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A time series analysis of brown eye spot progress in conventional and organic coffee production systems

A. G. C. Souza[a]*, L. A. Maffia[a], F. F. Silva[b], E. S. G. Mizubuti[a] and H. Teixeira[c]

[a]*Departamento de Fitopatologia, Universidade Federal de Viçosa, Viçosa, 36570-000, MG, Brazil;* [b]*Departamento de Estatística/Animal Science, Universidade Federal de Viçosa, Viçosa, 36570-000, MG, Brazil; and* [c]*Empresa de Pesquisa Agropecuária de Minas Gerais, Unidade Regional Epamig Sul de Minas, Campus da UFLA, s/n, 37200-000, Lavras, MG, Brazil*

Brown eye spot (BES), caused by *Cercospora coffeicola*, is an important coffee disease in Brazil. Losses related to this disease have increased over the last few years. Because the factors associated with the disease dynamics are not fully understood, it is important to gather information about this in different cropping systems. BES epidemics were compared from three production systems: organic (OS), organic under shade (OSS) and conventional under full sun (CS). This study was conducted in Ervália-MG, Brazil, from November 2004 to October 2008. Disease progress was modelled with all 4 years of data in a time series analysis. Disease intensity (severity (SEV) and incidence (INC)), leaf setting (LS) and leaf fall (LF) were assessed on a monthly basis. The highest values for SEV, INC, LF, LS, as well as a larger area under the disease progress curve and maximum disease occurred in CS and in the upper branches, whereas the lowest values for all variables occurred in OSS and in the lower branches. The highest values occurred for SEV and INC from May to July, for LF from July to September, and for LS from October to January. The disease progress was successfully modelled via a time series analysis. The seasonal behaviour of disease progress for all years and production systems was modelled with a nonlinear sinusoidal model with autoregressive moving average (ARMA) errors. Estimated parameters were generated which could be useful for comparative epidemiology, and it was shown that shade could be used in the field for BES management.

Keywords: ARMA errors, *Cercospora coffeicola*, epidemiology, shade production

Introduction

Brazilian coffee production is threatened by many abiotic and biotic factors, including brown eye spot (BES), which is caused by *Cercospora coffeicola*. Depending on the season and region, BES can be the most significant coffee disease and can lead to losses of up to 30%. Disease symptoms appear on the leaves as necrotic spots with light-coloured centres that are surrounded by a purplish-brown ring with yellowish edges. The coffee fruits present dark spots and a dry appearance (López-Duque & Fernández-Borrero, 1969). An increase in BES intensity in Brazilian coffee plantations occurred in the late 2000s. The factors underlying this increase are not fully understood but possibly include the following: coffee crop expansion from traditional areas into the Cerrado region (where low fertility soils and periods of severe drought prevail), the cultivation of new coffee varieties, changes in cultural practices, climate change and pathogen population shifts (Fazuoli *et al.*, 2002). Furthermore, the increase of the productive capacity of coffee plantations in recent years may have favoured higher BES intensity. Santos *et al.* (2008) report that coffee plantations with high production are more susceptible to the occurrence of BES as a result of the drain of nutrients from the leaves to the grains, which may have led to a nutritional imbalance in the leaves and favoured colonization by *C. coffeicola*.

*E-mail: agcsouza@yahoo.com.br

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Coffee can be grown conventionally in high input agricultural systems, which are the most common in Brazil, or in organic production systems. Reduced disease intensity has been observed in some crops under organic cultivation, including coffee (Workneh *et al.*, 1993; Abbasi *et al.*, 2002; Santos *et al.*, 2008). However, studies of BES progress within organic production systems are scarce and inconclusive. By surveying organic planting in the state of Minas Gerais, Martins *et al.* (2004) showed an estimated incidence of BES in the leaves of more than 32% in 2001 and 59% in 2002, whereas Santos *et al.* (2008) found a maximum leaf incidence of 11·5 and 15% in 2004 and 2005, respectively.

A smaller number of family farmers use shade-grown coffee production systems. Although coffee plants that are grown under full sun yield more than shade-grown plants (Miranda *et al.*, 1999), the BES intensity is higher in full sun-grown plants (López-Duque & Fernández-Borrero, 1969; Almeida, 1986; Salgado *et al.*, 2007). Despite this finding, the effects of shade on coffee diseases are controversial because shade may favour a given stage in the life cycle of one organism and hinder the progress of another organism (López-Bravo *et al.*, 2012). The shading effect may even be dependent on the shade tree. As reported by other authors, the type of shade tree may affect the BES incidence (Salgado *et al.*, 2007), pathogen populations

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(Soto-Pinto *et al.*, 2001), and even disease antagonists (Staver *et al.*, 2001). Some family farms use banana trees to shade their coffee plants. To the authors' knowledge, BES dynamics have not yet been evaluated in coffee that is grown under banana trees. There are reports that describe the association of BES occurrence and stressing conditions in coffee plants, especially nutritional and water stress (Pozza *et al.*, 2000, 2001; Santos Botelho *et al.*, 2005).

With the expansion of coffee crops in general, crop management and alternative strategies for control of diseases have been developed for organic systems (Pereira *et al.*, 2008; Botelho *et al.*, 2009; Galdeano *et al.*, 2010). Comparative epidemiological studies can contribute towards an understanding of the BES dynamics under different cropping systems and lead to new strategies for evaluating crop management systems. It is important to produce progress models that will allow for the detection and description of temporal disease dynamic patterns (Contreras-Medina *et al.*, 2009). The commonly used growth models for disease progress are not suitable for characterizing disease dynamics in perennial crops such as coffee because any sigmoidal behaviour is masked by periodic behaviour. In the case of the *C. coffeicola*–coffee pathosystem, given the periodic trajectory of the epidemic, a time series-based (Box *et al.*, 1994) model is an attractive and viable alternative to describe disease dynamics. These models account for the temporal dependence of experimental observations, because the same individual plant is evaluated repeatedly over time, and provide parameter estimates that are useful for making biological interpretations of disease dynamics. Although time series models are adequate for describing the stochastic aspects of disease dynamics, they are not widely used in plant pathology. It is worthwhile to note that important information about temporal/spatial events relating to disease epidemics has been generated using the time series approach (Yang & Zeng, 1992; Hudelson *et al.*, 1993; Xu *et al.*, 1995; Guerin *et al.*, 2001; Holb, 2008). Nevertheless, these studies did not account for seasonality effects, which are very important for disease progress in tropical regions. To the best of the authors' knowledge, there are no such studies of polyetic diseases in Brazilian perennial crops, even in tropical perennial crops.

The aim of this study was to provide comparative epidemiological information about coffee plants grown under conventional and organic cropping systems. Therefore, disease progress was investigated in coffee plants that were grown under organic shaded (OSS), organic unshaded (OS) and conventional systems (CS) in Ervália-MG, Brazil, from November 2004 to October 2008. A novel approach was used that focused on time series modelling to describe and compare epidemics.

Materials and methods

Experimental site and coffee crop systems

Evaluations were continuously performed from November 2004 to October 2008 in a small commercial coffee farm located at Boa Vista farm, Ervália, Minas Gerais State, Brazil, at 827 m a.s.l., 20°54′52″S, 42°37′20″W. The rainy season in this region lasts from October to January (data not shown). The area is hilly and has clay soil.

The farmer-grown coffee plants of the cultivar 'Catuaí Vermelho IAC44' (which flowers from September to October, with grain setting from January to April and harvesting from May to June) were grown in three cropping systems: (i) conventional under full sun (CS); 8-year-old plants were planted in 2004 over 0·6 ha with a spacing of 2·0 m between the rows and 1·5 m between each plant in the row and treated with the following chemicals: dolomitic lime, N-P-K fertilization at a rate of 20-05-20, copper oxychloride, the fertilizer Supermagro and the fungicide/nutrient mixture Calda Viçosa (contents of both are given below) (five sprays each month from December to April); (ii) organic shaded (OSS); 0·5 ha was planted with 16-year-old plants in 2004 with spacing of 2·5 and 1·5 m; from 2000 to 2008, the coffee plants were intercropped with banana plants between the rows with a spacing of 2·5 m between each row and 3·5 m between the plants in each row; and (iii) organic not shaded (OS), in which 0·8 ha was planted with 20-year-old plants in 2004, with a spacing of 2·5 and 1·8 m; from 2000 to 2008, the coffee plants were intercropped with banana plants between the rows, with a spacing of 15·0 m between the rows and 3·5 m between the plants in each row. In both the OS and OSS, the grower applied Supermagro and Calda Viçosa (two sprays, one in January and one in March) and incorporated banana plant debris. Cow and chicken manures were incorporated into the soil. Supermagro is a fertilizer consisting of 40 kg of green cow manure, 1 kg of micronutrient mixture (2 kg zinc sulphate, 300 g manganese sulphate, 300 g iron sulphate, 300 g copper sulphate, 50 g cobalt sulphate, 2 kg calcium chloride, 1 kg boric acid, 200 g phosphate, 2 kg magnesium sulphate, 100 g sodium molybdate), 1 L milk, 500 g commercial sugar, 100 mL fermented milk, 500 g lime, and 200 g bone meal in 200 L water. Calda Viçosa is a fungicide/nutrient mixture, derived from the Bordeaux mixture (Cruz Filho & Chaves, 1985), containing 50 g copper sulphate, 15 g zinc sulphate, 80 g magnesium sulphate, 15 g boric acid and 62·5 g hydrated lime in 10 L water. In the cropping systems the applications of Supermagro and Calda Viçosa were made with a manual backpack sprayer at a dilution of 7·5% and 5 kg ha^{-1}, respectively, and NPK was applied at 500 kg ha^{-1}.

Experimental design

A W-pathway was followed to select 10 plants from each cropping system. For each plant, 12 branches were marked: four in the upper (U) canopy, four in the middle (M) and four in the lower (L) canopy. In each canopy position, each branch faced in a cardinal direction. Plant and disease dynamics were monitored in a randomized block design, with four replications in a split-split plot design; the cropping system was equal to the whole plot, the positions within the canopy were the subplots, and the months were the sub-subplots. The experiment was performed using 10 replications (plants) for each treatment. The treatments were defined as the combination of crop system (CS, OSS or OS) levels, positions within the canopy (U, M or L), and month of evaluation (1, 2 … 48).

Dynamics of brown eye spot, leaf setting and leaf fall

The period lasting from the November of one year to the October of the next year was considered to be one year of evaluation. Disease incidence, disease severity and the number of leaves were assessed monthly in the marked branches. For disease incidence (INC), a leaf with at least one lesion was considered to be diseased. For disease severity (SEV), a diagrammatic scale was used with five scores: 1 = 0%, 2 = <3%, 3 = >3–6%, 4 = >6–12%, and 5 = >12–25% of diseased leaf area (Oliveira *et al.*, 2001). The midpoint values between the highest and lowest limits of each score were used for the analyses. Leaf setting (LG) was calculated as the proportion of leaves that emerged in comparison to the previous value, and the leaf fall (LF) was calculated as the proportion of leaves that fell in comparison to the previous evaluation.

The means of INC, SEV, LG and LF were plotted against months to generate disease progress curves and plant growth monthly. For each of the 4 years' evaluations and for each of the nine cropping system–canopy position combinations, the points of maximum INC and SEV were estimated and the area under the disease progress curve for the INC (AUDPCI) and SEV (AUDPCS) were calculated according to Shaner & Finney (1977).

The MIXED procedure from SAS v. 9.1 (SAS Institute) was used for the analysis of variance considering INC and SEV as dependent variables and systems, canopy, months and their interactions as independent factors. Once a significant ($P < 0{\cdot}05$) interaction of system–canopy–month was observed (Table S1), the slicing analysis was carried out in order to study the trajectory of INC and SEV means over months inside each combination of system–canopy levels, generating a total of nine progress curves to be analysed by regression models.

Modelling the dynamics of brown eye spot

The above interaction was sliced by system–canopy, i.e. analysing the INC and SEV over months in each combination of system and canopy factors, so that the means of both the INC and SEV were plotted against the months in order to fit regression models to describe this relationship. Thus, a nonlinear sinusoidal regression model was fitted by using time as the explanatory variable to describe trajectories and generate parameters that could be used in biological interpretations. The parameters were divided into years (periods) by using a dummy variable approach to identify intra-annual patterns of disease progress. The model is as follows:

$$y_i = \sum_{k=1}^{4} D_k \left[a_k + b_k \sin\left(\frac{c_k \pi x_i}{12}\right)\right] + e_i$$

where i and k are the indexes for the month and period (year), respectively. The term D_k is a dummy variable, where $D_k = 1$ for period k and $D_k = 0$ otherwise. The periods under consideration were as follows: $k = 1$ for $x_i \leq 12$, $k = 2$ for $12 < x_i \leq 24$, $k = 3$ for $24 < x_i \leq 36$, and $k = 4$ for $36 < x_i \leq 48$ months, during which i varied from the 1st to the 12th month (2004/2005, year I), from the 13th to the 24th month (2005/2006, year II), from the 25th to the 36th month (2006/2007, year III), and from the 37th to the 48th month (2007/2008, year IV), respectively; y_i is the dependent variable (as related to disease incidence or severity) for each month i, a is the y (disease incidence or severity) average value, and b is the increment of the incidence or severity that occurred over a period (year), i.e. the difference from a (incidence or severity yearly average value) to the peak (p_k) (incidence or severity maximum yearly value). Thus, the peak is defined as a function of a and b parameters ($p_k = a + b$), c is half the number of cycles of the epidemic, x_i is the time in months, and e_i is the random error. These parameters are shown graphically in Figure 1.

Both INC and SEV were assessed in the same branches over time. Thus, the residuals associated with the model were not considered to be independent and were modelled by an autoregressive process (p) of moving averages (q) and ARMA (p,q). The ARMA model consists of two parts, an autoregressive (AR) part and a moving average (MA) part (Box *et al.*, 1994). During this process, it was assumed that the value of the residual at time i depends on the values at the previous times ($e_{i-1}, \ldots e_{i-p}$) and that the new error (which represents the random effects associated with variables other than time) also has the same dependence ($z_{i-1}, \ldots z_{i-q}$); thus, the term z_i is regarded as the true error (white noise) associated with the model used (Box *et al.*, 1994). This stochastic process is expressed as follows:

$$e_i = \phi_1 e_{i-1} + \ldots + \phi_p e_{i-p} + \theta_1 z_{i-1} + \ldots + \theta_q z_{i-q} + z_i, z_i \sim N(0, \sigma^2).$$

The proposed model was fitted by the MODEL procedure with the %AR and %MA macros of SAS v. 9.1 by using the least-squares method for non linear regression by the Gauss–Newton algorithm. The quality of the model fit was verified by the coefficient of determination, which is given by:

$$R^2 = 1 - \frac{\text{SQE}}{\text{SQTotal}} = r(y, \hat{y})^2.$$

As mentioned previously, the estimate of the peak value, hereafter denoted by $\hat{p}_k$, is expressed as $\hat{p}_k = \hat{a} + \hat{b}$. This parameter was compared by overlapping the 95% confidence intervals among the three crop systems (CS, OS and OSS) and canopy

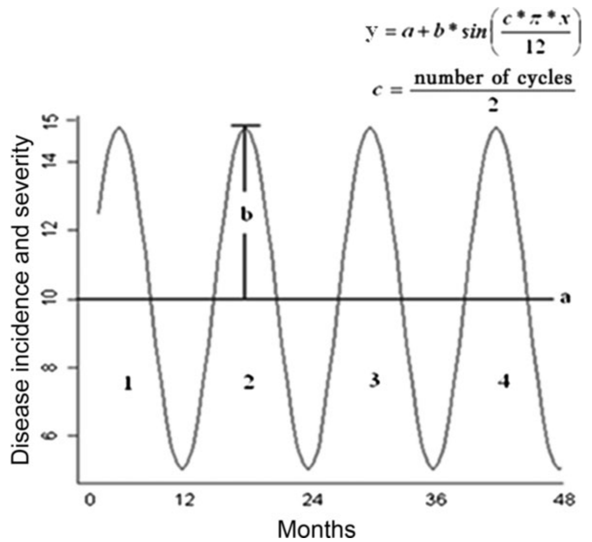

Figure 1 Graphical representation of the non linear model used to describe the progress of incidence and severity of brown eye spot in coffee plants over 48 months. The line *a* denotes the average value of disease incidence or severity, and *b* denotes the increment of the disease incidence or severity that occurred over a cycle (1 year), i.e. the difference between *a* (incidence or severity yearly average value) and the peak (p_k) (incidence or severity maximum yearly value).

positions (U, M and L) for each year. The confidence interval is expressed as follows:

$$\hat{p}_k \pm 1 \cdot 96\sqrt{\hat{V}(\hat{p}_k)}, \text{so that} \hat{V}(\hat{p}_k) = \hat{V}(\hat{a}) + \hat{V}(\hat{b}) + 2\text{cov}(\hat{a}, \hat{b}).$$

The estimates of the peaks between the two systems were considered to be different if the lower limit for the peak interval of one system was higher than the upper limit of the other, i.e. if there was no overlap.

Results

Dynamics of brown eye spot, leaf setting and leaf fall

BES occurred in all systems and years, although the disease intensity varied depending on both the systems and the years. In general, the disease incidence and severity followed the same trends: (i) they were both higher in CS and lower in OSS; and (ii) they were higher in the unshaded plants and lower in shaded plants. The disease dynamics were similar during the years I and IV. During year I, the intensity increased continuously from November to May, mainly in the CS. If only the years are considered, the higher intensity values occurred during year I: the maximum INCs were 26·43, 15·75 and 8·84%, and the maximum SEVs were 5·78, 2·44 and 0·86% in CS, OS and OSS, respectively. The highest values of INC and SEV occurred in the CS, whereas the lowest values of both variables occurred in OSS. In general, the intensity peaks occurred from May to July in the upper leaves (Figs 2 & 3).

Both the AUDPCI and AUDPCS values differed with regard to crop systems and canopy position (Table 1). Because the trends observed in the AUDPCI and AUDPCS were similar, both will be generalized as AUDPC. Over the course of 4 years, the AUDPCs were higher in the CS. There was a significant interaction between the systems and canopy positions in years I (P = 0·0284) and IV (P = 0·0003), and the AUDPCs were higher in the upper canopy in the CS and did not differ in the organic systems. In years II and III, the canopy position did not affect the AUDPC (Table 1). The leaf setting tended to occur from October to January and diminished from April to September. In general, higher setting occurred in the CS for all combinations of year–canopy position (Fig. 4a,b,c). From June to September, most leaf fall occurred, and it was higher in the CS and lower in the OSS (Fig. 4d,e,f).

Modelling the progress of brown eye spot

The non linear regression model with ARMA errors was able to efficiently describe the disease progress, with an average R^2 of 75·42% for SEV and 79·03% for INC. As mentioned, the curve fit was undertaken separately for each year–system–canopy position combination, generating a total of 72 equations (Table 2). The maximum disease intensity values were also estimated, allowing for the comparison of disease dynamics across different cropping systems (Table 2).

The predicted intensity values were similar to the observed values. The model fit was appropriate for both the INC and SEV for most combinations of year–system–canopy position. As before, the maximum INC and SEV peaks were similar, with higher values in the CS and lower values in the OSS, which were more pronounced in the upper leaves (Figs 2 & 3).

The peaks are easier to observe in the estimated maximum intensity plots (Figs 5 & 6). Because of the variability of the INC and SEV values, wide confidence

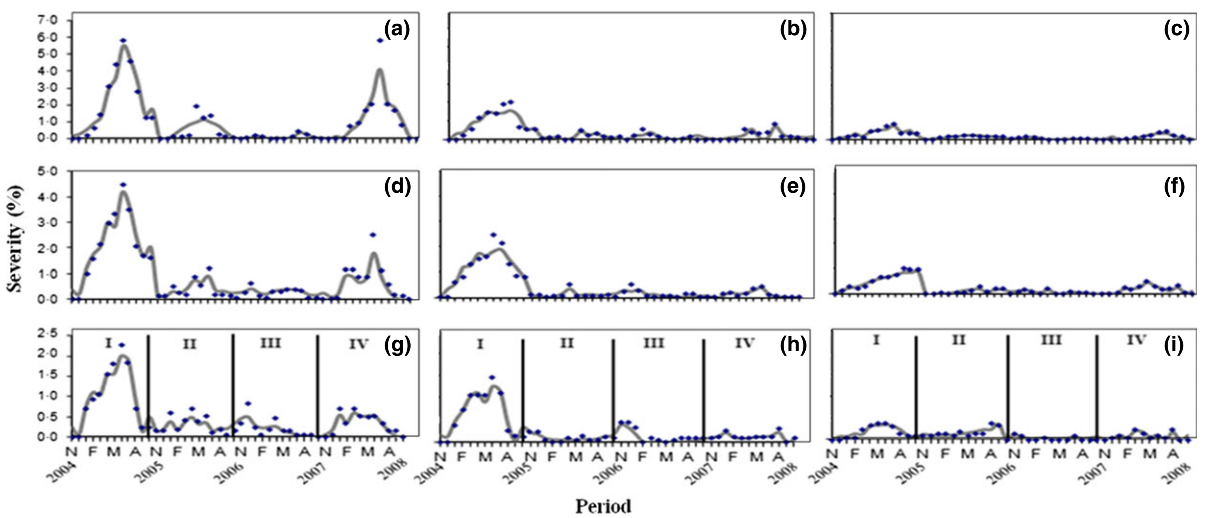

Figure 2 Severity of brown eye spot observed (◆) and predicted by nonlinear models (——) during years I (2004/05), II (2005/06), III (2006/07) and IV (2007/08) in the branches of the upper (a, b, c), middle (d, e, f), and lower (g, h, i) canopy positions of coffee plants in conventional (a, d, g), organic (b, e, h), and organic under shade (c, f, i) systems. The letters N, F, M and A refer to November, February, May and August, respectively. The models were independently fitted for each period using the dummy variable approach.

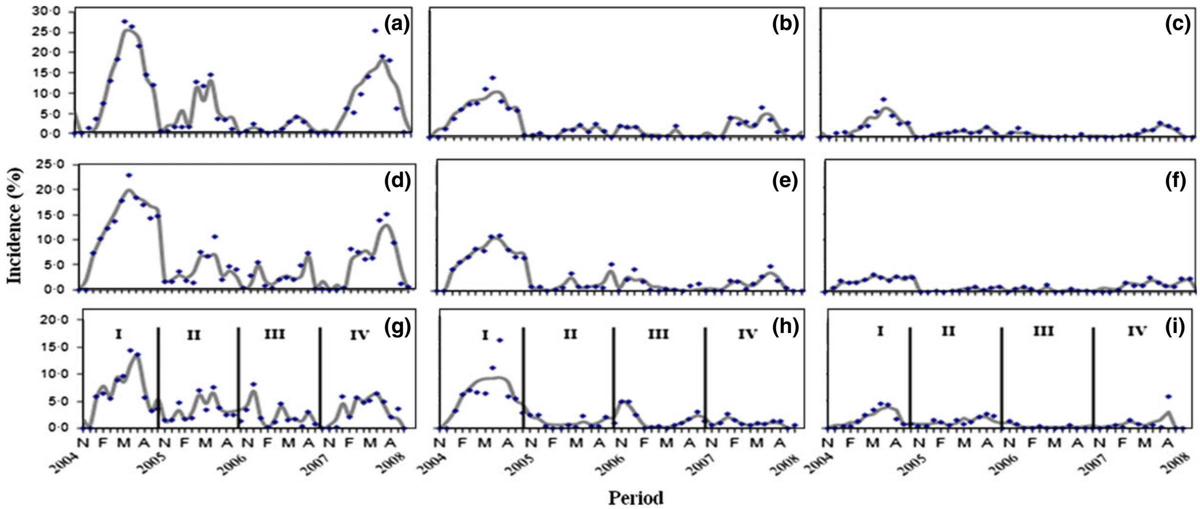

Figure 3 Incidence of brown eye spot observed (◆) and predicted by nonlinear models (——) during years I (2004/05), II (2005/06), III (2006/07) and IV (2007/08) for branches in the upper (a, b, c), middle (d, e, f), and lower (g, h, i) canopy positions of coffee plants in conventional (a, d, g), organic (b, e, h) and organic under shade (c, f, i) systems. The letters N, F, M and A refer to November, February, May and August, respectively. The models were independently fitted for each period using the dummy variable approach.

Table 1 Area under the progress curve for disease incidence (AUDPCI) and severity (AUDPCS) of brown eye spot in conventional (CS), organic (OS) and organic under shade (OSS) systems and branches of the upper (U), middle (M) and lower (L) canopy position (CP) of the coffee plants from 2004/05 to 2007/08 (years I to IV)

		AUDPCI			AUDPCS		
Year	CP	CS	OS	OSS	CS	OS	OSS
I[a]	U	140·06 Aa	71·73 Ba	32·75 Ba	24·76 Aa	10·16 Ba	4·05 Ba
	M	141·46 Aa	71·40 Ba	24·39 Ca	23·49 Aa	12·98 Ba	5·83 Ba
	L	75·19 Ab	67·67 Aa	19·59 Ba	11·18 Ab	7·26 Aa	1·95 Ba
II[b]	ns	45·57 A	12·44 B	10·15 B	4·45 A	1·43 B	1·20 B
III[b]	ns	22·65 A	12·31 B	3·99 C	2·15 A	1·39 A	0·46 B
IV[a]	U	104·44 Aa	27·77 Ba	13·32 Ba	15·94 Aa	2·78 Ba	1·80 Ba
	M	68·83 Ab	16·36 Ba	15·88 Ba	8·44 Ab	1·50 Ba	2·14 Ba
	L	41·19 Ab	11·43 Ba	10·30 Ba	3·98 Ac	1·35 Ba	0·90 Ba

[a]For years I and IV, the averages that are followed by the same uppercase letter in the row and lowercase letter in the column within the same year and variable (AUDPCI or AUDPCS) are not significantly different (Tukey's test, α = 0·05).

[b]For years II and III, the effects of the canopy position and the interaction canopy position–cropping system were not significant (ns). For each of these years and for each variable (AUDPCI or AUDPCS), the averages that are followed by the same uppercase letter in the line are not significantly different (Tukey's test, α = 0·05).

intervals were estimated (Figs 5 & 6). The confidence interval bars overlapped for the maximum SEV in all systems and canopy positions in year III, as well as in the lower and medium positions for year II. For the INC, the confidence interval bars overlapped in the medium position for years II and III and in the lower third for year IV (Figs 5c,f,g,j,k & 6f,g,l).

Discussion

Despite the significance of BES to coffee production, the basic aspects of this disease are still not well known. For instance, the pathogen penetration of coffee leaves has only recently been elucidated (Souza *et al.*, 2011). Information about the temporal dynamics of the disease is also lacking. To the authors' knowledge, no growth model has been produced to explain BES progress, either to study epidemics during just one season or, most importantly, over more than one season at the polyetic scale. In this pioneering study, a 4-year data set was gathered under Brazilian conditions to compare BES epidemics in conventional and organic (either shaded or unshaded) production systems using three approaches: AUDPC, components of the disease progress curve, and fitting time series models.

The progress of the disease was more intense in the CS than in either OS as shown by the higher values for the AUDPC, disease incidence, disease severity and disease peak in the CS. Taking into account the fact that the CS received more fungicide–nutrient treatments than the OS

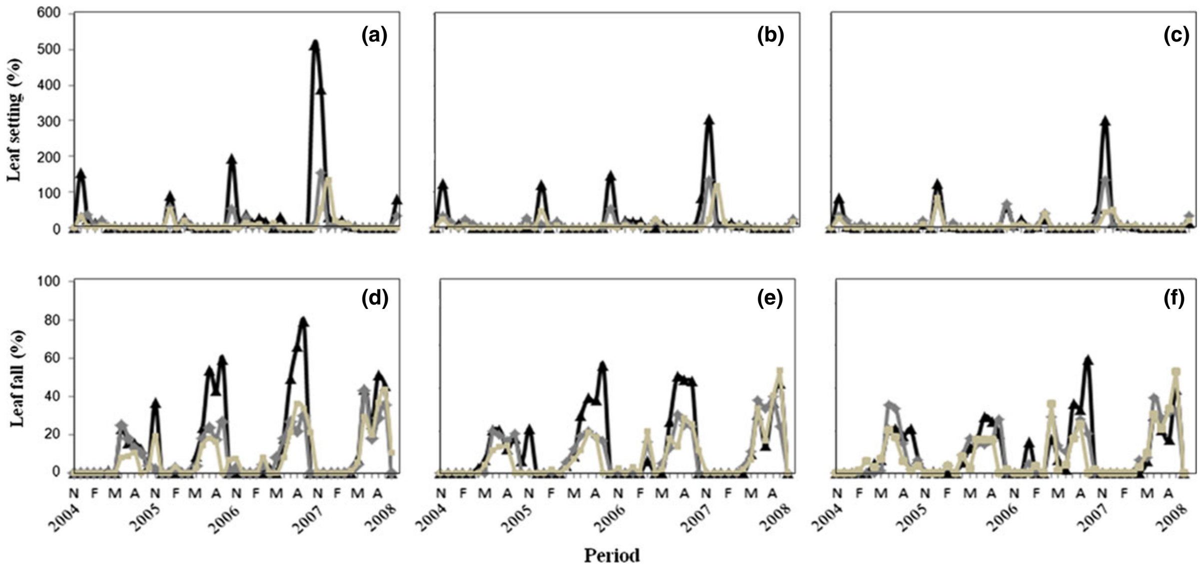

Figure 4 Percentage of leaf setting and leaf fall in coffee plants for branches in the upper (a, d), middle (b, e), and lower (c, f) canopy positions, in conventional (–▲–), organic (–◆–) and organic under shade (–■–) systems. The letters N, F, M, and A refer to November, February, May and August, respectively, between 2004 and 2008.

and OSS, a lower disease intensity would be expected in the CS system. Previous studies reported similar results (Samayoa & Sanchez, 2000; Santos *et al*., 2008), although there are other reports that disease intensity was higher in organic systems for Minas Gerais State (Martins *et al*., 2004) and Malawi (Phiri *et al*., 2001). It is hard to conclude which factors were responsible for high values of BES intensity in field cultivation but in the present study shade seemed to be more important for BES control than fungicide–nutrient treatment. A lower disease intensity could be expected under the CS as a result of intensive fungicide usage (Holb *et al*., 2009); however, the nutritional status of the OS was considered to be more balanced (Martins *et al*., 2004). The present study consisted of four production cycles, and the results showed that the intensity of BES was higher in the CS, despite plants being sprayed five times with the fungicide–nutrient formulation Calda Viçosa in the CS and only twice in the OS. It is probable that the two sprays in the OS were well timed and halted the disease without disturbing the system, particularly without affecting biota that were antagonistic to *C. coffeicola*. Furthermore, it is supposed that the unshaded conditions in CS were more favourable to *C. coffeicola* colonization than in the OSS, as discussed in more detail below. Another possible factor that may have led to high values of BES intensity in CS was the nutritional imbalance in the leaves that favours pathogen colonization (Pozza *et al*., 2000, 2001; Santos Botelho *et al*., 2005; Santos *et al*., 2008).

The disease intensity was also higher in the unshaded than in the shaded plants, most probably because of the higher solar radiation in the unshaded systems. Exposure to the sun has been reported to favour the occurrence of BES in coffee plants (Echandi, 1959; López-Duque & Fernández-Borrero, 1969; Lamouroux *et al*., 1995), which may be attributed to a greater water deficit and nutrition stress (Echandi, 1959; Salgado *et al*., 2007; Santos *et al*., 2008). Higher BES intensity occurred when there was a lack of rain and after fruit setting, most likely because the plants were more vulnerable to water and nutritional stresses (Santos *et al*., 2008). However, given that the shaded and unshaded plants were subjected to similar water regimens, other factor(s) may have also favoured the disease increase that was observed in the unshaded plants. As in other *Cercospora* spp., the *C. coffeicola* produces cercosporin, a photoactive toxin that is considered to be an aggressiveness factor (Souza *et al*., 2012). Thus, it is also possible that the highest disease intensity was found in treatments with more sun exposure in CS, OS, and the upper canopy because of the increased aggressiveness of *C. coffeicola* caused by higher cercosporin production.

The leaf setting and leaf fall were higher in the CS treatments. The maximum leaf setting occurred between October and January, and the minimum occurred between April and September. When the BES intensity was lower from November to December, the leaf setting was higher, which could be attributed to the low intensity of the disease in healthy new tissues, as well as the beginning of the rainy season and new cycles of infection. Rust caused by *Hemileia vastatrix* is also an important coffee disease that induces leaf fall. However, rust intensity remained low during the years of evaluation, especially in the CS (data not shown). Therefore, the higher BES intensity and leaf fall in the CS supports the role of BES in inducing coffee leaf fall (Phiri *et al*., 2001; Santos *et al*., 2008). In the present study, the greatest

Table 2 Parameters (*a*, *b* and *c*), ARMA (*p*;*q*) orders of the structures, and adjusted coefficients of determination (R^2) for non linear models of the progress of incidence and severity of brown eye spot on the branches of upper (U), middle (M) and lower (L) canopy positions of coffee plants in conventional (CS), organic (OS) and organic under shade (OSS) systems from 2004/05 to 2007/08 (years I to IV)

			Severity					Incidence				
			Parameters					Parameters				
Canopy position	Crop system	Year	*a*	*b*	*c*	ARMA (*p*;*q*)	R^2	*a*	*b*	*c*	ARMA (*p*;*q*)	R^2
U	CS	I	0·51	3·85	0·72	1;1	0·97	12·09	13·33	2·08	2;2	0·95
		II	0·29	0·80	1·60	1;1	0·55	4·15	4·37	1·59	1;1	0·82
		III	0·04	0·13	0·94	1;1	0·79	0·66	1·10	1·00	2;1	0·88
		IV	1·51	1·69	2·04	1;1	0·85	5·49	22·17	0·98	1;1	0·75
	OS	I	0·71	2·17	0·81	1;1	0·80	3·70	13·30	0·71	1;1	0·86
		II	0·14	0·19	2·81	1;1	0·82	1·14	1·06	2·02	2;1	0·93
		III	0·10	0·12	3·02	1;1	0·48	1·85	1·76	0·90	1;1	0·83
		IV	0·22	0·13	5·03	2;2	0·49	2·60	3·08	5·01	1;1	0·77
	OSS	I	0·09	0·62	0·66	1;1	0·86	2·80	3·19	1·98	1;1	0·80
		II	0·10	0·13	1·55	2;2	0·89	0·08	1·49	0·88	2;2	0·95
		III	0·05	0·02	4·74	1;1	0·59	0·73	0·74	1·30	1;1	0·52
		IV	0·18	0·19	2·92	1;1	0·79	1·38	2·03	2·65	1;1	0·95
M	CS	I	0·32	3·36	0·77	1;1	0·96	5·46	25·44	0·64	1;1	0·95
		II	0·44	0·52	1·58	3;3	0·79	2·83	1·08	1·43	1;1	0·77
		III	0·23	0·28	1·00	2;1	0·55	0·76	2·35	0·99	1;1	0·73
		IV	1·44	1·48	2·06	2;1	0·86	5·77	4·82	2·10	1;1	0·83
	OS	I	0·75	2·53	0·78	1;1	0·85	2·73	11·90	0·72	2;1	0·97
		II	0·16	0·12	2·89	1;1	0·66	1·09	0·57	1·09	1;1	0·83
		III	0·16	0·13	1·27	1;1	0·46	2·12	−1·98	0·91	1;1	0·54
		IV	0·13	0·17	2·44	2;2	0·91	0·81	0·60	5·12	2;2	0·80
	OSS	I	0·08	0·59	0·66	1;1	0·95	0·44	3·29	0·67	1;1	0·91
		II	0·07	0·09	1·38	2;2	0·66	0·37	0·37	1·34	2;2	0·83
		III	0·11	0·06	0·50	2;1	0·90	0·96	−0·40	2·24	1;1	0·49
		IV	0·18	0·17	2·42	1;1	0·85	0·58	1·61	2·27	2;2	0·84
L	CS	I	0·16	1·71	0·90	1;1	0·95	0·58	10·33	0·84	1;1	0·92
		II	0·77	0·62	1·36	1;1	0·63	3·00	2·12	1·58	1;1	0·78
		III	0·36	0·46	0·45	1;1	0·59	1·87	2·73	0·79	2;2	0·92
		IV	0·38	0·34	2·40	1;1	0·84	2·56	2·06	2·40	2;1	0·84
	OS	I	0·14	1·20	0·96	1;1	0·93	4·52	13·80	0·79	1;1	0·65
		II	0·15	−0·10	1·62	1;1	0·61	1·62	−0·78	1·58	1;1	0·54
		III	0·38	0·02	0·42	1;2	0·70	3·91	3·20	0·92	1;1	0·95
		IV	0·11	0·02	2·48	1;1	0·83	1·30	0·73	2·50	2;1	0·78
	OSS	I	0·07	0·35	0·84	1;1	0·84	0·46	3·15	0·83	1;1	0·81
		II	0·20	0·11	1·17	2;2	0·64	1·21	0·50	1·35	2;2	0·50
		III	0·14	−0·05	1·04	1;1	0·59	1·45	−0·58	1·04	1;1	0·63
		IV	0·08	0·08	2·44	1;1	0·72	1·29	1·49	0·15	1;1	0·63

leaf fall occurred between June and September, following a period of high BES intensity from May to July. Other authors have also reported maximum BES incidence during similar periods (Talamini *et al.*, 2003), which coincide with the dry season. However, in the present investigation it was observed that in some year–crop system–plant canopy combinations, the maximum disease intensity occurred earlier, as observed in coffee plants that were intercropped with *Inga vera* trees (Salgado *et al.*, 2007). Therefore, local rainfall, temperature and nutritional characteristics may also have contributed to the disease intensity.

The BES dynamics varied during all 4 years of the evaluation, regardless of the cropping system, although they were similar during the first 2 years. The biennial cycle of coffee plant production (Santos *et al.*, 2008) may be related to this observation. Because of the polyetic nature of BES, it is not possible to employ the growth models that are routinely used to describe plant disease epidemics. As reported elsewhere (Yang & Zeng, 1992; Hudelson *et al.*, 1993; Xu *et al.*, 1995; Guerin *et al.*, 2001; Holb, 2008), the ARMA models efficiently fit the progress of plant diseases. For the first time, a time series approach was used to model the progress of BES in coffee. Under this approach, a nonlinear sinusoidal model assuming ARMA residuals was fitted to INC and SEV trajectories over time. This same model was also fitted without ARMA residuals modelling, i.e. considering independent residuals, but the convergence was not verified. It occurred because the periodic oscillations of INC and SEV over the months did not support the assumption of residuals independence. Once using ARMA

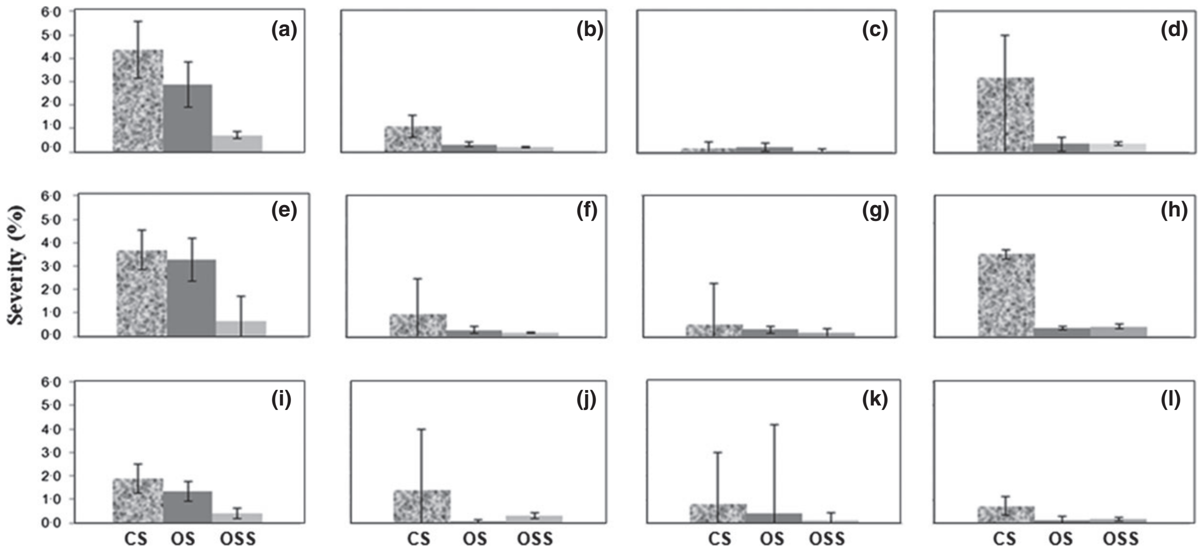

Figure 5 Estimates of maximum severity (sum of the estimates of the parameters *a* and *b*, as in Figure 1) for years I (2004/05 (a, e, i)), II (2005/06 (b, f, j)), III (2006/07 (c, g, k)) and IV (2007/08 (d, h, l)) in conventional (CS), organic (OS), and organic under shade (OSS) systems for branches in the upper (a, b, c, d), middle (e, f, g, h), and lower (i, j, k, l) canopy positions of coffee plants. Estimates with asymptotic limits with overlapping 95% confidence intervals within the same graph are not significantly different.

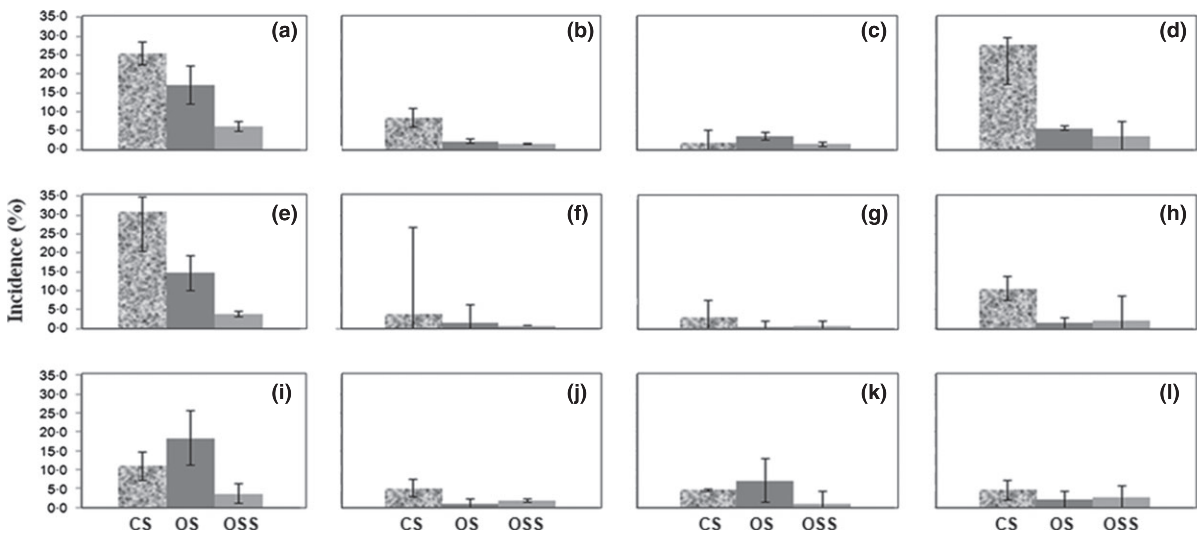

Figure 6 Estimates of maximum incidence (sum of the estimates for parameters *a* and *b*, as in Figure 1) for years I, 2004/05 (a, e, i), II, 2005/06 (b, f, j), III, 2006/07 (c, g, k), and IV, 2007/08 (d, h, l) in the evaluation of conventional (CS), organic (OS), and organic under shade (OSS) systems, for branches in the upper (a, b, c, d), middle (e, f, g, h), and lower (i, j, k, l) canopy positions of coffee plants. Estimates with asymptotic limits with overlapping 95% confidence intervals within the same graph are not significantly different.

modelling of residuals, it was necessary to identify the best ARMA structure, which was assessed by the coefficient of determination. The best fit was achieved by the time series model, most probably because the errors associated with this model are not independent. The intensity at any given time depended on the intensity at a previous time because the disease was always assessed on the same branches. The results were obtained by interpreting the graphs of predicted incidence and predicted severity, which were similar to the results that were obtained by descriptive analysis. In addition, the parameters that were generated by the time series model can be used towards a practical interpretation of an event (Box *et al.*, 1994). In the present study, the parameters *a* and *b* are those with more relevance under an epidemiological approach, because the maximum INC and SEV estimations are defined as a direct function of these parameters (Fig. 1). Thus, once the maximum values had been estimated, there was interest in comparing them between different treatments (combination of system–canopy levels).

Despite the apparent suitability of time series models for describing BES progress in coffee plants, these models have not been widely used to describe the temporal and spatial dynamics of plant diseases. To the best of the authors' knowledge, this is the first time that a time series model has been used to describe the temporal dynamics of a plant disease in Brazil. The efficiency of using time series models to describe disease dynamics is partly determined by the correct selection of the model and the structure of the order of errors (Box *et al.*, 1994). When time is included in series models to describe plant disease events, different models and orders of error structures are adopted, such as the AR (autoregressive), MA (moving averages), ARMA (autoregressive moving averages), and ARIMA (autoregressive integrated moving averages), according to the objective and the pathogen under study (Yang & Zeng, 1992; Hudelson *et al.*, 1993; Xu *et al.*, 1995; Guerin *et al.*, 2001; Holb, 2008). An advantage of using time series models is that they can be used to perform repeated evaluations in the same individual (plant or plant part) and that these evaluations are usually undertaken at different time intervals in polyetic experiments. Moreover, the time series model generated a parameter that was related to the maximum disease, which can be used for comparative purposes. It is expected that these models will soon be used to describe long-term disease dynamics, mostly in perennial crops.

In this investigation, BES epidemics in coffee plants have been comparatively analysed under conventional and organic crop systems. The approach used has facilitated an understanding of the dynamics of BES and the definition of cultural practices for lowering the disease intensity. These results are important for expanding the knowledge of disease epidemiology. Furthermore the use of time series analysis to describe BES dynamics was an innovative approach that is expected to be used more frequently in studies involving stochastic events in plant pathology. Further research is required to determine how environmental factors affect epidemic dynamics. In summary, it was found that coffee cropping systems do affect the progress of BES, that shade can be used in the field to assist BES management, and that the cultivation of coffee plants intercropped with banana plants between the rows is a good strategy to control BES. Together with knowledge about the effects of environmental and control strategies, this information may be used in defining the integrated management of BES on coffee plants in the context of crop management. However, to establish a suitable crop management strategy, additional knowledge about other diseases is also required. The most significant coffee diseases in Brazil are BES and leaf rust. An analysis of the temporal dynamics of rust is underway and it appears that both diseases behave differently in shaded and unshaded coffee plants, as previously noted (López-Bravo *et al.*, 2012). However, the same authors mention that it is possible to find higher rust intensity under full sun exposure. These contradictory reports are common because of differences in the environment, plant materials, evaluation criteria, and study duration. Therefore, more studies are required to determine the difference among coffee cropping systems with regard to the intensity of both diseases and for establishing rational management practices.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web-site.

Table S1 ANOVA results of brown eye spot incidence and severity evaluated monthly in three cropping systems from November 2004 to October 2008 as generated by the PROC MIXED procedure in SAS v. 9.1