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HOLISTIC RISK INDEX FOR DECISION-MAKING IN MANAGEMENT OF RUST *Hemileia vastatrix* IN COFFEE PLANTATIONS IN HONDURAS

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ABSTRACT

One of the diseases that most affect coffee plantations (*Coffea arabica*) is the fungus *Hemileia vastatrix*, which causes rust. The lack of a decision-making method with a holistic approach limits the effective management of this disease. Therefore, this study aimed to determine the Holistic Risk Index (HRI) for rust in coffee-growing zones of El Lago de Yojoa, El Paraíso and Olancho, Honduras. First, a participatory diagnosis of coffee industry was implemented; surveys were conducted to determine the socioeconomic status of 43 coffee producers, also their coffee farms were sampled. The diagnosis indicated that deficient management of the coffee plantations, the incidence of pests and a precarious economy for coffee growers were the most important problems. One threat variable (leaves with rust); three vulnerability variables (altitude, coffee variety and shade); and three response capacity variables (technification, harvesting and productive coffee trees) were identified. The HRI and resilience were related by means of a power equation and from that result the criteria for categories were determined. When comparing the three coffee-growing zones with a multivariate analysis of variance and a canonical discriminant analysis for the set of HRI component values, the El Paraíso coffee-growing zone was different from the Lago de Yojoa zone, but these two zones did not differ from the Olancho zone. The same result was found for the response capacity, where the harvest and technification variables had a greater influence in El Paraíso and the productive category variable of coffee trees was more important in Olancho. Finally, a work plan was proposed to reduce the risk and increase the resilience of producers to rust.

Keywords: coffee rust, *Coffea arabica*, vulnerability, response capacity, holistic approach, risk management.

INTRODUCTION

Coffee (*Coffea arabica*) is grown in tropical and subtropical regions of the world, where it contributes to the household economy of millions of people who depend directly and indirectly on the income generated by its cultivation, processing and marketing (ICO, 2015; 2020). Among the factors that limit the profits from the sale of coffee production, and that put the well-being of the producing families at risk, are various problems caused by pests (Krishnan *et al*., 2021). For the purposes of this study, and taking into consideration the definition proposed by FAO (2019), we will understand by pest any plant or animal species, race or biotype or pathogenic agent harmful to plants or plant products.

One of the phytosanitary problems with the greatest negative impact on this crop is coffee rust caused by the fungus *Hemileia vastatrix* Berk. & Broome. This fungus is a biotrophic parasite of coffee trees, among which the Arabica coffee varieties (*C. arabica*) are the most susceptible. Plants attacked by *H. vastatrix* decrease their production due to leaf loss, and some branches or the plant may even die as a consequence of the stress caused by this disease or by the action of other opportunistic plant pathogens (Avelino *et al*., 2015). Following the devastating outbreak of this disease in Central America and Mexico in 2012, monetary losses were estimated at USD $369.3 million in the 2012/13 cycle and USD $245 million in the 2013/14 cycle (ICO, 2015). Therefore, the effective management of the diverse plant pathogens that affect the production and quality of coffee represents one of the most important challenges for this industry in the world.

By harmoniously integrating the available control tactics, it is intended to prevent *H. vastatrix* from causing economic losses. For this purpose, the Integrated Pest Management (MIP) strategy uses action thresholds such as economic-injury level and economic threshold (Deguine *et al*., 2021). But decision-making in pest management based on action thresholds neglects relevant social, economic and environmental aspects of the socio-environmental system. To address this deficiency, Holistic Pest Management (MHP), a pest management strategy based on a holistic approach to the socio-environmental system has proposed the Holistic Risk Index (HRI) as a decision-making tool (Barrera, 2020).

This index is based on social, economic, and environmental variables grouped into three components: threats (plant pathogen agents), vulnerability and the response capacity of producers and their production units. Other studies agree in pointing out the importance of the risk approach in decision-making to manage socio-environmental systems (Altieri and Nicholls, 2013; Montalba *et al*., 2013; Gazzano *et al*., 2015).

The results of this study are expected to identify the most vulnerable zones and contribute with risk and resilience criteria to the decision-making process of producers for rust management. The hypothesis proposed that decision-making based on risk and resilience would make it possible to identify the most vulnerable coffee-growing zones with the least capacity to respond to the threat posed by rust in order to guide zonal management actions. Therefore, the objective of the study was to determine the holistic risk index to *H. vastatrix* for coffee producers by identifying production and marketing problems, determining the components of the holistic risk index and estimating resilience to rust in three coffee-growing zones of Honduras.

MATERIALS AND METHODS

Zone and period of study

The study was carried out in coffee plantations of producers in three coffee-growing zones of Honduras, Central America: Central North or Lago de Yojoa zone, which included producers located in the departments of Cortés, Santa Bárbara and Comayagua; in the East zone, with producers from the department of El Paraíso; and in the Central East zone with producers from the department of Olancho. For identification purposes in this study, producers in Lado de Yojoa will be referred to as producers located in the Central North zone, producers in El Paraíso will be referred to as producers in the East zone and producers in Olancho will be referred to as producers in the Central East zone. Field activities and analysis were carried out from September 2016 to April 2017, in coordination with the Instituto Hondureño del Café (IHCAFÉ).

Problem identification

The study began with a diagnosis workshop in which 32 coffee producers participated. Using the "brainstorming" technique, the producers expressed verbally and in writing their main problems in coffee production and marketing. Afterwards, each producer was asked to write on a sheet of paper the 20 most important problems and to identify the ten with the highest importance and mention them in ascending order (1: most important, 10: least important). To identify the ten most important problems of the group of producers, the average number of points obtained for each problem prioritized at the individual level was calculated.

Interactions between variables

The ten most important needs (now converted into variables) were analysed by means of a structural analysis. This analysis allows us to understand the functioning of the system by establishing the degree of interdependence and the degree of influence (mobility) between the variables (Barrera *et al*., 2013). As a result, by plotting the relationship between dependence (abscissae) with respect to mobility (ordinates), the four zones or zones of structural analysis were established in which the variables under study are distributed: autonomous zone (low interdependence, low mobility), power zone (low interdependence, high mobility), exit zone (high interdependence, low mobility) and conflict zone (high interdependence, high mobility).

Rapid Agroecological Sampling

The information was collected by Rapid Agroecological Sampling (RAS) according to the methodology described by Barrera (2020). The RAS consisted of a semi-structured interview with producers and a sampling of their coffee plantations. A total of 43 surveys were carried out because the sample consisted of 43 coffee plantations.

Interview with the producer

The semi-structured interview consisted of 47 questions to characterize the socioeconomic aspects of the producer (owner or manager) and his/her household such as age, sex, schooling, family composition, income, affiliation to an organization, level of interest in coffee cultivation, planting zones, varieties, planting density, agronomic management, shade trees, soil conservation, predominant pests, expected yield, coffee processing, coffee bean commercialization and production costs.

Sampling of the production unit

Location. A map of each farm or production unit was made and the geographic coordinates and altitude (m) were determined using an Android application.

Sampling area. Within the production unit an "internal plot" of 20 x 20 m was delimited to carry out the sampling of the coffee plantation.

Coffee and shade trees. The total number of coffee trees and shade trees in the internal plot was counted. For each of the shade trees, the species, height, and normal diameter were determined; normal diameter (at 1.3m high) was measured on trees with DN>5 cm. The presence/absence of epiphytes and parasitic plants on the shade trees was also determined.

Shade percentage. The percentage of shade (vegetation cover) in the inner plot was determined using the grid method. This method consisted of recording the number of coffee trees that were under a shade tree by sampling one coffee tree and another not.

Soil cover. The presence-absence of soil cover was recorded by empirical measurement with a fixed distance reference standard (the length of the shoe to the toe), known as the "toe of the shoe method". The absence of vegetation was recorded by finding leaf litter and bare soil, while the presence of vegetation was identified as living vegetation or soil cover (weeds) in 30 points (separated every 5 m) located between the rows of coffee trees in the internal plot. The soil vegetation cover was classified into the following groups of weeds: grasses, annual and perennial broad-leaved plants and herbaceous vines between the rows of coffee trees or on the coffee trees.

Pests. The most common coffee pests were sampled using the integral count method. Sampling for insects (coffee berry borer, scales, mealy bugs, etc.) and plan pathogen fungi that cause rust, American leaf spot (*Mycena citricolor*), or anthracnose (*Colletotrichum* spp.), among others, was carried out on a branch in the middle third of each of 20 coffee trees in the internal plot. The percentage of infestation of each organism was calculated based on the number of fruits or leaves affected per branch. For stem borers (Carambycidae) and crickets (Gryllidae), the stems of coffee trees were also sampled.

Estimated harvest. To estimate the harvest, 25 coffee trees were chosen in the internal plot distributed in a 5 x 5 square of coffee trees. These coffee trees were determined for age, variety, plant height, stem thickness, number of axes (orthotropic branches), defoliation and number of coffee trees in production (category I, normal; category II, coffee trees requiring pruning). Afterwards, the fruits of a representative coffee tree of each of these two production categories were counted. The total number of fruits per internal plot was estimated by multiplying the number of fruits per category of coffee tree by the number of coffee trees in each category.

Producer characterization

The 43 producers participating in the study were characterized on the basis of the information from the surveys and the sampling of coffee plantations. For this purpose, the IHCAFÉ classification was used as a reference, which classifies producers into four groups based on the agronomic management of their coffee plantations during the year.

According to this categorization, the 43 producers who participated in this study were classified into four groups (Table 1). Of the producers 11.6 % were classified in group 1; 51.2 % in group 2; 20.9 % in group 3; and 16.3 % in group 4. Regarding the geographic location of the producers, 25.6 % were located in Olancho; 27.9 % in El Paraíso; and 46.5 % in Lago de Yojoa.

The plantations of the producers of Lago de Yojoa who participated in the study were located at an altitude between 684 and 1577 m; those of El Paraíso between 806 and 1300 m; and those of Olancho between 638 and 1500 m. Regarding coffee varieties, the producers of Lago de Yojoa participating in the study cultivated Lempira, IHCAFÉ 90,

Table 1. Categorization of coffee producers participating in the study according to agronomic management of the crop in Honduras, Central America (2016-2017).

Groups or categories and description of the main agronomic activities in the year	Study zones			Total
	Lago de Yojoa	El Paraíso	Olancho	
1. Weed control and no agrochemicals are applied.	3	1	1	5
2. Weed control and apply 1-2 soil fertilizations and apply a fungicide.	11	5	6	22
3. Weed control and apply a minimum of three soil fertilizations, fungicides and pruning.	4	3	2	9
4. Weed control and apply more than four soil fertilizations, apply fungicides, prune and use a comprehensive pest control and plant nutrition program.	2	3	2	7
Total	20	12	11	43

Catuaí, Parainema, Catimor, Bourbon, San Ramón, Villalobo and Pacas; in El Paraíso they cultivated Lempira, IHCAFÉ 90 and Parainema; and in Olancho Lempira and Parainema. The percentage of farmers growing only rust susceptible varieties was 70 % in El Lago de Yojoa, 70 % in El Paraíso and 100 % in Olancho.

Calculation of the Holistic Risk Index

Once the information from the interviews with producers and the sampling of production units was tabulated, the variables were classified according to the risk components (HRI): threat (A), vulnerability (V) and response capacity (C) (Table 2). Next, the cause-effect relationship was established between the variables classified as V and C compared to A (coffee rust). The variables of the three components were then standardized on a scale of 1 to 100. Once the variables were standardized, the value of each risk component was calculated by adding the individual values of the variables that made it up. Finally, the risk (HRI) of each producer (n = 43) to rust was calculated with the formula HRI = (A + V) / C (Equation 1) (Barrera, 2020).

Analysis of the Holistic Risk Index

To contrast the risk values (HRI) between the coffee-growing zones under study (Lago de Yojoa, El Paraíso and Olancho), the analysis of variance (ANOVA) was applied, and

Table 2. Components and indicators of the holistic risk index (HRI) and its relationship with the pathogen causing coffee rust (*Hemileia vastatrix*) in Honduras.

Component. Indicators (variables)	Relation of factors (A, V, C) with rust incidence (%)
Threat (A). Percentage of leaves with rust (number of coffee leaves; incidence of rust).	Rust incidence: very low (0.1-4.9 %): A = 5 %; low (5.0 - 9.9 %): A = 20 %; medium (10.0 - 14.9 %): A = 30 %; high (15.0-19.9 %): A = 50 %; very high (≥20 %): A = 100 %.
Vulnerability (V). Altitude of the coffee plantation in meters above sea level (m).	Altitude: low (< 600 m): V = 50 %; medium (600 - 1000 m): V = 100 %; high (1001 - 1200 m): V = 75 %; very high (> 1200 m): V = 25 %.
Vulnerability (V). Variety[†] of coffee (rust susceptibility/tolerance ratio).	Coffee variety: susceptible: V = 100 %; moderately tolerant (mixture of susceptible and tolerant): V = 50 %; very tolerant: V = 0 %.
Vulnerability (V). % shade (number of coffee trees under shade).	Shade: none: V = 80 %; low: V = 40 %; medium: V = 20 %; very much: V = 100 %.
Response capacity (C). Degree of technification[¶] (agrochemicals, pruning).	Technification: low: C = 25 %; medium: C = 50 %; high: C = 75 %; very high: C = 100 %.
Response capacity (C). Difference between obtained and expected yield in quintals per manzana (Q per manzana[§]).	Yield: very poor (< -15 Q per manzana): C = 0 %; poor (-15 to < 0 Q per manzana): C = 25 %; equal (0 Q per manzana): C = 50 %; good (> 0 to ≤20 Q per manzana): C = 75 %; very good (> 20 Q per manzana): C = 100 %.
Response capacity (C). Productive categories[Þ] (% of coffee trees I and II).	% I and II: none, C = 0 %; low: C = 25 %; regular: C = 50 %; high: C = 75 %; very high: C = 100 %.

[†]All varieties are of the species *Coffea arabica*. [¶]Technification corresponds to the categories in Table 1. [§]One quintal of green coffee (Q) is equivalent to 46 kg and one manzana is equivalent to 0.70 ha. [Þ]In production category I the coffee trees are new, less than 10 years old, vigorous, leafy, well nourished, with abundant new and productive growth; their production is very good (more than 20 Q per manzana). Coffee trees in production category II are new trees less than 10 years old, with an abundance of branches that are not very vigorous or with signs of malnutrition; production is good but can be improved by pruning.

no significant difference was found, for this reason a multiple comparison test was not used. Then, the interaction between the risk components was analyzed by means of the Holistic Risk Triangle (HRT; the one THR proposed by Barrera, 2020). The HRT is a triangular graph whose sides are the risk components A: threat, V: vulnerability and C: response capacity, which are not independent. Therefore, with this *ad hoc* analysis this graph contains eight zones or zones representing different risk intensities, from very low to very high.

An analysis was also made by means of radial graphs to determine the relative importance of the variables within each risk component. The above analyses were carried out to establish comparisons between the three coffee growing zones; however, the ANOVA was only applied to the risk (HRI) and not to its components because they are not independent of each other.

Due to the existing correlation between the components (threat, vulnerability and response capacity), a multivariate analysis of variance (MANOVA) was applied to estimate the differences between the mean vectors of the coffee-growing zones (Lago de Yojoa, El Paraíso and Olancho). This parametric analysis was used to make a joint comparison of the components, and also to analyze each component separately when they were made up of more than one variable, as was the case for vulnerability and response capacity.

The MANOVA recorded a significant difference ($p \leq 0.05$), so a canonical discriminant analysis (CDA) was applied to observe the statistical differences between coffee-growing zones and the contribution of each variable to these differences. MANOVA calculations and plots were produced using R software (Friendly and Fox, 2021; R Core Team, 2021).

An analysis was also conducted to determine the resilience to rust of each producer's activities. For this purpose, an approximate estimate of resilience (E) was made, as an equivalent of response capacity from clearing C in Equation 1, as follows: $E \approx C = (A+V) / HRI$ (Equation 2); and the relationship was plotted graphically. Producer resilience E is distinguished by establishing the relationship between the risk index (HRI) and its response capacity (C) (Barrera, 2020).

RESULTS AND DISCUSSION

Identification of the problems that limit coffee industry in Honduras

According to the participatory diagnosis, the top 10 problems in order of importance that limited coffee production and marketing in coffee-growing zones of Honduras in 2016 were: 1) poor coffee plantation management; 2) high incidence of pests; 3) precarious producer economics; 4) lack of technical assistance from IHCAFÉ; 5) limited access to credit; 6) poor coffee drying and storage infrastructure; 7) low coffee prices; 8) low coffee quality; 9) pronounced climatic variation; and 10) producer disorganization. Unlike what has been reported by producers in Mexico (Chiapas), where the low price of coffee is usually the most important problem (Barrera *et al.*, 2004), in Honduras poor coffee plantation management was identified as the most important problem, while coffee price was ranked seventh.

The incidence of pests ranked second in importance, even one place above a precarious economy of the producer. This can be explained by the loss of resistance to *H. vastatrix* of the main coffee varieties grown in Honduras; such as the predominant variety (Lempira) which was identified as sensitive in 2015.

Both in Honduras (this study) and in Chiapas, Mexico (Barrera *et al*., 2004), the lack of technical personnel and consequently of advice to producers ranked fourth and fifth in importance. Another issue whose importance was ranked similarly by producers in both countries was poor production organization, which ranked tenth (Honduras) and ninth (Chiapas, Mexico). Honduran producers identified problems related to coffee quality among the ten most important (sixth and eighth place), while for Chiapas coffeee-producers quality was not among the problems (Barrera *et al*., 2004).

The difference in the problems reported by producers could be due to the fact that those studies were conducted at different times, in Mexico in 2004 and in Honduras in 2016. At that time, producers in both countries had just suffered very serious crises; in Honduras the rust infections (2012-2014) and in Mexico the impact of low international coffee prices (2000-2004). Despite this, this comparison made it possible to identify some coincidences in the overall coffee problem between these countries.

Interactions between problems

According to the structural analysis, the power zone has the most important problems because once solved they would have the capacity to contribute to the solution of other problems affecting coffee growers. These problems were related to coffee prices, producer organization and technical assistance (Figure 1). Therefore, a strategy to improve the welfare of producers should be based on solving the problems of the power zone.

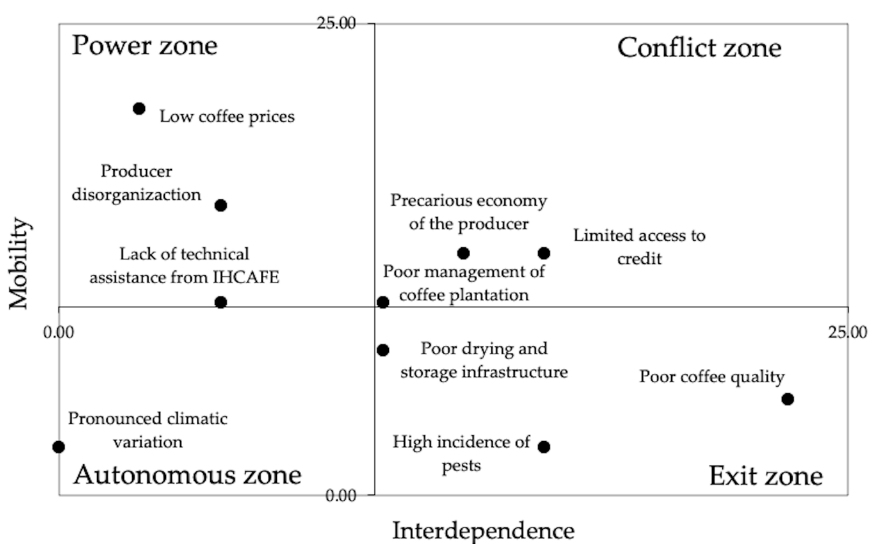

Figure 1. Structural analysis of the main problems that limit coffee production and commercialization in coffee-growing zones of Honduras (2016).

Other issues that deserve attention because once solved they could increase their contribution towards solving the whole problem were the precarious economy of the producer, the limited access to credit and the deficient management of the coffee plantation. However, these problems are located in the conflict zone (Figure 1), so that their solution becomes difficult because, according to the structural analysis, it is highly dependent on solutions to other problems in the system.

The incidence of crop pests, the second most important problem according to the participatory diagnosis with producers, is located in the exit zone of the structural analysis and has two characteristics that complicate solving (Figure 1). The first is that, due to a high level of interdependence, the solution of pest problems first requires solving other problems of the system. For example, once known the necessary resources to implement control methods or agronomic practices for coffee plantation management; and the second, which is perhaps even more important, refers to its low mobility, that is, the solution of pest problems contributes little to the solution of other problems of the system. Similar studies in Mexico have also found that pest problems were placed in the exit zone of the structural analysis (Barrera *et al*., 2013), which confirms the opinion of Barrera (2020) that a pest management strategy that ignores or gives little importance to other elements of the socio-environmental system will not only have poor results in its management, but also its contribution to solving other problems will be very limited. According to the structural analysis (Figure 1), coffee quality and coffee drying and storage infrastructure were found to be in the same situation as pest problems.

On the other hand, and as it was expected, pronounced climate variability was located in the autonomy or autonomous zone of the structural problem analysis (Figure 1). That is, in the zone of those problems that, due to their low dependence and mobility respect to the other problems of the socio-environmental system, their solution is perceived as very difficult or impossible by the common people. Like that perception on the part of Mesoamerican coffee producers that “nothing can be done” to avoid the impact of extreme weather events (droughts, torrential rains) and the disasters they entail is documented in the literature (Eakin *et al.,* 2014).

Risk to rust

According to the HRT (Figure 2), the majority (n = 31, 72.1 %) of the 43 producers evaluated were located in the low risk zone for the threat posed by coffee rust; the remaining producers (n = 12) were located in the very low (n = 2, 4.7 %), medium (n = 9, 20.9 %) and high (n = 1, 2.3 %) risk zones.

In all cases, risk was more influenced by the vulnerability component (V > 34.3 %) than by the threat component (A < 22.4 %). In turn, the response capacity ranged from C = 18.0 % for the producer located at the highest risk (HRI = 4.6) to C = 52.2 % for the producer with the lowest risk (HRI = 0.8) (Figure 2, Table 3).

The averages and dispersion measures (standard error and width of the interval) of the values of the HRI and its components indicated high variability within each coffee-

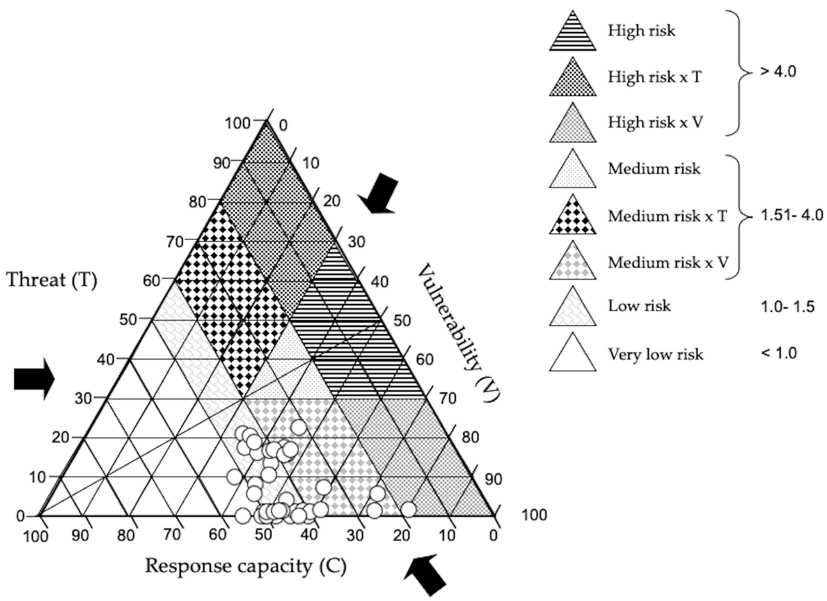

Figure 2. Holistic risk triangle for HRI components to rust (*Hemileia vastatrix*) from 43 coffee producers in Honduras (2016-2017).

growing zone, which could explain why the ANOVA showed no differences in the HRI when comparing the coffee-growing zones (F = 1.765, gl = 2, p = 0.184) (Table 3). When the risk components were broken down into their variables (Figure 3), it was observed that rust represented a greater threat (variable "infestation") for producers

Table 3. Holistic Risk Index (HRI) for coffee rust (*Hemileia vastatrix*) and its components of 43 coffee producers in three coffee-growing zones of Honduras (2016-2017).

Average and measures of dispersion†	HRI and its components¶				Number of producers in HRI§ category			
	A	V	C	HRIᵇ	MB	B	M	A
			Lago de Yojoa					
$\bar{x}$±ee (%)	5.4±1.6	53.9±2.6	40.6±2.2	1.7±0.2a	1	14	4	1
Range (%)	0-22.4	34.3-80.5	18.0-55.2	0.8-4.6				
			El Paraíso					
$\bar{x}$±ee (%)	11.5±2.2	44.1±1.6	44.3±1.2	1.3±0.1a	0	10	2	0
Range (%)	0-20.2	36.3-52.9	37.5-50.1	1.0-1.7				
			Olancho					
$\bar{x}$±ee (%)	5.8±2.2	49.5±1.9	44.7±1.8	1.3±0.1a	1	7	3	0
Range (%)	0-16.8	38.2-61.2	36.2-52.1	0.9-1.8				
			All study zones					
$\bar{x}$±ee (%)	7.2±1.2	50.1±1.5	42.7±1.2	1.5±0.1	2	31	9	1
Range (%)	0-22.4	34.3-61.2	18.0-55.2	0.8-4.6				

†$\bar{x}$: average, ee: standard error; ¶A: threat (rust), V: vulnerability, C: response capacity; §MB: very low, B: low, M: medium, A: high; ᵇequal letters between zones of the HRI column indicate non-significant differences (ANOVA, p > 0.05).

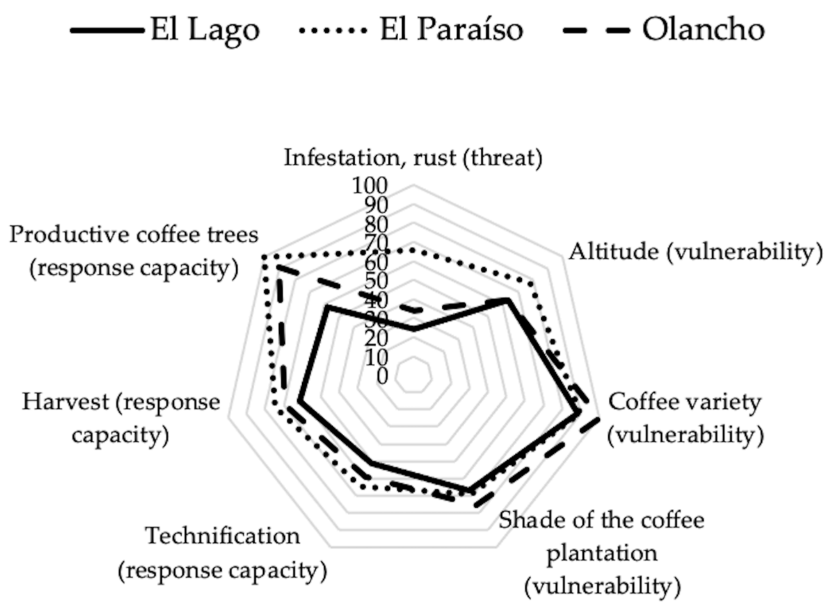

Figure 3. Comparison of the variables that integrate the components of the HRI against rust (*Hemileia vastatrix*) of 43 coffee producers in three coffee-growing zones of Honduras (2016-2017).

in El Paraíso (65.8 %) than for those in Olancho (33.6 %) or Lago de Yojoa (24.5 %). This could be explained in part by the fact that the coffee plantations of El Paraíso producers tended to be located at altitudes more vulnerable to this disease.

Although rust was less important for producers located in Lago de Yojoa, and the values of the vulnerability variables were similar to those of the other coffee-growing zones, the values of the response capacity variables of these producers tended to be lower, particularly in regard to the productive coffee trees variable (Figure 3).

On the other hand, the MANOVA applied to the three components of the HRI confirmed significant differences ($p < 0.003$) among the coffee-growing zones under study. According to the confidence circles (95 %) of the canonical discriminant analysis, the Olancho coffee zone was statistically equal to the El Paraíso and Lago de Yojoa zones, but the latter two were statistically different from each other (Figure 4A). The CDA also indicated that vulnerability and response capacity were more highly correlated with each other than either was with threat. Considering the length and orientation of the CDA arrows, it is observed that threat and response capacity were more important than vulnerability; in the case of farmers in El Paraíso, threat and response capacity were the most important constructs, while vulnerability and response capacity were the most important for farmers in Olancho (Figure 4A). In this analysis, the first canonical function (Can1) explained 91.9 % of the variability of the interaction.

On the other hand, the MANOVA applied separately to the vulnerability data revealed that there was no significant difference between coffee-growing zones

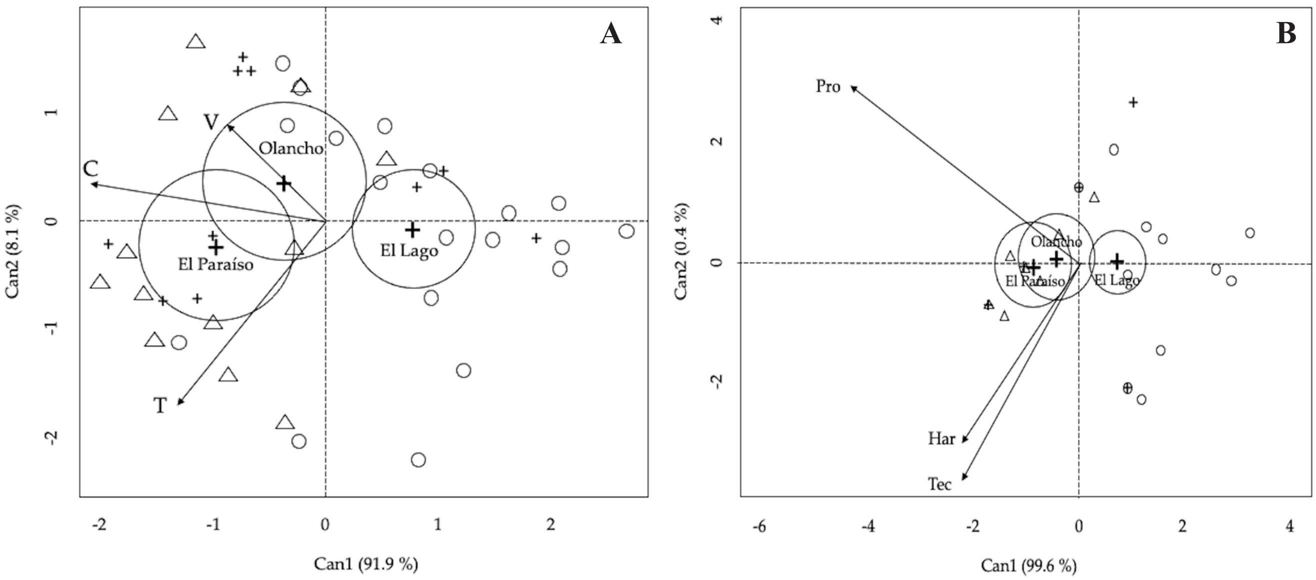

Figure 4. Comparison of the canonical discriminant structure of the components of the HRI (A) and the variables of the response capacity (B) of the coffee-growing zones of Lago de Yojoa (circle), El Paraíso (triangle) and Olancho (cross), Honduras. A: threat, V: vulnerability, C: response capacity, Pro: productive categories of coffee trees (% I and II), Cos: difference between harvest obtained and expected, Tec: technification.

(p = 0.109). However, this analysis applied to response capacity did detect significant differences between zones ($p \leq 0.015$). In this case, the confidence circles (95 %) of the CDA confirmed that the Olancho coffee zone was equal to the El Paraíso and Lago de Yojoa zones; there was also no significant difference between the latter two (Figure 4b). It was also observed that the variables "harvest" (Cos) and "technification" (Tec) were correlated, while the effect of these variables was less important than the effect of the variable "productive categories of coffee trees" (Pro). Furthermore, it was observed that the Cos and Tec variables were more influential in El Paraíso and the Pro variable was more important for Olancho (Figure 4B). The first canonical function (Can1) of this analysis explained 99.6 % of the variability of the interaction

Resilience to rust

The relationship of HRI to response capacity (C), considered an approximation for resilience (E), was fitted to a power equation with the coefficient *b* of negative value, i.e., resilience potentially decreased as the value of risk increased. For the whole data set corresponding to the 43 producers under study, the power equation was $E \approx C = 50.852 * HRI^{-0.637}$ ($R^2 = 0.99$).

With this equation, E values were obtained for HRI = 1.0, 1.5 and 4.0, risk values that correspond to the limits of the HRT zones (Figure 2), and with them, practical criteria were generated to determine the E categories (Table 4). According to these criteria, producers in Lago de Yojoa were less resilient because with HRI = 1.7 (Table 3) they were in the medium resilience category (E = 36.27 for HRI = 1.7), while producers in El Paraíso and Olancho with HRI = 1.3 (Table 3) were in the high resilience category (E = 43.01 for HRI = 1.3).

A study conducted with coffee growers in Chiapas, Mexico, to estimate the risk to rust with variables different from those used in this research, found that the equation that described the HRI relationship with E was $E \approx C = 54.325 * HRI^{-0.817}$ ($R^2 = 0.98$) (Barrera, 2020). Therefore, it is confirmed that a nonlinear relationship of the power type is established between the HRI and E. On the other hand, it was observed that, although there are differences in the estimation of E between the Mexican equation and the one generated with Honduran producers, the differences were small. In particular, it was observed that both equations estimated practically the same E values from HRI = 1.3. It remains to be verified whether these equations can be used as a reference to estimate the resilience to rust of producers in other latitudes.

Work plan with risk management-based decision making

Based on the knowledge of the main elements (problems) and functioning of the socio-environmental coffee system of the producers participating in this study (Figure 1), and the definition of the criteria for managing the risk that the rust threat represented for this system (Table 4), based on Barrera (2020), a work plan was proposed to reduce the risk and increase the resilience of the system in the face of coffee rust. The plan established as a general objective the improvement of the producers' economy, since without economic resources they would not have the means to carry it out. To achieve the plan, the general objective was broken down into specific objectives and strategies based on the results of the structural analysis (Figure 1). Five specific objectives (variables of the exit and autonomous zones of the structural analysis) and four strategies (variables of the power and conflict zones) were proposed. In order to review the fulfillment of goals (risk reduction and increased resilience), the state of the system should be evaluated at the beginning of each coffee cycle.

The risk analysis suggests starting the implementation of the plan with the producers of Lago de Yojoa. In particular, efforts should be made to reduce the vulnerability arising

Table 4. Criteria to define the categories of (E) an approach to resilience, based on the holistic risk index (HRI) in coffee plantations threatened by coffee rust (*Hemileia vastatrix*) in Honduras.

Risk (HRI)		Resilience (E)	
Categories	Values†	Values	Categories¶
Very low	< 1.0	> 50.85	Very high
Low	1.0 - 1.5	39.28 - 50.85	High
Medium	> 1.5 - 4.0	21.03 - 39.27	Medium
High	> 4.0	< 21.03	Low

†Values corresponding to the boundaries of the zones in Figure 2; ¶Values calculated using equation $E \approx C = 50.852 * HRI^{-0.637}$

from the characteristics of coffee varieties and shade, and to increase the proportion of productive coffee trees (categories I and II) through the renovation of coffee plantations to improve yields. Secondly, the risk and resilience results indicate that producers in the coffee-growing zone of Olancho, whose plantations are cultivated only with coffee varieties susceptible to rust, should be attended to. As for the producers in the coffee-growing zone of El Paraíso, despite the higher levels of rust infestation, their response capacity was the best. In general, the results showed that the 43 farmers who participated in the study need to reduce vulnerability (coffee varieties and shade) and increase response capacity (technification to improve yield and crop quality).

CONCLUSIONS

The elements necessary for the functioning of the socio-environmental system of coffee production in agroecosystems in Honduras were identified. Criteria were also defined for managing the risk posed by coffee rust caused by the fungus *Hemileia vastatrix* to these agroecosystems.

With the information obtained, a work plan was designed as a proposal to reduce the risk and increase the resilience of the system to coffee rust, in order to improve the economy of the producers.

Finally, the most vulnerable coffee-growing zones with the least capacity to respond to the threat of rust were identified, which can be used to guide decision-making in the management of this disease.

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