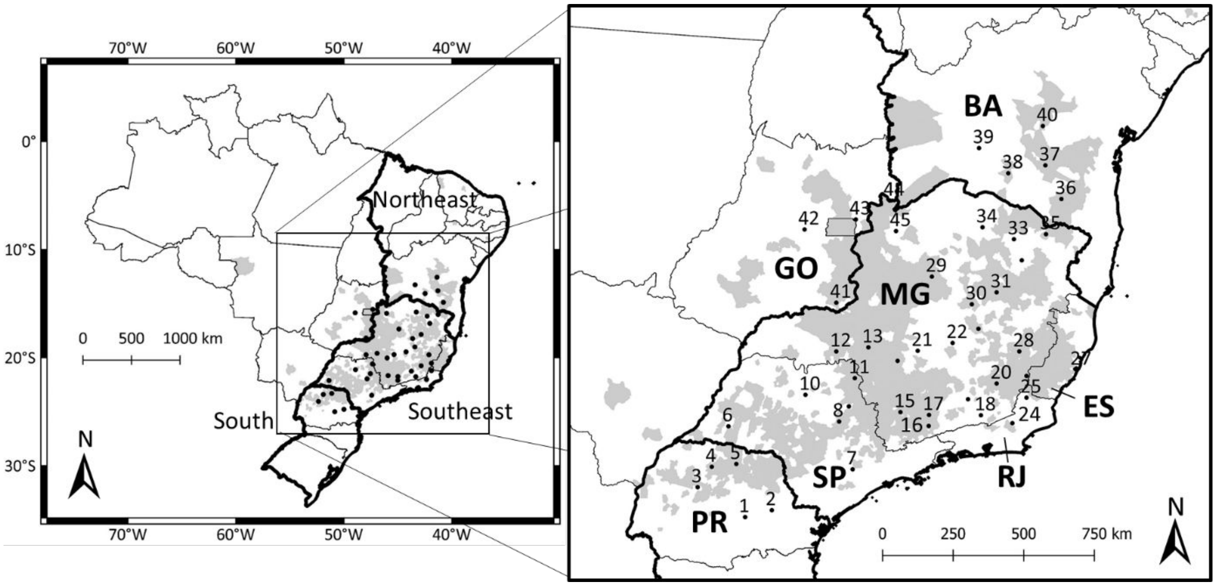

Fig. 1. Arabica coffee producing municipalities in Brazil (shaded) with the sites (dots) used in this study for coffee leaf rust infection rate estimation. The states' abbreviations are: PR = Paraná, SP = São Paulo, RJ = Rio de Janeiro, ES = Espírito Santo, MG = Minas Gerais, GO = Goiás, and BA = Bahia.

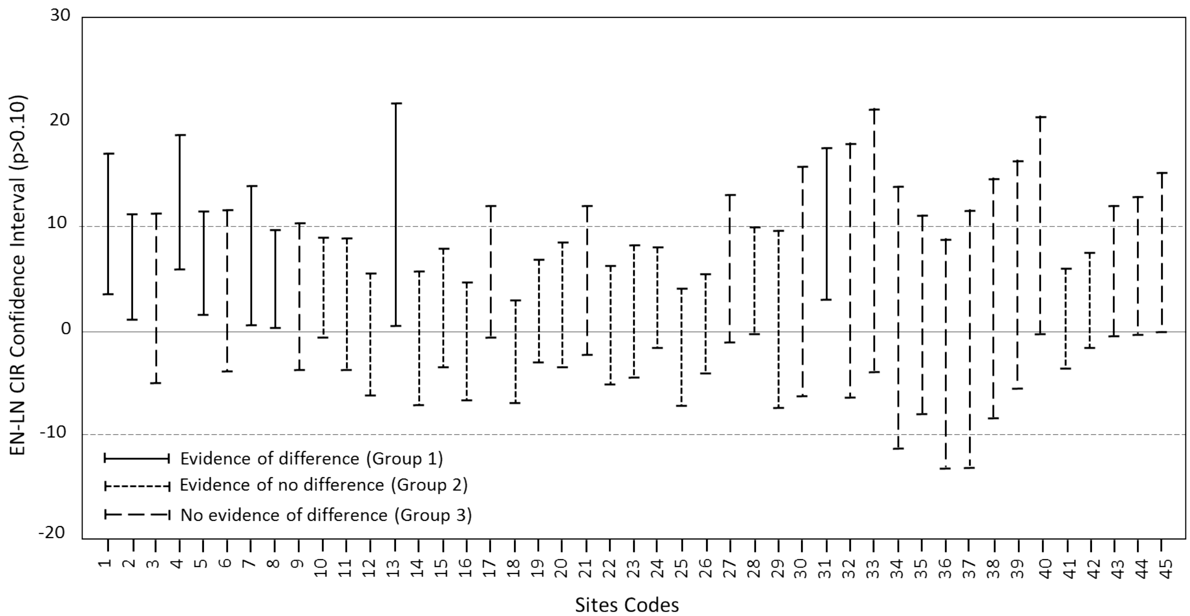

Fig. 2. Confidence interval bars of El Niño - La Niña impact on coffee leaf rust cumulative infection rates at 45 sites in the Brazilian coffee-producing regions. Bars completely above the 0 line represent evidence of difference between EN and LN for the site (solid line); Bars completely inside the -10 and 10 bounds represent evidence of no difference between EN-LN seasons for the site (dotted line); Bars crossing the -10 or 10 bounds indicate no evidence of difference for EN-LN for the site (dashed line).

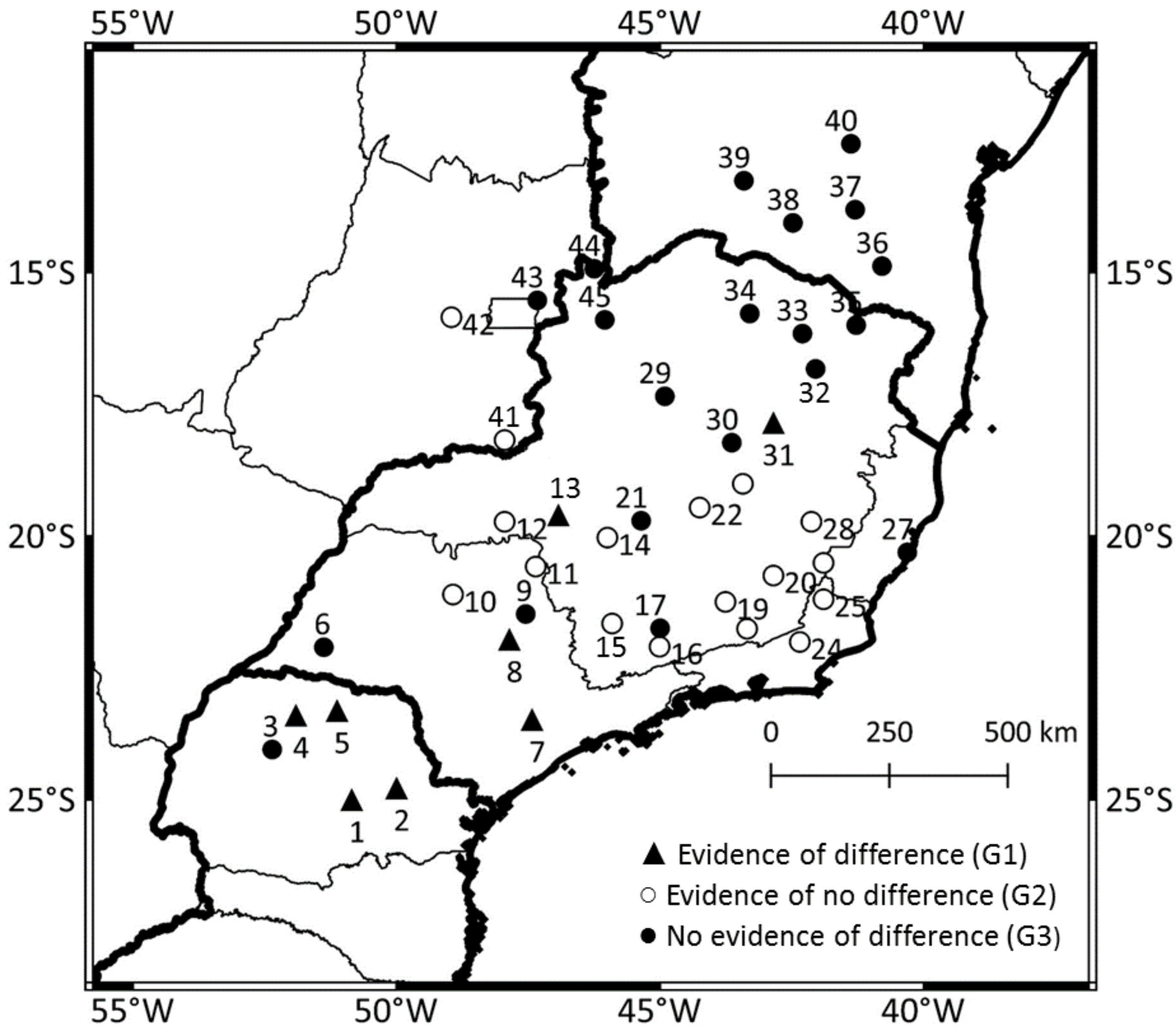

Fig. 3. Spatial distribution of El Niño Southern Oscillation (ENSO) effects on coffee leaf rust cumulative infection rate in Brazilian coffee production regions. Sites with evidence of difference (Group 1 ▲, G1); sites with evidence of no difference (Group 2, ○, G2); and sites with no evidence of difference (Group 3 ●, G3).

Supplementary Material

The Brazilian weather data used in this study are from conventional weather station measurements that have been made since the 1960s, since data from automatic weather station are available only from 2000s. During the period from the 1960s to the 2000s, trained personnel obtained daily measurements three times per day (9 am, 3 pm and 9 pm). These personal measurements may sometimes be of higher accuracy that measurements from automated weather stations that are visited less frequently. However, the datasets acquired by on-site personnel sometimes show missing data on days when holidays occurred or no personnel were available.

Xavier et al. (2015) tested several interpolation methods for each weather variable in order to achieve a large data set without missing data, allowing for studies such as the present one. These data were used to fill in the missing data in several sites, with different amount of percentage filled as shown in Table S1. These methods were assumed to be the best options to fill in missing data. Tables S2, S3 and Fig. S1 presents the quantitative performance of the coffee leaf rust infection model used in the presented study. Table S4 presents a qualitative analysis.

Table S1. Comparison among original and final data set of weather data for each site. The data used for filling were obtained from Xavier et al. 2015 gridded data.

		Original dataset		Final dataset		Percentage filled with gridded data*	
Site	Code	Tmin	RH	Tmin	RH	%Tmin	%RH
Ivaí	1	13315	12237	15924	15906	16.38	23.07
Castro	2	16881	17080	19257	19251	12.34	11.28
Campo Mourão	3	17327	17290	17918	17863	3.30	3.21
Maringá	4	13526	13496	16138	15906	16.38	23.07
Londrina	5	17341	12237	15924	15906	12.93	21.03
Presidente Prudente	6	14035	14149	16814	16808	16.53	15.82
Sorocaba	7	11222	11185	14382	14331	21.97	21.95
São Carlos	8	17677	17274	19001	18966	6.97	8.92
São Simão	9	17185	17469	19679	19663	12.67	11.16
Catanduva	10	15673	15295	17983	17955	12.85	14.81
Franca	11	18849	18942	18962	18949	0.60	0.04
Uberaba	12	14100	13984	16793	16734	16.04	16.43
Araxá	13	14813	14846	15884	15965	6.74	7.01
Bambuí	14	14269	14170	16623	15728	14.16	9.91
Machado	15	17124	17094	19417	19395	11.81	11.86
São Lourenço	16	17824	17272	19910	19828	10.48	12.89
Lavras	17	17301	17147	19436	19348	10.98	11.38
Juiz de Fora	18	16397	16290	18693	18652	12.28	12.66
Barbacena	19	17884	17843	20099	20075	11.02	11.12
Viçosa	20	14622	15595	17661	17654	17.21	17.33
Bom Despacho	21	11766	11796	12964	12965	9.24	9.02

Sete Lagoas	22	16785	16785	20069	19976	16.36	15.97
Conceição do Mato Dentro	23	17471	16823	19526	19458	10.52	13.54
Cordeiro	24	15332	9822	15822	14939	3.10	34.25
Itaperuna	25	13843	14236	16963	17012	18.39	16.32
Caparaó	26	11447	10977	15623	15464	26.73	29.02
Vitória	27	16051	15194	19488	19408	17.64	21.71
Caratinga	28	15819	15761	18113	18191	12.66	13.36
Pirapora	29	15647	15426	17011	16825	8.02	8.32
Diamantina	30	13940	13846	16481	16367	15.42	15.40
Itamarandiba	31	16270	16143	18951	18836	14.15	14.30
Araçuaí	32	17910	18207	18966	19119	5.57	4.77
Salinas	33	13826	13474	15438	15190	10.44	11.30
Janaúba	34	11111	10749	14058	13715	20.96	21.63
Pedra Azul	35	13850	13562	16001	15743	13.44	13.85
Vitória da Conquista	36	10008	11411	14709	14719	31.96	22.47
Ituaçu	37	8365	7975	14302	14273	41.51	44.13
Caetité	38	15612	16008	19216	19373	18.76	17.37
Bom Jesus da Lapa	39	13126	13146	16191	16218	18.93	18.94
Lençois	40	13346	14588	18586	18590	28.19	21.53
Catalão	41	18952	18969	19947	19953	4.99	4.93
Pirenópolis	42	13499	13544	13781	13780	2.05	1.71
Formosa	43	15381	16632	16650	16667	7.62	0.21
Formoso	44	10101	11091	13368	13879	24.44	20.09
Arinos	45	11595	12595	13790	14197	15.92	11.28
Maximum		18952	18969	20099	20075	41.51	44.13
Minimum		8365	7975	12964	12965	0.60	0.04
Average		14853	14714	17255	17199	14.23	14.75

* Percental based on the number of available data in the final data set.

Table S2. Errors and coefficient of determination for the validation of the models for coffee leaf rust infection rate estimation, for different field conditions. This table is the same as Table 4 of Hinnah et al. (2018), in which the models used in the present study were assessed.

Field condition	RMSE (pp)	MBE (pp)	MAE (pp)	R^2
HN	13.40	0.08	8.40	0.810
LN	14.50	9.50	10.90	0.729
HW	12.40	-1.40	8.90	0.820
LW	14.45	2.07	8.32	0.828

Table S3. Errors and coefficient of determination for validation of the best performance model (HN) for coffee leaf rust infection rate estimation, under the two possible field conditions: High = high fruit load and Low = low fruit load. This table is the same as Table 6 of Hinnah et al. (2018), in which the models used in the present study were assessed.

Field condition	RMSE (pp)	MBE (pp)	MAE (pp)	R^2
High	12.70	0.30	8.60	0.839
Low	14.20	5.30	9.50	0.785

Table S4. Contingency table of the HN model for coffee rust infection rate estimation under two fruit load conditions: High = high fruit load and Low = low fruit load. This table is the same as Table 7 of Hinnah et al. (2018), in which the models used in the present study were assessed.

Fruit load conditions	Threshold	
	5 pp (%)	10 pp (%)
High (n = 107 months)		
True negative	27.10	39.25
False positive	19.63	21.50
True positive	46.73	29.91
False negative	6.54	9.35
Precision	70.42	58.18
Recall	87.72	76.19
F-measure	78.13	65.98
Low (n = 107)		
True negative	26.17	42.06
False positive	38.32	35.51
True positive	29.91	17.76
False negative	5.61	4.67
Precision	43.84	33.33
Recall	84.21	79.17
F-measure	57.66	46.91

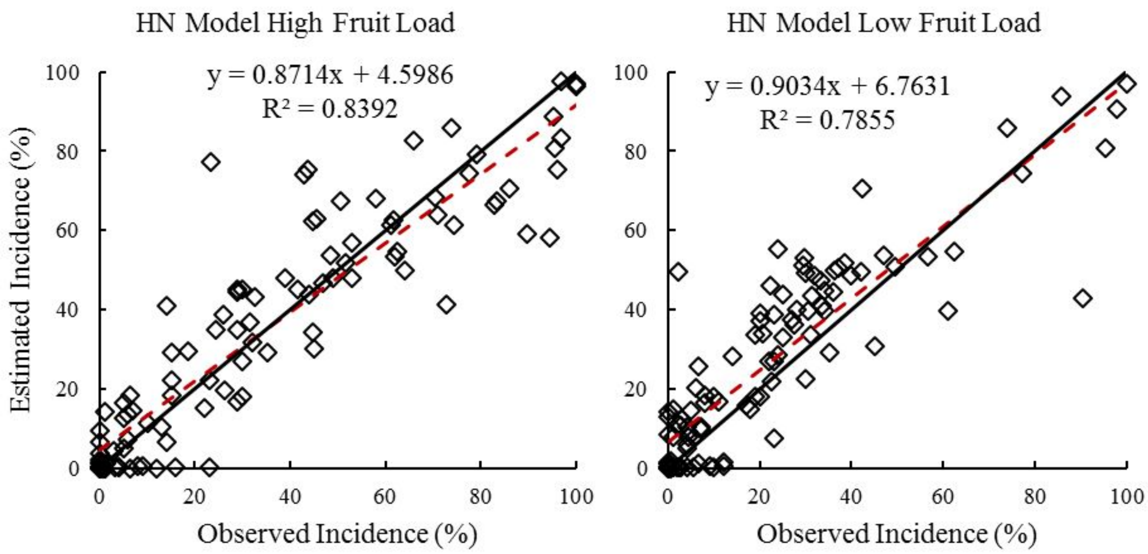

Fig. S1. Performance of HN model on two possible fruit load conditions, due to yield alternancy. High = high fruit load; Low = low fruit load field conditions. Trend line (red dashed line) and 1:1 (straight line). This Figure is the same as Figure 3 of Hinnah et al. (2018), in which the models used in the present study were assessed.

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Assessing Biogeography of Coffee Rust Risk in Brazil as Affected by the El Niño Southern Oscillation

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ABSTRACT

The El Niño Southern Oscillation (ENSO) is an oceanic-atmospheric phenomenon influencing worldwide weather and climate. Its occurrence is determined by the sea surface temperature (SST) anomaly of the 3.4 Niño region in the Pacific Ocean (5°N-5°S, 120°-170°W). El Niño (EN), Neutral (NT), and La Niña (LN) are the three possible phases of ENSO, respectively for warm, normal, and cold SST anomaly. As in other regions around the world, weather in Brazil is influenced by ENSO phases. The country is the major coffee producer in the world and production is strongly influenced by weather conditions, which affect plant yield, harvest quality, and interactions with pests and diseases. Coffee leaf rust (CLR), caused by the fungus *Hemileia vastatrix*, is a major cause of coffee yield and quality losses in Brazil, and requires fungicide spray applications every season. Because CLR is highly influenced by weather conditions, it is possible to use weather variables to simulate its progress during the cropping cycle. Therefore, the aims of this study were to estimate CLR infection rate based on a validated empirical model, which has daily minimum air temperature and relative humidity as inputs, and to assess the extent of ENSO influence on the annual risk of this disease at 45 sites in Brazil. Cumulative infection rates (CIR) were estimated daily from October to June of each growing season and location, based on the prevailing ENSO phase. Differences between the extreme phases (EN-LN), were assessed by the Two-One-Sided-Tests (TOST) method. Analysis of data from eight sites, located mainly in Paraná state, provided evidence of CIR differences between EN and LN phases (G1). Evidence of no difference of CIR between EN and LN was found in 18 sites (G2), whereas 19 sites showed no evidence of differences (G3), due to relatively large variation of CIR within the same ENSO phase. The G1 sites are located mostly in Southern Brazil, where ENSO exerts a well-defined influence on rainfall regime. In contrast, the G2 sites are mainly in Minas Gerais state, which is characterized as a transition region for ENSO influence on rainfall. The G3 sites are located between the northern region of Minas Gerais state and southern region of Bahia state, which is characterized by a sub-humid climate that is usually very dry during winter, and where rainfall can vary up to 300% from one year to another, influencing relative humidity and resulting in a high CIR variability. Therefore, ENSO had a well-defined influence on CIR only in Paraná state, a region with minor importance for coffee production in Brazil. No ENSO influence was found in more northerly zones where the majority of Brazilian coffee is produced. This is the first evidence of ENSO-linked regional impact on the risk of coffee rust.

Keywords: *Hemileia vastatrix*; Infection rate; ENSO; Temperature; Relative humidity.

The El Niño Southern Oscillation (ENSO) is a large-scale oceanic-atmospheric phenomenon which modifies regional and global air circulation, impacting rainfall and air temperatures regimes around the world (Fraisse et al. 2008; Nam and Baigorria 2015). The phenomenon is characterized by warming or cooling of the Pacific Ocean surface beyond the normal average. In turn, this warming affects air pressure in the equatorial portion of the Pacific; this is called the atmospheric effect. The atmospheric effect promotes weakening of trade winds in the warm phase and their intensification in the cold phase, with resulting modifications in global circulation patterns (McPhaden et al. 2006). It is the largest oceanic-atmospheric circulation phenomenon, impacting seasonal weather patterns and interannual variability in several regions around the world, and, consequently, agriculture and the relationship of crops with pests and diseases (Berlato and Fontana 2003; Gergis and Fowler 2009; Schuirmann et al. 2006; McPhaden et al. 2006).

Three possible ENSO phases are classified as a function of the average Pacific Ocean sea surface temperature (SST) anomaly (NOAA 2017): El Niño (SST anomaly ≥ 0.5°C); La Niña (SST anomaly ≤ -0.5°C); and Neutral (SST between -0.5 and +0.5°C). These phenomena occur from July of a given year to June of the next year, with the peak occurring around December. In

Brazil, El Niño (EN) normally causes above-average rainfall in Rio Grande do Sul, Santa Catarina and Paraná states (South region), which impacts agriculture, resulting in maximum grain yields (Alberto et al. 2006; Berlato et al. 2005) and higher risk for occurrence of certain diseases (Del Ponte et al. 2011). In Northeast Brazil, EN causes below-average rainfall, resulting in agricultural droughts (Costa et al. 2015). In the Southeast region, where most of the coffee is grown, there is no defined pattern for rainfall, but there is a trend of higher temperatures, mainly at night (INPE 2016; Marengo and Camargo 2008).

La Niña (LN) normally affects parts of Brazil in opposite ways compared to EN. For example, rainfall and temperatures in Southern Brazil are reduced, since colder and drier air masses can reach the region more frequently. On the other hand, in North and Northeast regions of the country, rainfall is more widely distributed, resulting in relatively favorable conditions for agriculture. In the Southeast region of the country, a transitional condition is again observed, with no defined weather patterns. In the Neutral phase (NT) periods, weather conditions in the different regions of Brazil tend to be within the normal range of variability. ENSO warm or cold phases tend to occur every 2 to 7 years and can persist for two or more consecutive years, and each rarely fails to re-occur within 10 years (McPhaden et al. 2006).

Considering the influence of ENSO as the largest weather phenomenon worldwide, with different episodes every season and strong impacts on crop yields and disease risk, it is important to understand how the different phases impact agriculture in Brazil. In this context, ENSO’s impact on plant diseases is important since it will help to define the most effective management strategies (Del Ponte et al. 2011; Nam and Baigorria 2015).

Coffee ranks as the fourth most valuable crop in Brazil, with a gross product around US$ 6.57 billion and a planted area around 2 million ha (IBGE 2017). Brazil produced around 55 million 60-kg bags in 2016 (ICO 2017), more than twice the total production of the second largest producer, Vietnam. Coffee leaf rust (CLR) is the most economically damaging coffee disease worldwide (McCook 2006). This disease, caused by the fungus *Hemileia vastatrix*, is responsible for up to 35% of disease-related losses where the weather conditions are favorable to the pathogen (Zambolim et al. 1997), mainly on Arabica coffee (*Coffea arabica*), which is more susceptible than Robusta coffee (*C. robusta*).

In Brazil the first symptoms of CLR usually appear in December (Meira et al. 2008) and epidemic severity varies according to fruit load, weather, and crop management (Avelino et al. 2006). The incubation period ranges from 28 to 65 days (de Moraes et al. 1976). Although the first symptoms appear in December, the CLR-infection-favorable period of the crop starts in October.

Because foliar diseases are highly influenced by weather conditions, management decision tools that use weather inputs can help to rationalize and optimize disease control as well as to increase spray efficiency (Avelino et al. 2006). The assessment of disease risk on a seasonal and regional basis via models can also help growers and other stakeholders to mitigate deleterious impacts of climate change (Ghini et al. 2011; Salinari et al. 2006), while studies focused on year-to-year climate variability can help growers to prepare for changes in the crop risk environment over longer time scales. For CLR, several disease risk assessment models have been developed (Kushalappa et al. 1983; Meira et al. 2008) to be applied at field scale for forecasts within the growing season. Even with these initiatives, application of decision support systems for disease risk forecasts is limited since they require extensive field validation under a wide range of weather conditions.

CLR epidemics happen frequently in Brazil because the prevalent coffee varieties are susceptible, the weather is often favorable, and pathogen inoculum is abundant in all producing regions (Ghini et al. 2011; Meira et al. 2008; Zambolim et al. 1997). Gaining a better understanding of the impact of ENSO phases on CLR risk is of great importance for achieving more effective and cost-efficient disease control. The influence of this phenomenon on the risk of soybean rust epidemics in Rio Grande do Sul (Brazil's southernmost state) was noted by Del Ponte et al. (2011). A different approach, based on a method called confidence intervals, is proposed here due to the inappropriateness of statistical tests in which the null hypothesis assumes that two means are equal (Ranganathan et al. 2015; Schuirmann et al. 2006). The hypothesis of this study is that ENSO events exert differential impacts on the risk of CLR epidemics in coffee-producing regions of Brazil. Therefore, the objective of this study was to estimate CLR incidence for different locations in the coffee- producing regions and growing seasons of Brazil, and to determine whether the CLR epidemics are ENSO-related.

Material and Methods

Weather Data. Weather data from 45 coffee-producing municipalities in seven states of Brazil were obtained from conventional weather stations of the National Institute of Meteorology (INMET) for the period 1 July 1961 to 31 August 2015 (Fig. 1). The data included daily mean relative humidity and minimum air temperature. The mean relative humidity is the average of three daily measurements, at 9 am, 3 pm and 9 pm, and the minimum air temperature is the lowest value observed for a given day. Measurements were made at 2-m height by instruments that were housed in weather station shelters, with a Vaisala calibrated Temperature-Relative humidity probe, model HMP-110.

Missing weather data from the assessed series were filled in with gridded data from the data base of Xavier et al. (2015), which has data for a grid of 0.25° * 0.25°. The data used for filling in gaps were extracted from a raster file. This procedure was applied to keep the weather data series as complete as possible. A comparison among the original and final data sets is shown at Supplementary Table S1.

Disease estimation model. A model for CLR infection rate estimation, developed with CLR progress curves from a total of 88 site-seasons in the main Brazilian coffee production region (Hinnah et al. 2018), was used to estimate daily CLR infection rate (r_{HN}), considering the highest-risk condition for the crop, which is with high fruit load and narrow row spacing (equation 1):

$$r_{HN} = -1.293 + 0.019\ Tmin_{(30\text{-}60d)} + 0.017\ RH_{(30\text{-}60d)} \qquad \text{(Equation 1)}$$

where: Tmin and RH are, respectively, the averages of daily minimum air temperature and mean relative humidity for 30 to 60 days before the estimation date (30-60d). This model presented a coefficient of correlation between observed and estimated infection rates of 0.516, and was significant at $P<0.01$. The quantitative and qualitative validation of this model with an independent dataset showed that the percentage of hits was 73.83%, for an infection rate limit of 5%, which can be considered sufficiently high for predicting risks of the complex CLR pathosystem. The performance of this model is presented in Hinnah et al. (2018) and these results are presented in Tables S1, S2, S3 and Figure S1 in the Supplementary material. The CLR infection rate (r_{HN}) was estimated every season from 1 October of a given year (designated as year 1) until 30 June of the subsequent year (year 2), encompassing the entire CLR-favorable period during the production of a single coffee crop.

Estimated daily infection rates were summed for each coffee growing season; this sum was termed the coffee leaf rust cumulative infection rate (CIR), which was used to identify the risk of CLR for each growing season. CIR should be considered as an index for disease risk assessment and not necessarily how much the disease is predicted to increase from the beginning to the end of the coffee production cycle.

El Niño Southern Oscillation. For defining ENSO phases, U.S. National Oceanic and Atmospheric Association (NOAA) temperature thresholds were used. When Pacific Ocean surface temperature in the Niño 3.4 region (5°N-5°S, 120°-170°W) was ≥ +0.5 °C above normal or ≤ -0.5 °C below normal for 5 consecutive 3-month running averages, El Niño (EN) or La Niña (LN), respectively, were considered to be established (NOAA 2017). The Niño 3.4 region is the most closely observed portion of the Pacific Ocean for detecting temperature changes associated with ENSO (Lyon and Barnston 2005; McPhaden et al. 2006). When five consecutive 3-month running averages were between +0.5 °C and -0.5 °C, the Neutral (NT) condition was assumed to be established.

Classification of years from 1962 to 2015 in relation to ENSO phases is presented in Table 1. As ENSO conditions start at the beginning of the second half of year 1 and finish at the middle of year 2 (Berlato and Fontana 2003), the weather consequences of ENSO conditions normally affect coffee yield during year 2 (e.g., the 2008 La Niña event in Table 1 started in the second half of 2007).

Data Analysis. Differences in CIR among growing seasons at each site during EN and LN conditions were evaluated by the Two-One-Sided-Tests (TOST) method (Schuirmann 1987), which was used to test the null hypothesis of non-equivalence. An equivalence test requires a priori specification of equivalence bounds that separate differences that are considered negligible from those that are considered large. For example, if differences in mean CIR between -10 and 10 were considered small but differences >10 or <-10 were considered large, the equivalence bounds could be set as -10 and 10. The TOST method is equivalent to constructing a (100-2α)% confidence interval for the mean difference and rejecting the null hypothesis at level α when that confidence interval falls completely inside the equivalence bounds. For example, a 90% confidence interval of (-1, 8) is completely inside equivalence bounds of (-10, 10), so its p-value is < 0.05. However, a 90% confidence interval of (-5, 11) is not completely inside (-10, 10), so the p-value is > 0.05. In other words, we can consider a figure whose upper and lower bounds are -10 and 10. When the bars that represent the locations are completely above the 0 line, it represents evidence of difference between EN and LN for a given site. When the bars are completely inside the -10 and 10 bounds it represents evidence of no difference between EN-LN. Finally, when the bars cross the -10 or 10 bounds it indicates no evidence of difference for EN-LN for the given site.

We proposed a novel statistical approach to assess these data. The usual test, with the null hypothesis that two means are equal, is not appropriate (Dixon and Pechmann 2005; Ranganathan et al. 2015). A large p-value, e.g. 0.4, could be from a small difference that is precisely known or a very large difference that is poorly known. The first p-value supports the conclusion of a negligible effect whereas the second does not. Equivalence tests as used here reverse the usual null and alternative hypotheses (McBride 2005; Wellek 2010). The equivalence null hypothesis is that two groups are not equivalent, i.e. that the difference between two groups is large. This is rejected, i.e. the associated p-value is sufficiently small, when the estimated difference is sufficiently precise and close to 0. When the equivalence null hypothesis is rejected, the data provide evidence of a negligible effect. Due to using equivalence bounds based on a confidence interval for the mean difference between EN-LN, we designated this method as the confidence intervals method.

Mean CIR for each contrasting ENSO phase (EN and LN) at each site was estimated by fitting a mean model with a first-order autoregressive temporal correlation to all site-seasons with valid data. Each site was fit separately. Inspection of the autocorrelation function of the residuals indicated that a first-order autoregressive pattern was appropriate at most sites. After that, 90% confidence intervals for the mean difference between EN and LN seasons at each site were calculated. A model with season as a linear trend in addition to the three categories of means was also considered. At most sites, the coefficient for the season trend was not significantly different from 0. At all sites, adding a season trend had minimal effect on the confidence interval for the EN-LN difference. All computations were done in SAS using the PROC MIXED procedure. In circumstances where weather data for some seasons were unavailable, a spatial exponential correlation structure was used to account for potentially irregularly-spaced observations. This structure is a reparameterization of a first-order autoregressive correlation structure. Table 2 presents the sites used for analysis with their respective number of seasons with EN, LN or NT occurrences.

Results

The results of this study are presented in two different ways: in a graph (Fig. 2), which allows to see CIR confidence intervals and how each location is classified according to ENSO phase impact on CLR risk; and a map (Fig. 3), which illustrates the spatial distribution of ENSO phase effect on CIR, according to the classification methods used - TOST.

The EN-LN analysis, representing the extreme phases of the ENSO phenomenon, showed no overall impact for CIR in the Brazilian coffee-producing region (Fig. 2). For eight sites (hereafter designated Group 1), the ENSO phenomenon significantly impacted the risk of CIR, showing evidence of difference. The remaining 37 sites showed no ENSO-related difference in CLR risk; these included 18 sites that showed evidence of no differences (designated Group 2) and 19 sites that showed no evidence of differences (designated Group 3).

The eight sites in Group 1 represented 17.7% of the total sites (Fig. 2). Of the five sites located in Paraná state, four presented evidence of difference between EN and LN years (sites 1, 2, 4, and 5). Other Group 1 sites are in the state of São Paulo (sites 7 and 8) and Minas Gerais (sites 13 and 31). At all eight sites, EN seasons showed more favorability for CIR than LN seasons (Fig. 3).

The Group 2 sites, which showed statistical evidence of no difference in CLR risk between EN and LN (Fig. 2 and 3), are located mainly between 17°S and 23°S. Only Pirenópolis (site 42) is located at a lower latitude. The sites in this group are located mainly in Minas Gerais, Rio de Janeiro, São Paulo and Goiás states. The majority of the Group 3 sites, with no evidence of difference (Fig. 2 and 3), are in latitudes lower than 17°S. The exceptions are Campo Mourão (site 3), Presidente Prudente (site 6), São Simão (site 9), Lavras (site 17), Bom Despacho (site 21), and Vitória (site 27).

When the extremes of the confidence interval bars occurred between the -10 and 10 bounds, the site showed evidence of no difference in CIR between EN and LN episodes (Group 2). In these situations, the null hypothesis of non-equivalence between the two groups was accepted, due to the precisely known difference between the groups. The 18 sites of Group 2 are located in a geographical transition region for the ENSO phenomenon, mostly between 17°S and 23°S. North of this line, only Pirenópolis (42) showed the same behavior.

Sites of Group 3 have their lines crossing at least one of bounds (-10 or 10), with 18 of the 19 sites crossing the upper bound of 10. This result implies a trend for higher CIR values in the EN episodes, but with so much variance between ENSO episodes that no evidence of difference could be confirmed. Except for site 31, the largest variation in Group 3 was for sites from 30 to 40, all located in northern Minas Gerais and southern Bahia, between 12°S and 17°S, in the most northern areas of the coffee-growing region.

As most of the confidence interval bars were placed above the -10 bound and crossing above the 10 bound, there was a trend of higher CIR during EN conditions than during LN, although it was highly variable among sites (Fig. 2). Due to these large variations, 19 of the sites exhibited no evidence of difference, which means very large variability. In other words, the differences of CIR between EN and LN were too large within each ENSO episode to be consistently separated.

Discussion

ENSO effects on coffee leaf rust infection rates. The present study is the first to assess coffee leaf rust risk on a regional basis using ENSO patterns and applying TOST. This method was used primarily to validate bioequivalence; it is uncommon in phytopathology, where studies normally use more traditional statistical analysis. In the present study it was possible to integrate a weather-based CLR intensity index (CIR), ENSO phases and a new statistical approach to generate relevant results for disease risk assessment. These results are valuable for Brazilian coffee growers because they show that ENSO's impact on CLR risk is confined primarily to the southernmost part of the country's coffee-growing region. The implication of this insight is that growers in this southern area can take note of a prevalent or developing ENSO phase when formulating their disease-management plans for a growing season; for example, in deciding how much fungicide they need to order each year. Equally important, the results showed that vast majority of Brazilian coffee farms were located in regions that showed no clear-cut ENSO impact on CLR risk; therefore, farmers in these regions need not include monitoring of ENSO phases in their disease risk assessment strategies. This type of ENSO-based disease risk assessment may have application for CLR risk assessment in other regions of the world, and may also be useful in management of other crop diseases for which weather-based assessment tools have been developed.

To our knowledge, this is the first study analyzing ENSO effects using the confidence interval methodology, which summarizes differences between ENSO seasons of a large data series with multiple sites in a simple figure. This approach paves the way for further long-term studies of ENSO impact on large geographic regions. Possible application could include not only disease risk assessment (disease prevalence, incidence, and severity as well as disease loss estimates), but also analysis of weather variables (e. g., air temperature, relative humidity, rainfall, solar radiation) under ENSO influence, which can yield multiple economic and social benefits beyond crop disease control.

A box-plot analysis was used previously to assess ENSO impact on crop disease risk (Del Ponte et al. 2011). The study area covered Rio Grande do Sul state in Brazil, which encompasses approximately 10% of the area considered in the present research. Predominance of a positive effect for soybean rust favorability was observed during EN seasons in the whole study area. However, evaluating differences between ENSO phases in larger data sets would result in a proliferation of plots, e.g., for three ENSO phases and 45 sites in our study, which could make interpretation more complex.

Three different ENSO influences were found in the present study. Overall, EN was more CLR-favorable than either LN or NT; the latter two ENSO patterns lacked consistent relationship to disease risk. In the present study, in all eight sites with evidence of difference of CIR between EN and LN episodes (Group 1), EN showed more favorability for CIR than LN. Six of these eight sites are located in Southern Brazil, where EN normally results in above average minimum temperature and rainfall (Berlato and Fontana 2003; Marengo and Camargo 2008). In these six sites, it is advisable to pay closer attention to CLR control during EN seasons. The other two sites of Group 1 (Araxá and Itamarandiba) are considered to be outliers, since they are in a geographic transition area (Coelho et al. 2002; Ropelewski and Halpert 1987). It is not clear that ENSO has the same impact on CLR in Araxá and Itamarandiba as in the six sites in the South, since ENSO tends to exert regional rather than local influences (Pezzi and Cavalcanti 2001; Berlato and Fontana 2003; Coelho et al. 2002; Ropelewski and Halpert 1987).

Fig. 2 and 3 suggest that the ENSO phenomenon had minor impact on CIR between 12°S and 17°S latitudes and east of 52°W longitude in Brazil. The sites with differences of CIR between EN and LN episodes (Group 1) are located in the South/Southeast regions of the country; therefore, the occurrence of ENSO phenomena may need to be incorporated into CLR management plans in these regions during EN years. EN occurred in 20 of the 65 analyzed growing seasons, whereas LN was present in only 16 seasons. Therefore, the EN effect on CIR affected coffee growers in Paraná state in approximately one of three seasons. Based on this information, the number of fungicide sprays in the field can be predicted in advance once EN is forecasted. The usual practice for CLR control in coffee fields entails two sprays during the coffee production season (de Souza et al. 2011); however, three fungicide sprays can be necessary when weather conditions are highly favorable for disease development.

Another management practice that can be adopted is to modify the rates (amount of fungicide per ha) at which fungicides are applied. In EN episodes, under favorable conditions for CLR occurrence in the season, the recommended doses of 0.5 L/ha can be raised to 0.75 L ha^{-1} for a triazole (cyproconazole) plus strobilurin (azoxystrobin) pre-mixed fungicide (AGROFIT 2017). This higher rate will extend the residual period. In the same way, the timing of the sprays can be improved by using a disease warning system, potentially resulting in more cost-effective CLR control (Hinnah et al. 2018).

The relatively minor impact of the ENSO phenomenon on the risk of CLR epidemics in the majority of the coffee-producing regions of Brazil is because the main growing areas are located in southern Minas Gerais state (around 22°S), where evidence of no difference between EN and LN episodes (Group 2) was found. This happens because this specific region is located in a transition area with low influence of ENSO. In Brazil, the regions more influenced by ENSO in regard to climate variability are located at the north of 8°S and at the south of 25°S (Ropelewski and Halpert 1987).

Even during EN seasons, for the regions with influence of this phenomenon on plant disease, exceptions are possible. A study by Del Ponte et al. (2011) for soybean rust risk assessment found higher favorability for the pathogen, *Phakopsora pachyrhizi,* in EN episodes than in NT and LN episodes. However, in the weak EN during 2004-05 in Rio Grande do Sul state (around 28°S), the weather was unfavorable to soybean rust epidemics. In another study about ENSO effects on plant disease, Nóia Jr et al. (2018) observed that eucalyptus rust was positively influenced by EN episodes in southern Brazil, which agrees with the study of Del Ponte et al. (2011). However, Nóia et al. (2018) also concluded that topography, mainly the aspect or direction the terrain faces, can make disease intensity higher or lower. On Brazil, terrain that faces south are wetter than those facing north, which implies a different level of disease risk between these two topographies.

The sites in Group 3 present a large degree of variation of CLR during the ENSO phases, which prevents defining presence or absence of ENSO effects on disease epidemics. As the sites are not located on areas with ENSO-related impact on rainfall and temperature, the lack of influence on CLR would be expected (Ropelewski and Halpert 1987). The region between 3°S and 17°S in characterized by relatively large interannual rainfall variation. As the latent and sensible heat balance is modified by the input of water in the environment (Lenters et al. 2011), the rainfall events are likely to impact temperature and relative humidity. The yearly variation of rainfall in the region can be as high as 300% (Kousky and Chu 1978), which may be the major

CIR factor in this region rather than ENSO phases. It explains the lack of evidence of differences of CIR between EN and LN episodes, and the large variation between seasons.

The results of this study confirm the different ENSO impact across several Brazilian coffee cultivation regions. Predominant evidence of differences or no differences typified regions, in line with the degree of ENSO impacts on these regions. Some sites present isolated effects; e.g., sub-regions near Campo Mourão (3), São Carlos (8), Araxá (13) and Itamarandiba (31). EN seasons tended to impact increasing CLR intensity in all regions, but evidence of differences was clear-cut only in the Southern region. The risk of CLR in the major coffee cultivation area - Minas Gerais state, borders with São Paulo and Goiás – showed evidence of difference between the warm and cold ENSO phases.

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Table 1. Classification of ENSO phases for the period between 1962 and 2015, according to the U.S. National Oceanic and Atmospheric Association (NOAA) sea surface temperature anomaly threshold[a]

ENSO phases		
El Niño	Neutral	La Niña
1964	1962	1965
1966	1963	1968
1969	1967	1971
1970	1979	1972
1973	1981	1974
1977	1982	1975
1978	1984	1976
1980	1986	1985
1983	1990	1989
1987	1991	1996
1988	1993	1999
1992	1994	2000
1995	1997	2001
1998	2002	2008
2003	2004	2011
2005	2006	2012
2007	2009	
2010	2013	
2015	2014	
2016		

[a] Source: NOAA – http://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php.

Table 2. Sites, their codes, and number of ENSO phases analyzed for coffee leaf rust cumulative infection rates calculation

			Number of seasons / ENSO phase			
Site	Code	State[a]	El Niño	Neutral	La Niña	Total
Ivaí	1	PR	11	15	9	35
Castro	2	PR	14	16	14	44
Campo Mourão	3	PR	15	15	15	45
Maringá	4	PR	13	16	11	40
Londrina	5	PR	17	18	16	51
Presidente Prudente	6	SP	15	14	13	42
Sorocaba	7	SP	10	15	9	34
São Carlos	8	SP	15	18	14	47
São Simão	9	SP	18	17	14	49
Catanduva	10	SP	15	15	14	44
Franca	11	SP	17	18	13	48
Uberaba	12	MG	13	15	11	39
Araxá	13	MG	11	15	12	38
Bambuí	14	MG	13	15	12	40
Machado	15	MG	16	18	16	50
São Lourenço	16	MG	17	18	15	50
Lavras	17	MG	16	16	16	48
Juiz de Fora	18	MG	15	16	13	44
Barbacena	19	MG	17	18	16	51
Viçosa	20	MG	14	15	14	43
Bom Despacho	21	MG	10	15	9	34
Sete Lagoas	22	MG	17	17	15	49
Conceição do Mato Dentro	23	MG	13	17	14	44
Cordeiro	24	RJ	11	14	13	38
Itaperuna	25	RJ	14	15	14	43
Caparaó	26	MG	12	15	11	38
Vitória	27	ES	12	14	14	40
Caratinga	28	MG	12	16	10	38
Pirapora	29	MG	12	14	9	35
Diamantina	30	MG	11	16	10	37
Itamarandiba	31	MG	15	17	13	45
Araçuaí	32	MG	15	16	13	44
Salinas	33	MG	12	15	10	37
Janaúba	34	MG	9	15	9	33
Pedra Azul	35	MG	13	15	12	40

Vitória da Conquista	36	BA	12	16	9	37
Ituaçu	37	BA	12	15	9	36
Caetité	38	BA	17	18	13	48
Bom Jesus da Lapa	39	BA	14	15	12	41
Lençois	40	BA	15	17	13	45
Catalão	41	GO	18	18	16	52
Pirenópolis	42	GO	11	15	9	35
Formosa	43	GO	13	16	10	39
Formoso	44	MG	10	15	9	34
Arinos	45	MG	10	15	9	34
Total	45	7	612	714	552	1878

[a] MG = Minas Gerais; SP = São Paulo; BA = Bahia; RJ = Rio de Janeiro; GO = Goiás; PR = Paraná; and ES = Espírito Santo.