YASMIM FREITAS FIGUEIREDO

NEW DIAGRAMMATIC SCALE AND RATE PROGRESS ANALYSIS OF COFFEE RUST

LAVRAS – MG
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Ficha catalográfica elaborada pelo Sistema de Geração de Ficha Catalográfica da Biblioteca Universitária da UFLA, com dados informados pelo(a) próprio(a) autor(a).

Figueiredo, Yasmim Freitas.
New diagrammatic scale and rate progress analysis of coffee rust / Yasmim Freitas Figueiredo. - 2022.
90 p. : il.

Orientador(a): Edson Ampélio Pozza.

Tese (doutorado) - Universidade Federal de Lavras, 2022.
Bibliografia.

1. Coffea arabica L. 2. Fungicides. 3. Hemileia vastatrix. I. Pozza, Edson Ampélio. II. Título.

YASMIM FREITAS FIGUEIREDO

NEW DIAGRAMMATIC SCALE AND RATE PROGRESS ANALYSIS OF COFFEE RUST

NOVA ESCALA DIAGRAMÁTICA E ANÁLISE DA TAXA DE PROGRESSO DA FERRUGEM DO CAFÉ

Tese apresentada à Universidade Federal de Lavras, como parte das exigências do Programa de Pós-graduação em Fitopatologia, área de concentração em Epidemiologia, para obtenção do título de Doutora.

APROVADA em 27 de junho de 2022
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LAVRAS – MG
2022

Eu dedico esta tese aos meus avós Adla Alhakim Figueiredo e João Figueiredo Filho.
(in memoriam)

À eles eu não pude dar meu último adeus antes das suas partidas, mas dedico esse trabalho e todo meu amor aos senhores que me ensinaram tanto e me carregaram tanto, que nem sei descrever.
Vocês não tem ideia da falta que fazem aqui na Terra.

Eu amo vocês
e até breve

AGRADECIMENTOS

Agradeço à Deus ao dom da vida e por ter me dado essa caminhada tão enriquecedora. Obrigada por me amparar nos momentos de desespero. Agradeço também aos meus protetores, Nossa Senhora do Rosário, São Benedito, São Mateus e todos amigos iluminados que me abençoaram e guiaram meus passos.

Agradeço à minha família por todo o suporte, sem vocês eu nada seria. Aos meus pais Angélica e Carlos Magno, por todo ensinamento, independência e por aprender a lutar pelos meus objetivos. Meus irmãos Adla e Alemão, meus exemplos, por todos os puxões de orelha, sacodes, mas também por serem meu porto seguro e me darem todo o apoio que eu poderia ter. Aos meu irmão Pedro Henrique por me aguentar nos estresses e estar se tornando um homem bom. Às minhas afilhadas e meu sobrinho Aila, Lara e Joaquim, por serem meus amorzinhos, me ensinar a educar e cuidar dessas coisinhas mais lindas que Deus me deu.

Agradeço à minha avó Maide por todos os bolos de fubá, marmitinhas e amor em forma de comida que me sustentou por muitas vezes. Agradeço a ela e também ao vovô Luiz *(in memoriam)* por terem criado uma família no amor. E por ter sido toda a base da Família Norte Recicla. Que agora além de ser minha família, estou podendo levar meus conhecimentos à empresa ao qual tio Lu (Luiz Mário) dirige com destreza e me acolheu de braços abertos. Estendo meu agradecimento a toda diretoria e colaboradores por todo ensinamento e paciência comigo. Meu muito obrigada à toda Família Norte Recicla!

Agradeço à todos meus médicos e profissionais que contribuíram para minha saúde física e mental. Meu psicólogo Flávio Santana por todo acompanhamento, explicação e papo cabeça. Meus treinadores Tiaguinho e Eric por me aguentarem falando nos seus ouvidos, tanto em Lavras, quanto em São Mateus. À Andrea e todo pessoal da Colônia Esperança por todas meditações, cafezinhos, almoço e todos os programas com muita luz e comida fluidificada.

À Aldeneide, minha amiga e manicure que tanto me aguentou nesses mais de 6 anos de Lavras entre mestrado e doutorado. Por toda parceria, puxão de orelha, conselhos, cafezinhos e me permitir entrar na sua casa e em sua família.

À todos os meus amigos que se fizeram presentes em minha vida e em toda a Jornada do doutorado. À Sueny por ter me conduzido para ir para UFLA, à toda amizade e suporte que me deu antes e ao longo da minha jornada de fitopatologista e congressista. Ao pessoal do cafezinho que não me larga Luiza Reis, Júlio Carlos e Rafaela Guimarães, valeu pela amizade e papos produtivos, apesar de encherem muito meu saco, vocês são uns presentinhos mais lindos, amo vocês! À Kize por sempre me sacudir e me mostrar o melhor caminho. À Larissa Carvalho por sempre se fazer presente e me socorrendo, mesmo estando longe para caramba.

À todos meus amigos de república. Principalmente a Júlia que é parceria do doutorado, na salinha e nas festinhas. Obrigada por ter me dado de presente a Família da República Tropicanas. Eu sou uma agregada muito feliz! Valeu meninas, vocês foram essenciais para meu melhor aproveitamento de Lavras. Vocês são meus amorzinhos, e me ensinaram: “Que sobre e nunca nos falte!”. Ao Lenjah (Diego) pela amizade, por escutar meus dramas e por todo companheirismo. Às meninas que dividiram meu ap404 comigo, principalmente a Marina Pacífico por toda a parceria desde montar o ap.

Agradeço à todos do Nefit, obrigada por terem confiado a presidência de 2018 à mim e a Taty (Thaisa Conrado). Obrigada Taty por ter sido meu braço na presidência e em todo o decorrer da nossa gestão. Agradeço também a Dramim (Vanessa Candido) por todos os perrengues vividos comigo, por toda ajuda na gestão e por entender que eu precisava de um espacinho a mais na mesa da salinha. Meninas vocês são demais... segue a frase “Nos poupe e se preserve Yasmim!”. E novamente ao Júlio Carlos por ter sido um oráculo e ter me ajudado muito na forma de conduzir o Nefit.

Agradeço à Universidade Federal de Lavras (UFLA), aos professores do Departamento de Fitopatologia (DFP), principalmente ao meu orientador Prof. Dr. Edson Ampélio Pozza por ter me recebido de braços abertos, me indicado o melhor caminho a seguir e me dar o melhor instrutor que eu poderia ter, o doutorando Mário Colares. Esse Agrônomo, Mestre e poderoso no R, Mário meu amigo você vai longe! Tenho muito orgulho da sua trajetória. Agradeço por poder dividir esse caminho do conhecimento com você. Agradeço por toda amizade, compreensão das minhas dificuldades e auxílio.

Agradeço à todo aporte financeiro dado pela Capes, por ter concedido a bolsa do doutorado. O presente trabalho foi realizado com apoio da Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Código de Financiamento 001. Agradeço à Fapemig pelo aporte financeiro às pesquisas. Agradeço ao INCT Café por toda disponibilidade para realização da pesquisa. E também a minha mãe que é a melhor diretora financeira da vida e que a Norte Recicla poderia ter.

Além de agradecer a todos que me ajudaram no meu caminho em Lavras. Não poderia deixar de agradecer a todos que me acolheram em São Mateus nesse período de retorno e *home office*. Agradeço à minha prima Fraennzy, João e Ricardo por terem me trazido para casa depois de 8 meses sem voltar, e bom, acabei ficando. Agradeço por terem facilitado a minha vida em São Mateus, valeu por todos os lanchinhos, escuta, consolo e amizade.

Agradeço também aos meus eternos amigos, que já estamos tão velhos que o tempo de amizade já passa de 20 anos. Eu amo vocês! Gregorye, Vinícius, Luciana e Naizillah. E também à Camila Regina por se fazer presente, me acolher em sua casa em São Paulo sempre que preciso e por ter me dado força na cirurgia e no hospital. Agradeço o pessoal da Agronomia, que está sempre presente na minha vida, principalmente Layane e André Covre.

E além de tudo, teve um súbito retorno à Lavras. Que loucura! O que seria algumas semanas, virou mais de três meses. Agradeço por toda a hospitalidade e loucura compartilhada pela Rafaela Guimarães e toda a trupe *pet* bagunceira: Branca, Capitú e Clarice. Que alegravam meus dias e agitavam até demais as noites. Ao longo dessa estadia a Branca virou uma estrelinha e está no céu cuidando de nós. Mas também chegaram na comitiva da loucura a Riquelme (Sarah), a Ana Alice e a Juju (vulgo Susi) também para alegrar nossas noites e com direito a várias risadinhas.

Ao pessoal que me acompanhou, me escutou e me deu incentivo da salinha da Epidemio: Mário, Felipe, Vitória e as visitas da Indiara. À família da Colônia Esperança e Tropicanas por aquecerem meu coraçãozinho. Brysa e Fraennzy, minhas primas que sempre estavam prontas para atender uma ligação. Agradeço à todos aqueles que me deram suporte nesse período que foi crucial para o fim das minhas atividades e obtenção desta tese.

Vendo agora minha trajetória, tudo que eu passei para chegar até aqui, desde o início do estudo para as provas do doutorado até esse momento de finalização, que demorou, mas chegou!!! Os dias foram árduos e difíceis, mas de muita realização e conquista ao longo desses 5 anos e 2 meses de doutorado. Eu vejo o quanto valeu a pena cada passo, como eu estou mais forte e mais madura depois de todo esse processo. Meu Deus, todo esforço valeu a pena!

... E por último e não menos importante eu agradeço à mim. Sim a mim, que fui forte, fraca, feliz, chorei para caramba, tive altos e baixos, errei e acertei, e errei novamente, mas estou aqui finalizando essa fase da melhor forma que eu poderia fazer. De cabeça erguida e muito amor por essa profissão. Hoje vejo o quanto a fitopatologia é linda e ampla.

Gratidão pessoal, sem vocês eu não seria nada. Agradeço à todas as pessoas que me deram suporte para chegar até aqui. Valeu Universo! Gratidão por tudo que aconteceu. Como diz minha amiga Andrea Carvalho: “Está tudo certo! Não tem nada errado! Vamos vivendo da melhor maneira possível e um dia de cada vez.”

Como diria meu avô Luiz Freitas:

“Sonhos não envelhecem!”

e já dizia Chorão..

“Para quem tem pensamento forte, o impossível é só questão de opinião.”

RESUMO

O Brasil é o maior produtor e exportador mundial de café (*Coffea* spp.). Minas Gerais é o principal estado produtor e a produção de café arábica representa mais de 70% da produção estadual. A produção cafeeira pode ser prejudicada por meio de perdas devido à diversos fatores, mas o principal é a presença de doenças. Sendo a ferrugem do cafeeiro (*Hemileia vastatrix*) a principal doença geradora de perdas na produção tanto em café arábica, quanto em conilon. O progresso da doença deve ser acompanhado para a escolha do manejo e melhor época de aplicação de fungicidas. Um dos métodos utilizados para avaliar de forma prática a quantificação de doenças no campo é o uso de escalas diagramáticas. Com isso, o primeiro experimento teve o objetivo de desenvolver uma nova escala diagramática para café arábica com fotografias coloridas e sete níveis de doença, baseado em outras três escalas existentes. Primeiramente, confeccionou-se a nova escala diagramática, a partir de 221 folhas coletadas de forma casualizada e posteriormente foi obtida a distribuição de frequência da doença. Posteriormente foi realizada três avaliações com 10 avaliadores diferentes para a validação da nova escala e comparação com as escalas diagramáticas existentes. A validação foi realizada por meio de regressão linear e análise de correlação concordante de Lin, realizadas no software R. Os avaliadores utilizando a escala proposta aumentaram a acurácia, precisão e reprodutibilidade das avaliações e reduziram a distribuição dos resíduos. O objetivo do segundo experimento foi de avaliar a taxa de progresso da ferrugem no café arábica com diferentes fungicidas e suas misturas. Os dados analisados foram obtidos entre 2014 a 2021, obtidos a partir de 23 experimentos de lavouras de café arábica, cultivar Catuaí Vermelho IAC 99, suscetível à ferrugem. As avaliações foram realizadas em lavouras com idade entre cinco e oito anos, espaçamento de 3,8 x 0,6m entre plantas e conduzidos segundo as recomendações técnicas para a cultura. O delineamento experimental foi em blocos casualizados, com quatro repetições e a parcela experimental composta por 10 plantas. Foi avaliada a incidência de ferrugem, a taxa de progresso da doença, linearização dos dados e ajustados modelos lineares e não lineares para todos os dados de tratamento obtidos, utilizando o software R. O melhor modelo ajustado foi escolhido a partir dos critérios de maior coeficiente de determinação (R2) e menor Critério de Informação de Akaike (AIC). O modelo integral não linear exponencial foi o de melhor ajustou para descrever a taxa de progresso da ferrugem em função do tempo.

Palavras-chave: *Coffea arabica* L. Controle químico. Escala Diagramática. Fungicidas. *Hemileia vastatrix*.

ABSTRACT

Brazil is the world's largest producer and exporter of coffee (*Coffeea* sp.). Minas Gerais is the central producing state and Arabica coffee production represents more than 70% of the state production. Coffee production can be harmed through losses due to several factors, but the main one is the presence of diseases. Coffee rust (*Hemileia vastatrix*) is the main disease causing production losses in both arabica and conilon coffee. The progress of the disease must be monitored to choose the best management and time of fungicides application. One of the methods used to practically evaluate the quantification of diseases in the field is the use of diagrammatic scales. Thus, the first experiment aimed to develop a new diagrammatic scale for arabica coffee with color photographs and seven disease levels, based on three other existing scales. First, a new diagrammatic scale was created, from 221 leaves collected at random and later the distribution of the frequency of the disease was obtained. Subsequently, three evaluations were performed with 10 different evaluators for the validation of the new scale and comparison with the existing diagrammatic scales. Validation was performed using linear regression and Lin concordant correlation analysis performed in the R software. The evaluators using the proposed scale improved the accuracy, precision and reproducibility of the evaluations and reduced the residues distribution. The aim of the second experiment was to evaluate the progress rate of rust in arabica coffee with different fungicides and fungicide mixtures. The analyzed data were obtained between 2014 and 2021, from 23 experiments of Arabica coffee crops, cultivar Catuaí Vermelho IAC 99, susceptible to coffee leaf rust. The evaluations were carried out in crops aged between five and eight years, with a spacing of 3.8 x 0.6 m between plants and carried out according to the technical recommendations for the culture. The experimental design was in randomized blocks, with four replications and the experimental plot consisted of 10 plants. Rust incidence, disease progress rate and linearization rate data were obtained, then linear and nonlinear rate models were fitted for all treatment data obtained using R software. The best adjusted model was chosen from the criteria of highest coefficient of determination (R2) and lowest Information Criterion of Akaike (AIC). The exponential nonlinear integral model was the best fit to describe the rate progress of rust as a function of time.

Keywords: *Coffea arabica* L. Chemical control. Diagrammatic Scale. Fungicides. *Hemileia vastatrix.*

SUMÁRIO

PRIMEIRA PARTE

1 INTRODUCTION

Coffee is one of the most common beverage in the world and its consumption has been growing over the years. Last years, global consumption increased by 1.5 million bags (60kg) due to higher European, American and Brazilian consumption. Brazil is the world's largest producer, followed by Vietnam, Colombia and Indonesia (USDA Foreign Agricultural Service, 2021). The total Brazilian estimated production for 2022 of processed coffee is over 55 million bags. Nowadays arabica coffee represents 69.57% of Brazil's estimated production. The state of Minas Gerais is the largest producer of coffee beans in the country and represents 70% of the arabica coffee planted area in Brazil (CONAB, 2022).

Coffea arabica is the *Coffea* species with the most planted areas and the highest production in the world (USDA Foreign Agricultural Service, 2021). Coffee production and quality of the beverage can be reduced by adverse situations such as problems in soil nutrition, bad weather, problems in crop management and diseases. The main disease in this crop is coffee leaf rust (CLR). CLR is caused by the fungus *Hemileia vastatrix* Berkeley & Broome that promotes premature defoliation, reduction of the photosynthetic area of the plant with subsequent death of plagiotropic branches in coffee trees (Pozza, 2021). Based on previous research, loss in arabica plantations has reduced global coffee production: by up to 20-25% (McCook, 2006), reach to 35% (Talhinhas et al., 2017) and up to 50% (Pozza et al., 2010). However, based on estimated mathematical modeling, loss ranges can reach 55.8% to 99.8% in CLR production (Colares, 2018).

The study of the temporal progress of the CLR helps to regulate the application time and choose the best management with isolated fungicides or with a combination of different products. This represents the best control of an epidemic in the best management way by optimizing the application of inputs, such as fungicides and fertilizers, and reducing costs (Custódio et al., 2011; Pozza, 2021; Pozza & Alves, 2008). Usually CLR progress are expressed by plotting the proportion of the disease as a function of time (Bergamin Filho, 2018; Jeger & Viljanen-Rollinson, 2001). The disease progress curve of CLR was described by Kushalappa & Chaves (1980), Kushalappa & Martins (1980), Kushalappa *et al.* (1983) e Pinto *et al.* (2002), the first signs of the disease appeared from December to January. The increase in the rate of disease progression occurred in March and April, assuming an exponential growth. The most intense signs of the disease occurred from June to July, due to the harvest in cold weather and

low humidity. As a consequence of the period of greater sporulation of the pathogen, a drastic fall of the leaves can occur, generating a severe reduction of the plant canopy.

The management of CLR are controlled by fungicides is carried out based on predefined dates (Pozza, 2021; Pozza et al., 2010) or based on monitoring for decision making (Belan et al., 2014). The second way is more suitable and reduces costs with unnecessary applications (Bergamin Filho, 2018; Jeger & Viljanen-Rollinson, 2001). Thus, to identify and evaluate the efficiency of fungicides, the best spraying times, the resistance of cultivars and management techniques, it is necessary to quantify the disease, by its incidence and/or severity. A good way to quantify disease in the field is using a diagrammatic scale as a standardized tool to assess the severity of CLR (Berger, 1980; Del Ponte et al., 2017). There are currently three scales to quantify CLR in Arabica coffee (Capucho et al., 2011; Custódio et al., 2011; A. C. Kushalappa & Chaves, 1980). However, these scales do not follow the current trend of using true-color photographs or stylized representations to assist assessors in quantifying the disease (Del Ponte et al., 2017).

Based on this, the first experiment aimed to evaluate and compare the rate progress of Arabica coffee rust in different experiments and years, comparing the fungicides positioning used with a different mode of action isolated and in combination mode of action regarding a effectiveness management for CLR. In this context, comparing the fungicides positioning used as mode of action, isolated and/or in combination regarding a effectiveness management for CLR using the epidemiology models. The second experiment aimed to develop a new diagrammatic scale for Arabica coffee with color photographs and seven disease levels, based on three other existing scales.

2 LITERATURE REVIEW

2.1 Coffee

Coffee is an Angiosperm (*Dicotyledons*) belonging to the *Rubiaceae* family. The *Coffea* genus includes 124 species (Davis et al., 2011). On the worldwide market, the main species of this genus are *Coffea arabica* L. and *Coffea canephora* Pierre ex A.Froehner. The origin and diversification of the genus occurred in the African continent. The coffee tree is restricted to tropical areas and preferably in humid locations (Ferreira et al., 2019). Therefore, Brazil, Vietnam, and Colombia were the main coffee producers and exporters from 2016 to 2020 (USDA, 2020). Brazil is the largest world producer, in 2020 its estimated production was

63.08 million bags (CONAB, 2020; USDA, 2020). Arabica coffee represents 77% of total production with 48.77 million bags. The main Arabica coffee producing states are Minas Gerais, São Paulo and Espírito Santo and they represent 92.85% of Arabica production. Minas Gerais alone represented 70% of Arabica production in 2020 with 34.34 million bags (CONAB, 2020).

Based on the coffee economic importance described above, it is important to appreciate the coffee production and productivity, and beverage quality. However, some factors hinder the good development of the plant, such as phytopathogens. The main coffee disease in Brazil and in the world is rust (Pozza, 2021).

2.2 Coffee leaf rust

Coffee leaf rust (CLR) was first recorded in 1861 in East Africa, but the first epidemic occurred in 1869 in Sri Lanka (formerly Ceylon), causing high social and economic losses (Talhinhas et al., 2017). The disease was first reported in 1970 in Brazil, southern Bahia state, and after four months it had already spread to almost all states. CLR occurs in most coffee-growing areas of the world, promoting defoliation of plants, and based on mathematical modeling the estimated loss in production by CLR ranges from 55.8% to 99.8% (Colares, 2018).

Coffee rust caused by the fungus *Hemileia vastatrix* Berkeley & Broome is the most important disease limiting coffee production (Waller et al., 2007). Symptomatology of CLR is the first yellow pale spots on the abaxial side of coffee leaves. After that, they develop into a yellow-orange lesion with a mass of spores. Where there is a spore mass, the adaxial side becomes chlorotic. With the progress of the disease, the area may become necrotic and induce premature leaf fall (Pozza et al., 2010; Talhinhas et al., 2017). In addition to defoliation of plants, the pathogen reduces the amount of product, the size of the grain and generates less plant longevity (Pozza, 2021).

2.3 Coffee rust progress rate

The environment can affect the plant-pathogen interaction, as it can influence the growth and susceptibility of the host plant and the dissemination, multiplication, survival, and activities of the pathogen. Thus, climate change can alter the occurrence and severity of plant diseases (Ghini et al., 2011). The main weather variables for the progress of fungal diseases in

coffee are temperature and humidity (Pozza & Alves, 2008). Favorable conditions for the occurrence and progression of CLR are: absence of light; high fruit load; high plant density; unbalanced nutrition; shading; and, climatic conditions with temperature between 21-25˚C, high relative humidity and the duration of the leaf wetness period (Pozza et al., 2010; Pozza & Alves, 2008).

The rate was described by Van der Plank (1963) naming it the Apparent Infection Rate. The disease progress rate was calculated by the proportion of the disease that increased in a given period (Van der Plank, 1963). The rate of disease progress expresses the speed of the epidemic and is influenced by host susceptibility, pathogen virulence, and favorable environmental conditions. The use of fungicide also interferes with the progress of the disease. For these, the rate is an important parameter to compare epidemics in different climatic weather conditions (Ghini et al., 2011; Van der Plank, 1963). Disease progress curve another way to represent an epidemic and is usually expressed by plotting the proportion of the disease as a function of time. The main parameters in the disease progress curve are initial inoculum (y_0), disease progress rate (r), shape and area of disease progress curve, the earliest date that disease is observed (t_0), maximum severity (y_{max}), and final disease severity (y_{final}) (Bergamin Filho, 2018; Jeger & Viljanen-Rollinson, 2001).

The first symptoms of CLR occur between December-January, the disease progression increases from March-April getting exponential rate progress growth. The maximum disease intensity occurs in June-July (Pinto et al., 2002). Therefore, it is necessary to observe the evolution of the disease to choose the best management and control (Pozza et al., 2010). The management of CLR in Arabica is done mainly with the integration of several measures. Genetic control and chemical control are used. Genetic control can use resistant or tolerant varieties resistance (McCook & Vandermeer, 2015). The resistances are divided into horizontal resistance which is more durable (slow-rust) than vertical resistance (hypersensitivity response by fleck lesion) (Silva et al., 2008). However, chemical control is the most usual, using protective and systemic fungicides, they are applied according to the need and the risk scenario. In this context, the rate measures the speed of the disease and is an important parameter for comparing epidemics (Ghini et al., 2011). The management of fungicides is carried out based on predefined dates (Pozza, 2021) or based on CLR monitoring for decision making (Belan et al., 2014).

2.4 Diagrammatic scale

As CLR is a leaf disease, the most appropriate way to quantify rust is due to the severity of the disease. Severity is the percentage or the proportion of area with disease symptoms (Amorim & Bergamin Filho, 2018). The quantification of the disease depends on standardized tools to assess the severity of CLR. A tool to be used must provide reliable results, easy to apply, and represent a wide range of disease development. Diagrammatic scales meet the requirements listed above (Berger, 1980) and are widely used for disease quantification (Del Ponte et al., 2017).

The assessment can classify the amount of disease qualitatively or quantitatively (Del Ponte et al., 2017). Qualitative assessment (nominal scales) is more subjective and not reproducible because it is divided by brief descriptions such as no disease, low, moderate, and high severity of the disease, or symbols. On the other hand, qualitative ordinal scales are clearer than nominal scales, because they have discrete descriptions of symptoms. The ordinal qualitative scale is used to compare diseases with symptoms that are difficult to quantify, however you cannot use the midpoints or means of those scales. Aiming a greater evaluation efficiency and reproducibility there are the quantitative ordinal scales. They are clear with a specific range of severity. For these, you can use the mean and mid-point conversion (Bock et al., 2020).

Diagrammatic scale or Standard area diagram (SAD) is a tool for estimating the severity of plant diseases, based on visual estimation (Del Ponte et al., 2017). The tool is made with illustrated representations of a series of plants or parts of plants showing the symptoms of the disease at different levels of severity (Amorim & Bergamin Filho, 2018). Previously the black-and-white drawings are the most typical diagrams. However, nowadays there is a trend to use real colors photographs or stylized representations to help assessors in the disease quantification (Del Ponte et al., 2017). SAD helps a lot in the experimental and field areas for quantification and management of diseases quickly and practically (Amorim & Bergamin Filho, 2018; Del Ponte et al., 2017). This tool is widely used in plant pathology for evaluating disease in different crops, organs, and pathogens (Belan et al., 2014; Capucho et al., 2011; Custódio et al., 2011; de Paula et al., 2016; Figueira et al., 2014; Freitas et al., 2015; Sussel et al., 2009).

In addition to building a SAD, after 1990 also need to validate the scale. There are two statistical models for use to validate, the coefficients of linear regression and Lin’s concordance correlation coefficient. Most articles use Linear regression (83.33%), just a few studies use both metrics, and nowadays there is a trend increasing the use of Lin’s coefficient (Del Ponte et al.,

2017). Linear regression compares the values of actual severity (independent variable) and estimated severity (dependent variable) of the disease. Although widely used, linear regression is not the most suitable method for this type of analysis, as it generates erroneous conclusions. Lin's method is the most suitable, as it combines measures of accuracy and precision in the same parameter and avoids erroneous conclusions that can be obtained in linear regression (Bock et al., 2010).

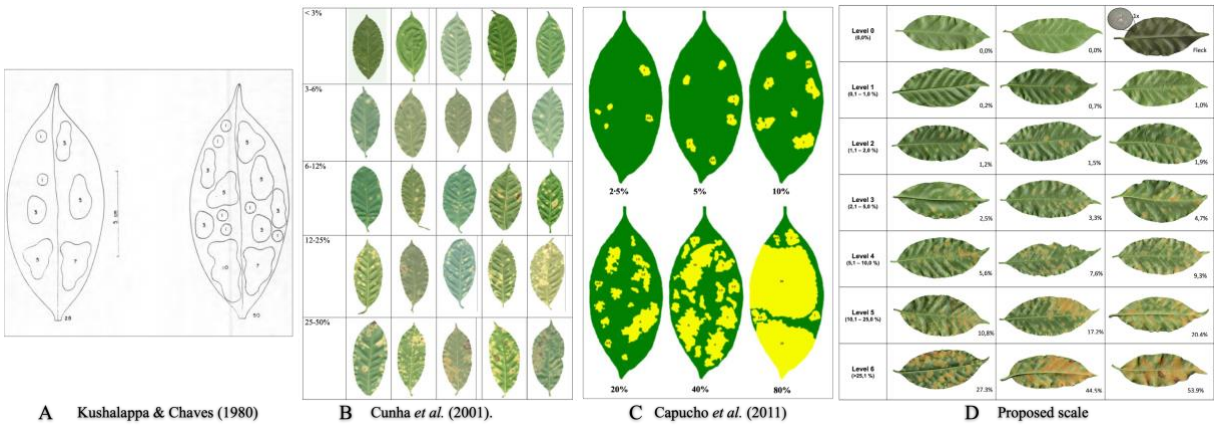

Figure 1 Diagrammatic scale to assess the severity of coffee leaf rust (*Hemileia vastatrix*) on coffee leaves. (A) The diagrammatic scale of Kushalappa & Chaves (1980), (B) diagrammatic scale of Cunha et al. (2001), (C) diagrammatic scale of Capucho et al. (2011) and (D) proposed diagrammatic scale.

For CLR there are three previous diagrammatic scales (Capucho et al., 2011; Cunha et al., 2001; A. C. Kushalappa & Chaves, 1980), but just Capucho et al. (2011) used Lin`s concordance. However, they use percentage colored drawings, without levels and use the same SAD to *C. arabica* and *C. canephora*. Showing the importance to make a new CLR scale, with both statistical methods, levels, and reals photographs.

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SEGUNDA PARTE - ARTIGOS

(Formatação baseada nas exigências do *European Journal of Plant Pathology*, versão **aceita** dia 19 de Agosto de 2022 e **Publicado** 24 de Agosto de 2022*)*

ARTIGO 1

Coffee leaf rust assessment: Comparison and validation of diagrammatic scales for *Coffea arabica*

Escala para ferrugem do café: Comparação e validação de escala diagramática para *Coffea arabica*

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New scale for arabica coffee leaf rust

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Publicado 24 de Agosto de 2022

https://doi.org/10.1007/s10658-022-02570-2

Coffee leaf rust assessment: Comparison and validation of diagrammatic scales for *Coffea arabica*

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DOI: https://doi.org/10.1007/s10658-022-02570-2

ABSTRACT

Coffee leaf rust (CLR) is the most important disease in coffee and is caused by *Hemileia vastatrix*. The use of a diagrammatic scale helps people more effectively evaluate rust severity and improves disease measurement by evaluators. Our goal was to develop a new scale with colored pictures and seven disease levels (0; 0.1–1.0; 1.1–2.0; 2.1–5.0; 5.1–10.0; 10.1–25.0; >25.0%) and then compare the severity results of CLR on arabica coffee leaves with those based on three other scales. Three evaluations were performed by ten different evaluators. The first assessment was performed without a scale. On the same day, raters performed four assessments with each of the four diagrammatic scales. The third evaluation was performed at seven-day intervals. We analyzed the statistics with linear regression and Lin's concordance correlation. The evaluators using the proposed scale improved the precision, accuracy and reproducibility of the evaluations and reduced residual distribution when compared to the evaluators who did not use the proposed diagrammatic scale or who used the other scales. Overall, the proposed diagrammatic scale is a tool that can assist users in producing a disease estimate close to the real value of CLR on arabica coffee leaves.

Declarations

Not applicable

1 Introduction

Brazil is the leading country in terms of coffee production and one of the largest coffee-exporting countries worldwide, followed by Vietnam, Indonesia and Colombia (Abreu, 2000; FAO, 2020). In 2020, the total Brazilian production of arabica (*Coffea arabica*) and conilon (*Coffea canephora*) coffee was 61.62 million bags and arabica coffee constitutes 77% of the national production (CONAB, 2020). However, the production and quality of coffee beans are strongly influenced by the occurrence of phytopathogens. Leaf diseases are caused by many pathogens, and most of them are difficult to control in tropical regions (Ghini et al., 2011).

Coffee leaf rust (CLR), caused by the obligate fungal parasite *Hemileia vastatrix* Berkeley & Broome, is the most important coffee disease in much of the world (Waller et al., 2007). During years with high incidence, CLR can reduce global coffee production by 20–25%, causing losses of 1–2 billion dollars annually (McCook, 2006). The first symptoms of CLR are characterized by yellow spots on the abaxial side of leaves. The symptoms develop to signs into large orange-yellow spore masses, leading to premature leaf drop. On the adaxial leaf side, areas with spores become chlorotic (Pozza et al., 2010; Talhinhas et al., 2017).

Despite the threat of diseases, most of the area cultivated with *C. arabica* is planted with susceptible cultivars (Porto et al., 2019). To assess the best methods of management, use of resistant cultivars and application of fungicides, it is necessary to quantify the symptoms of diseases. These quantifications require standardized tools to assess CLR severity. These tools should be simple and quick to use in different conditions in addition to being accurate, precise and reproducible (Berger, 1980). Diagrammatic scales are useful to accurately and reliably measure disease severity by assessors (Martins et al., 2004). These tools involve sets of plant illustrations or plant parts with symptoms representing a range of disease severities (Campbell & Madden, 1990).

For CLR in *C. arabica* leaves, diagrammatic scales have been developed. Kushalappa & Chaves (1980) and Capucho et al. (2011) developed a unique scale for both arabica and conilon coffee species. The first was obtained in black and white drawings and the second in colored drawings. These scales have been applied to assess disease severity both in nurseries and in the field. Cunha et al. (2001) made a scale for CLF in arabica with colored photographs. Nowadays there is a trend to use real high-resolution images to help assessors in disease quantification (Belan et al., 2020; Del Ponte et al., 2017; Franceschi et al., 2020). First, the upper and lower limits of the disease found in the field and the control level for coffee rust were considered. The symptoms and signs of the disease and vertical and horizontal resistance were also considered. The scale should be as close as possible to those symptoms observed in coffee leaves at various disease levels. The limits of visual acuity were considered

by employing the Weber–Fechner stimulus law, as described in previous studies on scale assessment (Angelotti et al., 2008; Belan et al., 2014; Belasque Júnior et al., 2005; Custódio et al., 2011; Salgado et al., 2009; Sussel et al., 2009).

Based on these scales, improvements have been made a new scale for arabica coffee with higher resolution color photographs of diseased leaves and shorter intervals were created based on the frequency distribution of the collected leaves. With these improvements, we reduced systematic errors and increased accuracy, precision and reproducibility. We show improvements via the new scale compared to the existing scales. This study aims to develop a new improved CLR scale by comparing its parameters with those of scales already used. Furthermore, we validate our new scale to achieve better CLR severity assessments.

2 Material and methods

2.1 Developing the diagrammatic scale

For scale development, 221 leaves were collected randomly from coffee trees on different dates. The samples were collected in the same month in different plants, with symptoms and signs of the disease present at several different severity levels. The leaves were naturally infected by *Hemileia vastatrix* in two experimental fields (21°13'45.394"S, 44°57'51.005"W and 21°13'35.998"S, 44°58'15.254"W) with different cultivars of *C. arabica* at the Federal University of Lavras. The collected leaves were scanned with a desktop scanner with 300 DPI (dots per inch) resolution on a white background. The real severity or the percentage of symptomatic leaf area was determined using Assess® v. 2.0 software (American Phytopathological Society, St. Paul, MN, USA). For this quantification, only the yellowish-orange sporulation area was considered.

Based on the minimum and maximum levels of severity found, the data frequency distribution was determined. Afterward, to define whether the scale intervals are logarithmic or have other distributions, all the maximum numbers of leaves in a given frequency range were subjected to linear, nonlinear, exponential, logarithmic and Gompertz adjustment models (Belan et al., 2014; Campbell & Madden, 1990).

Seven interval diagrammatic scales were created based on the Weber–Fechner visual acuity law (Horsfall & Barratt, 1945; Nutter & Schultz, 1995). The Weber–Fechner law says that the response to any stimulus is proportional to the logarithm of the stimulus intensity (Horsfall & Barratt, 1945). The minimum and maximum levels of disease severity on the new scale were then established for a model adjusted according to the frequency range and the percentage of disease to be controlled. After establishing severity percentages represented in the

scale, real images of leaves with and without spores were used for the CLR scale development. Healthy leaves and fleck lesions a hypersensibility reaction response originating from vertical resistance were included as a zero level (Silva et al., 2008).

2.2 Validation and comparison of the diagrammatic scales

For validation and comparison of the scales, 50 images of coffee leave corresponding to all the scale levels were used. These images were placed on individual slides in random order for display in Microsoft® PowerPoint® 2010 (Microsoft Corporation, Redmond, WA, USA). Ten evaluators with no experience in CLR quantification assessed the images at three different moments. For the first evaluation, all the evaluators estimated the CLR severity without the aid of any scale. Next, on the same day as the first evaluation, the evaluators assessed the same images but with the aid of all the scales. The evaluators used all the old scales and the new scale to perform the assessments and estimate the values with the different scales. Seven days later, a second evaluation with all the scales was done to verify the repeatability of the estimates, with the same evaluators and the same images of leaves (but in a different order). To validate and compare the scales, the repeatability, reproducibility, accuracy and precision were evaluated. The parameter used in the Kushalappa & Chaves (1980) and Capucho et al. (2011) scales was the percentage of area covered by lesions, whereas the scale developed by Cunha et al. (2001) and our proposed scale ranks by discrete values from 1 to 5 and 0 to 6, respectively. These values were subsequently converted to the percentage of the diseased area.

2.3 Validation by linear regression

Scale reproducibility was analyzed using the coefficient of determination and values from linear regressions between the estimated severities of the different evaluators in pairs (Campbell & Madden, 1990; Kranz, 1988; Nutter & Schultz, 1995; Nutter Jr et al., 1993). This was done with the new proposed scale and those developed by Kushalappa & Chaves (1980), Cunha et al. (2001) and Capucho et al. (2011).

To determine the accuracy and precision of each evaluator, simple linear regression was used, with the true severity obtained as an independent variable and the estimated severity according to the evaluator, using scales as the dependent variables. The accuracy of the estimation of each evaluator, as well as the group of evaluators, was determined by a *t*-test applied to the intercept of linear regressions ($\beta 0$) to verify the hypothesis Ho: $\beta 0 = 0$

and to the slope of the line (β1) to test the hypothesis Ho: β1 = 1 at 5% probability level (P = 0.05). Intercept values significantly different from 0 (zero) indicate overestimation (> 0) or underestimation (<0) of the actual severity at low levels. On the other hand, slope that deviates significantly from 1 indicates a systematic overestimation (>1) or a systematic underestimation (<1) of actual severity at all levels of the disease (Nutter & Schultz, 1995).

The repeatability of the estimation by the same evaluator was determined using the same parameters obtained from regression, in which the first assessment was compared to the second. The precision of estimation was determined via the regression determination coefficient (R^2), the absolute error variance and the estimated repeatability determined by regression analysis of the second evaluation in comparison to the first evaluation of the same sample (Nutter Jr et al., 1993). Statistical analysis was performed using R-3.4.0 software (R Core Team 2013), and the other calculations were performed in Microsoft® Excel® 2000.

2.4 Validation by Lin's concordance correlation

In addition to linear regression between the real and estimated disease severity, Lin's concordance correlation (LCC) analysis was used to determine the accuracy, precision and bias (Lin, 1989). This correlation combines accuracy and precision measurements to assess the level of the pairs of observations (intercept = 0 and slope = 1) and combines measures of bias and precision to assess fits to the line of concordance (45° = perfect concordance). The bias correction factor (C_b) is calculated from location bias and scale bias, derived from the means and standard deviations of x and y, respectively. Location bias estimates the change in the adjusted line in the regression regarding the concordant line by measuring the difference in height between the two lines (0 = perfect match between x and y). The bias scale shows the difference between the actual and estimated values, and the calculation is performed according to the difference between the slope of the adjusted line in the regression with the concordant line (1 = perfect match between x and y). The evaluators' precision was calculated via Pearson correlation. The confidence intervals (CIs) were estimated to verify the difference (P < 0.05) in the assessments between the evaluator groups with and without the scale. Statistical analyses were performed using R-3.4.0 software using the epi.ccc function of the epiR package (Stevenson, 2013), and the ICC was calculated using the icc function of the irrR package (Gamer et al., 2019).

3 Results

3.1 Development of the diagrammatic scale

The minimum and maximum values of CLR severity found were 0.01% and 36.83%, respectively. However, among the entire sample, 90% of the leaves presented a severity of less than 10% (Table 1).

Table 1. Frequency distribution at unit intervals of coffee leaf rust (*Hemileia vastatrix*) severity values (%) on coffee leaves (*Coffea arabica*)

Interval severity (%)	Frequency	Cumulative percentage (%)	Cumulative frequency	Cumulative percentage (%)
0–1	58	26.2	58	26.2
1–2	45	20.4	103	46.6
2–3	24	10.9	127	57.4
3–4	21	9.5	148	66.9
4–5	17	7.7	165	74.6
5–6	10	4.5	175	79.1
6–7	5	2.3	180	81.4
7–8	9	4.1	189	85.5
8–9	10	4.5	199	90.0
9–10	3	1.4	202	91.4
10–11	3	1.4	205	92.7
11–12	3	1.4	208	94.1
12–13	1	0.5	209	94.5
13–14	2	0.9	211	95.4
14–15	1	0.5	212	95.9
15–16	2	0.9	214	96.8
16–17	0	0.0	214	96.8
17–18	1	0.5	215	97.2
18–19	2	0.9	217	98.1
19–20	0	0.0	217	98.1
20–21	1	0.5	218	98.6
21–22	0	0.0	218	98.6
22–23	1	0.5	219	99.1
23–24	0	0.0	219	99.1
24–25	0	0.0	219	99.1

25–26	0	0.0	219	99.1
26–27	1	0.5	220	99.5
27–28	0	0.0	220	99.5
28–29	0	0.0	220	99.5
29–30	0	0.0	220	99.5
30–31	0	0.0	220	99.5
31–32	0	0.0	220	99.5
32–33	0	0.0	220	99.5
33–34	0	0.0	220	99.5
34–35	0	0.0	220	99.5
35–36	0	0.0	220	99.5
36–37	1	0.5	221	100.0

The best model adjusted for the frequency values of the severity intervals was the exponential model. The exponential model showed the highest R^2 value, the best parameters of the equations in the t test (β0 and β1), a relatively small mean squared error and significance of the parameters in the t test (Table 2). This model best fits the actual or observed data (Figure 1; Table 2).

Table 2. Parameters of linear and nonlinear models for the severity frequency of CLR at different severity intervals

Model	MSE	R^2	β0	β1
Exponential	3.404	0.979	79.874*	0.326*
Logistic	14.346	0.912	751.500^{ns}	0.015*
Gompertz	3.729	0.977	95.000*	0.106*
Linear	94.178	0.424	20.396*	-0.759*

MSE - mean squared error; R^2 - coefficient of determination; β0 - intercept; β1 - slope of the line; ^{ns} the null hypothesis (β0 = 0 and β1 = 1) was accepted in the t-test (P = 0.05); * the null hypothesis was rejected in the *t-test* (P = 0.05).

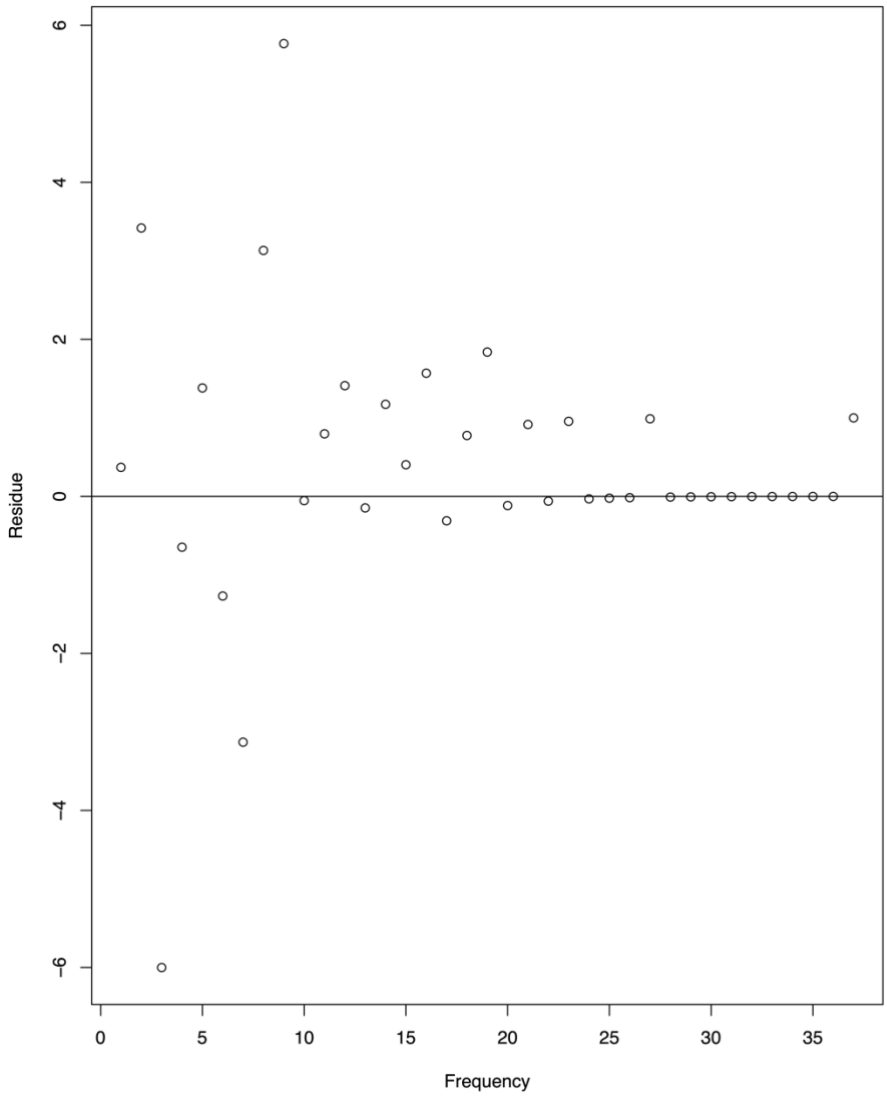


Figure 1 Residual distribution of an exponential model for frequency of coffee leaf rust for different severity intervals.

The scale was developed to include seven levels (Figure 2). These levels were distributed in intervals of 0 to >25.0% of the diseased leaf area (DLA). The Weber–Fechner law was used to represent relatively high frequency intervals (Table 1). The upper limit based on the frequency was 36.83%; however, for better visualization of level 6 on the new scale, we specifically collected more leaves from coffee farms with high severity. These leaves were collected from a highly susceptible cultivar used in breeding programs and are not representative of plants on yields. Thus, the upper limit of severity represented in the scale was 53.9% because we did not find leaves with a disease severity greater than this value.

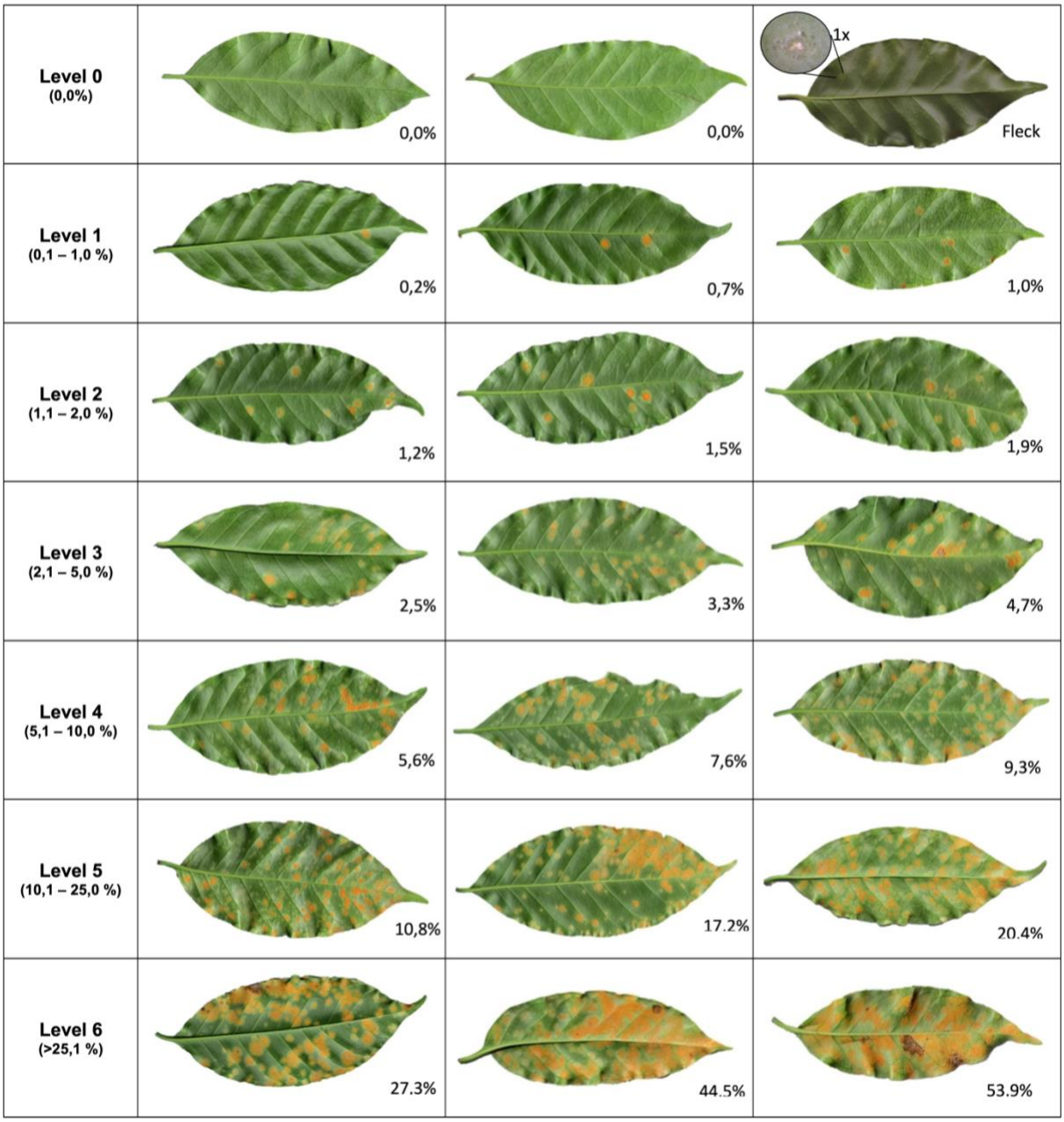
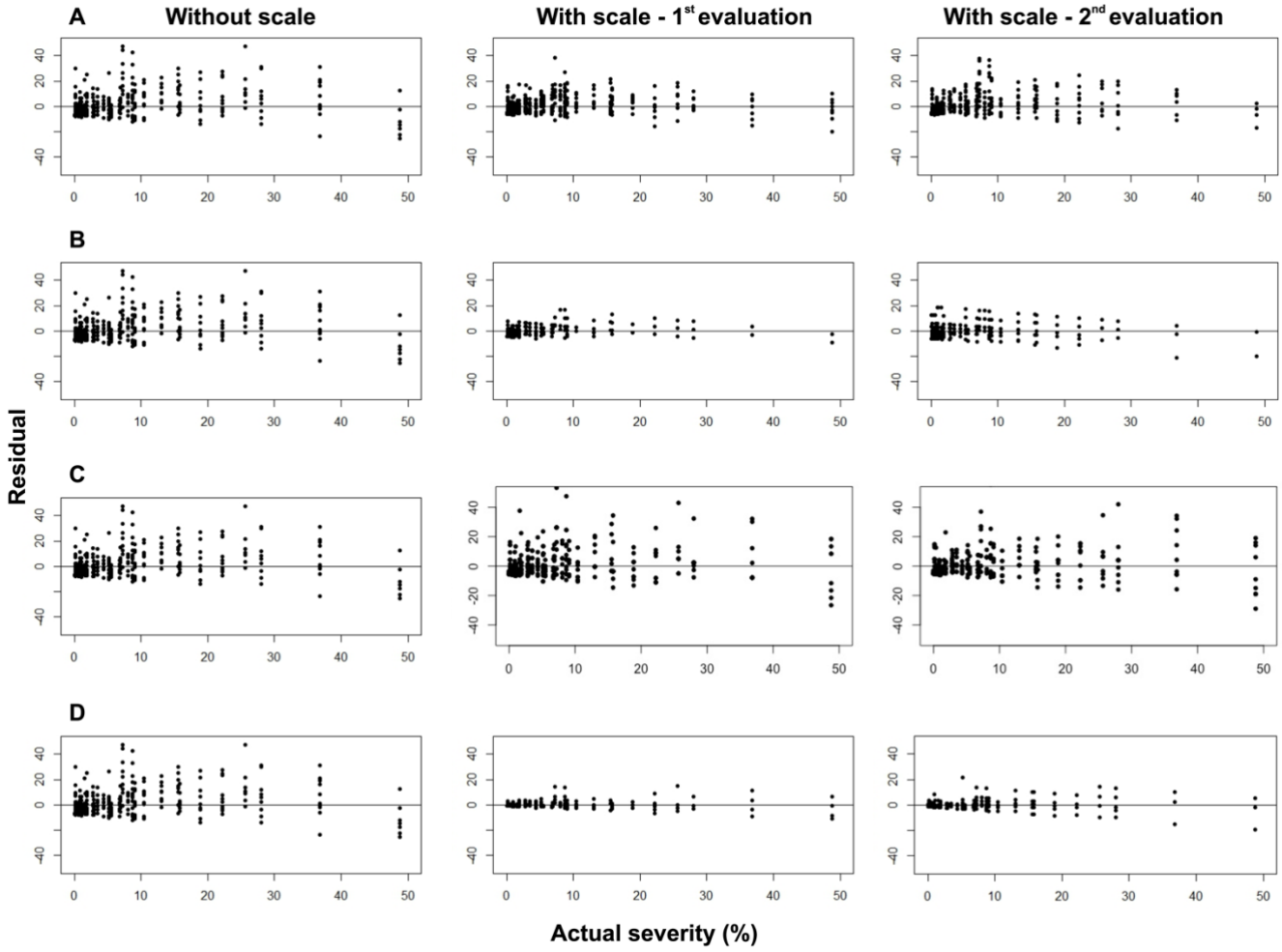


Figure 2 Diagrammatic scale to assess the severity of coffee leaf rust (*Hemileia vastatrix*) on coffee (*Coffea arabica*) leaves.

3.2 Scale validation by linear regression

Considering the joint analysis of the regression coefficients, greater accuracy and precision were obtained with the scales than without them and were higher with the use of the proposed scale (Table 3; Figure 3). The disease severity overestimation by all the evaluators occurred without the use of scales at all evaluations. The accuracy of the disease severity observed in the first assessment of all evaluators, without the use of the scale, at

188 the intercept (β0) and the angular coefficient (β1) of the linear regression line was different from 0 (zero) and 1
189 (one), respectively (Table 3).



190 **Figure 3** Residual distribution (estimated severity – actual severity) of coffee leaf rust (*Hemileia vastatrix*)
191 estimation on coffee tree (*Coffea arabica*) leaves, carried out without the use of a diagrammatic scale and with the
192 aid of a diagrammatic scale for two evaluations: (A) scale of Kushalappa & Chaves (1980), (B) scale of Cunha et
193 al. (2001), (C) scale of Capucho et al. (2011), and (D) proposed scale. The points represent 50 estimations by each
194 evaluator.

195

196 **Table 3.** Intercept (β_0), the slope of the line (β_1) and coefficient of determination (R^2) of linear regression equations
197 relating visual estimates of the severity of coffee leaf rust (*Hemileia vastatrix*) on coffee leaves (*Coffea arabica*),
198 conducted by evaluators with and without the diagrammatic scales: the (A) Kushalappa & Chaves (1980), (B)
199 Cunha et al. (2001), (C) Capucho et al. (2011) and (D) proposed scales, with real severity values determined
200 electronically.

A – Kushalappa & Chaves Scale (1980)

	Without scale			With scale					
				1st evaluation			2nd evaluation		
Evaluators	β0	β1	R²*	β0	β1	R²*	β0	β1	R²*
A	12.4731*	1.3846*	0.6864	5.4675*	0.8370*	0.7861	5.0732*	0.8025*	0.7899
B	3.2081*	1.2372*	0.8050	3.6138*	0.8764*	0.7809	4.2958*	0.9329*	0.7500
C	7.0894*	0.9916*	0.6296	8.7757*	0.9206*	0.6467	11.2376*	0.9425*	0.6303
D	8.2400*	1.2062*	0.7654	6.1921*	0.8865*	0.8217	5.8427*	0.8926*	0.7006
E	7.8318*	0.8458*	0.6647	10.2092*	0.7697*	0.5747	11.1387*	0.9769*	0.5885
F	2.6671*	0.8896*	0.7811	1.5831*	0.6878*	0.8626	2.8567*	0.7330*	0.6362
G	9.2458*	1.4484*	0.6756	8.0222*	0.7392*	0.6841	6.4570*	0.6318*	0.7023
H	6.5790*	1.1530*	0.6898	4.1722*	0.7187*	0.8171	3.6432*	0.7248*	0.8678
I	4.7579*	1.1744*	0.8213	4.3887*	0.8672*	0.8356	5.0787*	0.9276*	0.8079
J	12.7970*	0.8908*	0.4662	7.5735*	0.6618*	0.6590	5.5946*	0.7530*	0.6029

B - Cunha et al. Scale (2001)

	Without scale			With scale					
				1st evaluation			2nd evaluation		
Evaluators	β0	β1	R²*	β0	β1	R²*	β0	β1	R²*
A	12.4731*	1.3846*	0.6864	2.7855*	0.4759*	0.7049	5.7189*	0.4778*	0.6064
B	3.2081*	1.2372*	0.8050	4.1462*	0.4881*	0.5960	3.5763*	0.5144*	0.7223
C	7.0894*	0.9916*	0.6296	4.9877*	0.5042*	0.6690	6.3852*	0.4947*	0.5583
D	8.2400*	1.2062*	0.7654	3.5532*	0.4791*	0.685	7.4419*	0.4932*	0.5084
E	7.8318*	0.8458*	0.6647	5.1915*	0.4495*	0.5773	3.4831*	0.3722*	0.7379
F	2.6671*	0.8896*	0.7811	2.5236*	0.5305*	0.7221	2.5960*	0.5005*	0.6873
G	9.2458*	1.4484*	0.6756	5.5593*	0.3899*	0.4819	8.9928*	0.4616*	0.4774
H	6.5790*	1.1530*	0.6898	3.6998*	0.4292*	0.6755	2.9556*	0.3513*	0.6452
I	4.7579*	1.1744*	0.8213	4.3651*	0.5280*	0.6636	4.9841*	0.5091*	0.6608
J	12.7970*	0.8908*	0.4662	5.0591*	0.3919*	0.5597	4.4223*	0.4304*	0.6796

C - Capucho et al. Scale (2011)

	Without scale			With scale					
				1st evaluation			2nd evaluation		
Evaluators	β0	β1	R²*	β0	β1	R²*	β0	β1	R²*
A	12.4731*	1.3846*	0.6864	4.8653*	1.0945*	0.8784	3.8710*	1.0790*	0.8856
B	3.2081*	1.2372*	0.8050	3.6629*	1.4204*	0.8551	3.8918*	1.5574*	0.8267
C	7.0894*	0.9916*	0.6296	5.7872*	1.2373*	0.8578	5.8001*	1.2259*	0.8053

D	8.2400*	1.2062*	0.7654	8.3029*	0.9616*	0.6788	6.6822*	1.0382*	0.7951
E	7.8318*	0.8458*	0.6647	10.146*	1.5690*	0.6858	8.3376*	1.4556*	0.777
F	2.6671*	0.8896*	0.7811	-0.1864^{ns}	1.2859*	0.9558	-0.3271^{ns}	1.2440*	0.9563
G	9.2458*	1.4484*	0.6756	9.3664*	1.1185*	0.6522	7.7267*	0.8970*	0.7274
H	6.5790*	1.1530*	0.6898	2.8383*	0.7701*	0.8372	3.0959*	0.6319*	0.8738
I	4.7579*	1.1744*	0.8213	5.3733*	1.2464*	0.8215	4.8281*	0.6847*	0.8288
J	12.7970*	0.8908*	0.4662	4.5945*	0.7899*	0.7000	6.6051*	1.2376*	0.5400

D - Proposed Scale

	Without scale			**With scale**					
				1st evaluation			2nd evaluation		
Evaluators	β0	β1	R^{2}*	β0	β1	R^{2}*	β0	β1	R^{2}*
A	12.4731*	1.3846*	0.6864	0.3669^{ns}	0.3604*	0.9179	1.7294*	0.4674*	0.7842
B	3.2081*	1.2372*	0.8050	0.7350^{ns}	0.3658*	0.792	1.1264*	0.3447*	0.8299
C	7.0894*	0.9916*	0.6296	1.4733*	0.3772*	0.6308	0.9748*	0.4767*	0.8484
D	8.2400*	1.2062*	0.7654	0.3819*	0.3728*	0.9491	1.5991*	0.4709*	0.8179
E	7.8318*	0.8458*	0.6647	5.1915*	0.4495*	0.5773	3.4831*	0.3722*	0.7324
F	2.6671*	0.8896*	0.7811	-0.0316^{ns}	0.4169*	0.9124	0.00006^{ns}	0.4483*	0.8941
G	9.2458*	1.4484*	0.6756	1.6735*	0.3517*	0.6468	2.2298*	0.5218*	0.7473
H	6.5790*	1.1530*	0.6898	0.0476^{ns}	0.2820*	0.7995	0.1841^{ns}	0.2859*	0.8669
I	4.7579*	1.1744*	0.8213	0.4421^{ns}	0.4621*	0.9051	0.4917*	0.3741*	0.9431
J	12.7970*	0.8908*	0.4662	1.1088*	0.3056*	0.7783	1.3240*	0.3799*	0.7714

R^2 - coefficient of determination; β0 - intercept; β1 - slope of the line; ^{ns} the null hypothesis (β0 = 0 and β1 = 1) was accepted in the t-test (P = 0.05); * the null hypothesis was rejected in the *t-test* (P = 0.05).

The accuracy increased only in the Capucho et al. (2011) and proposed scale for some evaluators with an intercept equal to 0 (zero) for some evaluators, however, the slope of the regression line was not equal to 1 (one). With the scale of Capucho et al. (2011), the intercept was equal to 0 (zero) in both evaluations for one evaluator. For the proposed scale, five evaluators had an intercept equal to 0 (zero) in at least one evaluation. Based on these results, the evaluators were more accurate using the proposed scale. However, observing the angular coefficient occurred a systematic underestimation with the use of the proposed scale.

The evaluators presented a relative precision, regardless of the use of the scale. In the first evaluation with the scales of Kushalappa & Chaves (1980), Cunha et al. (2001) and Capucho et al. (2011), the precision of 50, 20 and 80% of the evaluators, respectively, was greater than that without scales. However, the assessments of 90% of the evaluators who had the help of the proposed scale yielded a coefficient of determination higher than that of

the evaluations without scales, which means that, compared with the other scales, this scale provided a more precise estimation of disease severity. Thereby, with the use of the proposed scale in the second evaluation, all the evaluators' assessments yielded an R^2 value (0.73–0.94, mean 0.82) greater than that of the initial evaluations without the scale (0.47–0.82, mean 0.70), so the evaluations with scales were more precise. The R^2 value in the second evaluation of others scales was: 0.58–0.84, mean 0.71, of Kushalappa & Chaves (1980) scale; 0.48–0.70, mean 0.63, of Cunha et al. (2001) scale; and, 0.62–0.96, mean 0.80, Capucho et al. (2011). The average value for the first evaluation was 0.62, without scale. The second and third evaluation was: 0.73, of Kushalappa & Chaves (1980); 0.63, of Cunha et al. (2001); 0.80, of Capucho et al. (2011); and, 0.81 for proposed scale. The higher precision was obtained in the proposed scale.

Additionally, there was a reduction in the absolute error when the proposed scale was used, with smaller residuals (Figure 3). The minimum and maximum values observed for the residuals of all the evaluators not using the scale were -34.66 and 47.71, respectively. However, when the proposed scale was used, the averages between the two evaluations with the same scale were reduced to -25.99 and 21.88. For the scales of Kushalappa & Chaves (1980), Cunha et al. (2001) and Capucho et al. (2011), the minimum and maximum values observed for the residues were -19.84 and 38.29, -31.45 and 18.90, and -41.42 and 67.00, respectively. Considering this, the error of the proposed scale is smaller than that of the scales of Kushalappa & Chaves (1980), Cunha et al. (2001) and Capucho et al. (2011).

When using Kushalappa & Chaves (1980), Cunha et al. (2001) and Capucho et al. (2011) and the proposed scale, the evaluators presented good repeatability around 80% in their estimation of CLR severity on *C. arabica* leaves; the average variation associated with the first assessment compared to the second assessment was 79, 81, 85 and 80%, respectively (Table 4).

Table 4. Intercept (β_0), angular coefficient of the straight line (β_1) and coefficient of determination (R^2) of the equations of simple regression line relating the second to the first estimation of coffee leaf rust (*Hemileia vastatrix*) in coffee tree leaves (*Coffea arabica*) by the same evaluator, with the aid of the diagrammatic scales of Kushalappa & Chaves (1980), Cunha et al. (2001), Capucho et al. (2011) and proposed scale..

	Kushalappa & Chaves Scale			**Cunha Scale**			**Capucho Scale**			**Proposed Scale**		
Evaluators	*β0*	*β1**	R^2	*β0*	*β1**	R^2	*β0*	*β1**	R^2	*β0*	*β1**	R^2
1	1.38^{ns}	0.94*	0.80	1.12^{ns}	0.81*	0.76	1.68^{ns}	0.96*	0.88	0.34^{ns}	0.66*	0.84

2	0.85^{ns}	0.83*	0.81	0.73^{ns}	0.95*	0.83	1.38^{ns}	0.84*	0.86	0.19^{ns}	0.90*	0.68
3	0.69^{ns}	0.90*	0.86	-0.29^{ns}	0.90*	0.93	1.28^{ns}	0.92*	0.89	0.74^{ns}	0.78*	0.73
4	2.44*	0.84*	0.89	1.04^{ns}	0.74*	0.77	2.48^{ns}	0.90*	0.81	0.14^{ns}	0.65*	0.79
5	1.90*	0.76*	0.92	1.38^{ns}	1.45*	0.71	1.54^{ns}	1.07*	0.87	0.40^{ns}	0.91*	0.76
6	2.30^{ns}	0.55*	0.45	0.45^{ns}	0.96*	0.85	0.17^{ns}	1.03*	1.00	0.33^{ns}	0.83*	0.81
7	2.11^{ns}	1.03*	0.75	0.64^{ns}	0.73*	0.76	1.61^{ns}	1.12*	0.72	0.44^{ns}	0.63*	0.76
8	1.30^{ns}	0.91*	0.80	1.27^{ns}	1.02*	0.72	0.82^{ns}	1.21*	0.93	0.26^{ns}	0.97*	0.89
9	0.51^{ns}	0.87*	0.88	0.61^{ns}	1.02*	0.96	1.35^{ns}	1.62*	0.78	-0.06^{ns}	1.21*	0.91
10	4.24^{ns}	0.74*	0.78	1.12^{ns}	0.90*	0.81	2.96*	0.48*	0.73	0.49^{ns}	0.70*	0.77
Average			0.79			0.81			0.85			0.80

R^2 - coefficient of determination; β0 - intercept; β1 - slope of the line; ^{ns} the null hypothesis (β0 = 0 and β1 = 1) was accepted in the t-test (P = 0.05); * the null hypothesis was rejected in the *t-test* (P = 0.05).

Reproducibility is an indicator for evaluating the efficiency of diagrammatic scales in addition to accuracy and precision. Without the use of the diagrammatic scale, the R^2 value of the regressions of the estimates among the pairs of evaluators varied from 0.55 to 0.81, with a mean percentage of 69.85% (Table 5). When the diagrammatic scales of Kushalappa & Chaves (1980), Cunha et al. (2001) and Capucho et al. (2011) and the proposed scale were used, the R^2 values varied in the second evaluation from 0.60 to 0.85, 0.49 to 0.73, 0.63 to 0.92 and 0.60 to 0.93, respectively. The average percentages were 72.72, 63.09, 79.69% and 80.72%, respectively.

Table 5. Coefficient of determination (R^2 values) of the linear regression equation for pairs of evaluators without and with the aid of diagrammatic scales of (A) Kushalappa & Chaves (1980), (B) Cunha et al. (2001), (C) Capucho et al. (2011) and (D) the proposed scale of visual estimates of coffee leaf rust (*Hemileia vastatrix*) by 10 evaluators.

Without scale									
Evaluators	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**
A	0.75	0.66	0.73	0.68	0.73	0.68	0.69	0.75	0.58
B		0.72	0.79	0.73	0.79	0.74	0.75	0.81	0.64
C			0.70	0.70	0.71	0.65	0.66	0.73	0.55
D				0.72	0.77	0.72	0.73	0.79	0.62
E					0.72	0.67	0.68	0.74	0.57
F						0.73	0.74	0.80	0.62
G							0.68	0.75	0.57
H								0.76	0.58
I									0.64
A – Scale of Kushalappa (1980)									
1st evaluation						2nd evaluation			

Evaluators	B	C	D	E	F	G	H	I	J	B	C	D	E	F	G	H	I	J
A	0.78	0.72	0.80	0.68	0.82	0.74	0.80	0.81	0.72	0.77	0.71	0.75	0.69	0.71	0.75	0.83	0.80	0.70
B		0.71	0.80	0.68	0.82	0.73	0.80	0.81	0.72		0.69	0.73	0.67	0.69	0.73	0.81	0.78	0.68
C			0.73	0.61	0.75	0.67	0.73	0.74	0.65			0.67	0.61	0.63	0.67	0.75	0.72	0.62
D				0.70	0.84	0.75	0.82	0.83	0.74				0.64	0.67	0.70	0.78	0.75	0.65
E					0.72	0.63	0.70	0.71	0.62					0.61	0.65	0.73	0.70	0.60
F						0.77	0.84	0.85	0.76						0.67	0.75	0.72	0.62
G							0.75	0.76	0.67							0.79	0.76	0.65
H								0.83	0.74								0.84	0.74
I									0.75									0.71

B - Scale of Cunha et al. (2001)

	1st evaluation									2nd evaluation								
Evaluators	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**
A	0.65	0.69	0.69	0.64	0.71	0.59	0.69	0.68	0.63	0.66	0.58	0.56	0.67	0.65	0.54	0.63	0.63	0.64
B		0.63	0.64	0.59	0.66	0.54	0.64	0.63	0.58		0.64	0.62	0.73	0.70	0.60	0.68	0.69	0.70
C			0.68	0.62	0.70	0.58	0.67	0.67	0.61			0.53	0.65	0.62	0.52	0.60	0.61	0.62
D				0.63	0.70	0.58	0.68	0.67	0.62				0.62	0.60	0.49	0.58	0.58	0.59
E					0.65	0.53	0.63	0.62	0.57					0.71	0.61	0.69	0.70	0.71
F						0.60	0.70	0.69	0.64						0.58	0.67	0.67	0.68
G							0.58	0.57	0.52							0.56	0.57	0.58
H								0.67	0.62								0.65	0.66
I									0.61									0.67

C – Scale of Capucho et al. (2011)

	1st evaluation									2nd evaluation								
Evaluators	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**
A	0.87	0.87	0.78	0.78	0.92	0.77	0.86	0.85	0.79	0.86	0.85	0.84	0.83	0.92	0.81	0.88	0.86	0.71
B		0.86	0.77	0.77	0.91	0.75	0.85	0.84	0.78		0.82	0.81	0.80	0.89	0.78	0.85	0.83	0.68
C			0.77	0.77	0.91	0.76	0.85	0.84	0.78			0.80	0.79	0.88	0.77	0.84	0.82	0.67
D				0.68	0.82	0.67	0.76	0.75	0.69				0.79	0.88	0.76	0.83	0.81	0.67
E					0.82	0.67	0.76	0.75	0.69					0.87	0.75	0.83	0.80	0.66
F						0.80	0.90	0.89	0.83						0.84	0.92	0.89	0.75
G							0.74	0.74	0.68							0.80	0.78	0.63
H								0.83	0.77								0.85	0.71
I									0.76									0.68

D – Proposed scale

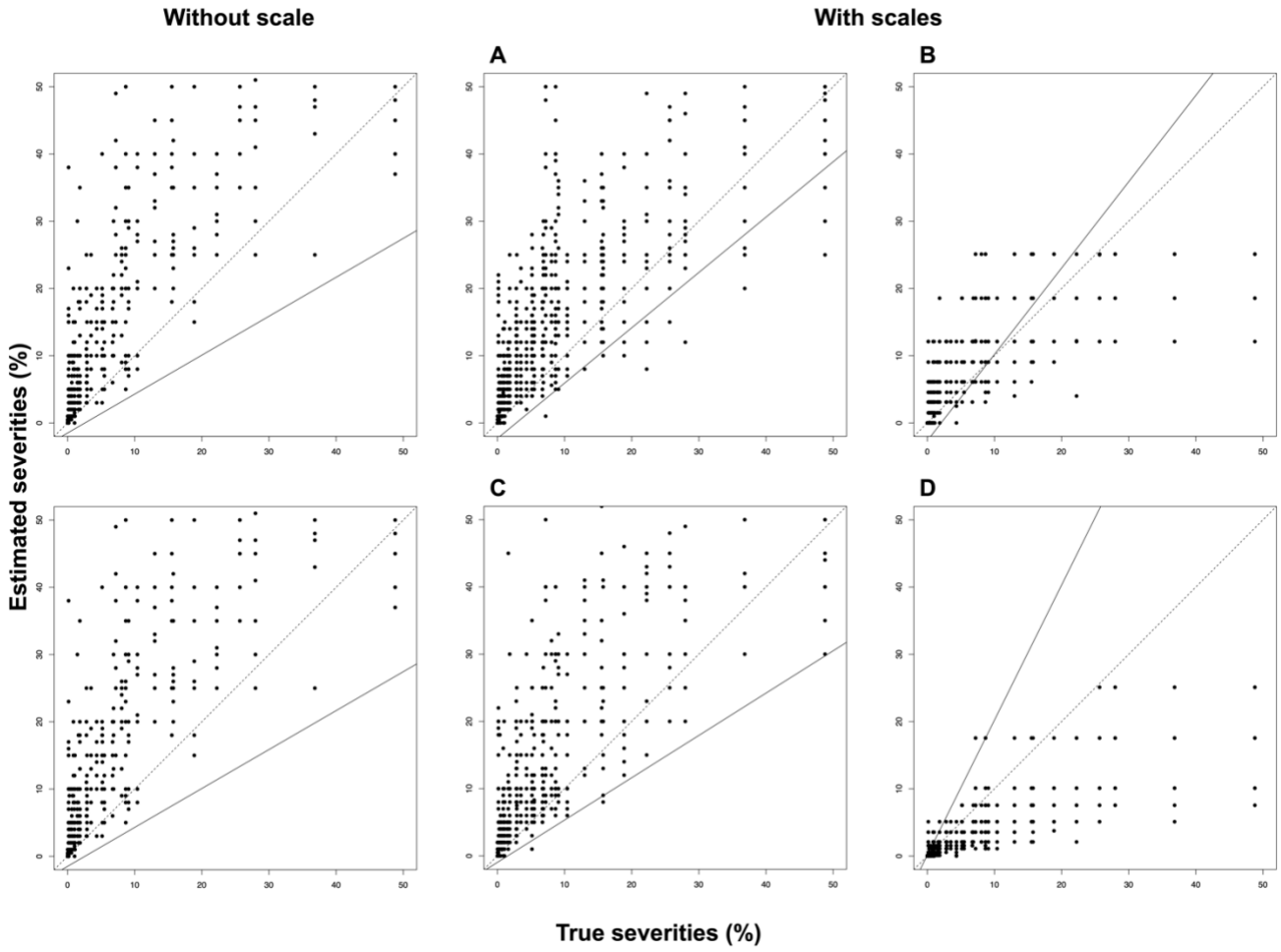
	1st evaluation									2nd evaluation								
Evaluators	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**
A	0.85	0.77	0.93	0.75	0.92	0.78	0.86	0.91	0.85	0.81	0.82	0.80	0.76	0.84	0.77	0.83	0.86	0.78
B		0.71	0.87	0.68	0.85	0.72	0.80	0.85	0.79		0.84	0.82	0.78	0.86	0.79	0.85	0.89	0.80
C			0.79	0.60	0.77	0.64	0.72	0.77	0.70			0.83	0.79	0.87	0.80	0.86	0.90	0.81
D				0.76	0.93	0.80	0.87	0.93	0.86				0.78	0.86	0.78	0.84	0.88	0.79
E					0.74	0.61	0.69	0.74	0.68					0.81	0.74	0.80	0.84	0.75
F						0.78	0.86	0.91	0.85						0.82	0.88	0.92	0.83

G	0.72	0.78	0.71	0.81	0.85	0.76
H		0.85	0.79		0.91	0.82
I			0.84			0.86

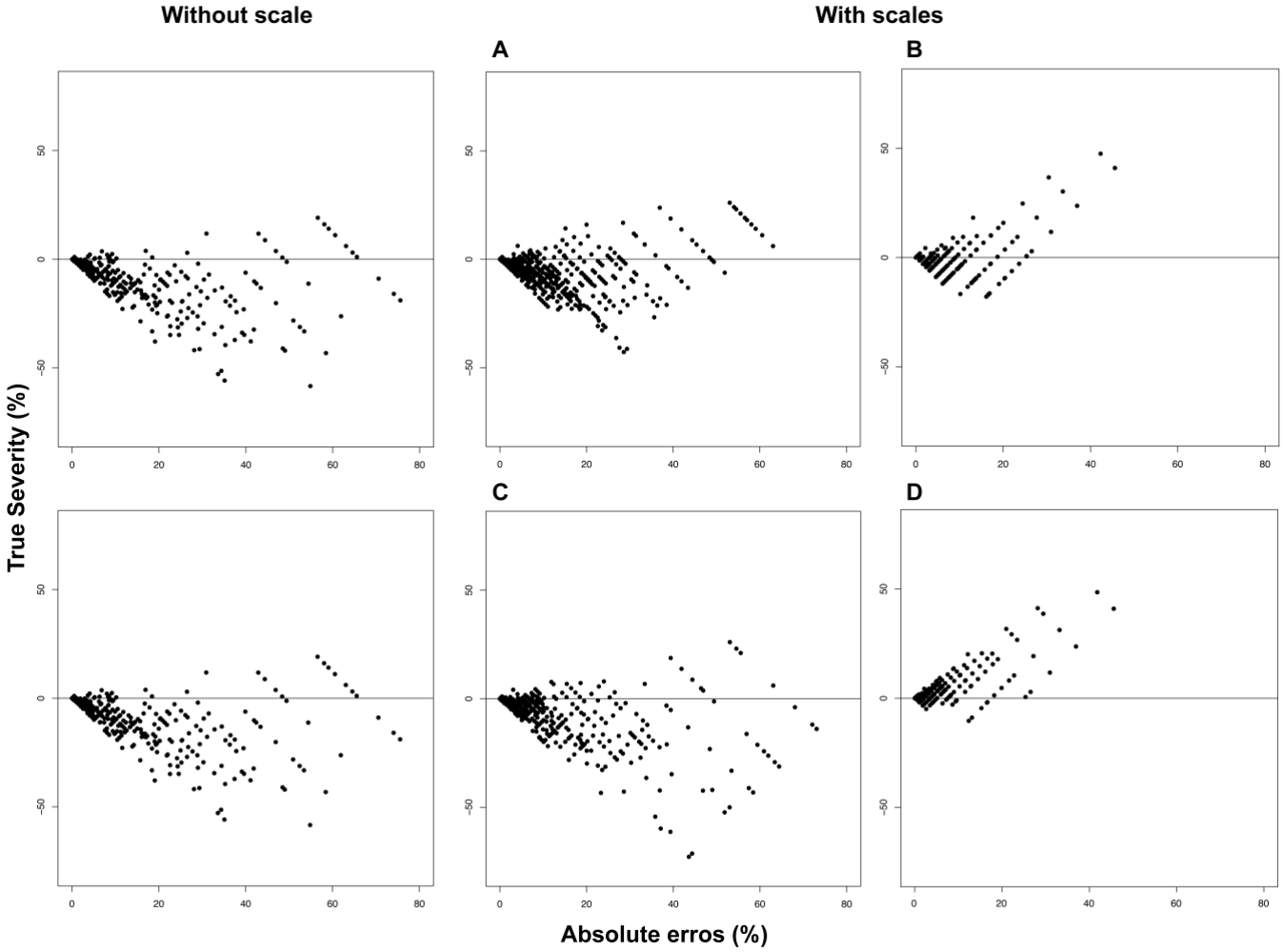
R^2 - coefficient of determination; β0 - intercept; β1 - slope of the line; ^{ns} the null hypothesis (β0 = 0 and β1 = 1) was accepted in the t-test (P = 0.05); * the null hypothesis was rejected in the *t-test* (P = 0.05).

3.3 Validation by Lin's concordance correlation

The second statistical method used to evaluate the scales studied and to validate the proposed diagrammatic scale was Lin's concordance correlation. The coefficient of correlation (LCC) and agreement between the actual and observed values indicates higher efficiency of quantification with the Capucho et al. (2011) scale compared to no scale (Table 6). The evaluators showed a tendency to overestimate the disease without the use of the scale (location shift = 0.55) and with the scales of Kushalappa & Chaves (1980) and Capucho et al. (2011). The best estimate was the location shift of 0.03 obtained from the scale of Cunha et al. (2001). Nonetheless, when the proposed scale was used, there was a tendency to underestimate the disease (-0.48), but the confidence interval for the proposed scale for location shift was not significantly different (Figure 4; Table 6). The value of the bias correction factor (Cb) without the scale was 0.83, and with the Kushalappa & Chaves (1980), Cunha et al. (2001) and Capucho et al. (2011) and proposed scales, the values were 0.94, 0.88, 0.89 and 0.67, respectively. For all scales except for the proposed scale, there was an increase in the deviation correction factor. The best correction factor was obtained using the Kushalappa & Chaves (1980). Pearson correlation coefficients (r values) were calculated to determine the precision of the evaluations. The highest value (r = 0.88) was obtained using the proposed scale for quantification of disease severity and consequently less absolute error of the disease estimates (Figure 5; Table 6). Without the scale and with the other scales resulted in a less precision disease quantification (r = 0.81). Kushalappa & Chaves (1980), Cunha et al. (2001) and Capucho et al. (2011) found r values of 0.82, 0.77 and 0.84, respectively. These coefficients pointed to an increase in the precision of the evaluators with the use of the scale as a basis for measuring the severity values. According to the significance range, the assessments without and with the diagrammatic scale for evaluating CLR were significantly different (P = 0.05), except for the location shift of the proposed scale.



278 **Figure 4** Relationship between true and estimated coffee leaf rust (*Hemileia vastatrix*), carried out: (A) without
279 the use of a diagrammatic scale; (B) with the diagrammatic scales of Kushalappa & Chaves (1980); (C) with the
280 diagrammatic scales of Cunha et al. (2001); with the diagrammatic scales of Capucho et al. (2011); and, (D) with
281 the proposed diagrammatic scale. The points represent 100 estimations by each evaluator.



282 **Figure 5** Residual of Lin's statistical method (A) with the aid of the diagrammatic scale of Kushalappa &
283 Chaves (1980), (B) the diagrammatic scale of Cunha et al. (2001), (C) the diagrammatic scale of Capucho et
284 al. (2011) and (D) the proposed diagrammatic scale. The points represent 100 estimations by each
285 evaluator.

286

287 **Table 6.** Comparison of the results of visual estimates of CLR performed by 10 evaluators with and without the
288 aid of the diagrammatic scales of (A) Kushalappa (1980), (B) Cunha et al. (2001), (C) Capucho et al. (2011) and
289 (D) the proposed scale according to Lin's statistics

290

A – Scale of Kushalappa (1980)

Lin's statistics	**Without scale**	**With scale**	**95% CI[f]**
Concordance coefficient [a]	0.67	0.77	**0.689; 0.787**
Scale shift [b]	1.39	1.00	**0.179; 4.488**
Location shift [c]	0.55	0.35	**0.347; 0.552**

Bias correction [d]	0.83	0.94	**0.832; 0.881**
Correlation coefficient [e]	0.81	0.82	**0.817; 0.865**

B - Scale of Cunha et al. (2001)

Lin's statistics	**Without scale**	**With scale**	**95% CI[f]**
Concordance coefficient [a]	0.67	0.68	**0.647; 0.725**
Scale shift [b]	1.39	0.60	**0.787; 1.163**
Location shift [c]	0.55	0.03	**0.146; 0.429**
Bias correction [d]	0.83	0.88	**0.812; 0.881**
Correlation coefficient [e]	0.81	0.77	**0.784; 0.835**

C – Scale of Capucho et al. (2011)

Lin's statistics	**Without scale**	**With scale**	**95% CI[f]**
Concordance coefficient [a]	0.67	0.75	**0.608; 0.780**
Scale shift [b]	1.39	1.34	**1.210; 1.440**
Location shift [c]	0.55	0.42	**0.390; 0.580**
Bias correction [d]	0.83	0.89	**0.810; 0.890**
Correlation coefficient [e]	0.81	0.84	**0.830; 0.880**

D – Proposed scale

Lin's statistics	**Without scale**	**With scale**	**95% CI[f]**
Concordance coefficient [a]	0.67	0.60	**0.596; 0.691**
Scale shift [b]	1.39	0.44	**0.650; 1.094**
Location shift [c]	0.55	-0.48	-0.220; 0.276
Bias correction [d]	0.83	0.67	**0.688; 0.800**
Correlation coefficient [e]	0.81	0.88	**0.841; 0.893**

[a] Lin's concordance coefficient combining the precision and accuracy to measure the agreement with the true values.
[b] Scale shift coefficient relative to the perfect match (1 = perfect match between x and y).
[c] Location shift coefficient relative to the perfect match (0 = perfect match between x and y).
[d] Bias correction factor (C_b) measures how much the best-fit line deviates from 45°. No deviation from the 45° line occurs when Cb = 1. Cb is a measure of accuracy calculated from scale shift and location shift coefficients.
[e] Pearson's correlation coefficient (r) measures the precision.
[f] Confidence intervals based on t tests (P = 0.05). The bold numbers indicate significant differences.

4 Discussion

Our diagrammatic scale should follow the Weber–Fechner Law (logarithmic increments); however, it does not necessarily use the same intervals chosen by Horsfall & Barratt (1945) due to the individual characteristics of each disease (Campbell & Madden, 1990). To construct the scale, instead of using black-and-white or even colored

engravings or drawings, digital images were used in which the sporulation area was measured through electronic systems for more than 200 leaves. Consequently, it was possible to develop a diagrammatic scale representing authentic symptoms and signs. For the evaluators to better visualize the actual percentage of leaf area injured in the range with the highest frequency of severity. Regardless of the disease, if the low levels of the scale represented increased ranges of severity, most of the sampled leaves would be concentrated in the first two or three levels of the scale. Thus, in the percentage range of severity with higher frequencies, more levels were added when the new scale was made to improve the visualization and identification of the severity level of the CLR with the scale.

Intermediate scale levels were determined based on the frequency of severity combined with the exponential increase in severity. They were obtained based on the fit of the regression model according to the number of leaves sampled. Where the exponential increase is the severity level is one of the scales characteristics responsible for the easy interpolation in the estimates of disease severity. These increments seek to follow the principles of the Horsfall and Barratt scale (Horsfall & Barratt, 1945), which is based on the Weber–Fechner Law (Campbell & Madden, 1990). The symmetry of the 50% severity intervals was not adopted because the maximum severity value observed in the field was 36.83%. Each pathosystem has its own features (Belan et al., 2014; Belan et al., 2020), and the absence of leaves with a severity greater than this percentage is an important characteristic of CLR for arabica and conilon coffee. The visible area with sporulation corresponds to one of the signs of the disease, which is visible, not characterizing the colonized area. The colonized area is larger, as it includes the growth of the fungus in the intra- and intercellular parts of the leaf tissue, not being allowed to be seen by the naked eye. In terms of disease progression, the leaves fall off the branches, resulting in early defoliation and justifying the absence of larger areas of pathogen sporulation on the leaves.

The diagrammatic scale developed by Kushalappa & Chaves (1980) shows 1, 3, 5 and 7% of the diseased leaf area of drawings as colors of yellow and green, showing areas with sporulation and areas that are asymptomatic. Capucho et al. (2011) adopted the same idea and used drawings that show the percentage of diseased leaf area, although they have values of 2.5, 5, 10, 20, 40 and 80%. Cunha et al. (2001) developed their scale, likes the scale proposed in this study, to include discrete values converted to the percentage for the different intervals levels. These scales follow the principles of the Horsfall and Barratt scale, in which severity values of 0–3, 3–6, 6–12, 12–25 and 25–50% are used. This type of scale provides better distinctions to assess disease severity. Cunha et al. (2001) used real images, but due to the lack of high-resolution image technology at the time, the quality of the images was not able to reflect as in the proposed scale accurately. In this case, the use of a scale such as the one proposed in this study, with intervals including the smaller severity levels, contributes to providing an

improved tool to be able to distinguish resistance levels in cultivars. In addition, the proposed scale contains an image of a coffee leaf with a fleck lesion, facilitating the assessment of resistant plants by breeders. For researchers and plant pathologists who study plant resistance, fungicide efficacy, and biocontrol agents, among other management techniques, it is important to select plants or treatments with relatively low severity. Generally, these scientists define the range or the maximum level of disease or symptoms that is considered to represent a resistant cultivar or effective disease control using fungicides. Precision and accuracy are essential for the early symptoms of infection, as severity is the most appropriate way to quantify rust (Amorim & Bergamin Filho, 2018). Our scale represents a wide range of disease development stages. Providing reliable and easy-to-apply results. It can help evaluators in the quantification and management of the disease in experimental and field areas in a quick and practical way.

According to Amorim & Bergamin Filho (2018), an evaluator's ability to quantify disease severity depends on, among other factors, the training, experience, and individual perception of each evaluator. To reduce the subjectivity of assessors the scale should be used for training, aiming to improve the accuracy of the evaluations (de Paula et al., 2016). Overestimation of CLR severity by evaluators without using the scale is a consequence of the visual stimuli caused by the chlorotic halo of lesions that already existed or of those that have not yet sporulated. In this study, only the mass of yellow-orange spores was considered. In most studies involving the validation of a diagrammatic scale, there is a tendency for evaluators to overestimate disease, mainly in phytopathological studies (Andrade et al., 2019; Capucho et al., 2011; Custódio et al., 2011; de Paula et al., 2016; Menge et al., 2013; Perina et al., 2019). In some cases, like in our study, underestimation of disease severity levels has also occurred (Gomes et al., 2004; Michereff et al., 2000).

Analysis of the coefficients of the linear regression equation revealed that the ratings were more accurate and precise with the use of the proposed scale. The precision refers to the repeatability of the severity values of the sample, with the least possible variation between them. On the other hand, evaluator accuracy describes the minimum deviation pattern between the estimated value and the actual severity (Vale et al., 2004). In this study, the value of the repeatability coefficient was close to that found in other studies the same crop with other diseases. Custódio et al. (2011) obtained coefficient values to determine a repeatability of 90% for brown eye spots in coffee leaves, and Belan et al. (2014) found a mean determination coefficient for repeatability of 83.2% for a diagrammatic scale of bacterial blight. De Paula et al. (2016) obtained percentages of 96% and 97% of brown eyespot on red and yellow cherry fruits, respectively. Belan et al. (2020) obtained a mean percentage of 87% for

CLR in conilon. The values of the second evaluation of the evaluators using scales were similar to those of the first evaluation, indicating that the severity estimates were close to the ideal severity.

Absolute errors using the proposed scale are smaller than that using existing scales (Figure 3). This reduction can be explained by the distribution of the scale comprising seven severity levels, leading to greater accuracy of the evaluators and smaller error. The seven levels of the proposed scale distributed in the 0–25% severity range allowed the evaluators to have a greater accuracy. Despite the larger errors for real values of severity greater than 25%, these represented only 10% of the leaves sampled from field crops and nurseries of coffee seedlings.

The reproducibility of severity assessments without the use of the diagrammatic scale and with the scales developed by the Kushalappa & Chaves (1980), Cunha et al. (2001) and Capucho et al. (2011) (diagrammatic scales) was lower than that of the proposed scale (Table 5). Therefore, the reproducibility of the evaluations using the proposed scale varying between 60 and 93% was considered good, according to the criteria in the literature (Angelotti et al., 2008; Pereira et al., 2021; Salgado et al., 2009; Sussel et al., 2009).

Lin's concordance and the correlation coefficient have been effective and recommended for assessing the accuracy and precision of scales (Bock et al., 2010; Lin, 1989) and for assessing common scab disease of potato tubers (Andrade et al., 2019). In this paper, the use of the linear regression method showed a better efficacy of the scale analysis than did the use of Lin's statistics, because the use of Lin's statistic was not conclusive for determine the best scale.

5 Conclusion

The diagrammatic scale proposed to assess the severity of coffee leaf rust in arabica coffee provides an improvement in terms of precision, accuracy and reproducibility in severity estimation.

Acknowledgments

The authors would like to thank all the evaluators who were involved in the evaluation stages of the disease severity. This work was supported by the Conselho Nacional de Pesquisa e Desenvolvimento Científico e Tecnológico (CNPq); Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (Capes); Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG) and Instituto Nacional de Ciência e Tecnologia do Café (INCT-Café).

Ethics declarations

Conflict of interest

There are no potential conflicts of interest.

Research involving humans or animals

This article does not contain any studies with human participants or animals.

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(Formatação baseada nas exigências da revista *Plant Pathology*, versão preliminar)

ARTIGO 2

Coffee leaf rust progress rate in Arabica coffee

Taxa de progresso da ferrugem do café em café arábica

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Coffee leaf rust progress rate in Arabica coffee

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ABSTRACT

Brazil is the world's largest producer and world exporter of coffee. Coffee production can be harmed through losses due to several factors, but the main one is the presence of diseases. Coffee rust (*Hemileia vastatrix* Berkeley & Broome) is the main disease causing production losses in both arabica and conilon coffee. The progress of the disease must be monitored to obtain the best management of fungicides. The aim of this work was to evaluate the progress rate of rust in arabica coffee with different fungicides and fungicide mixtures. The analyzed data were carried out between 2014 and 2021, obtained from 23 experiments of Arabica coffee crops, cultivar Catuaí Vermelho IAC 99, susceptible to coffee leaf rust. The evaluations were carried out in crops aged between five and eight years, with a spacing of 3.8 x 0.6 m between plants and carried out according to the technical recommendations for the culture. The experimental design was in randomized blocks, with four replications and the experimental plot consisted of 10 plants. Rust incidence, disease progress rate and linearization rate data were obtained, then linear and nonlinear rate models were fitted for all treatment data obtained using R software. The best adjusted model was chosen from the criteria of highest coefficient of determination (R2) and lowest Information Criterion of Akaike (AIC). The exponential nonlinear integral model was the best fit to describe the rate progress of rust as a function of time.

Keywords: *Coffea arabica* L. Chemical control. Fungicides. *Hemileia vastatrix*.

1 Introduction

Coffee is the most drink beverage in the world. Brazil is the largest producer and exporter of this grain, and the third-largest consumer in worldwide (USDA Foreign Agricultural Service, 2021). The estimated production of processed coffee in Brazil for 2022 is more than 55 million bags of 60 kg (CONAB, 2022). *Coffea arabica* L. or Arabica coffee represents 69.57% of Brazilian production. Currently, Minas Gerais state produce 70% of the arabica coffee cropped and is the largest producer of coffee beans in Brazil (CONAB, 2022). Based on this, losses in the production and quality of the beverage cause damage to producers and the coffee market (Pozza et al., 2010). The main factors that are resulting of losses are abiotic factors relation of the environmental conditions, soil nutrition, and management of pests and plant diseases (Pozza, 2021).

Coffee leaf rust (CLR) caused by the biotrophic fungus *Hemileia vastatrix* Berkeley & Broome, is the major disease in Arabica coffee. CLR damage in coffee trees are beginning with premature defoliation, and reduction of the photosynthetic area with subsequent death of plagiotropic branches (Pozza, 2021). Losses described by CLR in research are up to 20-25% (McCook, 2006), up to 35% (Talhinhas et al., 2017), up to 50% (Pozza et al., 2010), and the loss ranges can reach 55.8% to 99.8%, based on estimation by mathematical modeling (Colares, 2018). Regarding of disease management some tools are used in context of tropical agriculture as optimizing the application of inputs. The specific timing of sprayed of fungicides and fertilizers; choosing the best active principles of chemical fungicide/biological fungicide management, either alone or with a combination and consequently reduced the cost of production (Custódio et al., 2011; Pozza, 2021; Pozza & Alves, 2008).

Improvements in crop management are made to reduce losses and, consequently, reduce the coffee leaf rust progress rate (Talamini et al., 2003) . The disease progress rate was

calculated by the proportion of the disease that increased in a given period (Van der Plank, 1963). The reduction of the rate integrates the host, pathogen, and effect on the environment conditions during the epidemic. In this context, the rate measures the speed of the disease and is an important parameter for comparing epidemics (Ghini et al., 2011). Thus, the objective of this study was to evaluate and compare the rate progress of Arabica coffee rust in different experiments and years. In this context, comparing the fungicides positioning used with a different mode of action isolated and in combination mode of action regarding a effectiveness management for CLR.

2 Material and methods

2.1 Description of the study area

The data of the CLR incidence were analyzed in 23 experiments in seven consecutive crop seasons (2014/2015, 2015/2016, 2016/2017, 2017/2018, 2018/2019, 2019/2020, 2020/2021) and evaluated monthly between December to May. The experiments was located in the municipality of Lavras - MG, in two different locations: the experimental area of the Federal University of Lavras (21º 13' 40"S, 44º 57' 42"W, 970 m altitude), and in the Limeira Farm (21º 22' 63"S, 44º 96' 06"W, 948 m altitude). The cultivar seedling were Catuaí red group of Coffea arabica, susceptible to Coffea Rust. The assessments were carried out in crops aged between five and eight years, with a spacing of 3.8 x 0.6 m between plants, and carried out according to the technical recommendations for the culture (Allen, R. G., Pereira, L. S., Raes, D., & Smith, 1998). The management of weeds and pests was carried out according to the control level. Soil fertility and crop nutrition management were performed based on the results of soil chemical analysis (Alvarez et al., 1999; Alvarez & Ribeiro, 1999).

2.2 Experimental design

The experimental design was in randomized blocks, with four replications, and the number of treatments varied according to the experiment, ranging from 5 to 15 treatments. The experimental plot had ten plants, with the six central, aiming to remove all drift and border effects in the evaluations for obtain different levels of rust incidence.

The treatments used in the experiments were the absolute control or check and different chemical and biological fungicides formulation. The fungicides were used alone or in association with other fungicides, and in some experiments, different concentrations were used. To establish the different levels of disease intensity (Table 1). The sprayed volume used was 400 L/ha and spraying using a motorized backpack sprayer.

Table 1 - Fungicides were used alone or in association with other fungicides and different concentrations in seven consecutive seasons, 2014/2015, 2015/2016, 2016/2017, 2017/2018, 2018/2019, 2019/2020, and, 2020/2021.

Active principle	Chemical group	Action mode	Formulation	Dosage
Azoxystrobin + Benzovindiflupyr	Strobilurin + Carboxamide	Mesostemic Protector + Contact	WG	0,4 Kg ha^{-1}
Azoxystrobin + Mancozeb	Strobilurin + Dithiocarbamate	Mesostemic Protector + Contact	WG	0,1 kg ha^{-1}
Boscalid	Anilide	Systemic	WG	0,15 kg ha^{-1}
Boscalid + Pyraclostrobin	Anilide + Strobilurin	Systemic + Mesostemic Protector	WG + EC	0,15 hg ha^{-1} + 0,6 L ha^{-1}
Kasugamycin	Antibiotic	Systemic	SC	2,00 - 3,00 L/ha
Cyproconazole	Triazole	Systemic	WG	0,5 - 0,7 kg ha-1
Cyproconazole + Azoxystrobin	Triazole + Strobilurin	Systemic + Mesostemic Protector	SC	0,5 L ha^{-1}
Cyproconazole + Azoxystrobin + Mancozeb	Triazole + Strobilurin + Dithiocarbamate	Systemic + Mesostemic Protector + Contact	WG	1,5 - 3,0 kg ha-1
Cyproconazole + Azoxystrobin + Copper hydroxide	Triazole + Strobilurin+ Inorganic	Systemic + Mesostemic Protector + Contact	SC + WG	0,5 L ha^{-1} + 1,7 kg ha^{-1}
Cyproconazole + Difenoconazole	Triazole	Systemic	SC	0,3 L ha^{-1}
Cyproconazole + Picoxystrobin	Triazole + Strobilurin	Systemic + Mesostemic Protector	SC	0,5 L ha^{-1}
Cyproconazole + Trifloxystrobin	Triazole + Strobilurin	Systemic + Mesostemic Protector	SC	0,4 L ha^{-1}
Difenoconazole + Azoxystrobin	Triazole + Strobilurin	Systemic + Mesostemic Protector	SC	0,3 - 0,4 L ha-1
Difenoconazole + Pydiflumetofen	Triazole + Carboxamide	Systemic	SC	0,5 - 0,7 kg ha-1
Epoxiconazole + Kresoxim-methyl	Triazole + Strobilurin	Systemic+ Mesostemic Protector	SC	0,6 L ha^{-1}
Epoxiconazole + Pyraclostrobin	Triazole + Strobilurin	Systemic + Mesostemic Protector	SE	1,5 L ha^{-1}

Epoxiconazole + Pyraclostrobin + Copper hydroxide	Triazole + Strobilurin+ Inorganic	Systemic + Mesostemic Protector + Contact	SE + WG	1,5 L ha^{-1} + 1,7 kg ha^{-1}
Flutriafol	Triazole	Systemic	SC	2,0 L ha^{-1}
Flutriafol	Triazole	Systemic	SC	2,0 - 3,0 L ha-1
Flutriafol	Triazole	Systemic	SC	1,5 L ha^{-1}
Flutriafol + Azoxystrobin + Iprodione	Dicarboximide + Triazole + Strobilurin	Systemic + Mesostemic Protector + Contact	SC	1,0 L ha^{-1} + 0,8 L ha^{-1}
Flutriafol + Thiophanate-methyl + Iprodione	Dicarboximide + Triazole + Benzimidazole	Systemics + Contact	SC	1,0 L ha^{-1} + 1,0 L ha^{-1}
Fluxapyroxad + Copper oxychloride	Pyrazole-4-carboxamide + Inorganic	Systemics + Contact	SC	0,8 - 1,2 L ha-1
Copper hydroxide	Inorganic	Contact	SC	2,0-3,0 L ha-1
Copper hydroxide	Inorganic	Contact	WG	1,7 - 2,25 kg ha-1
Iprodione	Dicarboximide	Contact	SC	1,0 L ha^{-1}
Mancozeb	Dithiocarbamate	Contact	WP	4,0 kg ha^{-1}
Pyraclostrobin	Strobilurin	Mesostemic Protector	EC	0,6 - 0,8 L ha-1
Tebuconazole + Azoxystrobin	Triazole + Strobilurin	Systemic + Mesostemic Protector	SC	0,75 L ha^{-1}
Tebuconazole + Azoxystrobin + Mancozeb	Triazole + Strobilurin + Dithiocarbamate	Systemic + Mesostemic Protector + Contact	WG + EC	1,5 kg ha^{-1} + 1,0 L ha^{-1}
Tebuconazole + Metominostrobin	Triazole + Strobilurin	Systemic + Mesostemic Protector	EC	1,2 - 1,5 L ha-1
Tebuconazole + Trifloxystrobin	Triazole + Strobilurin	Systemic + Mesostemic Protector	SC	0,75 L ha^{-1}

Legend:

EC: Emulsifiable Concentrate; SC: Suspension Concentrate; SE: Suspo-Emulsion; WG: Water dispersible Granule; WP: Wettable Powders

Supplementary Table 1 - Fungicides were used alone or in association with other fungicides and different concentrations in seven consecutive seasons, 2014/2015, 2015/2016, 2016/2017, 2017/2018, 2018/2019, 2019/2020, and, 2020/2021.

Year	Beginning	End	Experiment	Treatment	Active principle	Chemical Group	Mode of action	Group[1]
2014	16/12/2014	08/07/2015	1	1	na	na	na	na
2014	16/12/2014	08/07/2015	1	2	Epoxiconazole + Pyraclostrobin + Mancozeb + Copper hydroxide	Triazole + Strobilurin + Dithiocarbamate + Inorganic	Systemic + Mesosystemic Protector + Contact	h
2014	16/12/2014	08/07/2015	1	3	Azoxystrobin + Copper hydroxide	Strobilurin + Inorganic	Mesosystemic Protector + Contact	c
2014	16/12/2014	08/07/2015	1	4	Azoxystrobin + Mancozeb + Copper hydroxide	Strobilurin + Dithiocarbamate + Inorganic	Mesosystemic Protector + Contact	c
2014	16/12/2014	08/07/2015	1	5	Epoxiconazole + Pyraclostrobin + Mancozeb	Triazole + Strobilurin + Dithiocarbamate	Systemic + Mesosystemic Protector + Contact	h
2014	16/12/2014	08/07/2015	1	6	Azoxystrobin + Mancozeb	Strobilurin + Dithiocarbamate	Mesosystemic Protector + Contact	c
2014	16/12/2014	08/07/2015	1	7	Mancozeb	Dithiocarbamate	Contact	a
2014	16/12/2014	08/07/2015	1	8	Epoxiconazole + Pyraclostrobin + Copper hydroxide	Triazole + Strobilurin+ Inorganic	Systemic + Mesosystemic Protector + Contact	h
2015	09/12/2015	24/05/2016	2	1	na	na	na	na
2015	09/12/2015	24/05/2016	2	2	Epoxiconazole + Pyraclostrobin + Mancozeb + Copper hydroxide	Triazole + Strobilurin + Dithiocarbamate + Inorganic	Systemic + Mesosystemic Protector + Contact	h
2015	09/12/2015	24/05/2016	2	3	Azoxystrobin + Copper hydroxide	Strobilurin + Inorganic	Mesosystemic Protector + Contact	c
2015	09/12/2015	24/05/2016	2	4	Azoxystrobin + Mancozeb + Copper hydroxide	Strobilurin + Dithiocarbamate + Inorganic	Mesosystemic Protector + Contact	c
2015	09/12/2015	24/05/2016	2	5	Epoxiconazole + Pyraclostrobin + Mancozeb	Triazole + Strobilurin + Dithiocarbamate	Systemic + Mesosystemic Protector + Contact	h
2015	09/12/2015	24/05/2016	2	6	Azoxystrobin + Mancozeb	Strobilurin + Dithiocarbamate	Mesosystemic Protector + Contact	c
2015	09/12/2015	24/05/2016	2	7	Mancozeb	Dithiocarbamate	Contact	a
2015	09/12/2015	24/05/2016	2	8	Epoxiconazole + Pyraclostrobin + Copper hydroxide	Triazole + Strobilurin+ Inorganic	Systemic + Mesosystemic Protector + Contact	h
2015	16/12/2015	25/05/2016	3	1	na	na	na	na
2015	16/12/2015	25/05/2016	3	2	Flutriafol	Triazole	Systemic	d
2015	16/12/2015	25/05/2016	3	3	Cyproconazole	Triazole	Systemic	d
2015	16/12/2015	25/05/2016	3	4	Triadimenol	Triazole	Systemic	d

2015	16/12/2015	25/05/2016	3	5	Flutriafol	Triazole	Systemic	d
2015	16/12/2015	25/05/2016	4	1	na	na	na	na
2015	16/12/2015	25/05/2016	4	2	Tebuconazole + Azoxystrobin + Mancozeb	Triazole + Strobilurin + Dithiocarbamate	Systemic + Mesosystemic Protector + Contact	h
2015	16/12/2015	25/05/2016	4	3	Tebuconazole + Azoxystrobin + Mancozeb	Triazole + Strobilurin + Dithiocarbamate	Systemic + Mesosystemic Protector + Contact	h
2015	16/12/2015	25/05/2016	4	4	Tebuconazole + Azoxystrobin + Mancozeb	Triazole + Strobilurin + Dithiocarbamate	Systemic + Mesosystemic Protector + Contact	h
2015	16/12/2015	25/05/2016	4	5	Cyproconazole + Azoxystrobin + Mancozeb	Triazole + Strobilurin + Dithiocarbamate	Systemic + Mesosystemic Protector + Contact	h
2015	16/12/2015	25/05/2016	4	6	Cyproconazole + Azoxystrobin + Mancozeb	Triazole + Strobilurin + Dithiocarbamate	Systemic + Mesosystemic Protector + Contact	h
2015	16/12/2015	25/05/2016	4	7	Cyproconazole + Azoxystrobin + Mancozeb	Triazole + Strobilurin + Dithiocarbamate	Systemic + Mesosystemic Protector + Contact	h
2015	16/12/2015	25/05/2016	4	8	Epoxiconazole + Pyraclostrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2015	16/12/2015	25/05/2016	4	9	Epoxiconazole + Kresoxim-methyl	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2016	29/10/2016	14/03/2017	5	1	Iprodione	Dicarboximide	Contact	a
2016	29/10/2016	14/03/2017	5	2	Iprodione	Dicarboximide	Contact	a
2016	29/10/2016	14/03/2017	5	3	Flutriafol + Azoxystrobin + Iprodione	Triazole + Strobilurin + Dicarboximide	Systemic + Mesosystemic Protector + Contact	h
2016	29/10/2016	14/03/2017	5	4	Flutriafol + Thiophanate-methyl + Iprodione	Triazole + Dicarboximide	Systemic + Contact	e
2016	29/10/2016	14/03/2017	5	5	Flutriafol + Thiophanate-methyl + Azoxystrobin + Iprodione	Triazole + Strobilurin + Dicarboximide	Systemic + Mesosystemic Protector + Contact	h
2016	29/10/2016	14/03/2017	5	6	Boscalid	Anilide	Systemic	d
2016	29/10/2016	14/03/2017	5	7	Boscalid + Pyraclostrobin	Anilide + Strobilurin	Systemic + Mesosystemic Protector	f
2016	29/10/2016	14/03/2017	5	8	Tebuconazole + Azoxystrobin + Mancozeb	Triazole + Strobilurin + Dithiocarbamate	Systemic + Mesosystemic Protector + Contact	h
2016	29/10/2016	14/03/2017	5	9	Tebuconazole + Trifloxystrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2016	29/10/2016	14/03/2017	5	10	na	na	na	na
2016	29/10/2016	14/03/2017	6	1	Iprodione	Dicarboximide	Contact	a

2016	29/10/2016	14/03/2017	6	2	Iprodione	Dicarboximide	Contact	a
2016	29/10/2016	14/03/2017	6	3	Flutriafol + Azoxystrobin + Iprodione	Triazole + Strobilurin + Dicarboximide	Systemic + Mesosystemic Protector + Contact	h
2016	29/10/2016	14/03/2017	6	4	Flutriafol + Thiophanate-methyl + Iprodione	Triazole + Dicarboximide	Systemic + Contact	e
2016	29/10/2016	14/03/2017	6	5	Flutriafol + Thiophanate-methyl + Azoxystrobin + Iprodione	Triazole + Strobilurin + Dicarboximide	Systemic + Mesosystemic Protector + Contact	h
2016	29/10/2016	14/03/2017	6	6	Boscalid	Anilide	Systemic	d
2016	29/10/2016	14/03/2017	6	7	Boscalid + Pyraclostrobin	Anilide + Strobilurin	Systemic + Mesosystemic Protector	f
2016	29/10/2016	14/03/2017	6	8	Tebuconazole + Azoxystrobin + Mancozeb	Triazole + Strobilurin + Dithiocarbamate	Systemic + Mesosystemic Protector + Contact	h
2016	29/10/2016	14/03/2017	6	9	Tebuconazole + Trifloxystrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2016	29/10/2016	14/03/2017	6	10	na	na	na	na
2016	01/11/2016	15/03/2017	7	1	na	na	na	na
2016	01/11/2016	15/03/2017	7	2	Cyproconazole + Difenoconazole + Azoxystrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2016	01/11/2016	15/03/2017	7	3	Cyproconazole + Difenoconazole + Azoxystrobin + Picoxystrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2016	01/11/2016	15/03/2017	7	4	Cyproconazole + Tebuconazole + Trifloxystrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2016	01/11/2016	15/03/2017	7	5	Epoxiconazole + Tebuconazole + Azoxystrobin + Kresoxim-methyl + Mancozeb	Triazole + Strobilurin + Dithiocarbamate	Systemic + Mesosystemic Protector + Contact	h
2016	01/11/2016	15/03/2017	7	6	Epoxiconazole + Boscalid + Pyraclostrobin	Triazole + Anilide + Strobilurin	Systemic + Mesosystemic Protector	f
2016	17/12/2016	17/05/2017	8	1	na	na	na	na
2016	17/12/2016	17/05/2017	8	2	Cyproconazole + Tebuconazole + Azoxystrobin + Mancozeb	Triazole + Strobilurin + Dithiocarbamate	Systemic + Mesosystemic Protector + Contact	h
2016	17/12/2016	17/05/2017	8	3	Cyproconazole + Tebuconazole + Azoxystrobin + Mancozeb	Triazole + Strobilurin + Dithiocarbamate	Systemic + Mesosystemic Protector + Contact	h
2016	17/12/2016	17/05/2017	8	4	Cyproconazole + Azoxystrobin + Mancozeb	Triazole + Strobilurin + Dithiocarbamate	Systemic + Mesosystemic Protector + Contact	h
2016	17/12/2016	17/05/2017	8	5	Cyproconazole + Azoxystrobin + Mancozeb	Triazole + Strobilurin + Dithiocarbamate	Systemic + Mesosystemic Protector + Contact	h

2016	17/12/2016	17/05/2017	8	6	Cyproconazole + Azoxystrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2016	17/12/2016	17/05/2017	8	7	Cyproconazole + Epoxiconazole + Pyraclostrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2016	17/12/2016	17/05/2017	8	8	Cyproconazole + Picoxystrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2016	17/12/2016	17/05/2017	8	9	Tebuconazole + Azoxystrobin + Mancozeb	Triazole + Strobilurin + Dithiocarbamate	Systemic + Mesosystemic Protector + Contact	h
2016	17/12/2016	17/05/2017	8	10	Tebuconazole + Azoxystrobin + Mancozeb	Triazole + Strobilurin + Dithiocarbamate	Systemic + Mesosystemic Protector + Contact	h
2016	17/12/2016	17/05/2017	8	11	Cyproconazole + Azoxystrobin + Mancozeb	Triazole + Strobilurin + Dithiocarbamate	Systemic + Mesosystemic Protector + Contact	h
2016	17/12/2016	17/05/2017	8	12	Cyproconazole + Azoxystrobin + Mancozeb	Triazole + Strobilurin + Dithiocarbamate	Systemic + Mesosystemic Protector + Contact	h
2016	17/12/2016	17/05/2017	8	13	Cyproconazole + Azoxystrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2016	17/12/2016	17/05/2017	8	14	Epoxiconazole + Pyraclostrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2016	17/12/2016	17/05/2017	8	15	Cyproconazole + Picoxystrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2016	17/12/2016	17/05/2017	9	1	na	na	na	na
2016	17/12/2016	17/05/2017	9	2	Tebuconazole + Azoxystrobin + Mancozeb	Triazole + Strobilurin + Dithiocarbamate	Systemic + Mesosystemic Protector + Contact	h
2016	17/12/2016	17/05/2017	9	3	Tebuconazole + Azoxystrobin + Mancozeb	Triazole + Strobilurin + Dithiocarbamate	Systemic + Mesosystemic Protector + Contact	h
2016	17/12/2016	17/05/2017	9	4	Tebuconazole + Azoxystrobin + Mancozeb	Triazole + Strobilurin + Dithiocarbamate	Systemic + Mesosystemic Protector + Contact	h
2016	17/12/2016	17/05/2017	9	5	Epoxiconazole + Pyraclostrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2016	17/12/2016	17/05/2017	9	6	Epoxiconazole + Kresoxim-methyl	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2017	01/10/2017	25/05/2018	10	1	na	na	na	na
2017	01/10/2017	25/05/2018	10	2	Tebuconazole + Azoxystrobin + Mancozeb	Triazole + Strobilurin + Dithiocarbamate	Systemic + Mesosystemic Protector + Contact	h
2017	01/10/2017	25/05/2018	10	3	Tebuconazole + Azoxystrobin + Mancozeb	Triazole + Strobilurin + Dithiocarbamate	Systemic + Mesosystemic Protector + Contact	h

2017	01/10/2017	25/05/2018	10	4	Tebuconazole + Azoxystrobin + Mancozeb	Triazole + Strobilurin + Dithiocarbamate	Systemic + Mesosystemic Protector + Contact	h
2017	01/10/2017	25/05/2018	10	5	Tebuconazole + Azoxystrobin + Mancozeb	Triazole + Strobilurin + Dithiocarbamate	Systemic + Mesosystemic Protector + Contact	h
2017	01/10/2017	25/05/2018	10	6	Boscalid	Anilide	Systemic	d
2017	01/10/2017	25/05/2018	10	7	Tebuconazole + Trifloxystrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2017	18/10/2017	09/05/2018	11	1	na	na	na	na
2017	18/10/2017	09/05/2018	11	2	Cyproconazole + Tebuconazole + Azoxystrobin + Mancozeb	Triazole + Strobilurin + Dithiocarbamate	Systemic + Mesosystemic Protector + Contact	h
2017	18/10/2017	09/05/2018	11	3	Cyproconazole + Tebuconazole + Azoxystrobin + Mancozeb	Triazole + Strobilurin + Dithiocarbamate	Systemic + Mesosystemic Protector + Contact	h
2017	18/10/2017	09/05/2018	11	4	Cyproconazole + Tebuconazole + Azoxystrobin + Mancozeb	Triazole + Strobilurin + Dithiocarbamate	Systemic + Mesosystemic Protector + Contact	h
2017	18/10/2017	09/05/2018	11	5	Epoxiconazole + Tebuconazole + Boscalid + Pyraclostrobin	Triazole + Anilide + Strobilurin	Systemic + Mesosystemic Protector	f
2017	18/10/2017	09/05/2018	11	6	Epoxiconazole + Tebuconazole + Kresoxim-methyl + Trifloxystrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2017	15/11/2017	24/04/2018	12	1	na	na	na	na
2017	15/11/2017	24/04/2018	12	2	Flutriafol	Triazole	Systemic	d
2017	15/11/2017	24/04/2018	12	3	Flutriafol	Triazole	Systemic	d
2017	15/11/2017	24/04/2018	12	4	Cyproconazole	Triazole	Systemic	d
2017	15/11/2017	24/04/2018	12	5	Triadimenol	Triazole	Systemic	d
2017	15/11/2017	24/04/2018	12	6	Flutriafol	Triazole	Systemic	d
2018	16/12/2018	15/05/2019	13	1	Cyproconazole + Epoxiconazole + Picoxystrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2018	16/12/2018	15/05/2019	13	2	Cyproconazole + Epoxiconazole + Boscalid + Pyraclostrobin	Triazole + Anilide + Strobilurin	Systemic + Mesosystemic Protector	f
2018	16/12/2018	15/05/2019	13	3	Cyproconazole + Epoxiconazole + Boscalid + Pyraclostrobin	Triazole + Anilide + Strobilurin	Systemic + Mesosystemic Protector	f
2018	16/12/2018	15/05/2019	13	4	Cyproconazole + Epoxiconazole + Boscalid + Pyraclostrobin	Triazole + Anilide + Strobilurin	Systemic + Mesosystemic Protector	f
2018	16/12/2018	15/05/2019	13	5	Cyproconazole + Epoxiconazole + Boscalid + Pyraclostrobin	Triazole + Anilide + Strobilurin	Systemic + Mesosystemic Protector	f

2018	16/12/2018	15/05/2019	13	6	Cyproconazole + Epoxiconazole + Boscalid + Pyraclostrobin	Triazole + Anilide + Strobilurin	Systemic + Mesosystemic Protector	f
2018	27/11/2018	15/05/2019	14	1	na	na	na	na
2018	27/11/2018	15/05/2019	14	2	Cyproconazole + Azoxystrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2018	27/11/2018	15/05/2019	14	3	Cyproconazole + Triadimenol + Trifloxystrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2018	27/11/2018	15/05/2019	14	4	Tebuconazole + Flutriafol + Metominostrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2018	27/11/2018	15/05/2019	14	5	Flutriafol + Azoxystrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2018	27/11/2018	15/05/2019	14	6	Cyproconazole + Azoxystrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2018	27/11/2018	15/05/2019	14	7	Tebuconazole + Metominostrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2018	27/11/2018	15/05/2019	14	8	Tebuconazole + Trifloxystrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2018	06/11/2018	20/04/2019	15	1	na	na	na	na
2018	06/11/2018	20/04/2019	15	2	Epoxiconazole + Pyraclostrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2018	06/11/2018	20/04/2019	15	3	Epoxiconazole + Pyraclostrobin + Copper hydroxide	Triazole + Strobilurin+ Inorganic	Systemic + Mesosystemic Protector + Contact	h
2018	06/11/2018	20/04/2019	15	4	Epoxiconazole + Pyraclostrobin + Copper hydroxide	Triazole + Strobilurin+ Inorganic	Systemic + Mesosystemic Protector + Contact	h
2018	06/11/2018	20/04/2019	15	5	Epoxiconazole + Pyraclostrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2018	06/11/2018	20/04/2019	15	6	Epoxiconazole + Pyraclostrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2018	06/11/2018	20/04/2019	15	7	Epoxiconazole + Pyraclostrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2018	06/11/2018	20/04/2019	15	8	Epoxiconazole + Pyraclostrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2018	19/09/2018	15/04/2019	16	1	na	na	na	na
2018	19/09/2018	15/04/2019	16	2	Epoxiconazole + Boscalid + Pyraclostrobin	Triazole + Anilide + Strobilurin	Systemic + Mesosystemic Protector	f
2018	19/09/2018	15/04/2019	16	3	Epoxiconazole + Boscalid + Pyraclostrobin	Triazole + Anilide + Strobilurin	Systemic + Mesosystemic Protector	f

2018	19/09/2018	15/04/2019	16	4	Epoxiconazole + Boscalid + Pyraclostrobin + Bacillus subtilis	Triazole + Anilide + Strobilurin + Bacillus	Systemic + Mesosystemic Protector + Biologic	g
2018	19/09/2018	15/04/2019	16	5	Epoxiconazole + Boscalid + Pyraclostrobin + Bacillus subtilis	Triazole + Anilide + Strobilurin + Bacillus	Systemic + Mesosystemic Protector + Biologic	g
2018	03/10/2018	20/05/2019	17	1	na	na	na	na
2018	03/10/2018	20/05/2019	17	2	Tebuconazole + Azoxystrobin + Mancozeb	Triazole + Strobilurin + Dithiocarbamate	Systemic + Mesosystemic Protector + Contact	h
2018	03/10/2018	20/05/2019	17	3	Tebuconazole + Azoxystrobin + Mancozeb	Triazole + Strobilurin + Dithiocarbamate	Systemic + Mesosystemic Protector + Contact	h
2018	03/10/2018	20/05/2019	17	4	Tebuconazole + Azoxystrobin + Mancozeb	Triazole + Strobilurin + Dithiocarbamate	Systemic + Mesosystemic Protector + Contact	h
2018	03/10/2018	20/05/2019	17	5	Tebuconazole + Azoxystrobin + Mancozeb	Triazole + Strobilurin + Dithiocarbamate	Systemic + Mesosystemic Protector + Contact	h
2018	03/10/2018	20/05/2019	17	6	Epoxiconazole + Boscalid + Pyraclostrobin	Triazole + Anilide + Strobilurin	Systemic + Mesosystemic Protector	f
2018	03/10/2018	20/05/2019	17	7	Cyproconazole + Difenoconazole + Azoxystrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2019	04/10/2019	29/05/2020	18	1	na	na	na	na
2019	04/10/2019	29/05/2020	18	2	Epoxiconazole + Boscalid + Pyraclostrobin	Triazole + Anilide + Strobilurin	Systemic + Mesosystemic Protector	f
2019	04/10/2019	29/05/2020	18	3	Epoxiconazole + Boscalid + Pyraclostrobin + Bacillus subtilis	Triazole + Anilide + Strobilurin + Bacillus	Systemic + Mesosystemic Protector + Biologic	g
2019	04/10/2019	29/05/2020	18	4	Epoxiconazole + Boscalid + Pyraclostrobin + Bacillus subtilis	Triazole + Anilide + Strobilurin + Bacillus	Systemic + Mesosystemic Protector + Biologic	g
2019	04/10/2019	29/05/2020	18	5	Epoxiconazole + Boscalid + Pyraclostrobin + Bacillus subtilis	Triazole + Anilide + Strobilurin + Bacillus	Systemic + Mesosystemic Protector + Biologic	g
2019	04/10/2019	29/05/2020	18	6	Epoxiconazole + Boscalid + Pyraclostrobin + Bacillus subtilis	Triazole + Anilide + Strobilurin + Bacillus	Systemic + Mesosystemic Protector + Biologic	g
2019	04/10/2019	29/05/2020	18	7	Epoxiconazole + Boscalid + Pyraclostrobin + Bacillus subtilis	Triazole + Anilide + Strobilurin + Bacillus	Systemic + Mesosystemic Protector + Biologic	g
2019	07/10/2019	29/05/2020	19	1	na	na	na	na
2019	07/10/2019	29/05/2020	19	2	Difenoconazole + Pydiflumetofen	Triazole + Carboxamide	Systemic	d
2019	07/10/2019	29/05/2020	19	3	Difenoconazole + Azoxystrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2019	07/10/2019	29/05/2020	19	4	Boscalid	Anilide	Systemic	d

2019	07/10/2019	29/05/2020	19	5	Tebuconazole + Trifloxystrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2019	07/10/2019	29/05/2020	19	6	Tebuconazole + Azoxystrobin + Mancozeb	Triazole + Strobilurin + Dithiocarbamate	Systemic + Mesosystemic Protector + Contact	h
2019	02/10/2019	29/05/2020	20	1	na	na	na	na
2019	02/10/2019	29/05/2020	20	2	Boscalid	Anilide	Systemic	d
2019	02/10/2019	29/05/2020	20	3	Tebuconazole + Trifloxystrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2019	02/10/2019	29/05/2020	20	4	Tebuconazole + Azoxystrobin + Mancozeb	Triazole + Strobilurin + Dithiocarbamate	Systemic + Mesosystemic Protector + Contact	h
2019	02/10/2019	29/05/2020	20	5	Tebuconazole + Azoxystrobin + Mancozeb	Triazole + Strobilurin + Dithiocarbamate	Systemic + Mesosystemic Protector + Contact	h
2019	02/10/2019	29/05/2020	20	6	Kasugamycin	Antibiotic	Systemic	d
2019	02/10/2019	29/05/2020	20	7	Kasugamycin	Antibiotic	Systemic	d
2019	02/10/2019	29/05/2020	20	8	Tebuconazole + Azoxystrobin + Mancozeb	Triazole + Strobilurin + Dithiocarbamate	Systemic + Mesosystemic Protector + Contact	h
2020	05/11/2020	26/06/2021	21	1	na	na	na	na
2020	05/11/2020	26/06/2021	21	2	Tebuconazole + Trifloxystrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2020	05/11/2020	26/06/2021	21	3	Difenoconazole + Azoxystrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2020	05/11/2020	26/06/2021	21	4	Boscalid	Anilide	Systemic	d
2020	05/11/2020	26/06/2021	21	5	Boscalid + Pyraclostrobin	Anilide + Strobilurin	Systemic + Mesosystemic Protector	f
2020	05/11/2020	26/06/2021	21	6	Fluxapyroxad + Copper oxychloride	Carboxamide + Inorganic	Systemic + Contact	e
2020	05/11/2020	26/06/2021	21	7	Boscalid + Pyraclostrobin + Fluxapyroxad + Copper hydroxide	Anilide + Carboxamide + Strobilurin + Inorganic	Systemic + Mesosystemic Protector + Contact	h
2020	05/11/2020	26/06/2021	21	8	Boscalid + Pyraclostrobin + Fluxapyroxad + Copper hydroxide	Anilide + Carboxamide + Strobilurin + Inorganic	Systemic + Mesosystemic Protector + Contact	h
2020	04/11/2020	01/06/2021	22	1	na	na	na	na
2020	04/11/2020	01/06/2021	22	2	Tebuconazole + Metominostrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2020	04/11/2020	01/06/2021	22	3	Tebuconazole + Metominostrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f

2020	04/11/2020	01/06/2021	22	4	Tebuconazole + Metominostrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2020	04/11/2020	01/06/2021	22	5	Tebuconazole + Metominostrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2020	04/11/2020	01/06/2021	22	6	Tebuconazole + Trifloxystrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2020	07/12/2020	20/07/2021	23	1	na	na	na	na
2020	07/12/2020	20/07/2021	23	2	Cyproconazole + Azoxystrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2020	07/12/2020	20/07/2021	23	3	Cyproconazole + Azoxystrobin + Copper hydroxide	Triazole + Strobilurin+ Inorganic	Systemic + Mesosystemic Protector + Contact	h
2020	07/12/2020	20/07/2021	23	4	Cyproconazole + Azoxystrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2020	07/12/2020	20/07/2021	23	5	Cyproconazole + Azoxystrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f
2020	07/12/2020	20/07/2021	23	6	Cyproconazole + Benzovindiflupyr + Azoxystrobin	Triazole + Carboxamide + Strobilurin	Systemic + Mesosystemic Protector	f
2020	07/12/2020	20/07/2021	23	7	Cyproconazole + Difenoconazole + Azoxystrobin	Triazole + Strobilurin	Systemic + Mesosystemic Protector	f

Legend: [1] Treatments classified by the mode of action; na: not applicable, because is the control treatment.

2.3 Disease incidence assessment

The coffee rust incidence was assessment monthly, with differences between the experiments, from December to May. The point of evaluated the disease progress is when beginning of symptoms in December until the final of the exponential growth of the disease, between March and April (Pinto et al., 2002). Coffee leaves assessments were made in a randomly by a non-destructive method. Each plant was evaluated in the middle third, in six plagiotropic branches, with three branches on each side of the planting line (Barbosa Junior et al., 2019). In each branch, the third or fourth pairs were evaluated and 12 leaves per plant were sampled, a total of 72 leaves in six plants per plot. The incidence of coffee rust was obtained with the equation to determine the percentage of the number of leaves with lesions or signals related to the total number evaluated (Campbell & Madden, 1990).

$$\mathrm{I}(\%) = \left(\frac{\mathrm{NLL}}{\mathrm{NTL}}\right) * 100 \quad (1)$$

where:

I (%) = Coffee rust incidence;

NLL = Number of lesioned leaves;

NTL = Number of total leaves sampled on the coffee tree.

2.4 Evaluation of the progressive disease rate

The disease proportion increased in a given period calculated the disease progress rate. Initially, we calculated the rust progress of absolute rate for each check treatment per experiment per year to obtain the disease progress rate per year from December to May. Second, was calculate the average absolute rate between December to May by year. Third, was calculated the absolute rate with the progress of Coffee rust for all studied treatments grouped

by the mode of action (Table 1). The average was obtained for the eight treatment groups based on the mode of action for all treatments and experiments in different year crops. Obtained between the years 2014 to 2021 in the range from December to May. After we calculated the partial rate monthly for the eight groups from December to May individually and plotted graphs using Microsoft® Excel® 2022 software. The rate was described by Van der Plank (1963) naming it the Apparent Infection Rate was:

$$r = \left(\frac{I_f - I_i}{T_f - T_i}\right) \quad (2)$$

where:

r = Disease progress rate;

I_f = Incidence final;

I_i = Incidence initial;

T_f = Time final;

T_i = Time initial.

2.5 Comparison of the disease progress rate

The comparison analysis of the disease progress rate was made by analysis of variance (ANOVA). The assumptions of the ANOVA were verified by normality tests of Shapiro-Wilk and homogeneity of Bartlett. Significant variables in the F test of ANOVA were submitted to the test of means between the treatments and compared by Scott-Knott clustering and Tukey test ($p \leq 0.5$). The statistical analyses were performed with the statistical software "R" version 4.0.4 (R Core Team, 2021) using the packages: ExpDes.pt, factoextra, and readxl. Comparisons were made by Coffee rust absolute rate for each check treatment per experiment per year from December to May between the years 2015 to 2021. Comparison analysis by the average

absolute rate between December to May by year for the check treatment. In the sequence, we made a comparison with all check treatments of all experiments together between the years 2014 to 2021 in the range from December to May. After we compare the absolute rate with the progress of coffee rust for all studied treatments grouped by the eight groups of the mode of action. Comparing the groups with all treatments and experiments obtained between the years 2014 to 2021 in the range from December to May. Subsequently, we compare the annual rate calculated and linearized by the nonlinear exponential model for the check treatment between the years 2014 to 2021 in the range from December to May.

2.6 Fitting models and estimating equation parameters

Model fitting for incidence over time was obtained by linear and non-linear models widely used to express disease progress (Campbell & Madden, 1990). Exponential, monomolecular, logistic, and Gompertz non-linear regression models were adjusted, in addition to the linear regression model:

$$y_i = y_0 + rt_i \quad \text{(Linear)} \quad (3)$$

$$y_i = y_0 e^{rt_i} \quad \text{(Exponential)} \quad (4)$$

$$y_i = 1 - \left(1 - y_0\right)e^{-rt_i} \quad \text{(Monomolecular)} \quad (5)$$

$$y_i = \frac{1}{1 + e^{\left(-\frac{lny_0}{1-y_0} + rt_i\right)}} \quad \text{(Logistic)} \quad (6)$$

$$y_i = e^{\left(lny_0 e^{(-rt_i)}\right)} \quad \text{(Gompertz)} \quad (7)$$

where:

y_i = disease quantity in t_i time;

y_0 = initial inoculum quantity;

r_i = disease progress rate;

t_i = time.

After the model adjustment, the Akaike Information Criterion (AIC) was used to assess the quality of the adjustments and identify the best fitted model. The calculation of this distance can be estimated by the following equation:

$$AIC = -2\ln\big(L(\theta)\big) + 2p \qquad (7)$$

where:

$L(\Theta)$ = Estimate of the maximum likelihood function;

p = Number of parameters of the evaluated model.

2.7 Fitting models statistical analysis

The statistical analysis for incidence was submitted to the Shapiro-Wilk (normality) and Breush–Pagan (homoscedasticity) test to evaluate the assumptions of the analysis of variance ($p>0.05$), including the normal distribution of residuals. After that, regression analyzes were performed to adjust of linear and non-linear models mentioned above. The t-test of parameters at 0.05% significance was performed for the coefficients of the adjusted models. The adjusted model of equation was chosen and calculated from the model based on the significance of the parameters of the regression equation ($p < 0.05$) in the t-test. Selecting by the criteria of the highest coefficient of determination (R^2) and adjusted R^2, and lowest values of the Akaike information criterion (AIC), errors mean of errors, standard deviation, and mean squared deviation. The statistical analyses were performed with the statistical software “R”

version 4.0.4 (R Core Team, 2021) using the packages: AICcmodavg, car, dplyr, lmtest, nlme, and readxl.

3 Results

The coffee rust progress rate or apparent infection rate in the studied plantations from 2015 to 2021 varies mainly between crop years. We found a significant difference ($p \leq 0.05$) between check treatments of experiments in the crop year 2015/16 and also in 2016/17 (Table 2. Based on Tukey's test for both years, we obtained two connected groups and there is an interconnection between groups when analyzing the mean letters obtained. Normality and homogeneity were obtained in the analysis within the harvest years, except for the normality test for the 2015/16 harvest.

Table 2 – Coffee rust progress rate (r) for the check treatment or check in different experiments from December to May per crop year between the years 2015 to 2021.

Harvest	Significance	Normality	Homogeneity	Tukey		
2015/16	**	0.02606901	0.848125	Groups	Treatments	Means
				a	control exp 3	0.01139323
				ab	control exp 2	-0.00508282
				b	control exp 4	-0.02817085
2016/17	*	0.3543469	0.3886959	Groups	Treatments	Means
				a	control exp 6	0.07416397
				a	control exp 7	0.07385361
				ab	control exp 5	0.06009615
				ab	control exp 8	0.05034722
				b	control exp 9	0.02083333
2017/18	n/s	0.7168007	0.2876047			
2018/19	n/s	0.1477072	0.2218226			
2019/20	n/s	0.7189388	0.5329599			
2020/21	n/s	0.6561784	0.4882649			

Legend: Total control experiments in the different year crop: 2015/16 (3); 2016/17 (5); 2017/18 (3); 2018/19 (5); 2019/20 (3); and, 2020/2021 (3); **: 0,01 significance in the F-test

($p \leq 0.01$); *: 0,05 significance in the F-test ($p \leq 0.05$); n/s: not significative in the F-test ($p > 0.05$).

Comparing all check or control treatments for the years 2014 to 2021 in the same statistical analysis, there was a significant difference in the F-test ($p \leq 0.001$), and the data were normal and homogeneous (Table 3). A reduction in the amount of the disease was observed, through negative values of the rate, probably there was leaf fall caused by coffee rust. The data were studied over seven years, but based on the mean test, they were divided into four distinct groups. Therefore, there is no clear grouping for experiments in the same year crop.

Table 3 – Analysis of the annual rate of progress check treatments of coffee rust in different experiments for different crop years. Obtained between the years 2014 to 2021 in the range from December to May.

Average of experiment			**Scott-Knott**		
Significance	**Normality**	**Homogeneity**	Groups	Treatments	Means
***	0.2786718	0.07793543	a	Control exp 1	0.100557547
			a	Control exp 12	0.076978512
			a	Control exp 6	0.074163967
			a	Control exp 7	0.073853613
			a	Control exp 5	0.060096150
			b	Control exp 8	0.050347222
			b	Control exp 23	0.044753086
			b	Control exp 10	0.039950283
			b	Control exp 18	0.031757622
			b	Control exp 11	0.031043042
			b	Control exp 21	0.030120482
			b	Control exp 19	0.023809524
			c	Control exp 9	0.020833332
			c	Control exp 20	0.015782828
			c	Control exp 22	0.014204545
			c	Control exp 3	0.011393232
			c	Control exp 15	0.010822511
			c	Control exp 2	-0.005082825
			d	Control exp 17	-0.015964240
			d	Control exp 13	-0.021825397
			d	Control exp 4	-0.028170850
			d	Control exp 14	-0.033460130

	d	Control exp16	-0.060703186

Legend: Experiments in the different year crop: 2014/ 2015 (Control exp2); 2015/16 (Control exp3, Control exp4, Control exp5); 2016/17 (Control exp7, Control exp8, Control exp9, Control exp13, Control exp14); 2017/18 (Control exp15, Control exp16, Control exp18); 2018/19 (Control exp21, Control exp22, Control exp23, Control exp24, Control exp25); 2019/20 (Control exp27, Control exp28, Control exp29); and, 2020/201 (Control exp31, Control exp36, Control exp37);
***: 0,001 significance in the F-test ($p \leq 0.001$).

The biennial nature of coffee influences its production and the number of plant diseases. In seven years, the coffee biennial character was almost always reflected in the presence of rust (Table 4). Therefore we can see a significant difference in F-test ($p \leq 0.001$) between the rate by the years. From 2014/15 to 2015/16, 2015/16 to 2016/17, 2017/18 to 2018/19, and 2018/19 to 2019/20 harvests, the biennial rates are clear and with different letters by the average in a Scott-Knott test. However, in the average test, 2016/17 to 2017/18 and 2019/20 to 2020/21 harvests obtained the same means and were in the same group. In the 2020 crop, the rust came late, being found from April 2021. In 2017, we observed a drop in incidence between April and May, probably caused by the fall of leaves with rust.

Table 4 – Analysis of the average rate progress of the average check treatments of the coffee leaf rust in different experiments for different crop years. Obtained between the years 2014 to 2021 in the range from December to May.

Average year crop			**Scott-Knott**		
Significance	**Normality**	**Homogeneity**	Groups	Treatments	Means
*******	0.5481582	0.5522452	a	T2014	0.1005575
			b	T2016	0.05585886
			b	T2017	0.04932395
			c	T2020	0.0296927
			c	T2019	0.02378332
			d	T2015	-0.007286814
			d	T2018	-0.02422609

Legend: Number of experiments in the different year crop: 2014/ 2015 (1); 2015/16 (3); 2016/17 (5); 2017/18 (3); 2018/19 (5); 2019/20 (3); and, 2020/201 (3); ***: 0,001 significance in the F-test ($p \leq 0.001$).

Disease progress data for all treatments studied grouped by mode of action based on the mean rate obtained for each of the eight groups obtained showed a significant difference. Although the grouping by mode of action obtained eight groups but based on the mean test we obtained five groups only (Table 5). There are three groups of the mode of action higher or in the same group by the mean test of the Check treatment mean. The highest rate was obtained in the Contact or Protective group or pr (b), using only the Dicarboximide or Dithiocarbamate chemical group. Observing the average monthly rate analyzed according to the mode of action of the fungicides, we can observe the crescent growth rate of the contact group during the assessment period (Figure 1). The second mean test grouping stays the Systemic + Contact treatment (e). In the third mean test group, there are two modes of action groups. Were in the same group the check (a) and the Mesostemic Protector + Contact treatments (c) and we can observe the high rate of variation during the months. The fourth mean test group is the last group with a minimal positive rate and is composed of Systemic (d) and Systemic + Mesostemic Protector + Contact (h). The monthly evolution rate for the Systemic group shows a variation with a negative peak in February and a positive peak in March. Therefore, the Systemic + Mesostemic Protector + Contact group takes a constant rate of progress (Figure1). The last group by the average test is composed of two types of treatments Systemic + Mesostemic Protector (f) and Systemic + Mesostemic Protector + Biological (g). The mean obtained was the lowest, but it obtained a negative rate for both modes of action present in this group (Table 5, Figure 1).

Table 5 – Analysis of the progress rate of coffee rust for all studied treatments grouped by the mode of action. The average of the treatments is based on the mode of action for all experiments in different crop years. Obtained between the years 2014 to 2021 in the range from December to May.

Average mode of action	**Scott-Knott**			**Type of grouping by the mode of action**	
Significance	**Groups**	**Treatments**	**Means**	**Mode of action**	**Chemical Group**
***	a	b	0.07465179	Contact	Dicarboximide; Dithiocarbamate
Normality	b	e	0.04611748	Systemic + Contact	Triazole + Dicarboximide; Carboxamide + Inorganic
0.01307157	c	c	0.03275063	Mesostemic Protector + Contact	Strobilurin + Dithiocarbamate + Inorganic;
Homogeneity	c	a	0.03192141	Check	-
0.1092241	d	d	0.01843385	Systemic	Triazole; Anilide; Triazole + Carboxamide; Antibiotic
	d	h	0.01195129	Systemic + Mesostemic Protector + Contact	Triazole + Strobilurin + Dithiocarbamate + Inorganic; Triazole + Strobilurin + Dithiocarbamate; Triazole + Strobilurin + Inorganic; Triazole + Strobilurin + Dicarboximide; Triazole + Strobilurin + Inorganic; Anilide + Carboxamide + Strobilurin + Inorganic
	e	f	-0.00837845	Systemic + Mesostemic Protector	Triazole + Strobilurin; Anilide + Strobilurin; Triazole + Anilide + Strobilurin; Triazole + Pyrazole carboxamide + Strobilurin
	e	g	-0.01608944	Systemic + Mesostemic Protector + Biologic	Triazole + Anilide + Strobilurin + Bacillus

Legend: Treatments classified by the mode of action; ***: 0,001 significance in the F-test ($p \leq 0.001$).

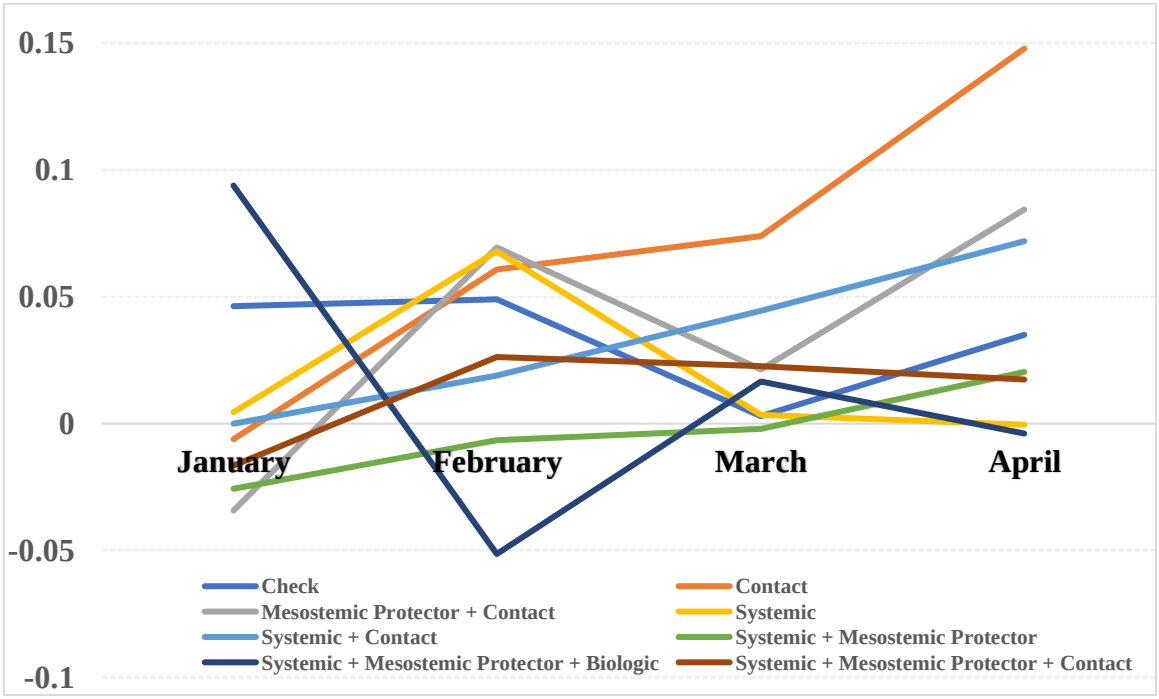

Figure 1 – Average monthly rate analyzed according to the mode of action of fungicides of coffee rust progress for all studied treatments grouped by the mode of action for all experiments in different crop years by months. Obtained between the years 2014 to 2021 in the range of the monthly analysis from December to May.

Data fit was obtained by having the best epidemiological model for the average rate of rust progression for all years using linear and non-linear models. Based on the parameters obtained between the analyzed models, the best fit model obtained was the non-linear Exponential model (Table 6). This model was chosen because it has a combination of low AIC value, the high R2 value, the best parameters of the equations in the t-test (β0 and β1), a relatively small mean square error, and the significance of the parameters in the t-test. Comparing linear, nonlinear, exponential, logarithmic, and Gompertz adjustment models (Table 6, Figure 2). To obtain the annual epidemiological analysis of rust, we linearized the rate values by the Exponential model (Table 7), based on the analysis made in Table 6. We compare the annual rate calculated by all experiments per year and linearized it by the nonlinear exponential model for the check treatment of coffee rust in different experiments. During the years 2014 to 2021, in the range from December to May all the linearized data stay in the same

mean based on Scott-Knott mean test (Table 7). Comparing the mean obtained in Table 7 and the mean obtained in Table 6 by the Exponential model we can use these rates obtained by the average of the linearized data.

Table 6 – Linear and nonlinear model (Exponential, Monomolecular, Logistic, Gompertz) fit for check treatment of coffee rust obtained between the years 2015 to 2021 in the range from December to May.

Model	MSR	AIC	R^2	r	y0	Normality	Homogeneity
Linear	221,121	11,54332	0,9168976	0,02659*	3,67500**	0,40990	0,91330
Exponential	**19,96616**	**14,19707**	**0,8587089**	**0,004369***	**3,988219****	**0,8822**	**0,5507**
Monomolecular	19,64485	14,64311	0,8455253	-0,00521*	4,054331**	0,943	0,4726
Logistic	18,39481	16,23933	0,7874292	-0,00083$^{n/s}$	4,29148**	0,9902	0,3028
Gompertz	19,15477	15,29479	0,8240208	-0,00239*	4,14851**	0,9838	0,3845

Legend: ***: 0,001 significance in the t-test ($p \leq 0.001$); **: 0,01 significance in the t-test ($p \leq 0.01$); *: 0,05 significance in the t-test ($p \leq 0.05$); n/s: not significative in the t-test ($p > 0.05$);
AIC: Akaike Information Criterion;
MSR: Mean Square Residual.

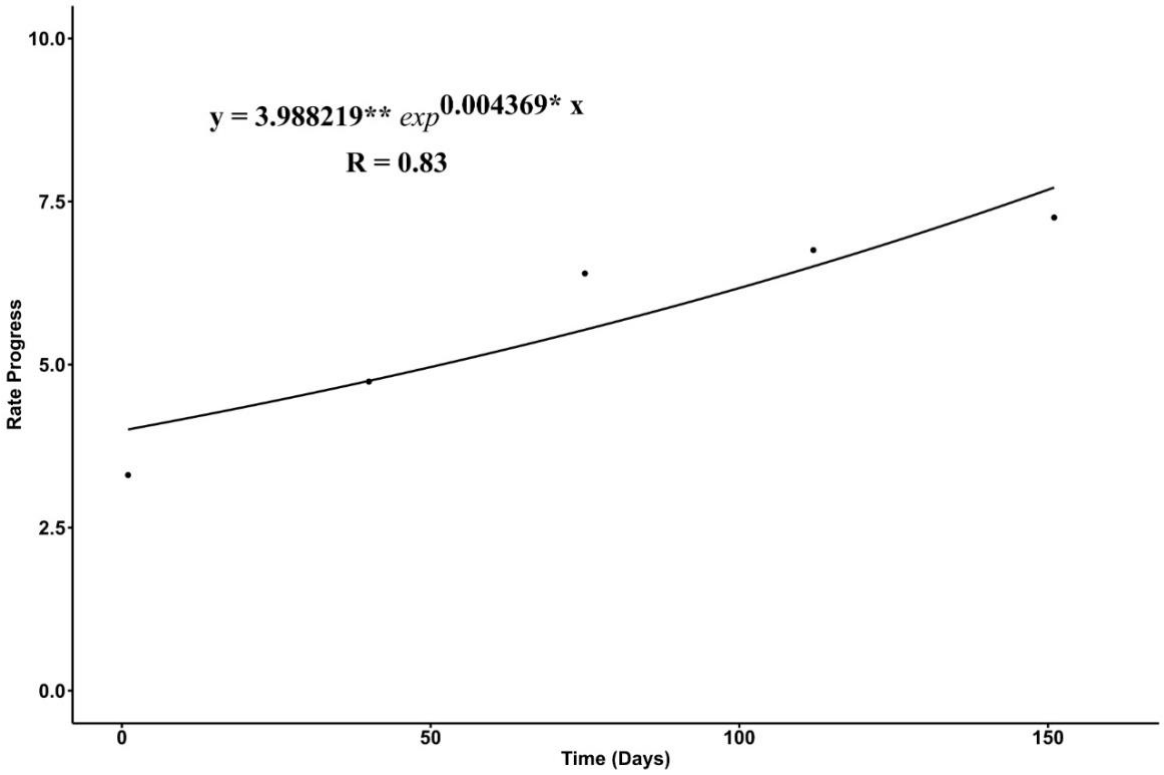

Figure 2 – Nonlinear Exponential model fit for check treatment of coffee rust obtained between the years 2015 to 2021 in the range from December to May**.** The parameters of the equation were significant at 0,05 significance in the t-test ($p \leq 0.05$).

Table 7 – Comparison analysis of the annual rate calculated by all experiments per year and linearized by the nonlinear exponential model for the check treatment of coffee rust in different experiments for different crop years. Obtained between the years 2014 to 2021 in the range from December to May.

Average of experiment			**Scott-Knott**		
Significance	**Normality**	**Homogeneity**	Groups	Treatments	Means
***	2,20E-06	3,86E-08	a	5	10,6082
			b	2	8,1375
			c	1	6,6146
			d	3	4,8021
			e	4	3,9022
			f	7	1,6984
			f	6	1,2731
			f	13	0,5161
			f	14	0,4224
			f	11	0,1747
			f	10	0,1351
			f	8	0,0947
			f	9	0,0932
			f	12	0,0695

Legend: Number of experiments in the different year crop: 2014/ 2015 (1); 2015/16 (3); 2016/17 (5); 2017/18 (3); 2018/19 (5); 2019/20 (3); and, 2020/201 (3);
Treatments represents the mean by the mean rate and are divided for calculated mean and linearized rate: 2014/15 (1- calculated, 8- linearized), 2015/16 (2- calculated, 9- linearized), 2016/17 (3- calculated, 10- linearized), 2017/18 (4- calculated, 11- linearized), 2018/19 (5- calculated, 12- linearized), 2019/20 (6- calculated, 13- linearized), and, 2020/21 (7- calculated, 14- linearized);
***: 0,001 significance in the F-test ($p \leq 0.001$).

4 Discussion

The rate of disease progress expresses the speed of the epidemic and its influenced by host susceptibility, pathogen virulence, and favorable environmental conditions. The fungicides also interferes with the disease progress. For these, the rate is an important parameter to compare epidemics in different climatic weather conditions (Campbell & Madden, 1990; Van der Plank, 1963).

The progress rate of coffee rust changed between years. There was no significant difference in the rate within the same season. Although the 2015/16 and 2016/17 harvests had a significant difference, the groups between them were interconnected. The difference obtained between witnesses from experiments in the same year may have been caused by adverse factors such as irregular distribution of rust in the field, differences between evaluators, different productivity between areas, leaf fall, varied soil fertility, and also other possible diseases and pests (Pozza, 2021). Rust attack causes the plant to produce more ethylene than normal, being responsible for the early fall of the leaves (VALENCIA, 1970).

The check grouping of all experiments was more comprehensive than the number of years. Evidencing the normality and homogeneity of the data. Although both positive and negative rates were observed. The presence of negative rates is unexpected according to the progress of the disease demonstrated by Pinto *et al.* (2002) between December to May. Symptomatology can explain the rate decrease by the biologic nature of leaf rust causing premature leaf fall (Pozza et al., 2010; Talhinhas et al., 2017).

In relation the average check treatments of the CLR per year for 2014 to 2021 we observe an almost always the reflection of coffee biennial production in the progress rate. The rates ranged from 0.1000 to -0.0242. Negative rate values were observed in the 2015/16 and 2018/19 harvests. Observing the rates obtained in the harvests from 1972/73 to 1977/78 in the municipalities of Alfenas, Jacutinga and Ponte Nova, in Minas Gerais, there were only positive rates (Chalfoun, 1980). In the work carried out by PIPAEMG (1973), nowadays called EPAMIG (Empresa de Pesquisa Agropecuária de Minas Gerais). Also in the 1972/73 harvest in six more cities in addition to those analyzed in the work by Chalfoun (1980), negative rates were observed in three cities. Between October and December, the highest rates of infection were observed, followed by a decrease in the disease.

In the literature, there are few studies on the rate of progress of coffee diseases. In our study, we observed that the lowest rate values were obtained in treatments with the presence of different modes of action. We found better disease control in the Systemic + Mesostemic and Systemic + Mesostemic + Biological Protector. The mixture of Mesostemic fungicides with triazoles or carboxamides or both characterize strobymix (Pozza, 2021; Pozza et al., 2010, 2021). Followed by Systemic and Systemic + Mesostemic Protector + Contact treatments. When we relate our data with those presented in studies that show the disease evolution curve, we observe that the best management occurs with the use of products with combined modes of action (Belan et al., 2014; Pozza, 2021; Talhinhas et al., 2017).

The model used for adjustment was the non-linear exponential model. This criterion is a measure of proximity between the ideal (perfect) model and the candidate model and is based on the Kullback-Leibler distance or information minimization. In which the lowest AIC value is considered the closest to the ideal and the best-fitted model (Akaike, 1974). The non-linear exponential model for was adjusted between the rates obtained from December-May. It is in agreement with the rate obtained by Pinto *et al.* (2002) between the months of March-April.

5 Conclusion

The rate of disease progression varied both between experiments and years for the control treatments. The variation was approximately 0.101 to -0.061 between the evaluated treatments and 0.1005575 to -0.02422609 for the evaluated years. The lowest rates obtained were with negative values. The best fitted epidemiological model was the non-linear Exponential model.

Based on the rate progress of Arabica coffee rust the best effectiveness management based on mode of action was with combination of Systemic and Mesostemic and Systemic, Mesostemic and Biological Protector.

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