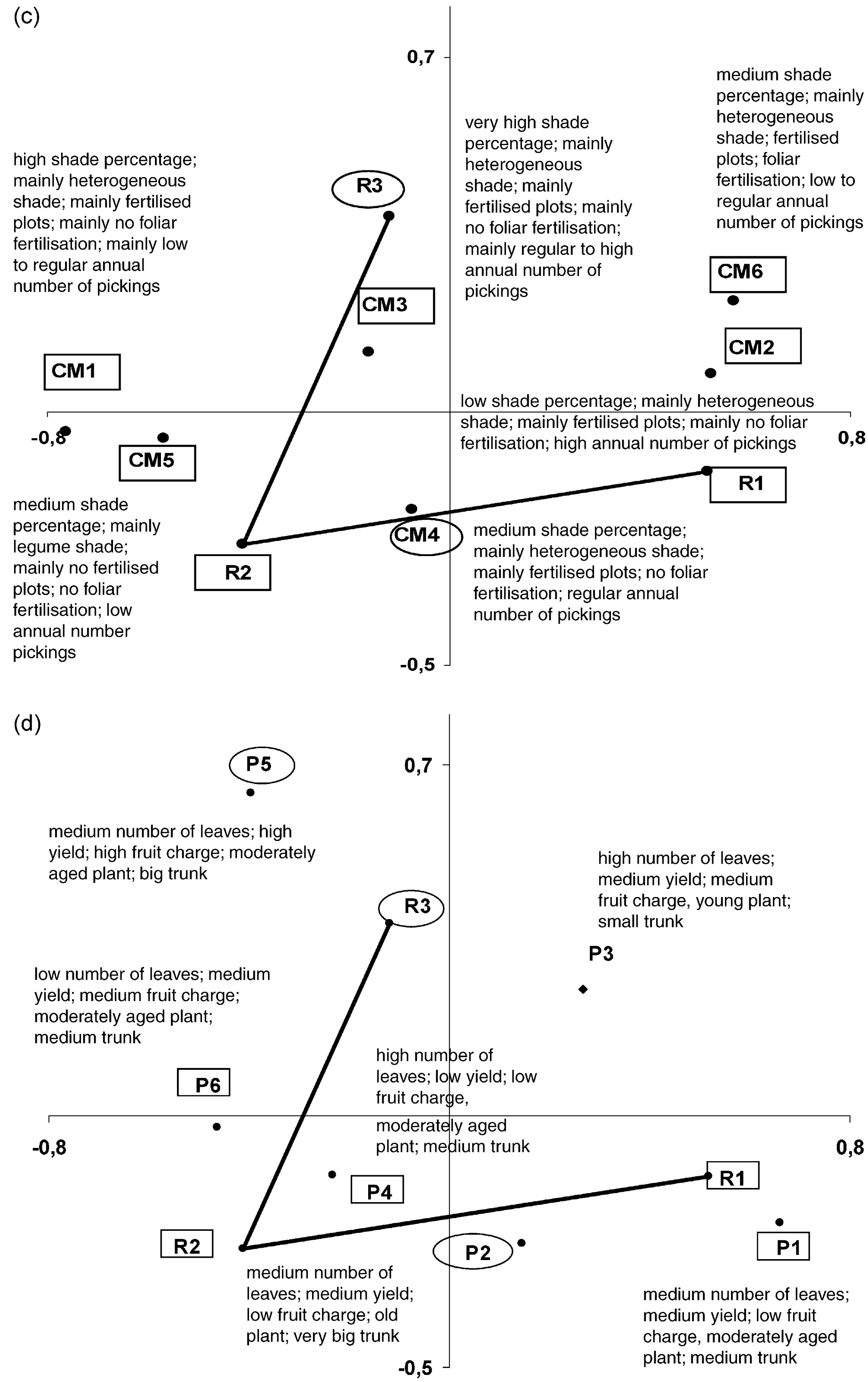


Fig. 2 – (*Continued*).

resistance to coffee rust would doubtless be worth looking at more closely.

The negative effect of the altitude on coffee rust has been found on different continents (Bock, 1962a; Avelino et al., 1991; Brown et al., 1995). Temperature is a factor that particularly plays a role in uredospore germination. The optimum has been found to be 22 °C (Nutman and Roberts, 1963), which is fairly close to the annual average temperatures found in Honduras between 700 and 900 m, i.e. at the altitudes of climates C4 and C2 associated with the highest *R* values. Rainfall too plays a decisive role. Liquid water acts on various stages of the life cycle of the fungus, such as uredospore germination (Rayner, 1961a; Nutman and Roberts, 1963; Kushalappa et al., 1983), but also for some authors on their release and dissemination (Nutman et al., 1960; Rayner, 1961a, 1961b; Bock, 1962b; Nutman and Roberts, 1963; Rasajab and Rajendran, 1983).

The favourable effect of shade on the development of coffee rust epidemics has already been reported (Machado and Matiello, 1983; Staver et al., 2001). In particular, shade maintains a humid environment in the coffee plantation, creates low light conditions, and buffers temperatures (Barradas and Fanjul, 1986; Jaramillo-Robledo and Gómez-Gómez, 1989; Caramori et al., 1996; DaMatta, 2004), which are all factors that are conducive to spore germination (Rayner, 1961a; Nutman and Roberts, 1963; Kushalappa et al., 1983). Negative effects of foliar fertilisations on coffee rust development have also been found (Pereira et al., 1996). These authors suggest that fertilisation has a direct effect on the host–parasite relation. We feel that good nutritional conditions may lie behind a dilution of the disease, resulting from quicker growth of foliage than of the coffee rust epidemic (Kushalappa and Ludwig, 1982).

Yet, a high number of leaves at the beginning of the rainy season seems propitious to coffee rust development. This high number of leaves probably reflects only a slight water stress during the dry season, hence greater preservation of the leaves and of the inoculum they bear, thereby favouring an epidemic outbreak (Muller, 1980; Muthappa, 1980; Kushalappa and Chaves, 1980; Avelino et al., 1991). The effects of high yields that we saw on the development of coffee rust epidemics were compatible with those reported on several occasions in Latin America (Zambolim et al., 1992; Silva-Acuña, 1994; De Carvalho et al., 1996; Avelino and Savary, 2002).

4.1.2. *A hierarchy of factors linked to coffee rust*

The segmentation tree tended to show that yield had the main effect on coffee rust. However, that effect was lessened, or even cancelled out, or conversely increased, by factors linked to nutrition, such as fertilisation, soil acidity or fruit load. Fertilisation was important: it came just after yield in the hierarchy defined by segmentation. It was in fact an absence of fertilisation that was linked to R. A lack of fertilisation in the plots with good fruit yields was associated in most cases with high R values. On the other hand, the fact of applying fertiliser was not in itself a guarantee of obtaining lower R values. Indeed, all the modalities were represented in this situation. The diversity of fertilisation programs used by Honduran growers, concerning the type of fertilisers employed, quantities applied, and frequencies of use, could contribute to explain the diversity of coffee rust levels observed on the fertilised plots. The use of urea at least once a year was actually the only constant in the fertilisation schedules characterised in our study.

In our survey, local factors, such as fertilisation and shade, or the productive characteristics of the coffee trees, generally seemed to be more important than regional factors. For instance, altitude only came third in the segmentation, and annual rainfall did not appear. The limited apparent importance of rainfall had already been found, by Phiri et al. (2001) during a survey conducted in Malawi.

4.1.3. *A complex pathosystem*

Our study illustrates the complexity of coffee rust epidemics, with a large number of factors involved. The complexity of many plant pathosystems (e.g. Colbach et al., 1999; Savary et al., 2005), is probably associated with interactions among factors, which may be addressed using factorial experimentations. Our analysis enables to suspect some interactions among factors.

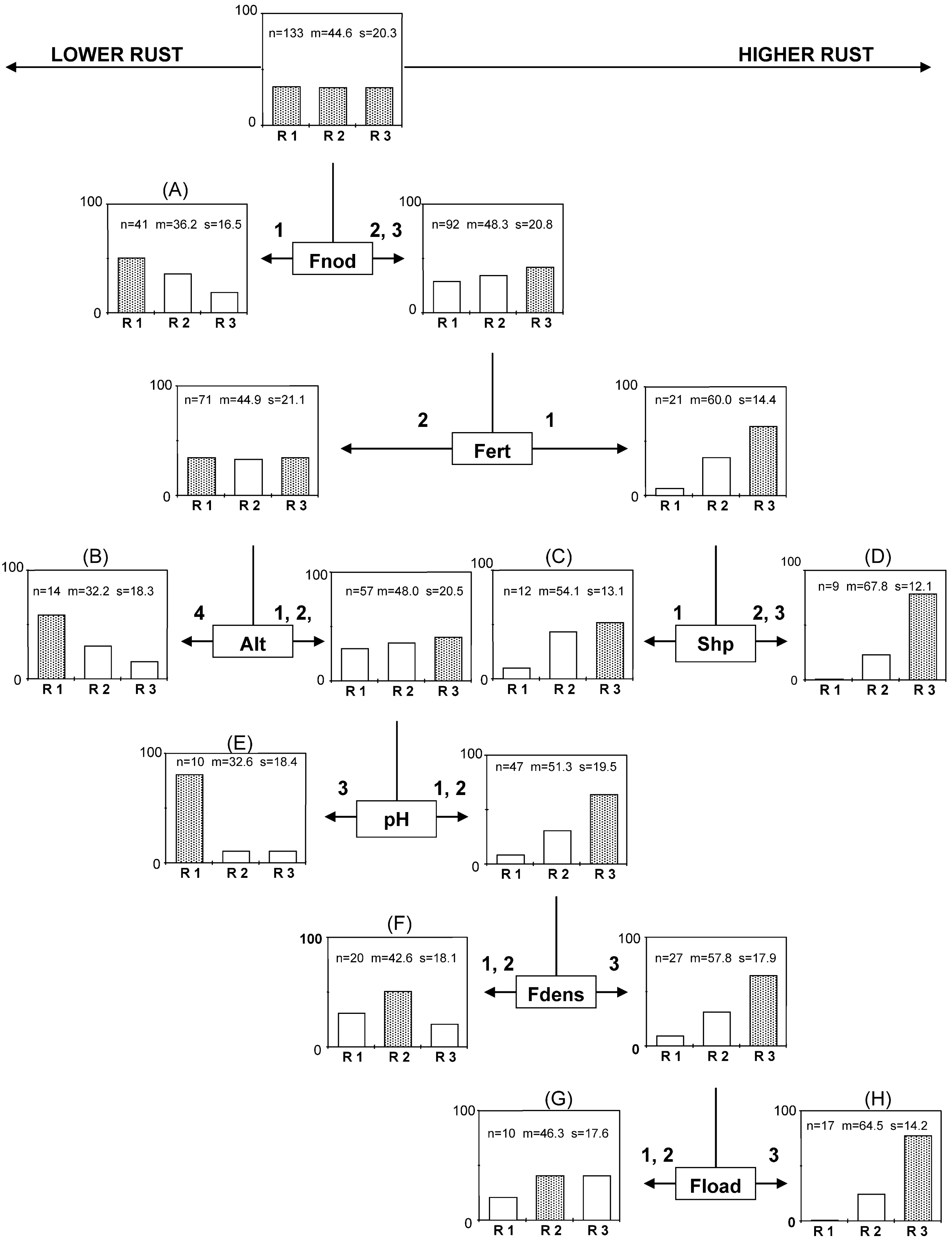
Determining typologies is a first step towards identifying interactions among factors. For example, the analysis of relations between the coffee tree productive characteristics and R suggested interactions between the amount of fruiting nodes and foliar density on coffee rust intensity, as the effect of the amount of fruiting nodes on coffee rust seemed to depend on foliar density.

The characteristics of the segmentation tree groups provide another possibility to identify possible interactions. It was especially noticeable that 57% of the plots displaying high shade percentages (between 61% and 83%) were found in group A, which was characterised by low yields. Excess shade is well known to reduce coffee yield (Cannell, 1985; Soto-Pinto et al., 2000; DaMatta, 2004). These results suggested that shade had negative effects on coffee rust by keeping yields at low levels, and on the other hand favoured coffee rust (group D) as soon as yields reached a certain threshold (230 fruiting nodes per coffee tree in our study), probably by promoting spore germination. This interpretation reconciles contrasting views on the effect of shade on coffee rust. Some authors have reported low attack intensities under shade (Soto-Pinto et al., 2002), whilst others have reported a high rust incidence (Machado and Matiello, 1983; Staver et al., 2001). These different results could be explained by coffee tree yield and its interaction with shade.

4.2. *Towards a decision support tool for coffee rust control*

The fact that the intensity of coffee rust epidemics depends on production situations explains why all the characteristics of plantations, particularly those of the crop management pattern, and not just environmental characteristics need to be taken into consideration when developing decision support tools for controlling this disease. Subsequently, the segmentation tree was used to simply assess how susceptible plots were to the development of coffee rust epidemics depending on these characteristics, and to draw up certain control methods.

For the individuals in group A, the relevance of disease control seems doubtful, insofar as these were low-yielding plantations. However, a closer examination of a coffee plantation in this group ought to reveal whether this is a permanent or a transient state. In the first case, no control will be recommended. In the second case, a single spraying with copper fungicide at the right moment ought to be enough. All the other groups contained productive plots in which control methods would be economically viable and were probably necessary. Groups B and E had low R values: a single spraying would be recommended. Groups C and D had high R values, but these were probably plantations managed by modest farmers, because they did not apply fertilisers. It is therefore highly unlikely they would be able to implement control programmes. For these farmers, resistant varieties are doubtless an option that ought to be promoted. Group F had average R values. However, restoration of the foliage is a priority. It would therefore undoubtedly be necessary to combine chemical control (two spraying rounds) with cultural practices designed to improve the nutritional status of the plant (soil improvement


LOWER RUST
HIGHER RUST
n=133 m=44.6 s=20.3
(A)
n=41 m=36.2 s=16.5
1
2, 3
Fnod
n=92 m=48.3 s=20.8
n=71 m=44.9 s=21.1
2
1
Fert
n=21 m=60.0 s=14.4
(B)
n=14 m=32.2 s=18.3
4
1, 2,
Alt
n=57 m=48.0 s=20.5
(C)
n=12 m=54.1 s=13.1
1
2, 3
Shp
(D)
n=9 m=67.8 s=12.1
(E)
n=10 m=32.6 s=18.4
3
1, 2
pH
n=47 m=51.3 s=19.5
(F)
n=20 m=42.6 s=18.1
1, 2
3
Fdens
n=27 m=57.8 s=17.9
(G)
n=10 m=46.3 s=17.6
1, 2
3
Fload
(H)
n=17 m=64.5 s=14.2
R 1
R 2
R 3
100
0

operations or more suitable fertilisation). Groups G and H were in situations where chemical control was essential. For group G, at least two spraying rounds would be recommended. For group H, the three spraying rounds locally recommended for control appeared necessary.

The limits of the categories of explanatory variables used in the segmentation played the role of decision thresholds. To a large degree, those limits had been chosen. The logic of the results obtained tended to back the choice made. Although no general rule can be imposed when choosing category limits (Savary et al., 1995), it is necessary to validate them experimentally, particularly if they have to influence decision-making, such as the decision to carry out chemical control. In addition, to complete this tool, it would be a good idea to estimate yield losses. For example, the plantations located in group D or H had similar *R* values but there was nothing to confirm that yield losses were identical in both cases. The segmentation tree made it possible to define the set of situations in which trials will have to be conducted on yield losses.

4.3. Effects on coffee rust of intensifying coffee cultivation

The segmentation tree technique also made it possible to see how intensifying coffee production may affect coffee rust development. The intensification of coffee growing results in higher yields, primarily through the use of dwarf varieties, a reduction in shade and increased fertilisation (Fernández and Muschler, 1999). Our results provide information on how the main components in crop intensification may affect coffee rust development, with the exception of the change in variety, since all the plots we surveyed were planted with dwarf varieties. For instance, our results indicated that increasing yields increased the risk of a coffee rust epidemic. In the short term, reducing shade and applying fertilisers appeared to be detrimental to coffee rust development. However, in the long term, such practices may cause a soil acidification (Fassbender and Bornemisza, 1994; Fernández and Muschler, 1999). Those effects might then bring some plantations, in particular those located below 1100 m above sea level, from a low epidemic risk group (group E, Fig. 3) to a high epidemic risk group (groups G and H, Fig. 3). In this case, harmful and irreversible effects would have to be expected on production, linked to substantial epidemic development and to soil acidification. These plantations might then switch to average epidemic risks (group F) then low epidemic risks (group A), due to foliage and production conditions that became less and less propitious to disease development. Coffee rust would thereby contribute to a decline in intensified coffee growing. The link between agricultural intensification and change in epidemic risk (in this case, an increase) has often been described in annual crops (Zadoks and Schein, 1979; Savary, 1987a, 1987b; Yarham and Giltrap, 1989; Savary et al., 1994, 2000, 2005; Cu et al., 1996; Matson et al., 1997; Colbach et al., 1999). To our knowledge, this study is one of the first illustrations of a probably similar phenomenon in a perennial crop.

These results are a warning on the risks of intensification, but also highlight the need for caution before any attempt to alter crop management. This especially concerns certification systems aiming at sustainability, and proposing, with good will, transformations of the coffee growing system, without sufficient consideration of their impact on its pests and diseases components.

4.4. Modelling coffee rust epidemics

The multivariate analysis used in this study showed that coffee rust development is linked to three sets of factors: the environment, plant growth and development, and grower practices. In this study, we used a statistical segmentation technique, which allowed to define some recommendation domains to control coffee rust, based on these three sets of factors. To our knowledge, it is the first attempt to integrate cropping practices in an approach aimed at analysing coffee rust epidemics.

Our analysis leads to logical interpretations, which concur with the literature. However, further understanding of the mechanisms that govern coffee rust epidemics requires different approaches, including the development of mechanistic models, which permits analysing in a quantitative manner the way a system is functioning (Forrester, 1961). It has been widely used for modelling plants diseases (e.g. Zadoks and Schein, 1979; Rabbinge et al., 1983; De Jong et al., 2002; Papastamati et al., 2002; Willocquet et al., 2002) as it allows quantitative integration of the individual effects, and interactions, of various factors on complex biological processes (De Wit and Goudriaan, 1978).

It may for instance be possible to consider the effect of factors influencing the dynamic of coffee rust epidemic at two levels. The first level would be the coffee tree, during one season. At this level, the system considered can be composed of a population of foliar sites at various stages (non-infected, latent, infectious, eliminated). The second level is the plantation (or a coffee field surrounded by analogous spatial fractions) in the course of successive production cycles. At this level, the system could be a population of leaves (healthy,

Fig. 3 – Segmentation tree obtained by the automatic interaction detection method (Morgan and Sonquist, 1963) explaining maximum annual coffee rust incidence (*R*), taken as the quantitative variable, from the following explanatory variables: number of fruiting nodes per plant (Fnod), annual number of fertiliser applications (Fert), altitude (Alt), shade percentage (Shp), soil pH (pH), foliage density (Fdens), fruit load (Fload) (Table 1). *n*: number of plot-year individuals, *m*: mean of *R*, *s*: standard deviation of *R*. The figures on the arrows correspond to the modalities of the explanatory variables (Table 2) on which the dichotomy was performed. Letters in bold in the histograms identify the groups formed. All the dichotomies were significant according to the Student's *t*-test at 5%. As an illustration, for each of the groups formed, the histograms show the frequencies of the individuals in the three categories of *R*, R1 (between 8.2% and 32.0%), R2 (between 32.0% and 53.4%), and R3 (between 53.4% and 93.3%). The shaded columns correspond to the highest frequencies. See text for more details of the analysis.

infected, and fallen) sorted by age classes. Those two levels, which differ by their physical size and time steps, would permit to address different mechanisms and their interactions. The first level enables to focus on the direct intra-annual effects on the disease kinetic: for example, the effects of foliar growth and of climate on the parasitic cycle. The second level enables addressing more complex, and often indirect, effects on epidemics: especially the effects of the yield, which is known to follow a biennial rhythm. To our knowledge, such a coffee rust model does not exist, but its development would trigger the mobilisation of current knowledge, and new insight towards coffee rust management.

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