Economic constraints as drivers of coffee rust epidemics in Nicaragua

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ABSTRACT

Coffee rust (*Hemileia vastatrix*) epidemics of an intensity never seen before have hit Central America since 2012. This study set out to identify management and socio-economic factors that facilitate coffee rust development in Nicaragua and to learn how farmers perceive these epidemics. To that end, we conducted a series of interviews with farmers and carried out field observations a year after the peak of the 2012-13 epidemic. Twenty-nine pairs of plots (a pair was one heavily hit plot and another slightly hit plot in the same location) in the municipalities of Jinotega, Tuma-La Dalia and San Ramón were characterized for their management and coffee rust impact. This information was completed through interviews with the farmers. In addition, farmers provided their perception of the reasons for differences of coffee rust intensities between plots and information about their socio-economic situation. From multivariate analyses, we deduced that young coffee trees, timely applications of fungicides based on disease monitoring, shade pruning, and soil and foliar fertilizers seemed to be key practices in managing coffee rust. These practices were well known by the farmers, but socio-economic difficulties severely held back their application, as revealed by a mental model approach. Low coffee economic resources were particularly mentioned by farmers as a constraint to applying the practices needed to manage coffee rust. The highest coffee rust intensities and impacts were found in plots where the farmers, in general, had no education, no training, a low number of direct technical advices, and low incomes. To our knowledge, this is the first time that poor economic conditions have been related to the development of intense plant disease outbreaks. These relationships indicated that technical solutions to manage coffee rust are not sufficient and that economic solutions, where the market has a crucial role to play, need to be implemented.

1. Introduction

Coffee rust is a leaf disease caused by the fungus *Hemileia vastatrix*, an obligate parasite affecting the living leaves of the genus *Coffea*. Among the cultivated species, *C. arabica* is the most attacked. The fungus causes defoliation that, when severe, can lead to the death of the branches and heavy yield losses. Coffee rust was first reported in 1869 on the Asian island of Ceylon (Kushalappa and Eskes, 1989). In Ceylon, *H. vastatrix* found suitable conditions for disease development, particularly in terms of crop management. European settlers established large, uniform plantations with susceptible varieties and full sun exposure leading to high yields, a factor conducive to the disease (McCook, 2006). In addition, no chemical control options were available at the time when coffee rust was detected in Ceylon. The fungicide properties of Bordeaux mixture, one of the first fungicides used with success against coffee rust, were only described in 1885, in France (Viennot-Bourgin, 1985). Before the arrival of coffee rust, Ceylon was the world's third largest coffee producer. Saccas and Charpentier (1971) mentioned that coffee exports, which had reached 41 855 t in 1879, dropped to 9 000 t in 1884 and 2 300 t in 1893 under the pressure of the disease. Coffee growing was then gradually converted to tea cultivation (Rayner, 1972). From Ceylon, coffee rust quickly spread throughout Asia and wreaked havoc, particularly in the lowlands where temperatures were more suitable for the disease. At the same time, the disease was detected in all the coffee plantations of East Africa, from where coffee rust originated, with similar effects. In the early twentieth century, the Arabica coffee crop in Asia and Africa was concentrated in some high altitude areas where the cool climate prevented the disease from developing (McCook, 2006).

Coffee rust was first reported in Latin America in 1970, in the state of Bahia, Brazil, a few years after it was reported in Angola (Monaco, 1977; Muller, 1971; Waller, 1982). Coffee rust introduction into America raised a great concern: the destruction seen in Ceylon and in other old-world coffee areas could happen in Latin America. As a consequence, the first reaction when coffee rust arrived in Brazil (Monaco, 1977; Muller, 1971; Waller, 1972) and in Central America in 1976 (Schuppener et al., 1977) was to try to eradicate the disease, relying on the experiences of Papua New Guinea. In this last country, three successful eradication campaigns were launched in 1892, 1903 and 1965 (Shaw, 1968), and up until 1986, when the disease had become definitively established. However, the disease was soon considered to be manageable, as chemical control was effective and because of the relatively low epidemic intensities observed, particularly at high altitudes. This was the general view until intense epidemics hit Colombia in 2008, then Central America and Mexico in 2012, followed by Peru and Ecuador in 2013 (Avelino et al., 2015; Cressey, 2013).

Coffee rust has been the cause of heavy crop and economic losses throughout history, due to the implementation of expensive eradication and preventive actions to delay the establishment and spread of the disease, and by preventing coffee growing in areas suitable for the disease, thereby reducing coffee production. Coffee rust epidemics, which have hit Mesoamerica since 2008, have also been the cause of heavy yield losses. On average, Colombian production decreased by 31% during the epidemic years (2008-2011), compared with 2007 (Avelino et al., 2015). In Central America, production decreased by 10% in the 2012-13 harvest, and by 20% in the 2103-14 harvest, compared with the 2011-12 harvest (http://www.ico.org/new_historical.asp, consulted on March 2019), as a result of the epidemics occurred in 2012 and 2013. These epidemics also had serious impacts on the food security of coffee farmers and laborers, as most of the coffee farmers are smallholders, who need the earnings generated by coffee to buy food, and most laborers, hired during coffee harvest, use part of their income to finance their maize and bean crops (Avelino et al., 2015).

The Central American coffee rust epidemic had weather drivers, as higher than normal rainfall in the first half of the year and lower than normal rainfall in the second half, reduced the daily thermal amplitude and increased the minimum temperature (Avelino et al., 2015). It probably had economic causes also, since during the period coffee prices were below their long-term average and in anticipation many farmers may not have applied their usual level of inputs (Avelino et al., 2015). Unlike previous epidemics occurred in the region, the 2012-13 epidemic was almost generalized throughout Central America and Mexico. However, some differences were noted between coffee areas due to small environmental differences. For instance, in Guatemala coffee plantations over 1400 m above sea level were less impacted by coffee rust than plantations located at lower altitudes (Avelino et al., 2015). There was also variability on a local scale

(Avelino et al., 2015), indicating that, in some cases, local factors may have helped to decrease or, on the contrary, increase coffee rust intensity. This view tallies with previous studies where local factors, such as fruit load, the number of fertilizer applications and shade management were found to be the main predictors of coffee rust incidence in plots with no fungicide spraying (Avelino et al., 2006). Fungicide applications are obviously also a source of variability in coffee rust intensity.

This intense epidemic can be seen as an opportunity to learn about the factors that favored or hampered coffee rust development, particularly regarding cropping practices that helped to maintain the disease at low levels, and to understand why they were implemented, or not. These practices could be part of a package of best practices to manage coffee rust, especially if they were effective during the 2012-13 epidemic. It was also an opportunity to learn about how farmers, particularly smallholders, perceived the epidemic. For both purposes, we conducted a series of interviews with coffee smallholders and carried out field measurements on coffee farms diversely impacted by the disease in Nicaragua, in the municipalities of Jinotega, Tuma-La Dalia and San Ramón.

2. Materials and Methods

2.1. Study area

The municipality of Jinotega is located in the department of Jinotega, and Tuma-La Dalia and San Ramón are located in the department of Matagalpa, (Fig. 1), where most Nicaraguan coffee is produced. Jinotega and Matagalpa account for 35% and 25% of the total coffee area in the country, respectively (INIDE and MAGFOR, 2012). These two mountainous departments are under Pacific Ocean influence, with a marked dry season and cool temperatures due to altitude.

Rainfall is concentrated in 7 months from May to November, reaching 3000 mm on average per year in some areas. The coffee farmers in Matagalpa and Jinotega are mostly smallholders. Coffee is normally associated with shade trees, as is the case for almost all the coffee stands in the country.

Nicaraguan exportable coffee production decreased by 16% in the 2012-13 harvest compared to 2011-12 (http://www.ico.org/new_historical.asp, consulted on March 2019), which was mainly attributed to coffee rust. The disease heavily hit the country, particularly Jinotega and Matagalpa, despite these coffee areas being high altitude. This situation was quite frequent in Central America during the "Big Rust" (Baker, 2014). It was demonstrated in Guatemala that coffee rust behaved somewhat similar between 400 and 1400 masl, whereas it rarely affected coffee plantations above 1000 masl before then. This was attributed to an increase in minimum temperatures (Avelino et al., 2015).

2.2. Farm and plot selection

Farms with limited yield impact from coffee rust attacks in 2012-13, despite being planted with susceptible varieties, were identified through interviews with technicians from the cooperatives centre located in Matagalpa and Jinotega, from specific cooperatives, and from CATIE national office, and through ground verifications by visits to farms and short interviews with the farmers. Once a farm with limited yield impact from coffee rust was chosen, a neighboring farm with high yield impacts from coffee rust was identified. Twenty-nine pairs of farms (one farm with high impacts and one farm with almost no impacts at 29 sites, Fig. 1) were selected following this methodology. Care was taken to select only farms with coffee trees that were at least three years old, planted with varieties susceptible to coffee rust (mainly Caturra), and belonging to smallholders. The range of altitudes was restricted to 800-1200 masl, where coffee rust attacks were the most intense.

A representative plot on each farm, based on the farmers' indications, was used for most of the field measurements. The plot size was 10 rows x 20 coffee trees. However, shade tree density was assessed on a 1000 m^2 area with this coffee plot at the center.

Farms and plots were selected in December 2013 and January 2014. Data were obtained in February and May 2014, around one year after the peak of the 2012-13 epidemic.

2.3. Causes of the different impacts of coffee rust according to farmers

Before asking any questions about coffee rust, coffee management, fertilizer applications and socio-economic characteristics (see following sections), farmers were asked two questions to elicit cognitive elements on the causes of coffee rust; Q1: Do you think your farm has been more or less impacted by coffee rust than surrounding ones?; Q2: Why do you think your farm has been less/more impacted than surrounding ones? Mainly local causes (management, socio-economic characteristics) were targeted by these questions, as each farm and its neighbors were in the same macro-environment (similar altitude, similar weather conditions). According to a conceptual initial model built with Nicaraguan coffee experts, farmers' actions are the result of a cascade of effects starting with international coffee prices (Fig. 2). Economic factors seem to be particularly important, as they determine the farmer's financial capacity to act. Management is theoretically also under the influence of labels and certifications, which impose specific management (e.g. organic coffee) and of training, which contributes to increasing a farmer's knowledge of best practices for coffee, and for pest and disease management.

2.4. Coffee rust impact and intensity assessment

Coffee rust impact and intensity were assessed through interviews with farmers, along with field measurements.

As the epidemic occurred in 2012-13, most of the impacts were not visible at the time of the study. Farmers were therefore asked to qualify coffee rust infection and the resulting impact in their plantation. They were first asked to describe disease intensity on a plantation scale: low, moderate or heavy infection. They then qualified coffee rust intensity and impact in terms of the proportion of coffee trees heavily infected, the proportion of the plantation area heavily infected, and proportion of fallen leaves and of dead branches per tree, according to three categories: <25%, 25-50%, >50-75%. An additional question was intended to understand when defoliation occurred: mainly before, during, or after harvest. It is known that the earlier defoliation occurs, the heavier primary and secondary losses will be (Avelino et al., 2015). In order to complete the impact assessment, the pruning intensity applied after the epidemic was also documented as the proportion of pruned coffee trees (<20%, 20-50%, >50%), assuming that heavily impacted coffee plots required severe pruning. In addition, the pruning system applied after the 2012-13 epidemic (entire coffee block, individual pruning by coffee tree, or both systems) was indicated by the farmers. A drastic pruning system (by entire coffee blocks) indicated that the coffee trees were exhausted or heavily impacted over large areas. Lastly, the estimated green coffee losses in the 2012-13 and 2013-14 harvests were deduced from the expected yields, with no rust in 2012, and actual yields, as indicated by the farmers.

Two field measurements were also carried out in the selected plots. The first consisted in assessing the number of fruiting nodes, on ten coffee trees systematically distributed throughout the plot, as a proxy of coffee production (Upreti et al., 1992). Although the 2013-14 harvest was at the end when this study started, the locations of harvested fruits were still visible and enabled counting. For that purpose, we used a methodology derived from that developed by Avelino *et al.* (2012). In each coffee tree i, we counted the number of productive branches (PB_i) and the number of fruiting nodes on three productive branches ($FN3PB_i$) selected in three different strata. The total number of fruiting nodes (TFN_i) for coffee tree i was deduced as follows: $TFN_i = PB_i * FN3PB_i/3$. The data were then averaged on a plot scale to obtain the total number of fruiting nodes per coffee tree in each plot. The second measurement allowed us to assess pruning intensity. Based on the signs of recent pruning (less than one year old), we deduced the number of stems per coffee tree that were pruned in 2013 ($NPrS_i$), in each coffee tree i of the three central rows of the studied coffee plots. We also counted the number of productive stems >1 year old present per coffee tree ($N1St_i$). The observed pruning intensity was then calculated as the proportion of pruned stems with respect to the total number of productive stems that were theoretically present at the end of 2012: $\frac{\sum_i NPrSi}{\sum_i (NPrSi+N1Sti)}$

2.5. Characterization of coffee plot management

We characterized the structure of the coffee plots, which was generally stable over time, and cropping practices, which could change over the years.

Within the structure, the vegetation making up the coffee plots was described from field assessments. Shade trees >2m tall were identified with farmers on the delimited area of 1000 m^2, which included the study plot. We deduced the number of species. All the timber, fruit, fuel wood and service trees were classed together according to their height: 2-8 m, 9-17 m and 18-24 m. We determined the number of strata, the density of trees per stratum, and also the presence-absence of legume trees, timber trees, fuel wood trees and fruit trees. In addition, the density of banana plants was recorded. Coffee tree age, the orientation of coffee tree rows and the pruning system applied in the plot before the 2012-13 epidemic were also characterized with the farmer's help. Pruning can be applied uniformly per plot, or row, or specifically by coffee tree or orthotropic stems within the tree.

Other measurements needed the selection of five coffee trees distributed in a cross shape within the 200 coffee trees of each plot. The number of coffee trees per planting hole was assessed on these coffee trees. The distance between coffee trees in the planting row and the distance between rows were assessed by measuring the distances between the five identified coffee trees and their neighboring trees. We deduced the coffee tree planting density. The vegetation description was completed with an evaluation of the average shade cover on these five coffee trees, using a spherical densiometer (Lemmon, 1957). Furthermore, the ground cover stratum was visually estimated on five 1 m^2 units located close to the five selected coffee trees. The percentage of the area with bare ground, litter, weeds (mainly climbing, *Graminaceae* and *Cyperaceae* plants, plants with deep roots), and good cover plants (small plants with short roots), was assessed in each square and then averaged.

The cropping practices applied in 2011 and 2012 were documented through interviews with farmers. We asked the farmers whether or not they pruned shade trees in 2011 and 2012, and the number of shade management operations carried out in 2012. We also asked for the number of chemical and mechanical weeding operations carried out that year. In addition, disease chemical control was described through six variables. We documented whether the farmers used a monitoring system to keep track of the growth of coffee rust epidemics. We asked in which half of the year they applied the first fungicide application in 2012. Fungicides need to be applied preventatively, normally at the beginning of the rainy season, to control coffee rust (Avelino et al., 2015; Zambolim, 2016). The number of fungicide sprayings carried out by the farmers in 2011 and 2012 was recorded, as well as the number of protective and curative fungicide sprays carried out in 2012.

Fertilizer applications were studied in more detail. As demonstrated in Honduras (Avelino et al., 2006) and verified in recent epidemics in Colombia (Avelino et al., 2015; Cristancho et al., 2012), high intensity epidemics are associated with sub-optimum nutrition programs. However, the underlying mechanisms of fertilizer applications involved in the intensity of coffee rust epidemics are not known. This study was an opportunity to verify how fertilizers affected the disease. The information on the number of fertilizer applications, the nature of the fertilizers, the amounts and how they were applied (foliage, soil) were obtained from farmers through interviews. In addition, the doses applied to soil and foliage for each nutrient were calculated and considered as variables.

2.6. Other variables: topography and socio-economic characterization

Topography was described through three variables: plot altitude (assessed with a GPS), slope aspect (determined with a compass) and slope percentage (evaluated with a clinometer).

In addition to biophysical characterization, several socio-economic variables were documented through interviews with farmers. First, the number of family members and the age of the farmer were documented. Farmer education levels and the highest education level in the family were identified. Farmers were then asked to indicate whether they benefited from direct (on-farm) technical advice through the visits of technicians and whether they received training. The number of technician visits in the last three years was recorded, as well as the number of training topics covered for each farmer. Lastly, farmer income related to coffee sales and access to credit were also recorded.

2.7. Analyzes

In order to capture the way farmers perceived the causes of coffee rust epidemics (information obtained from the first two open questions Q1 and Q2), we used a mental model approach. This approach has previously been used to identify and visually map expert knowledge and/or lay people's cognitive elements and their linkages, regarding complex issues such as climate change (Bostrom et al., 1994; Lowe and Lorenzoni, 2007) and, more specifically related to agriculture, weed management (Wilson et al., 2008). This approach consisted in identifying key elements that farmers shared in understanding the causes of coffee rust. These causes were represented in a cognitive map with the direct and indirect linkages between elements (Carley and Palmquist, 1992).

In addition, multivariate analyzes were used for other data. In survey data, associations between variables are unavoidable. Specific variables can therefore not be studied outside their context. For that reason, we chose an analytical approach based on typologies, as already used for explaining different diseases or injury profiles (Allinne et al., 2016; Avelino et al., 2006; Savary et al., 1994; Savary et al., 1995; Savary et al., 2000). We specifically followed the analytical methodology proposed by Avelino *et al*. (2006) in their study on coffee rust. This approach has three main stages: (i) building a typology of disease impact and intensity with all the coffee rust variables, and exclusion of potential coffee rust explanatory variables not associated with disease impact and intensity (ii) building management (except fertilizer applications), fertilizer application, and socio-economic typologies with the remaining variables (iii) analyzing the relationships between typologies through a correspondence analysis. The analyzes were performed using InfoStat software (Di Rienzo et al., 2016) and the R package (R Core Team, 2015).

Lastly, the results obtained from the two approaches (mental model and multivariate analyzes) are discussed.

For each step, the detailed methodology is presented below:

2.7.1. Mental model

We coded transcribed textual responses to Q1 and Q2 using keywords representing the conceptual elements of the pre-defined expert model represented in Figure 2. Taking a confirmatory perspective in the farmer mental model analysis (Carley and Palmquist, 1992), we identified the most cited causes, their relation to and perceived direction of influence on the actual impacts of coffee rust in farmers' coffee plots. As we interviewed 58 farmers, the representation of their mental model was actually a shared mental model (Cannonbowers et al., 1993), as already used to represent the overall mental model of 22 experts in the UK about the dangers of climate change (Lowe and Lorenzoni, 2007).

2.7.2. Disease impact typology building and elimination of explanatory variables not associated with coffee rust

We carried out a multivariate cluster analysis on coffee rust variables, using the Gower distance and the Ward aggregation criterion, to build a disease impact and intensity typology. The contribution of these variables to the typology was assessed through a Fisher's exact test for qualitative variables, and a non-parametric Kruskal-Wallis test for quantitative variables. The association between this typology and each potential coffee rust explanatory variable was then evaluated with the same tests. Variables that were considered as not associated with coffee rust impact and intensity (P>0.1) were discarded from the subsequent analyzes.

2.7.3. Building of management, fertilizer application and socio-economic typologies, and factorial analysis

As for disease impact and intensity typology, we carried out multivariate cluster analyzes to build typologies with different groups of explanatory variables selected. A factorial analysis was then carried out on a contingency table, where the disease impact and intensity typology was in columns and the other typologies in rows. The relationships between rows and columns were tested by a Fisher's exact test. Relationships between explanatory variables and the disease impact and intensity typology were then graphically represented. To assess the proximity between the different modalities, a principal component analysis was carried out on the coordinates of the categories on the axes of the factorial analysis.

3. Results

3.1. Causes of the different impacts of coffee rust according to farmers

All the interviewed farmers recognized that coffee rust impacted their farm in the direction indicated by the coffee technicians, i.e. either more or less than their neighbors' farms. According to Figure 3, elements related to coffee rust impacts mentioned by the farmers were mostly direct plot level factors, rather than indirect factors that determined a farmer's ability to deal with the disease, i.e., which had an influence on his management decisions, contrary to the expert conceptual model (Fig. 2). The most cited factors were good agronomic management in general, fertilizer and fungicide applications, shade management, and coffee tree age. There was overall agreement among farmers on the positive influence on coffee rust management of the first three factors, and on the negative influence of the last. This agreement was general for all factors, except in the case of shade management, where a slight controversy arose: of the 16 farmers who mentioned that shade had an impact on coffee rust, only one said shade favored the disease. Although farmers recognized that management factors were mainly the cause of the differences in coffee rust impacts between farms, they also considered that the sub-optimum management they applied was due to economic constraints, beyond their control (i.e. some of the indirect causes represented in the expert conceptual model).

3.2. Coffee rust impact and intensity typology

Three categories of increasing coffee rust impact and intensity were built based on variables quantified through field assessments, or interviews with farmers. The low-impact coffee farm category included 29 farms that were described by farmers as slightly affected by coffee rust (Table 1): low infection level, small proportion of coffee trees and small plantation area heavily infected, small proportion of fallen leaves and of dead branches, large proportions of leaves falling during harvest, small proportion of coffee trees requiring pruning and pruning applied according to the specific condition of each coffee tree, and the cumulative loss estimated in 2012-13 and 2013-14 was low (69 kg of green coffee ha^{-1}). In addition, we checked that this category had the largest number of fruiting nodes per coffee tree in the 2013-14 production year (135 on average) and the pruning intensity was the lowest (only 13% of existing stems in 2012 were pruned in 2013). On the other hand, the high-impact coffee farm category included 19 coffee farms that were heavily affected by coffee rust according to farmers (Table 1): high infection level, large proportion of coffee trees and plantation area heavily infected, large proportion of fallen leaves and of dead branches, large proportion of leaves falling before harvest, large proportion of coffee trees requiring pruning and pruning mainly applied on entire blocks of coffee trees, and the cumulative loss estimated by farmers in 2012-13 and 2013-14 was high (662 kg of green coffee ha^{-1}). Fruit load in 2013-14 was almost null according to field assessments (only 8 fruiting nodes per coffee tree on average) and pruning intensity was high (55% of existing stems in 2012 were pruned in 2013). An additional category with only 10 individuals comprised farms with intermediate coffee rust impact and intensity values (Table 1).

3.3. The coffee rust explanatory variables selected and the typologies obtained

Thirty-seven variables were selected after testing their relationship with the coffee rust impact and intensity typology (Table 2). Ten of these variables characterized coffee plot management, mainly cropping practices, related to shade management and chemical control. Only the pruning system applied before the epidemic and the coffee tree age were chosen from the coffee plot structure variables. None of the variables characterizing shade structure were retained (Table 3). In addition, most of the variables characterizing fertilizer applications were selected (19 variables). Nutrients applied to foliage were almost all selected. The remaining eight variables described socio-economic aspects, such as the farmer’s age and education, training activities and technical advice, along with income and access to credit. None of the three topography variables was related to coffee rust (Table 3). This is understandable as we chose one plot with almost no impact and one impacted plot in each location (see section 2.2.), i.e. in similar topographical situations.

Cluster analyzes gave management (except fertilizer applications), fertilizer application, and socio-economic typologies with three categories each (sub-optimum, intermediate, and intense; Tables 4-6).

Five of the six plots with unpruned coffee trees were included in the sub-optimum management category (Table 4). This category also comprised the oldest coffee trees. Farmers, in general, did not manage shade and did not monitor coffee rust for chemical control purposes. The number of fungicide sprays was small. On the other hand, in the intense management category, farmers managed shade, monitored coffee rust, and sprayed fungicides more than twice on average in 2011 and more than three times in 2012. The spraying schedule always started in the first half of the year, i.e. before or at the time of the onset of the epidemic. The intermediate management category included plots with in-between characteristics.

The cluster analysis gave three categories of increasing numbers of fertilizer applications per year (on soil and on foliage), which we considered as categories of increasing intensity of fertilizer applications. The 33 plots included in the category with the smallest number of fertilizer applications also showed the smallest quantities of nutrients applied, except for P and Cu applied to foliage (Table 5). The largest quantities were split within the other two categories. Four nutrients showed increasing values in accordance with the increasing number of fertilizer applications: K applied to soil, N, Mg and Fe applied to foliage.

The socio-economic categories were based on the farmer’s academic education, technical training and advice, and income (Table 6). The sub-optimum socio-economic category included 15 plots owned by farmers with no academic education in general, no access to training, and limited access to direct technical advice (on-farm). These farmers had the lowest incomes. The other two categories comprised plots whose farmers received some training in their lifetime. They also received direct technical advice in general. They had the highest income and the highest academic level.

3.4. Relationships between the typologies

Fisher's exact tests revealed that the relationships between the coffee rust impact and intensity typology and the management ($P<0.001$), fertilizer application intensity ($P<0.001$), and socio-economic level ($P=0.007$) were all significant. From the correspondence analysis and cluster analysis (Fig. 4), we deduced that high coffee rust impacts and intensities were related to sub-optimum management and sub-optimum fertilizer application intensity, whereas moderate coffee rust impacts and intensities were related to intermediate management. On the other hand, low coffee rust impacts and intensities were associated with intense management and high and intermediate fertilizer application intensities. The socio-economic conditions of the farmers also appeared to be associated with coffee rust impacts and intensities: high and moderate impacts and intensities were related to sub-optimum socio-economic conditions, whereas low impacts and intensities were related to intermediate and high socio-economic conditions.

4. Discussion

Nicaraguan coffee farmers know how to manage coffee rust. There were almost no contradictions between farmers' statements regarding cropping practices that help to manage coffee rust, particularly fertilizer applications and liming, coffee rust monitoring and fungicide sprays, coffee varieties, coffee tree age and pruning. Most of these effects were also found in the plot characterization study and are reported in the literature. However, many coffee farmers did not apply the required management practices in 2012 despite knowing how to manage the disease. Based on farmers' statements and field evidence, our results confirmed that coffee rust epidemics had economic drivers, that determined crop and disease management, as previously proposed (Avelino et al., 2015), and did not only depend on meteorological aspects and host plant characteristics. Crop management was probably sub-optimum over that period, because management is normally adjusted each year to adapt on-farm investment to the economic context (Taugourdeau et al., 2014), and the coffee crop was not profitable in 2012. International prices dropped sharply (by 55% between September 2011 and December 2013) below the production costs, which reached high levels never seen before at the same time (Avelino et al., 2015). Technical solutions for coffee rust management, however useful, are therefore not sufficient to manage the disease. In the absence of government subsidies to farmers, the coffee market needs to revise its economic strategy to help farmers to implement these technical solutions and to continue supplying the market with good quality coffee. To our knowledge, this is the first time that economic constraints are seen as being partly responsible for a plant disease epidemic.

In the propitious weather conditions for coffee rust development that occurred in 2012, some farmers avoided intense epidemics and losses. The management they applied is instructive for improving coffee rust management.

One of the decisive factors was chemical control and particularly the time when the fungicides were applied. Fungicide needs to be sprayed preventatively to be efficient, as soon as disease incidence reaches 5% with curative fungicides, and even lower incidences with protective ones (Belan et al., 2015a; Zambolim, 2016). Coffee rust monitoring helps to identify the right timing for fungicide sprays. That is why low coffee rust impacts and intensities were found in most of the plots where disease monitoring was implemented. Disease monitoring is particularly useful for addressing unexpected disease developments (Belan et al., 2015a), as probably occurred in

2012 with coffee rust (Avelino et al., 2015). It has been proposed that the wetter conditions of the first half of 2012 were propitious to the sooner than usual development of the epidemic (Avelino et al., 2015). That year, low coffee rust impacts and intensities were found in plots where, based on disease monitoring, fungicides were sprayed more than three times a year on average, mainly with curative products, starting in the first half of the year.

We found no relationship between variables characterizing shade structure and cover, and coffee rust, possibly because all the studied coffee plots had shade, as is usual in Nicaragua. Differences in shade structure and cover were probably not enough to highlight effects on coffee rust. However, in the plots with low and moderate coffee rust impacts and intensities, shade trees were pruned at least once a year, whereas no shade tree pruning was implemented in the heavily impacted plots. Having shade is generally considered by farmers as a good practice to manage coffee rust. However, shade tree pruning helped to prevent excessive shade cover and could have helped to regulate coffee rust by reducing three unwanted effects of shade. Shade buffers temperatures and maintains temperatures within a range (never too high, never too low with respect to the optimum disease temperature), which shortens the latent period of the disease (Lopez-Bravo et al., 2012). Shade increases the kinetic energy of raindrops, whose strong impacts on coffee leaves promote the release and dispersal of uredospores into the air (Boudrot et al., 2016). Recently, it has also been demonstrated that shade is conducive to the conservation of uredospores by reducing throughfall and wash-off of spores (Avelino et al., 2019). As *H. vastatrix* is an obligate parasite, uredospores carried by rainwater to the ground can be considered as lost for epidemic growth. It is interesting to note that the only discrepancy between farmers regarding factors that help to manage coffee rust concerned shade. Shade effects on coffee rust are complex and controversial, possibly because there are (i) many pathways involved (Avelino et al., 2011) (ii) opposite effects depending on the stimulated pathway (Lopez-Bravo et al., 2012) and (iii) interactions with meteorological variables (Boudrot et al., 2016).

Old coffee trees, particularly when unpruned, have been associated with high coffee rust impacts and intensities. Old coffee trees have reduced growth compared to young trees. When vegetative growth is substantial, the result is a dilution of the disease and a decrease in disease intensity due to the appearance of new healthy leaves (Ferrandino, 2008). This dilution effect has already been reported for coffee rust (Kushalappa and Ludwig, 1982; Lopez-Bravo et al., 2012). In addition, in young coffee trees with ample branch growth, fallen leaves due to coffee rust are continuously replaced with new healthy ones. This recovery effect can help to reduce the number of dead branches and impacts on yield. The effects of fertilizer applications on coffee rust can also be partly attributed to dilution and recovery effects, as nutrients are incorporated into vegetative growth. These effects have already been reported (Avelino et al., 2006; Cristancho et al., 2012). However, fertilizer effects on leaf receptivity, i.e. physiological resistance, cannot be ruled out. Recently, nitrogen applications were reported to reduce coffee leaf receptivity to coffee rust (Toniutti et al., 2017). In our study, most of the nutrients that were adopted for building the fertilizer application typology were probably not crucial for coffee leaf physiological resistance because they were applied to foliage at low doses. In addition, the largest quantities of the nutrients applied were split within two fertilizer application categories, both of which were associated with the lowest disease impacts and intensities, indicating that differences between these two categories did not affect coffee rust. For that reason, we took a closer look at only two nutrients that were almost equally high in both typologies: K applied to soil and foliage, and S applied to foliage. Potassium has been reported to decrease plant susceptibility in a series of pathosystems, particularly in cases of K soil deficiencies, through different mechanisms, such as increased outer cell wall rigidity or increased activity of K-dependent enzymes that contribute to the biosynthesis of starch or amino acids, reducing the availability of soluble sugars (Amtmann et al., 2008; Dordas, 2008; Walters and Bingham, 2007). Recently, high concentrations of K were found at the periphery of coffee rust lesions, suggesting a kind of defense reaction linked to K (Belan et al., 2015b). Similarly, S is a micronutrient that is known to be involved in plant defense reactions (Walters and Bingham, 2007). The effects of these two nutrients on coffee rust probably deserve further investigation.

Our results also highlighted that medium to high education levels, as well as access to training and on-farm advice, were related to low coffee rust impacts and intensities. The role of training and education in increasing coffee farmers' capabilities has been recognized on many occasions (Avelino et al., 2015; Flood and Day, 2016). Our results provided new evidence of the impact of education, training and on-farm advice in reducing the vulnerability of coffee farmers. However, despite being so important, most of the domestic public and semi-public extension services have reduced their activities due the reduction in their core budget, which mainly depends on the value of the coffee exported. In periods of low coffee prices and of reduced production due to coffee rust impacts, this activity has been severely hit.

5. Conclusions

The main drivers of the coffee rust epidemic were meteorological. However, in these propitious weather conditions for coffee rust, some farmers were able to avoid intense epidemics and losses, whereas the great majority of them suffered heavy losses. Rational fungicide spraying and fertilizer applications were key practices in managing coffee rust. These practices are well known by farmers. However, precarious economic conditions were a strong obstacle to their application. To our knowledge, this is the first time that relationships between poor economic conditions and the development of intense outbreaks have been highlighted. The solution to the coffee rust issue therefore has a strong economic component that the market needs to recognize.

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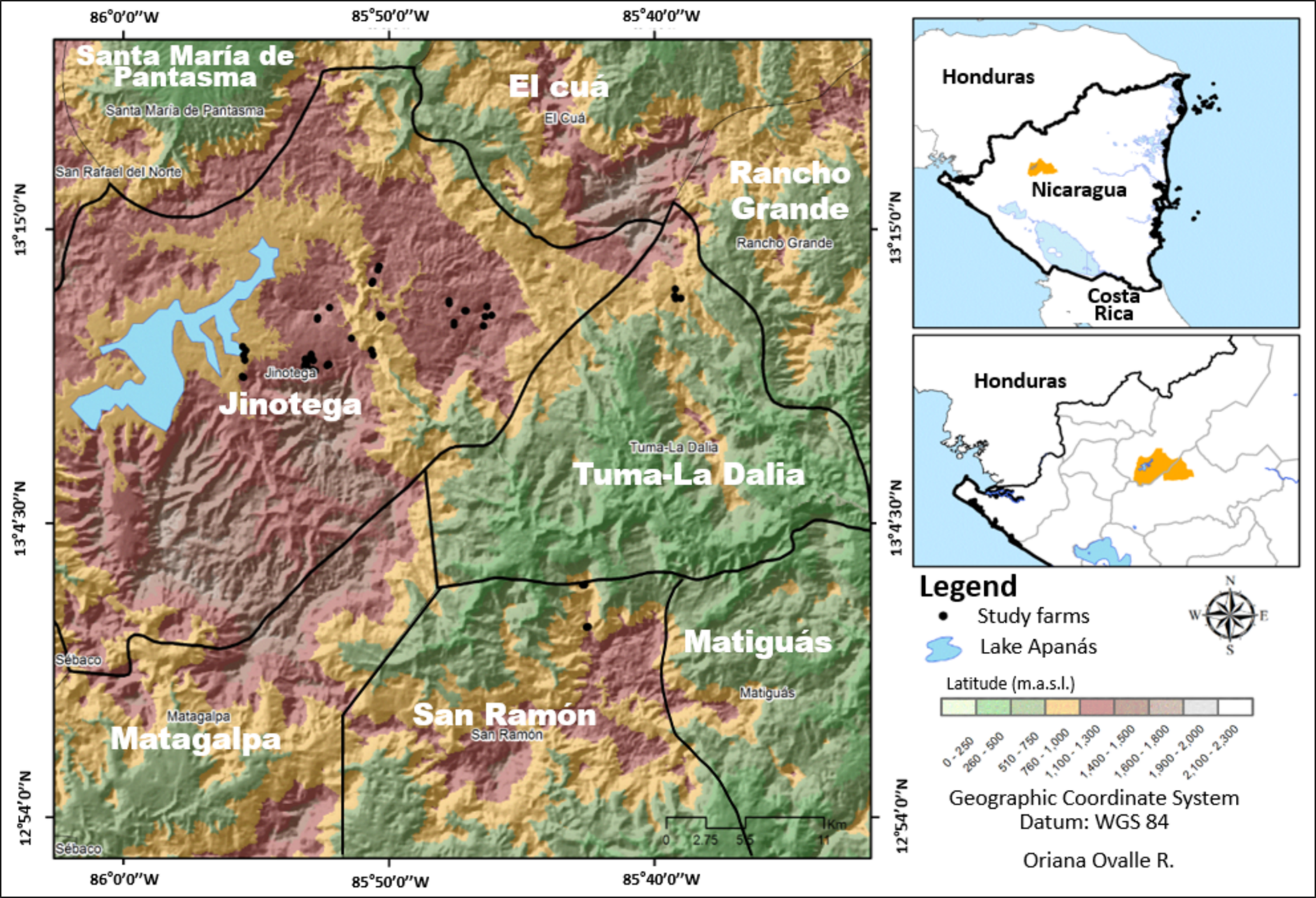
Fig. 1. Map of the study area showing the study farms. Courtesy of O. Ovalle.

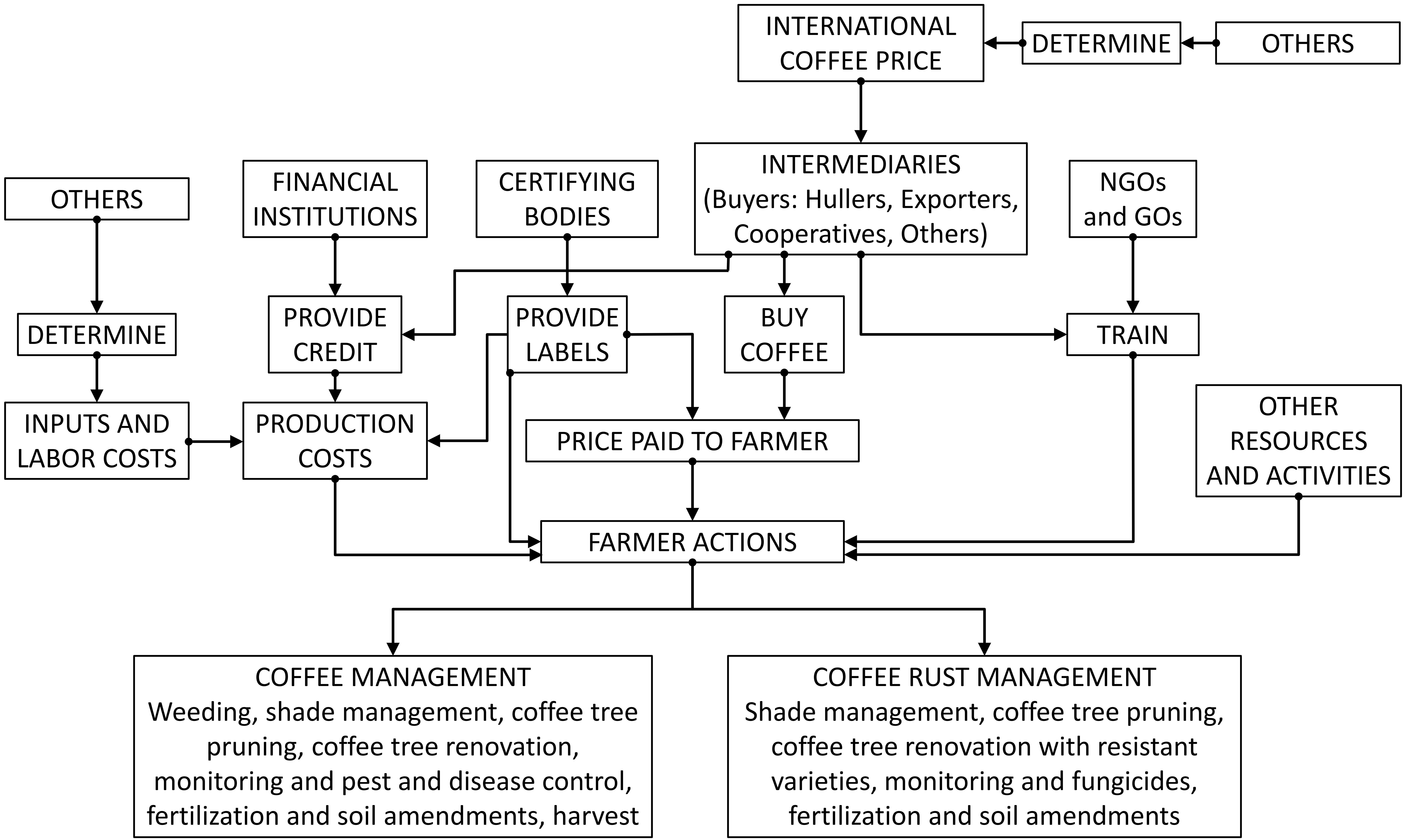
Fig. 2. Expert conceptual model about the drivers of farmer actions

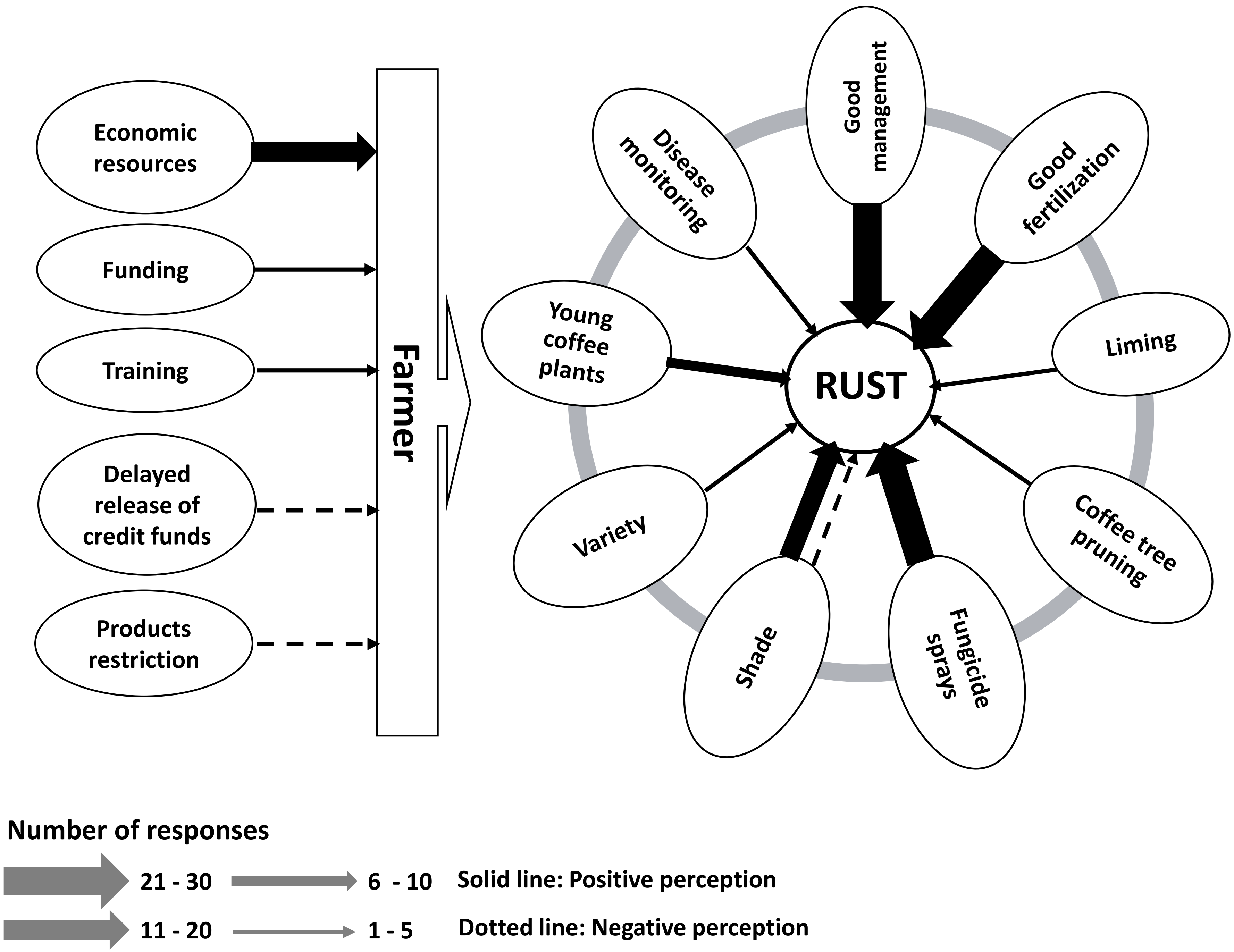
Fig. 3. Factors that favored or hampered coffee rust in 2012 according to farmers (mental model)

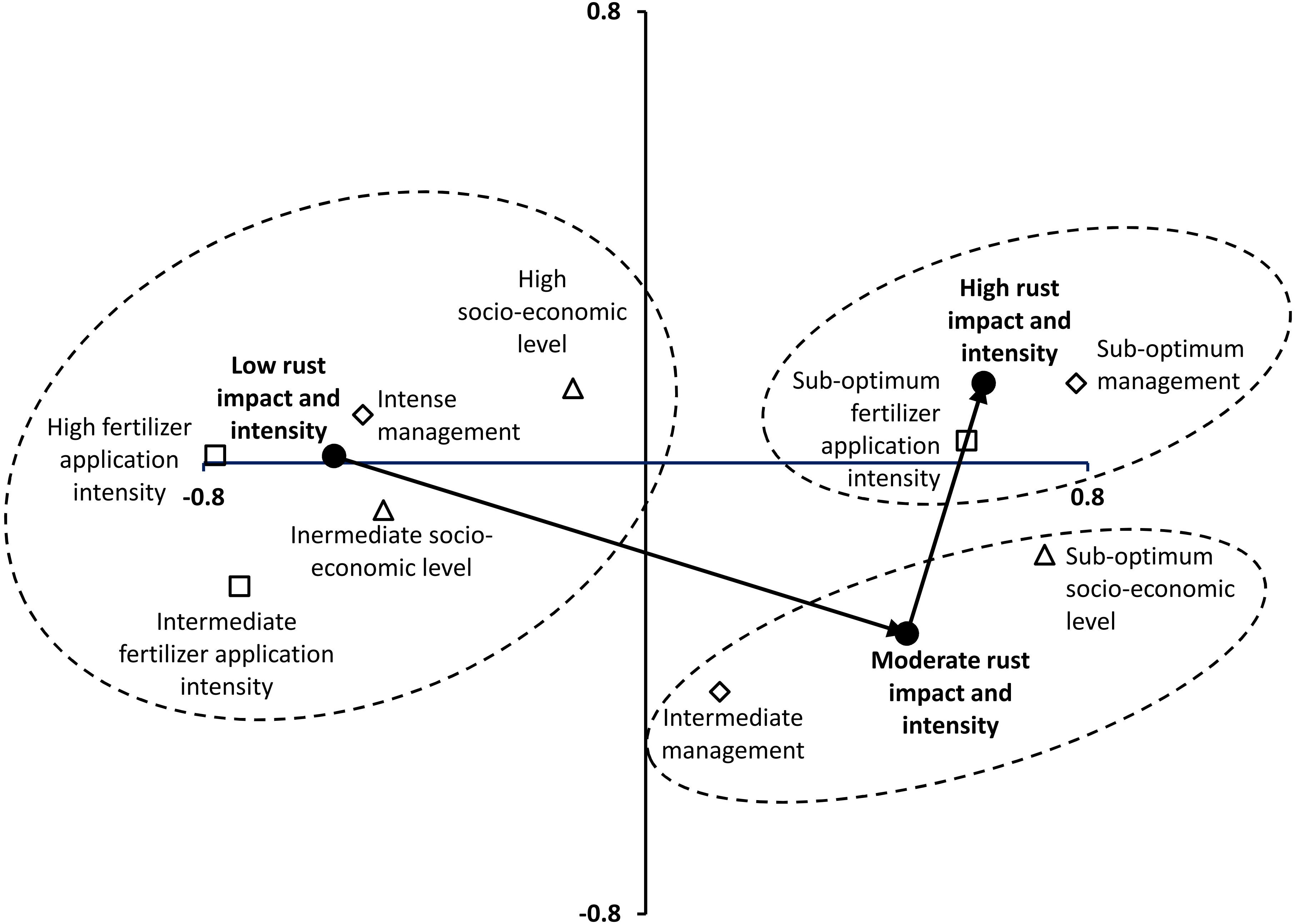
Fig. 4. Correspondence analysis highlighting the relationships between crop management, particularly fertilization, farmer socio-economic level and coffee rust impact and intensity, according to field measurements and variables informed by farmers. Axis one comprises 93% of the variability and axis two 7%.



86°0'0"W
85°50'0"W
85°40'0"W
13°15'0"N
13°4'30"N
12°54'0"N
Santa María de Pantasma
Santa María de Pantasma
El cuá
El Cuá
San Rafael del Norte
Rancho Grande
Rancho Grande
Jinotega
Jinotega
Tuma-La Dalia
Tuma-La Dalia
Sébaco
Matagalpa
Matagalpa
San Ramón
San Ramón
Matiguás
Matiguás
Sébaco
0 2.75 5.5 11 Km
Honduras
Nicaragua
Costa Rica
Honduras
Legend
Study farms
Lake Apanás
Latitude (m.a.s.l.)
0 - 250
260 - 500
510 - 750
760 - 1,000
1,100 - 1,300
1,400 - 1,500
1,600 - 1,800
1,900 - 2,000
2,100 - 2,300
N S E W
Geographic Coordinate System
Datum: WGS 84
Oriana Ovalle R.


INTERNATIONAL COFFEE PRICE
DETERMINE
OTHERS
OTHERS
FINANCIAL INSTITUTIONS
CERTIFYING BODIES
INTERMEDIARIES (Buyers: Hullers, Exporters, Cooperatives, Others)
NGOs and GOs
DETERMINE
PROVIDE CREDIT
PROVIDE LABELS
BUY COFFEE
TRAIN
INPUTS AND LABOR COSTS
PRODUCTION COSTS
PRICE PAID TO FARMER
OTHER RESOURCES AND ACTIVITIES
FARMER ACTIONS
COFFEE MANAGEMENT
Weeding, shade management, coffee tree pruning, coffee tree renovation, monitoring and pest and disease control, fertilization and soil amendments, harvest
COFFEE RUST MANAGEMENT
Shade management, coffee tree pruning, coffee tree renovation with resistant varieties, monitoring and fungicides, fertilization and soil amendments


Economic resources
Funding
Training
Delayed release of credit funds
Products restriction
Farmer
RUST
Good management
Disease monitoring
Good fertilization
Liming
Young coffee plants
Variety
Shade
Fungicide sprays
Coffee tree pruning
Number of responses
21 - 30
6 - 10
Solid line: Positive perception
11 - 20
1 - 5
Dotted line: Negative perception



0.8
-0.8
-0.8
0.8
High socio-economic level
Low rust impact and intensity
Intense management
High fertilizer application intensity
Inermediate socio-economic level
Intermediate fertilizer application intensity
High rust impact and intensity
Sub-optimum management
Sub-optimum fertilizer application intensity
Sub-optimum socio-economic level
Moderate rust impact and intensity
Intermediate management

Table 1

Description of the coffee rust impact and intensity categories obtained by cluster analysis (percentages of plots in the main modalities and means, for qualitative and quantitative variables, respectively), and contribution of the variables to the typology (*P* values of Fisher's exact test and Kruskal-Wallis test for qualitative and quantitative variables, respectively)

Variable	**Low coffee rust impact and intensity category**	**Moderate coffee rust impact and intensity category**	**High coffee rust impact and intensity category**	**Overall (for all plots)**	***P***
Infection level on a plantation scale in the 2012-13 production year	100% Low	60% Severe 40% Moderate	100% Severe	50% Low 7% Moderate 43% Severe	<0.001
Proportion of coffee trees heavily infected on a plantation scale in the 2012-13 production year	100% with <25%	80% with 25-50%	100% with >50%	50% with <25% 14% with 25-50% 36% with >50%	<0.001
Proportion of the plantation area heavily infected in the 2012-13 production year	100% with <25%	90% with 25-50%	100% with >50%	50% with <25% 16% with 25-50% 34% with >50%	<0.001
Proportion of dead branches on a plantation scale in the 2012-13 production year	100% with <25%	70% with <25%	47% with 25-50% 47% with >50%	64% with <25% 21% with 25-50% 15% with >50%	<0.001
Proportion of fallen leaves on a plantation scale in the 2012-13 production year	97% with <25%	50% with 25-50% 50% with >50%	100% with >50%	48% with <25% 11% with 25-50% 41% with >50%	<0.001
Defoliation time in the 2012-13 production year	38% during harvest 34% before harvest	90% before harvest	89% before harvest	62% before harvest 24% during harvest 14% after harvest	<0.001
Proportion of pruned coffee trees on a plantation scale after the epidemic in 2013	97% with <20%	80% with 20-50%	74% with >50%	50% with <20% 22% with 20-50% 28% with >50%	<0.001
Pruning system applied after the epidemic	90% on a coffee tree basis	50% with both systems	84% on a coffee block basis	50% on a coffee tree basis 33% on a coffee block basis 17% with both systems	<0.001
Observed pruning intensity in 2013 (%)	13 (7)*	27 (11)	55 (29)	29 (26)	<0.001
Estimated green coffee losses in the 2012-13 production year on a plantation scale (kg ha^{-1})	21 (40)	62 (69)	181 (274)	81 (174)	0.004
Estimated green coffee losses in the 2013-14 production year on a plantation scale (kg ha^{-1})	45 (47)	393 (165)	481 (334)	248 (288)	<0.001
Total number of fruiting nodes per coffee tree in the 2013-14 production year	135 (73)	41 (32)	8 (15)	77 (79)	<0.001
Number of plots	29	10	19	58	

* Standard deviation in brackets

Table 2

Explanatory variables adopted according to their relationship with coffee rust impact and intensity categories (*P* values <0.1 of Fisher's exact test and the Kruskal-Wallis test for qualitative and quantitative variables, respectively)

Variable group	Variable	Range or modalities	*P*
Management (except fertilizer applications)			
Coffee tree characteristics	Pruning system	On a Plot, Row, Tree, Stem basis, No pruning	0.005
	Coffee tree age (years)	4-45	<0.001
Cropping practices	Number of shade management operations in 2012	0-2	0.020
	Shade pruned in 2011	Yes, no	0.001
	Shade pruned in 2012	Yes, no	<0.001
	Monitoring system for coffee rust	Yes, no	0.007
	First fungicide application in 2012	First half of year, second half of year, none (no spray)	0.050
	Number of fungicide applications in 2011	0-5	0.039
	Number of fungicide applications in 2012	0-8	<0.001
	Number of curative fungicide applications in 2012	0-8	0.003
Fertilizer applications	Number of soil fertilizer applications in 2011	0-4	0.017
	Number of soil fertilizer applications in 2012	0-4	<0.001
	K applied to soil in 2012 (kg ha^{-1})	0-344	0.003
	B applied to soil in 2012 (kg ha^{-1})	0-42	0.092
	Number of foliar fertilizer applications in 2011	0-6	<0.001
	Number of foliar fertilizer applications in 2012	0-6	<0.001
	N applied to foliage in 2012 (g ha^{-1})	0-7676	<0.001
	P applied to foliage in 2012 (g ha^{-1})	0-2562	0.009
	K applied to foliage in 2012 (g ha^{-1})	0-4014	<0.001
	Ca applied to foliage in 2012 (g ha^{-1})	0-961	<0.001
	Mg applied to foliage in 2012 (g ha^{-1})	0-1708	<0.001
	S applied to foliage in 2012 (g ha^{-1})	0-352	0.084
	B applied to foliage in 2012 (g ha^{-1})	0-640	<0.001
	Cu applied to foliage in 2012 (g ha^{-1})	0-31	0.081
	Zn applied to foliage in 2012 (g ha^{-1})	0-640	<0.001
	Fe applied to foliage in 2012 (g ha^{-1})	0-71	0.081
	Mn applied to foliage in 2012 (g ha^{-1})	0-1550	0.005
	Polysaccharides applied to foliage in 2012 (g ha^{-1})	0-559	0.021
	Amino Acids applied to foliage in 2012 (g ha^{-1})	0-753	0.017
Socio-economic characteristics	Producer age (years)	32-79	0.030
	Producer education level	No academic education, primary school, high school, university	<0.001
	Direct technical advice	Yes, no	0.082
	Training activities on coffee	Yes, no	0.002
	Number of technician visits per year (average of	0-36	0.024
	Number of topics covered	0-10	0.010
	Producer income related to coffee sales in the 2011-	195-4783	0.008
	Access to credit	Yes, no	0.002

Table 3

Explanatory variables rejected according to their relationship with coffee rust impact and intensity categories (*P* values >0.1 of Fisher's exact test and the Kruskal-Wallis test for qualitative and quantitative variables, respectively)

Variable group	Variable	Range or modalities	*P*
Management (except fertilizer applications)			
Vegetation structure	Number of shade strata	1, 2, 3	0.49
	Number of shade tree species	1-13	0.79
	Density of banana plants (ha^{-1})	0-640	0.27
	Density of trees in the 2-8 m stratum (ha^{-1})	30-460	0.36
	Density of trees in the 9-17 m stratum (ha^{-1})	0-300	0.66
	Density of trees in the 18-24 m stratum (ha^{-1})	0-50	0.52
	Presence-absence of legume trees	Presence, Absence	0.50
	Presence-absence of timber trees	Presence, Absence	0.53
	Presence-absence of fuel wood trees	Presence, Absence	0.68
	Presence-absence of fruit trees	Presence, Absence	0.11
	Shade cover (%)	14-85	0.67
	Area with bare ground (%)	0-56	1.00
	Ground cover with litter (%)	0-49	0.11
	Ground cover with weeds (%)	0-52	0.11
	Good cover plants (%)	33-100	0.13
Coffee tree characteristics	Orientation of coffee tree rows (°)	0-180	0.25
	Density of coffee trees (ha^{-1})	0-7926	0.11
	Number of coffee trees per planting hole	1-2	0.25
Cropping practices	Number of chemical weedings in 2012	0-3	0.28
	Number of mechanical weedings in 2012	0-3	0.69
	Number of protective fungicide applications in 2012	0-3	0.68
Fertilizer applications	N applied to soil in 2012 (kg ha^{-1})	0-659	0.22
	P applied to soil in 2012 (kg ha^{-1})	0-216	0.21
	Ca applied to soil in 2012 (kg ha^{-1})	0-115	0.16
	Mg applied to soil in 2012 (kg ha^{-1})	0-97	0.13
	S applied to soil in 2012 (kg ha^{-1})	0-134	0.13
Topography	Altitude (m)	836-1213	0.32
	Slope aspect (° from N to E)	0-347	0.66
	Slope inclination (%)	0-80	0.76
Socio-economic characteristics	Number of family members	2-10	0.35
	Highest education level in the family	Primary school, high school, university	0.40

Table 4

Description of the management categories (except fertilizer applications) obtained by cluster analysis (percentages of plots in the main modalities and means, for qualitative and quantitative variables, respectively), and contribution of the variables to the typology (*P* values of Fisher's exact test and the Kruskal-Wallis test for qualitative and quantitative variables, respectively)

Variable	**Sub-optimum management category**	**Intermediate management category**	**Intense management category**	**Overall (for all plots)**	***P***
Pruning system	65% on a coffee tree or stem basis 29% with no pruning	100% on a coffee tree or stem basis	90% on a coffee tree or stem basis	84% on a coffee tree or stem basis 10% on a coffee block or row basis 16% with no pruning	<0.001
Coffee tree age	22.1 (10.3)*	12.2 (5.4)	14.1 (7.9)	16.0 (9.1)	0.001
Number of shade management operations in 2012	0.5 (0.5)	1.0 (0.0)	1.2 (0.4)	1 (0.5)	<0.001
Shade pruned in 2011	94% no	75% yes	93% yes	64% yes 36% no	<0.001
Shade pruned in 2012	71% no	100% yes	100% yes	79% yes 21% no	<0.001
Monitoring system for coffee rust	88% no	75% no	66% yes	59% no 41% yes	<0.001
First fungicide application in 2012	53% in the 1st half of the year 29% in the 2nd half of the year	100% in the 2nd half of the year	100% in the 1st half of the year	66% in the 1st half of the year 29% in the 2nd half of the year 5% with no spraying	<0.001
Number of fungicide applications in 2011	0.9 (1.0)	1.8 (1.2)	2.4 (1.5)	1.8 (1.4)	0.003
Number of fungicide applications in 2012	1.4 (1.0)	1.9 (0.9)	3.6 (1.6)	2.6 (1.6)	<0.001
Number of protective fungicide applications in 2012	1.0 (1.0)	1.3 (0.9)	3.2 (1.8)	2.2 (1.8)	<0.001
Number of plots	17	12	29	58	

* Standard deviation in brackets

Table 5

Description of the fertilizer application categories obtained by cluster analysis (means), and contribution of the variables to the typology (*P* values of the Kruskal-Wallis test)

Variable	Sub-optimum fertilizer application category	Intermediate fertilizer application category	High fertilizer application category	Overall (for all plots)	*P*
Number of soil fertilizer applications in 2011	1.2 (0.8)*	2.0 (0.6)	2.4 (1.1)	1.7 (1.0)	<0.001
Number of soil fertilizer applications in 2012	1.4 (0.7)	2.4 (0.5)	2.7 (1.0)	1.9 (1.0)	<0.001
K applied to soil in 2012 (kg ha^{-1})	37 (30)	114 (92)	141 (94)	79 (80)	<0.001
B applied to soil in 2012 (kg ha^{-1})	2.8 (3.5)	2.5 (2.9)	12.5 (15.9)	5.8 (10.2)	0.100 ^{NS}
Number of foliar fertilizer applications in 2011	0.7 (0.7)	1.7 (0.8)	3.2 (1.5)	1.6 (1.5)	<0.001
Number of foliar fertilizer applications in 2012	0.9 (0.9)	2.1 (0.4)	3.7 (1.1)	1.9 (1.6)	<0.001
N applied to foliage in 2012 (g ha^{-1})	117 (137)	527 (375)	1137 (1817)	483 (1106)	<0.001
P applied to foliage in 2012 (g ha^{-1})	95 (129)	37 (97)	811 (642)	310 (499)	<0.001
K applied to foliage in 2012 (g ha^{-1})	186 (295)	1171 (1122)	1163 (1080)	608 (877)	<0.001
Ca applied to foliage in 2012 (g ha^{-1})	13 (39)	549 (292)	154 (130)	122 (211)	<0.001
Mg applied to foliage in 2012 (g ha^{-1})	4 (18)	61 (104)	145 (395)	55 (228)	<0.001
S applied to foliage in 2012 (g ha^{-1})	2 (10)	58 (102)	46 (102)	23 (69)	0.009
B applied to foliage in 2012 (g ha^{-1})	16 (37)	388 (193)	135 (105)	98 (150)	<0.001
Cu applied to foliage in 2012 (g ha^{-1})	0.5 (1.3)	0.1 (0.3)	6.4 (9.4)	2.3 (5.9)	<0.001
Zn applied to foliage in 2012 (g ha^{-1})	23 (45)	397 (192)	170 (124)	114 (159)	<0.001
Fe applied to foliage in 2012 (g ha^{-1})	1.0 (2.0)	1.8 (4.8)	13.6 (18.4)	5.0 (11.8)	0.005
Mn applied to foliage in 2012 (g ha^{-1})	0.5 (1.3)	122.4 (208.0)	14.0 (24.2)	19.4 (79.1)	0.006
Polysaccharides applied to foliage in 2012 (g ha^{-1})	0 (0)	332 (172)	11 (28)	44 (122)	<0.001
Amino Acids applied to foliage in 2012 (g ha^{-1})	27 (75)	119 (156)	95 (197)	59 (137)	0.004
Number of plots	33	7	18	58	

* Standard deviation in brackets

NS Non-significant (*P*>0.05)

Table 6

Description of the socio-economic categories obtained by cluster analysis (percentages of plots in main modalities and means, for qualitative and quantitative variables, respectively), and contribution of the variables to the typology (*P* values of Fisher's exact test and the Kruskal-Wallis test for qualitative and quantitative variables, respectively)

Variable	**Sub-optimum socio-economic category**	**Intermediate socio-economic category**	**High socio-economic category**	**Overall (for all plots)**	***P***
Producer age (years)	55 (14)*	49 (12)	48 (9)	50 (12)	0.160 [NS]
Producer education level	73 % with no academic education	60 % with primary school	93% with high school	52% with high school 31% with no academic education 27% with primary school	<0.001
Direct technical advice	53% no	100% yes	72% yes	72% yes 28% no	0.007
Training activities on coffee	100% no	100% yes	100% yes	74% yes 26% no	<0.001
Number of topics covered	0 (0)	3.9 (1.5)	4.6 (2.0)	3.2 (2.5)	<0.001
Number of technician visits per year (average of 2011, 2012 and 2013	4.5 (8.1)	9.3 (7.4)	9.3 (10.8)	8.1 (9.3)	0.031
Producer income related to coffee sales in the 2011-12 and 2012-13 harvests, on average (USD ha^{-1})	1046 (1207)	1402 (993)	1471 (840)	1343 (983)	0.032
Access to credit	80% yes	100% yes	82% yes	86% yes 14% no	0.130 [NS]
Number of plots	15	15	28	58	

* Standard deviation in brackets

[NS] Non-significant (*P*>0.05)