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Driving Factors Aggravate the Incidence and Severity of Coffee Leaf Rust (*Hemileia vastatrix* Be & Br.) in Ethiopia

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Abstract: Driving factors aggravating coffee leaf rust caused by biotrophic fungus *Hemileiavastatrix* Be & Br. was critically assessed and examined in 406 sample coffee farms from 27 districts, nine zones across major coffee growing two regions (Oromia and SNNPR) of Ethiopia. All associated environmental and soil factors were noted carefully from each plot. Univariate analysis as of linear mixed model was fitted separately to each variables for testing the effect of categorical factors as fixed effects tested individually in the model. A linear regression model was fitted to data on the relationship between dependent and independent variables. Multiple correspondence analysis was used to identify individuals with similar profile and the associations between categorical variables. Based on the study, CLR is widely distributed all over coffee growing areas of the country with varying intensities. There was a highly significant ($p < 0.001$) and negative correlation between altitude, management practice and shade level with CLR intensity. Moreover, there is highly significant ($p < 0.001$) and positive correlation between coffee production systems and coffee cultivars with disease intensity. Based on the study number of factors affect the disease epidemics, such as climate change effect of high temperature, lack of known durable resistant coffee varieties, lack of disease management practice and lack of recommended fungicide application. This empirical evidence shows that CLR was an upsurge and interacting with number of factores and will be remains a major challenge to Arabica coffee production in Ethiopia.

Keywords: Ethiopia, Driving Factors, *Hemileia vastatrix*, Incidence, Severity

1. Introduction

Coffee plant belongs to genus Coffea of the Rubiaceae family, of which two of 124 known species are commercially grown: *Coffea arabica* L. (Arabica) and *Coffea canephora* (Robusta), which account for 70% and 30% of world's production, respectively [1]. The primary center of origin and diversity of Arabica coffee is the southwestern Ethiopian highlands. In Ethiopia, coffee is the main pillar of the country's economy - among the top three agricultural exports, coffee ranks first followed by oil seeds and pulse crops, and accounts for 29% of the total export and 37% of agricultural export earnings of the nation. Ethiopia is the leading coffee producer in Africa, ranks fifth in production and export, following Brazil, Vietnam, Colombia and Indonesia, and produces premium quality coffee [2].

A total of 4.7 million smallholder Ethiopian farmers are directly involved in coffee production and about 15 million people depends directly or indirectly on the coffee sector for their livelihoods [3]. However, Ethiopian coffee production is threatened by several diseases which remain among the major constraints to production in many parts of the country. Fourteen fungal diseases and one bacterial disease have been reported to attack the crop, but three of major economically importante are: Coffee berry disease (CBD) caused by *Colletotrichum kahawae,* coffee wilt disease (CWD) caused by *Gibberella xylarioides* and coffee leaf rust (CLR) caused by *Hemileia vastatrix* [4]. A few other diseases have become potentially important to Ethiopian farmers including coffee thread blight and bacterial blight of coffee [4].

Coffee leaf rust was firstly reported in Ethiopia over a half century ago in 1934 [5] from where it has been spread to all main coffee production regions of the country. In Ethiopia, coffee rust is widespread and found in all regions where crop is grown and under various production systems including forest, semi-forest, garden and plantations at all sorts of altitudes [6]. The disease has never caused epidemics or eradication of *Coffea arabica* as in other countries. The long-term coexistence of coffee and rust would have created a balanced pathosystem in which the pathogen is countered by efficient resistance of the host [7, 8]. Moreover, the high genetic diversity of coffee population and high level of horizontal resistance might have kept the rust at low level in Ethiopian condition [9-11]. Over time coffee leaf rust situation in Ethiopia changed and become an important in coffee production of the country [11, 12]. The disease resurged as of major importance to Ethiopian coffee production likely due to climatic shifts that favour the virulence of the pathogen as well as changes in coffee management system that favours disease development [11]. The growing CLR incidence has been associated with a changing climate, especially increased temperatures and annual rainfall, earlier rain in the season and sunshine duration reduction, which favour the life cycle of *H. vastatrix* [13]. An early onset of the rainy season favours early development of the disease, as reported for CLR epidemics in Nicaragua [13]. A reduction in the daily thermal amplitude during the rainy season on set further shortens the CLR latent period [13, 14]. In the Americas, CLR prevalence is strongly linked to rainfall, with severe outbreaks of CLR occurring during the two annual rainy seasons [14, 15]. After each rainy season, CLR strongly declines and the coffee shrubs shed infected leaves [15]. The epidemiology, including knowledge of favorable conditions and the temporal and spatial dynamics of CLR epidemics, as well as management practices that suppresses the diseases, is well known from research conducted in regions where the disease has been threatened production [16, 17]. The peak of the CLR symptom development in Ethiopia occurs during fruit harvesting in the dry season but primary crop losses during initial infection are generally low. Secondary crop losses as a result of decreased plant fitness following previous infections tend to be more substantial [18].

However, the driving factors that affect CLR intensity mean incidence and severity at different growing conditions and altitudes have not yet been documented for Ethiopian condition. Therefore, it is critical to assess and identify the driving factors for current increasing of the diseases across the main coffee growing areas of Ethiopia. For such, we summarized data from extensive and comprehensive survey on CLR intensity and associated factors for upserge the disease across the main coffee growing areas of Ethiopia.

2. Materials and Methods

2.1. Study Area and Sampling

A large-scale survey to obtain data on the coffee leaf rust occurrence and intensity was conducted at the major coffee growing regions of Ethiopia, from September to January 2017/18. A hierarchical sampling focused on two Ethiopia Regions that accounts for more than two-thirds of the country's coffee production and export: South Nations and Nationalities Peoples Region of Ethiopia (SSNPR) and Oromia. Three main coffee-production districts were selected within each of the nine zones from these two regions, totally 27 districts (Figure 1).

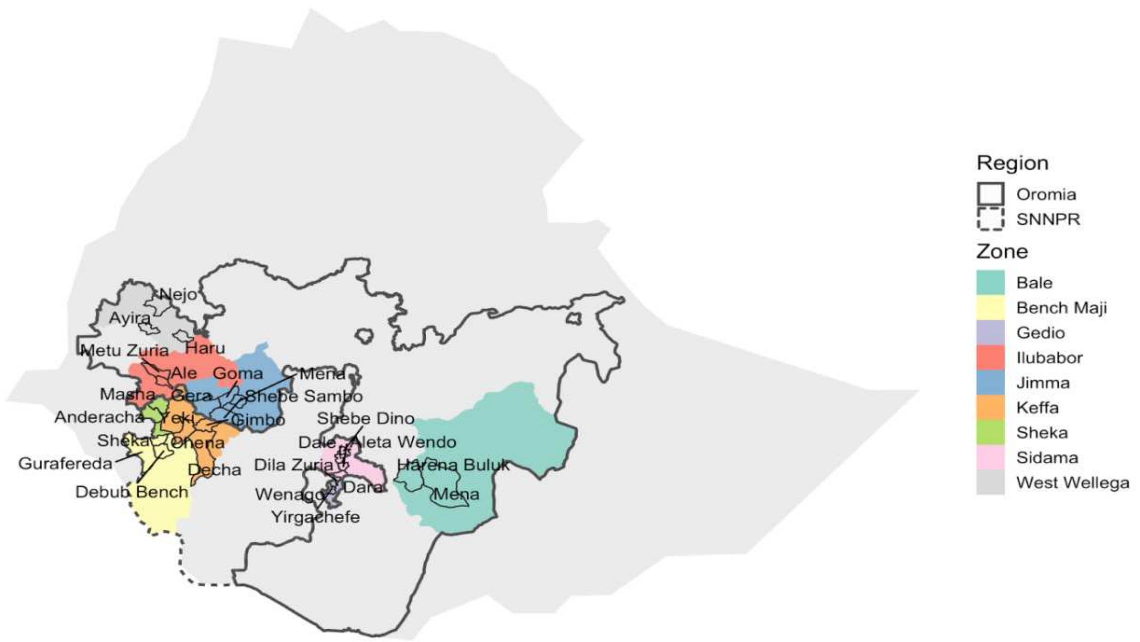

Figure 1. Ethiopia map depicting locations of 27 districts (text labels) within which 15 coffee farms (3 peasant associations x 5 plantations) were selected and assessed for incidence and severity of coffee leaf rust survey program in 2017/18 growing season, totalling 405 plantations. Three districts were selected within each of the nine Zones (colored legend) within two major Ethiopian Regions: Oromia (solid line) and Southern Nations, Nationalities, and Peoples' Region (SNNPR) (dashed line).

On each of the 27 districts, three peasant associations (*kebeles*), defined at a 5–15 km distance from each other along accessible rural roads, were selected and five coffee farms from each *kebele* were sampled, totalling 15 farms per district. In total, 405 (9 zones x 3 districts x 15 farms) farms from 81 (27 x 3 *kebeles*) *kebeles* were visited.

2.2. Disease Assessment

On each farm, a sample of 10 to 30 coffee trees, variable according to farm size and age uniformity, were systematically selected at a distance of about 6-8 meter interval. This sample size was determined based on previous report that at least ten plants, each providing data from all leaves of six branches, provide sufficient precision for estimating disease intensity in the field [8]. On each plant, three branch pairs, each representing the upper, middle and lower canopy layers of the coffee plant, were selected to assess three disease variables: 1) leaf rust incidence (INC), scored as the percent diseased leaves per sampled branch; 2) leaf rust severity (SEV), scored visually as the percent diseased leaf area aided by a diagrammatic scale Kushalappa and Chaves, 1980, with five scores (1%, 3%, 5%, 7% and 10% severity); and 3) the number of sporulating lesions per leaf (SPORL). Agronomic data including field history, altitude, production systems, cultivars type, seedling source, spacing between plant and over all farm management practices were obtained and recorded from each farm.

2.3. Data Analysis

Univariate analysis. A linear mixed model was fitted separately to INC, SEV and SPORL data for testing the effect of categorical factors as fixed effects tested individually in the model (Figure 2). Coffee farms within districts were considered as a random effect in the model. Effect of altitude was also tested as a continuous factor by fitting a three-level (nested) random intercept or a random intercepts and slopes model. Farms were nested within districts. The multi-level model best fitting the data was selected based on the lowest Akaike Information Criterion (AIC). In addition, we tested whether the effect of altitude as continuous factor was dependent on categorical factors by testing the effect of the interaction term added (slope) to the three-level model (Figure 2).

Multivariate analysis. Besides the categorization of altitude, disease incidence, another numerical continuous variable, was also categorized into three groups using tertile splits to the data, which gave: low INC: < 22.7; medium INC: 22.7 to 42.4 and high INC: > 42.4. This categorization was performed to conduct a multiple correspondence analysis (MCA), which is suitable to summarize data from two or more categorical variables. MCA has been used in similar work on coffee rust with the goal of linking between certain production situations and the intensity of coffee rust epidemics using categorical variables [8]. A biplot graph of the variables depicted the associations.

3. Results

3.1. Disease Data and Effect of Production Region and Zone

Coffee leaf rust was present in all visited farms at various levels. Disease data were summarized at the farm level as a single mean value after aggregating responses obtained from all assessed trees. Mean INC on leaves for each farm ranged from 9.5 to 86.7% (X = 35.3%), mean SEV ranged from 2.2 to 64.1% (X= 22.5%) and mean SPORL ranged from 2 to 34 (X = 13.64). The appraisal of the distribution of the disease intensity variables and results of the random intercept model, which best fitted data of all three disease variables (lowest AIC, data not shown), suggested that region did not affect the three variables: log-transformed INC (P = 0.24), non-transformed severity (P = 0.76) and root-squared SPORL (P = 0.35) (Figure 2). Similarly, when the nine zones of the two regions were compared, no difference in the log-transformed INC (P = 0.1), non-transformed SEV (P = 0.37) and root-squared SPORL (P = 0.13) was detected based on likelihood ratio test for the mixed model estimates. Across zones, median INC ranged from 15 to 50%, median SEV ranged from 10 to 40% and SPORL ranged from 4 to 23 (Figure 2).

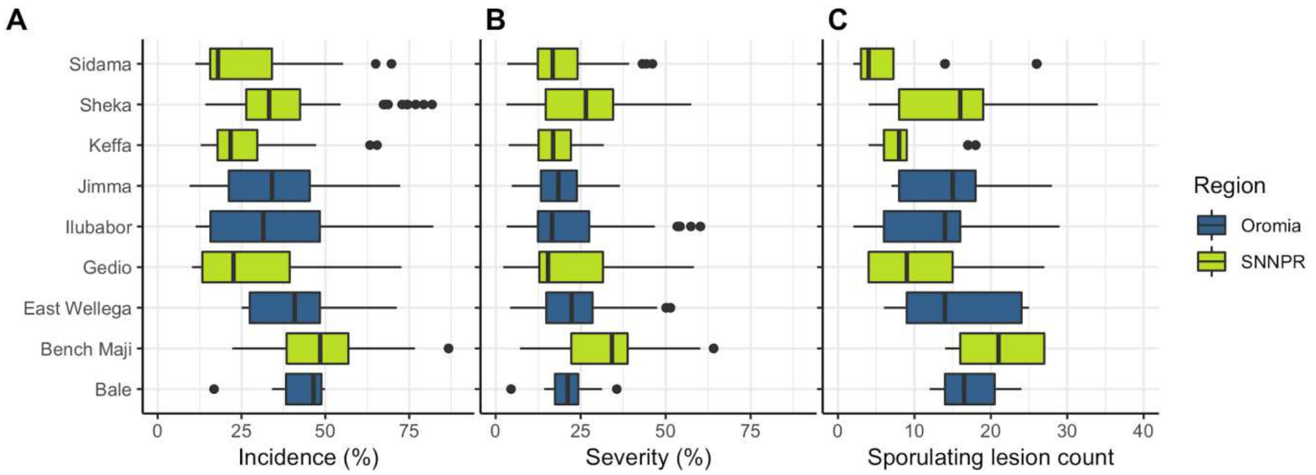

Figure 2. *Distribution of three disease intensity for coffee leaf rust: incidence (A) severity (B) and number of sporulating lesions (C) across nine zones and two regions, Oromia (black box) and South (grey box). The width of the horizontal boxes represents 50% of the data and the white vertical line within the box represents the median. The dots represent a coffee farm as an outlier in the distribution.*

Table 1. *Incidence of Coffee Leaf Rust in major coffee Growing areas of Ethiopia in 2017/2018 cropping season.*

Region	Zone	District	Altitude (masl)	Disease Incidence (%)	
				Range	Mean
Oromia	Jimma	ShebeSombo	1461 - 1795	21.2 – 50.6	42.25
		Gera	1910 - 1969	9.5 – 40.6	19.89
		Gomma	1593 - 1683	22.4 – 72.3	43.19
	Illuababor	Mettu	1550 - 1780	24.3 – 57.2	37.34
		Ale	1737 - 1974	11.3 – 20.7	14.53
		Yayo	1262 - 1515	33.2 – 82.2	55.79
	Bale	Harena	1600 - 1965	34.5 – 49.7	43.69
		Delo-Menna	1560 - 1650	16.8 – 49.4	42.87
	W. Wollega	Haru	1461 - 1525	25.3 – 65.3	47.52
		Aira	1561 - 1930	27.4 – 71.3	41.71
		Nejo	1434 - 1729	26.7 – 61.4	33.42
SNNPR	Bench Maji	Debub B	991 - 1068	43.2 – 86.7	57.40
		Gurafarda	1020 - 1705	32.5 – 71.4	46.30
		Sheko	1072 - 1715	22.2 – 72.7	45.65
	Sheka	Yeki	1195 - 1262	23.2 – 81.8	50.94
		Anderecha	1220 - 1830	31.2 – 79.3	42.52
		Masha	1730 - 2010	14.2 – 38.3	24.43
	Kafa	Gimbo	1720 - 2010	13.3 – 63.3	22.02
		Chena	1754 - 1940	12.8 – 50.8	19.86
		Decha	1754 - 1852	19.6 – 65.4	34.59
	Sidama	Dale	1730 - 1810	16.5 – 48.2	18.93
		Shebedino	1834 - 1877	13.3 – 35.2	17.27
		Dara	1450 - 1517	21.7 – 69.7	47.89
		Aletawondo	1852 – 1953	16.7 – 36.7	16.98
	Gedeo	Y/chefe	1880 – 2056	10.2 – 26.7	12.69
		Wonago	1707 – 1930	14.7 – 39.4	24.16
		Di/Zuria	1434 - 1544	27.2 – 72.7	49.67
Mean					35.31
SE					11.24

Table 2. *Severity of Coffee Leaf Rust in Major coffee Growing areas of Ethiopia in 2017/2018 cropping season.*

Region	Zone	District	Altitude (masl)	Disease Severity (%)	
				Range	Mean
Oromia	Jimma	Shebe-Sombo	1461 - 1795	5.0 – 36.5	21.59
		Gera	1910 - 1969	4.7 – 21.5	14.17
		Gomma	1593 - 1683	6.6 – 34.5	22.68
	Illuababor	Mattu	1550 - 1780	4.2 – 29.5	19.32
		Ale	1737 - 1974	3.2 – 24.6	12.53
		Yayo	1262 - 1515	14.4 – 60.2	35.74
	Bale	Harena	1600 - 1965	14.6 – 25.3	19.17
		Delo-Menna	1560 - 1650	4.5 – 36.5	23.31
	W. Wollega	Haru	1461 - 1525	7.3 – 51.4	30.08
		Aira	1561 - 1930	4.2 – 28.5	16.16
		Nejo	1434 - 1729	6.2 – 42.1	26.68
SNNPR	Bench Maji	Debub B	991 - 1068	9.1 – 64.1	36.77
		Gurafarda	1020 - 1705	7.1 – 49.2	32.48
		Sheko	1072 - 1715	9.3 – 37.0	26.53
	Sheka	Yeki	1195 - 1262	8.3 – 57.5	34.15
		Anderecha	1220 - 1830	4.2 – 38.1	28.08
		Masha	1730 - 2010	3.1 – 26.5	14.22
	Kafa	Gimbo	1720 - 2010	3.9 – 27.5	14.15
		Chena	1754 - 1940	4.1 – 27.1	18.45
		Decha	1754 - 1852	3.8 – 31.8	19.00
	Sidama	Dale	1730 - 1810	4.1 – 28.5	17.86
		Shebedino	1834 - 1877	3.6 – 18.4	11.75
		Dara	1450 - 1517	5.6 – 46.1	31.77
		Aletawondo	1852 – 1953	3.4 – 28.2	14.53
	Gedeo	Y/chefe	1880 – 2056	2.2 – 25.6	12.31
		Wonago	1707 – 1930	12.3 – 36.2	21.07
		Di/Zuria	1434 - 1544	5.3 – 58.3	32.31
Mean					22.48
SE					7.59

3.2. Incidence and Severity Relationship

As expected, these two variables were strongly and positively associated. The model that best fitted the SEV-INC relationship was the random coefficients (lowest AIC, *data not shown*). Population average estimates of the unconditional (no covariates) model for the intercept and slope coefficients were -0.481 (SE = 1.64, t[Satterthwaite] = 15.63) and 0.63 (SE = 0.04, t[Satterthwaite] = -0.324) respectively. In other words, SEV would increase 6.3 percent points (p.p.) for each 10 p.p. increase in INC.

The inclusion of altitude as categorical variable, as surrogate of temperature, in the mixed (conditioned) model showed that the interaction term was significant (F = 3.84, df = 210.2, P = 0.02), meaning that the slopes differed slightly among the three elevation categories. However, since other factors than altitude alone affected the disease intensity variables (see next section), we report the coefficients of the unconditional model. The fitted line is depicted together with data for each farm (dots) colored by altitude (Figure 2).

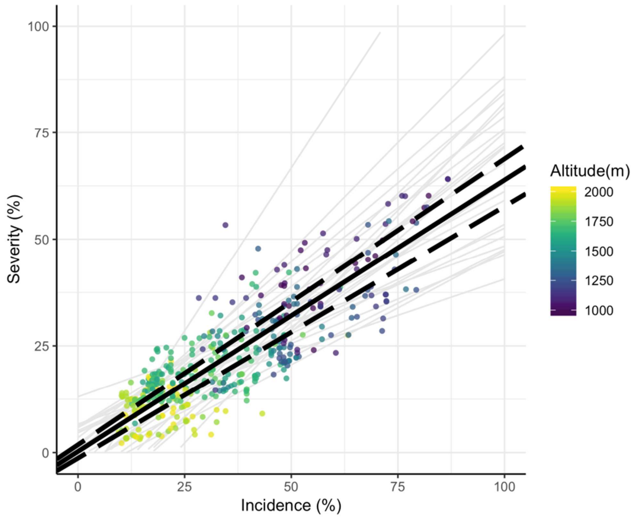

Figure 3. *Scatter plot and best fitted line for the relationship between coffee leaf rust severity and incidence assessed on 405 coffee farms in Ethiopia located a different altitude.*

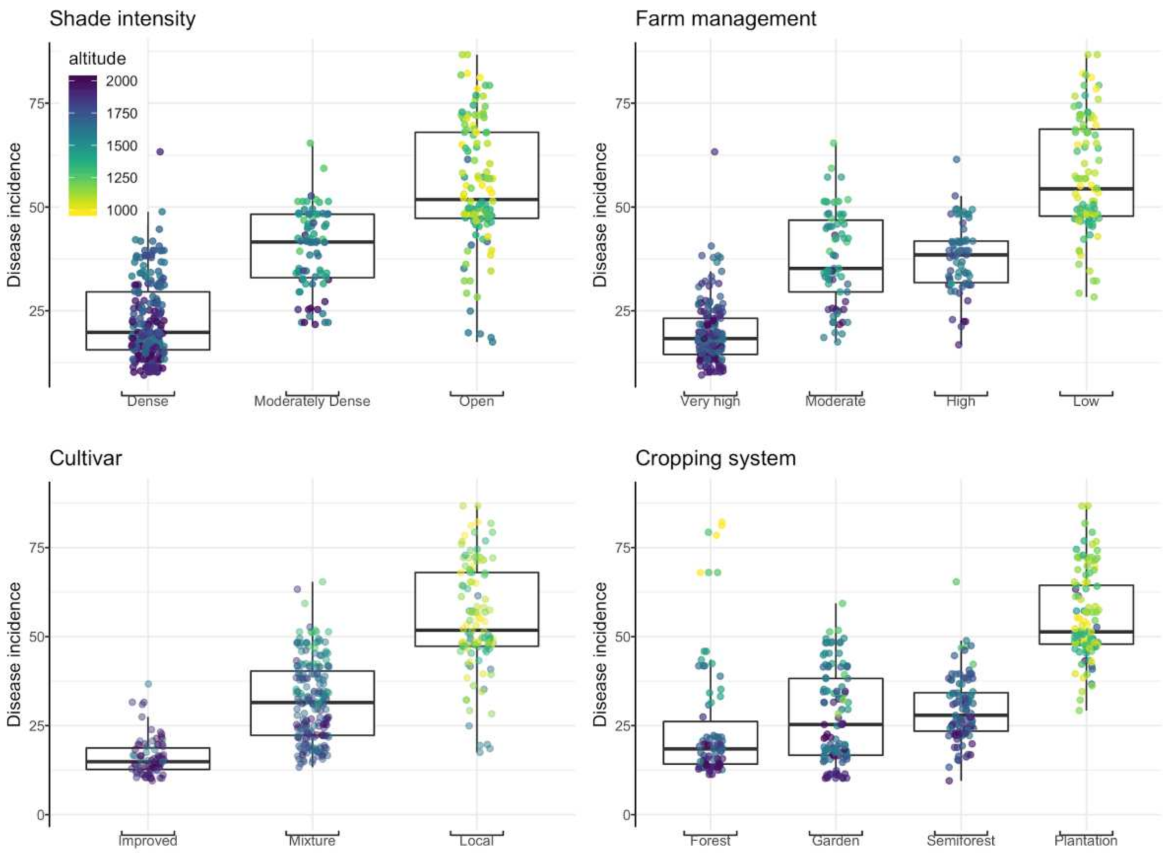

Figure 4. *Distribution of coffee leaf rust incidence data at different levels of shade, farm management, cultivar and cropping system. Dots represent the farms and colors represent the altitude of the farm in meters above sea level.*

3.3. Effect of Crop Features and Agronomic Practices

The inclusion of one of the four agronomic-related factors in the mixed model showed that both INC and SEV were affected by all factors (P < 0.001). The distribution of INC across levels of factors is depicted together with a colored mark by the altitude of each farm (Figure 4). With the exception of farm management, for which means of "fair" and "good" management did not differ according to a Tukey's comparison at 5% probability, levels of all other factors differed significantly from each other ($P < 0.05$). It is also clear that some levels of factors were more frequent under specific altitude ranges as depicted by colors of the dots representing the farms (Figure 4).

For example, disease levels tended to be lowest in farms at higher altitude (> 1800 m), but these were mostly represented by a high-input cropping system where improved cultivars are grown under full shade at forest and semi-forest conditions. This is confirmed by the correspondence analysis which showed that these variables grouped together (bottom left) due to similarity in their profiles, and were most negatively correlated (opposite quadrants) with a group of farms using plantation of unshaded (sun) local varieties that are poorly managed (low-input) and grown at lower altitude (< 1500 m) (Figure 4). Farms showing intermediate levels of incidence included garden and semi-forest mixture of cultivars grown under mid-shade and fair management practices at altitudes ranging from 1500 to 1800 m.

The first and two dimensions were sufficient to retain 57% (36.5% + 20.6%) of the total inertia (variation) contained in the data. The MCA plot colors each variable by the sum of their squared cosine (Figure 4). In other words, variables that were most represented by two dimensions have $\cos^2$ close to 1. The top-five agronomic-variables ($\cos^2 > 0.76$) were: open sun, local variety, low managed, plantation and low altitude. Garden category was not well represented by the first two dimensions ($\cos^2 < 0.1$), implying that its position on the plot should be interpreted with caution and a higher dimensional solution may be necessary. It is also important to identify variable categories, the top-15 in our study, that most contributed (in %) to the definition of the dimensions 1 and 2, separately. The red dashed line in indicates the expected average value, If the contributions were uniform (data not seen). It can be seen that low management, local variety, open sun, plantation and improved varieties contribute the most to the first two dimensions. The red dashed line on the graph above indicates the expected average value, If the contributions were uniform.

4. Discussion

In our study we confirm previous report of a widespread occurrence of CLR in Ethiopia at most coffee growing areas with varying intensities. In a previous study, the highest incidence and severity were recorded on Hararghe coffee type [9]. According to [6], the earlier national percent tree attack in 1980 was 12.9% which latter raised to 36.3% incidence in 1990 after 10 years. Moreover, the existence of coffee leaf rust infection on forest coffee production system reported and the incidence reached up to 29.6% [11]. According to [18], the highest CLR record 27% severity was in Hararghe, and this might be attributed to the distribution of susceptible host, occurrence of virulent races and non-shade coffee cultivation.

The high record in intensity of CLR in our report conceivably emanated from the extensive planting of susceptible local coffee landraces and improved varieties, occurrence of virulent pathogen races aggravated by non-application of fungicides to control the disease and existence of favourable weather variables for the pathogen infection process. In line with this, most of the released good yielding and high-quality improved coffee varieties gradually became susceptible after planting for many growers in major coffee growing areas of Ethiopia [4, 19]. In addition, the recent climatic changes like unexpected decreased or increased amount and duration of rainfall and raise in day temperature and drop of night temperature have reasonably predisposed and favoured the coffee plants to be infection by CLR pathogen.

The negative relationship between altitude and level of CLR is also demonstrated by [20] in Kenya, [21] in southern American continents and [22], in Pauna New Guinea, whom were reported that the CLR pathogen was more intense at lower altitude coffee farms, however, decreased intensity of CLR when the elevation increases. [6, 9] also found that CLR was more common in lower elevated coffee growing regions in Ethiopia.

Shade trees regulate micro-environment of coffee farm and modifies extreme temperature keep cooler or warmer within the coffee plantations, with this it reduces fruit load. According to [23], shading modifies microclimatic conditions by reducing ambient temperature (2°C to 4°C) that helped to reduce over bearing and delay fruit ripening, which might have reduced the tree stress and exposure to CLR. In shaded plantations, however, shading generally allows for intermediate yields that are always sufficient to render coffee leaves susceptible enough to CLR infection [13, 24]. At the beginning of coffee cultivations, coffee bushes were planted under shade canopy to simulate their natural habitat [24, 25]. Coffee grown without shade potentially out yielded shade coffee [25]. In Ethiopia, decreasing shade to increase coffee production caused losses of plant species diversity and expose to CLR. Optimum shaded coffee tends to flower and produce balanced good crop each year, whereas under unshaded plantation conditions, heavy flowering and fruiting exist then coffee tree becomes committed to filling all the beans that are formed after the fruit expansion stage resulting in a large sink capacity in the seed endosperms [25]. Overbearing exhausts the tree's and predispose for heavy CLR infection [25]. Although [7], using artificial inoculation of leaves found that increased shading was associated with increased *Coffea arabica* resistance to CLR.

The heterogeneous nature of the coffee populations, existence of undisturbed natural mycoparasites coupled with the low inputs and low human inference in forest and semi-forest coffee production systems could attribute to the relatively reduced disease intensity. According to [6], other factors such as the low average productivity associated with shade and the existence of biological agents such as the hyperparasite *Verticillium lecanii*, were also believed to play an important role in maintaining CLR at low levels at forest and semi-forest coffee production systems.

There were three major categories of coffee cultivars (local cultivars, mixed and improved varieties) recorded in the study areas. The local cultivars "landraces" have the age of >20 years and are most preferred by coffee growers for their adaptability, quality and relatively better yield but susceptible to coffee leaf rust and other major coffee diseases as observed from the study. Based on the study, the local cultivars constituted nearly 21.3% of the surveyed farms whereas improved varieties in the form of plantation were only 9.52%. Crop management practices may affect the development of the disease through their influence on the microclimate and the host which, in turn, act on the life cycle of the fungus. Significantly, higher disease intensity was recorded on those neglected coffee farms where there were no cultural management practices than that of coffee farms with different cultural practices like shade tree adjustment, pruning, rejuvination/stumping, soil fertility management or use of compost, removing and burning of infected dead detached leaves during the end of harvest season and tree density adjustment.

Soil fertility management play significant role to reduce tree stress during heavy bearing, then increase tolerance and reduce the rust intensity. Based on the report by [13, 24], fertilisation has a direct effect on the host–parasite relation and the negative effects of foliar fertilisations on coffee rust development have been found. These authors suggest that good nutritional conditions may lie behind a dilution of the disease, resulting from quicker growth of foliage than of the coffee rust epidemic [21, 26]. [13] demonstrate, there is clear correlation between CLR intensity and soil nutrition, which plays a critical role in the resistance or susceptibility to the diseases.

Based on our study rejuvenation and stumping of old coffee trees and or replanting old farms with new coffee plants play significant roll to reduce the pressure of CLR disease as coffee tree age influence the host tolerance. Thus, one of the most important factors influencing CLR incidence was tree age [25]. Eskes and Toma-Braghini [16] noted that with increasing coffee tree age, CLR incidence increased for two coffee varieties the Catimor and Caturra. The authors found that the critical age at which CLR infection increases substantially even for the resistant Catimor variety seems to be between 15 and 20 years. Therefore, when coffee plants reach this threshold, they should be rejuvenated and or replaced with new ones. Moreover [25], studied the influence of leaf age on incomplete resistance to CLR in Brazil and found that for, the susceptible variety Catuai there was no effect of leaf age on the latency period, but for Catimor, the resistance to CLR decreased with increasing leave age.

5. Conclusion

These factors strongly influence coffee rust epidemics through effects on microclimate and plant physiology which, in turn, influence the life cycle of the fungus. Moreover, lack of known durable resistant coffee varieties, evolution of new virulent aggressive races and lack of fungicide application have prominent impact on the incidence and severity of CLR with direct implication on the quantity and quality of coffee yield. This empirical evidence shows that CLR was an upsurge, derived by number factors such as production system, management practices, variety used and climate change induced high temperature and thus it will be remains a major challenge to Arabica coffee production in Ethiopia.

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