Literature review on Coffee Leaf Rust

The revised literature is consistent in pointing out important factors that influence coffee leaf rust epidemics. However, the direction of correlation (*i.e.* positive or negative) is not the same across all studies, as study conditions may cause these factors to behave differently.

Factors are generally split into four main groups: 1) climate or environmental factors, 2) socio-economic factors, 3) production or crop management factors, and 4) Epidemiological factors (Table I). I have included the ones for which a mechanism or direct effect is explained in the literature. For instance, soil moisture is used in Avelino *et al.* (2004), but a specific mechanism explaining how this affects the disease is not provided. Presented factors were consistently reported as important factors that could act at different scales (plant, plot, and region).

It is important to mention that few studies considered the covariance between factors, which could change the way in which interactions occur. As explained by Avelino et al., (2004), the gap between epidemiological knowledge and understanding for management is explained by the lack of connection to production situations, which often cause the explanatory variables to interact differently. For instance, Temperature and rainfall may interact differently with the disease according to the intensity of plots, the shading used, and the foliage density (often controlled by trimming). Another example is the interaction between temperature and altitude, where the first is governed by the later. However, today's warming climate has caused temperatures in high altitudes to increase. Thus, altitude may not be a limiting factor if isotherms keep shifting up to higher altitudes.

Through time, we observe a shift in the type of variables used to explain coffee leaf rust incidences. These move from a set of only environmental factors to a more complex list of environmental, socio-economic, and crop management factors. For instance, Bock (1962) explains coffee leaf rust incidence in terms of environmental variables (rainfall, temperature, altitude, and wind). Avelino *et al*. (2004) introduces the hypothesis that crop management patterns might explain incidence levels and disease cycles of coffee leaf rust. He later produces a typology of plots, based on a set of management factors and environmental conditions, which provide an insight on the dynamics of coffee leaf rust epidemics under different management conditions (Avelino *et al.,* 2006). A few years later, landscape factors are incorporated, and interactions with land cover and other environmental factors are included (Avelino *et al.,* 2012). Finally, the socio-economic dimension is taken into account in Avelino *et al*. (2015), where lack of income appears to explain increased incidence of coffee leaf rust due to lack of investment in proper crop management.

Avelino *et al.* (2006) calls for the creation of mechanistic models that allow us to understand the functioning of the system. One of the proposals is developing a plantation-level model though a series of production cycles, consisting of a population of healthy leaves, infected, and fallen. Along with information provided by Bock (1962), a simple epidemic model could be built and confronted with data to adjust the parameters. Parameters could then vary according to management situations.

Table I- Compilation of important factors affecting intensity and occurrence of coffee leaf rust.

Group	Factor	Source	Count
Climate / Environmental	Rainfall	1, 2, 3, 5, 6	5
	Wind	1, 2	2
	Temperature / Temperature variability	1, 2, 5, 6	4
	Altitude	1, 2, 3, 4	4
	Soil nutrient composition	3	1
	Soil pH	3, 4	2
Socio-economic	Coffee price	5	1
	Fertilizer price	5	1
	Credits / Government participation	5	1
Production / crop management	Frequency of fertilization	4, 5	2
	Amount of fertilization	5	1
	Amount of fungicide	5	1
	Shade cover	3, 4	2
	Number of pickings per year	3	1
	Fruiting nodes	3, 4	2
	Foliage density	1, 3	2
	Fruit load	2, 3, 5, 6	4
Epidemiological factors	Amount of residual inoculum	1	1

References: (1) Bock, 1962; (2) Avelino et al., 2004; (3) Avelino et al., 2006; (4) Avelino et. a., 2012; (5) Avelino et al., 2015; (6) Cilas et al., 2016

Bock, K.R. 1962. Seasonal Periodicity of Coffee Leaf Rust and Factors Affecting the Severity of Outbreaks in Kenya Colony. Trans. Brit. mycol. Soc, 45(3): 289-300.

As opposed to previous ideas, in which wind was the main vector for dispersal of the fungus (*Hemileia vastatrix*), Bock (1962) provided the first evidence and explanation of the mechanisms that allowed rainfall to distribute coffee leaf rust. The paper explains that if air dispersal was the main vector, one would expect a homogeneous distribution of uredospores and therefore infection on the leaves of the tree. **Nevertheless, maximum infection consistently occurs in the lower leaves.** With water dispersal, spread occurs mainly downwards, with some of it also occurring laterally and, under extreme rainfalls, upwards through splash. The study suggests that samples of infected leaves should be taken from the lower portion of the trees, as the inclusion of upper-section leaves could greatly increase error and uncertainty.

The work further explains that in areas where temperature is not a limiting factor, the outbreaks can be determined by 1) distribution and intensity of rainfall, 2) foliage of the tree, and 3) the amount of residual inoculums present at the end of the dry season. With three clearly marked phases, outbreaks always begin after the start of rain season. The first phase is characterized by low, constant incidence levels where no fresh infection takes place. Then, with the beginning of rainy season, incidence increases significantly (second phase), usually with an onset of three to four weeks (mean of 23 days) from first rains. The duration of this sustained maximum depends on rain, foliage density, and inoculum dispersal. The last phase is characterized by a decline in incidence, brought by premature shedding of infected leafs, natural leaf-fall, and lack (or reduced) of dispersal due to reduced rainfall.

Rainfall is referred to as the most important factor determining the course and severity of seasonal disease cycles. The study claims that the relationship between rainfall intensity and uredospore dispersal is linear, yet this is only true for rains with showers higher than 0.3 in, which will effectively disperse spores with inoculums levels of 2 – 2.5 actively sporing rust spots per leaf. Showers of 2 – 2.5 in may disperse the disease only if inoculums levels are higher than 2.5 actively sporing rust spots per leaf.

This work also reports on the relationship between altitude and incidence. The author explains that, as with the coffee berry disease (caused by *Colletotrichum coffeanum*), altitude and topography may affect diurnal temperature gradients, which may in turn affect development of spores and hinder the development of outbreaks; altitude negatively impacts coffee leaf rust incidence. On more recent works (described in more detail below), the "protection" effect of altitude might not prevail though time, due to increased temperatures and changing weather conditions at higher altitudes.

While this work was based in Kenya, the important factors (i.e. rainfall and temperature) are also mentioned in studies from South and Central America (e.g. Avelino et al.,2004; Avelino et al., 2006; Avelino et al., 2015, described below).

Avelino, J., Willocquet, L., Savary, S. 2004. Effects of crop management patterns on coffee rust epidemics. Plant Pathology, 535: 541 – 547.

This paper presents the first evidence that crop management is an important factor influencing the epidemic cycles of coffee leaf rust. They evaluate the effect that multiple factors (climatic or productive) have on a set of stages of monocyclic process (Spore dispersal, deposition, germination, penetration, tissue colonization or sporulation) across four different crop management patterns: Crop shading, planting density, fertilization, and pruning.

They find that, under a same management pattern, a specific factor may have different effects on the stages of monocyclic process. For example, absence of shading increases primary production, which increases fruit load. Fruit load is positively correlated with the infection processes, and could explain why unshaded plantations in high-yield years present higher incidences of coffee leaf rust. However, shading may cause rain to accumulate in the mesh, creating larger drops that can then promote dispersal of the disease through splash. Similarly, other management practices can cause factors to have differential effects on the infection cycle.

The study describes how some more interactions could take place, providing a concise reasoning but little field evidence that supports their hypothesis. Aside from suggesting experimentation and further data collection, they state that a management tool that can be used at the beginning of every rainy season could be useful in managing the invasion. However, they explain that recommendations of such a management tool should be made based on site, crop management patterns, and biological criteria, and call for the **characterization of production typologies and corresponding epidemic risks.** An answer to this need is provided in Avelino *et al.* (2006), where they perform a characterization of different "types" of plots based on a set of climatic and production situations and associate these to the differential risk levels of contracting coffee leaf rust.

Avelino, J. Zelaya, H., Merlo, A., Pineda, A., Ordoñez, M., Savary, S. 2006. The intensity of a coffee rust epidemic is dependent on production situations. Ecological modeling, 197: 431-447.

This represents one of the most comprehensive analysis of coffee rust epidemics, taking into account multiple environmental factors (*e.g.* rainfall, altitude, nutrients in soil), but also a large set of factors that describe cropping practices and productive characteristics. The study leaves aside some of the important environmental factors (*e.g.* wind direction and speed, temperature, humidity) mentioned in other studies (*e.g.* Avelino *et al.* 2004). Yet, the objective of the work is more **focused in identifying typologies of production situations and their corresponding epidemic risks**, rather than explaining the associations between coffee rust incidence and environmental factors.

Throughout their study, they use the maximum percentage of young affected leaves for each year as the outcome variable. A list of 44 variables is considered at the beginning of the study. These range from altitude of the plot to coffee tree age, and annual number of fertilizations, among others. The full list is included in Table I of the paper. **After performing initial exploratory analysis, they report that altitude and rain are amongst the important factors determining the maximum percentage of young affected leaves, in addition to soil nutrient composition, amount and frequency of fertilization, fruit load, and tree age.** Based on these variables, they create **six discrete categories for types of soils, climates, crop management, and productive characteristics**. Observed plots of coffee were then listed under the corresponding category of each group; a plot could be listed as S1, C2, CM5, P6 if it occurred in soil type one, climate type 2, under management type 5, and with productive characteristics type 6.

A segmentation tree of this groups showed that the variable that best explained the disease was the number of fruiting nodes per plant, followed by annual number of fertilizations, shade percentage, altitude, soil pH, foliage density, and fruit load (in decreasing importance). The study, rather than explaining the drivers and processes of the epidemic, provides an in depth description of "plot types" (a combination of soil, climate, management, and productive characteristics) more susceptible to contracting coffee leaf rust.

While this study reports on which variables explain the maximum incidence per year, it does not explain the epidemic's dynamics, and ignores interaction among variables. For instance, shading may reduce temperature by covering sunlight (negative for the disease), but might also produce larger drops of water by accumulating it on the surface, therefore increasing the dispersal of the disease. Some of these interactions are further described in Avelino *et al.* (2004).

Avelino, J., Romero-Guardián, A., Cruz-Cuellar, H.F., Declereck, A.J.F. 2012. Landscape context and scale differentially impact coffee leaf rust, coffee berry borer, and coffee root-knot nematodes. Ecological Applications, 22(2): 584 – 596.

This study reports a strong correlation between coffee leaf rust incidence and percentage of pasture in a 200 m scale. This correlation is stronger for the months of September – November. However, this does not imply causation, and rainfall could be a better explanatory variable for this correlation. As observed by Avelino et al. (2015), heavy rainfall occurs in August. The lag observed between August and September corresponds for previously reported lags between rainfall and coffee leaf rust incidence (three to 4 weeks; Bock, 1962). Increased percentage of pasture could also be explained by increased water availability. **A mechanism that explains how increased pasture percentage within a 200 m radius during the month of September increases coffee leaf rust is absent.**

A partial correlation analysis of other landscape factors indicates that **coffee leaf rust incidence was positively correlated with number of fruiting nodes and shading percentage**. On the other hand, **elevation, number of fertilizer applications, and soil pH were negatively correlated**. However, this analysis was made for plots in similar environmental conditions (e.g. rainfall and altitude). Thus, areas with increased rainfall could invert the direction of some of these correlations (e.g. shading). The direction of the correlations here presented should be handled with care, as dynamics and interactions among variables may change under different conditions.

Avelino, J., Cristancho, M., Georgiou, S., Imbach, P., Aguilar, L., Bornemann, G., Läderach, P., Anzueto, F., Hruska, A.J., Morales, C. 2015. The coffee rust crises in Colombia and Central America (2008 – 2013): impacts, plausible causes and proposed solution. Food Security, 7: 303 – 321.

This paper proposes that the main drivers of the epidemics are economic and meteorological. Low prices observed in the 2008 – 2011 period reduced profit for coffee farmers, which in turn led to suboptimal coffee management. The inappropriate crop management (i.e. lack of fertilization and reduction in application of fungicide) increased plant vulnerability. In addition to low profits for farmers in Latin American countries, Colombia had especially high prices for fertilizer (associated to increase in gas prices); this factor further contributed to the inappropriate crop management.

In addition, **a common factor across countries studied was the reduction in diurnal thermal amplitude (i.e. higher minimum and lower maximum temperatures), allowing a more stable, temperature throughout the day and likely increasing the latency period of the disease.** Authors claim that this weather conditions are consistent with climate change.

While authors do not perform a quantitative analysis, they do provide a list of "presumed factors" related to the coffee rust epidemic. These factors are divided into economic, meteorological, and phonological factors. In the first group, **drop of coffee prices, inefficient credit, and increase of fertilizer prices** are described as factors that "Reduce coffee profitability which led to suboptimal management in coffee plots". Within the meteorological factors, **increased rainfall, a reduction in sunshine, decreased variability in daily temperature, and an earlier rainy season** are presumed to directly favor effects on coffee rust cycle and epidemic. In phonological factors, "**high production**" is said to increase coffee plant physiological susceptibility to epidemics.

Cilas. C., Goebel, F.R., Babin, R., and Avelino, J. 2016. Chapter 6: Tropical Crop Pests and Diseases in a Climate Change Setting – A Few Examples. Torquebiau (ed), Climate Change and Agriculture Worldwide. DOI: 10.1007/978-94-017-7462-8_6

This chapter provides an overall view of coffee rust epidemic. **It explains that the main drivers are fruit load on coffee trees, temperature, rainfall, humidity, cultivar, treatments and landscape configuration**. These factors are mentioned in most of Avelino's papers, described above. The text explains that lower temperatures, which would usually slow down or stop dissemination of the disease are less common. Furthermore, it expands on the fact that coffee leaf rust incidence in highlands has increased in the last years. This text does not elaborate deeper into the mechanisms and processes that control outbreaks and dispersal of the disease.