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Evasive Planning for the Management of Eucalyptus Rust *Austropuccinia psidii* for Espírito Santo State, Brazil

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Abstract: Eucalyptus is one of the most exploited forest genera on the planet. Eucalyptus has a variety of uses, mainly because of its great diversity and versatility. Brazil is among the main producers of cellulose, paper, and wood panels in the world. One of the factors limiting the production of *Eucalyptus* spp. is the occurrence of diseases such as rust caused by the fungus *Austropuccinia psidii*. This work aimed to map areas at risk of eucalyptus rust in the state of Espírito Santo, Brazil. The study was carried out in two stages: (i) mapping the rust risk areas in the state through the Geographic Information System (GIS) and (ii) applying fuzzy standardization to the infection index to generate a risk index. It was found through GIS and fuzzy standardization that most of the areas surveyed presented medium to high risk of rust occurrence. Thus, it becomes necessary to adopt complementary management measures to control the disease, especially for the months of April to November. The methodology used in this study can be implemented for other diseases and forest species in other parts of the world.

Keywords: *Austropuccinia psidii*; risk areas; fuzzy standardization

1. Introduction

Forestry has played an important role in the socio-economic development of Brazil. This is because forestry plantations in the national territory have been expanding considerably, mainly forests planted with eucalyptus [1,2]. In 2020, eucalyptus plantations occupied 7.47 million hectares, representing around 80% of the total area planted with trees in Brazil. These were mainly concentrated in the states of Minas Gerais, Mato Grosso do Sul, and São Paulo. Pine plantations accounted for 18% of the total area, and most were found in the south of the country. Other species are distributed as follows: rubber in Mato Grosso do Sul, acacia in Rio Grande do Sul and Roraima, and teak in Mato Grosso as well as other states [2]. The country presents itself as a world leader in the production of eucalyptus derivatives, with more than 80% of the plantations of the *Eucalyptus* genus [2–4]. According to study [5], the most planted species, due to the characteristics of their woods, are: *E. grandis*, *E. saligna*, *E. urophylla*, *E. viminalis*, *hybrids of E. grandis* and *E. urophylla*, and *E. dunnii* (southern region of Brazil). Additionally, for the southern region, the potential for using *E. benthamii* also stands out, due to its tolerance to frost. Eucalyptus planting represents the forestry base of the state of Espírito Santo; eucalyptus harvested in Espírito Santo is primarily used to produce cellulose, but also is a raw material for construction, furniture, firewood, and coal production [1,6].

Eucalyptus rust, considered a major crop disease, is caused by the biotrophic fungus *Austropuccinia psidii* Winter, which causes severe damage to plantations in tropical and subtropical areas worldwide [7–9]. Such importance is due to damage caused and its influence on management of eucalyptus, which can even affect the conduction of sprouting in periods favorable to occurrence of the disease, considering susceptible clones [10]. The predominance of air temperatures ranging between 18 and 25 °C, associated with periods with leaf wetness greater than 6 h for 5 to 7 consecutive days, as well as the existence of juvenile organs, including new and terminal growth leaves, favor infections caused by the pathogen [11]. The fungus infects juvenile leaves of young plants or shoots after trees are cut. In addition to eucalyptus, it also causes disease in several other species belonging to Myrtaceae and Heteropixidaceae families [12]. Under favorable conditions for the disease, such as the occurrence of a susceptible host, adequate humidity, and temperature, the disease can manifest aggressively [13,14]. In the planting areas of Myrtaceae species, where climatic conditions are favorable for the development of rust, the disease limits eucalyptus regeneration and development [9]. Repeated foliage infections cause prominent decreases in photosynthesis, due to reduction of photosynthetic area, leading to defoliation and aggravation of photochemical processes. This manifests by reducing plant height, fecundity, and biomass, enabling secondary pathogen infection, and causing death in some cases [15].

The economic losses due to this disease are the result of infections of seedlings, young trees, and coppice [7]. Depending on the severity caused by *A. psidii* infection, annual tree growth can be reduced by half, as observed by [16]. Considering that approximately 270,000 ha would be at risk of infection by pathogens, study [17] estimated that economic costs derived from this risk could reach USD 200 million per year, considering a 20% reduction in wood production due to the impact of eucalyptus rust.

Knowledge of the influence of environmental factors on plant epidemiology is an important mechanism for the development of management and control measures [18]. Thus, the knowledge of meteorological factors that influence the incidence and severity of rust allows us to identify the seasons and planting sites in which conditions are favorable for the pathogen [11]. For this, climatic mapping is necessary due to the importance of identifying areas with a high risk of disease occurrence [19–21]. The risk zone maps, coupled with the simulation models and the geographic information system (GIS), make it possible to identify places and times of the year that are most favorable to the occurrence of epidemics [22]. In this sense, the present study aimed to map the risk areas of eucalyptus rust caused by the fungus *Austropuccinia psidii* using the state of Espírito Santo, Brazil, as the study area.

2. Materials and Methods

In order to carry out the study, it was divided into two phases: (i) mapping of areas with higher risk of infection by eucalyptus rust in Espírito Santo, aiming to determine areas where the disease escapes, in other words, areas most suitable for planting (considering only the risk of infection by eucalyptus rust), and (ii) monthly evaluation of eucalyptus rust in three different areas, and analysis of the respective data based on the infection index and fuzzy standardization. The aforementioned phases are described below:

2.1. Phase 1—Mapping of Areas of Risk to Rust in the State of Espírito Santo

The study was carried out for the State of Espírito Santo, which has a territorial area of 46,053.19 km^2. It is located between the parallels of $17°53'2''$ to $21°18'03''$ south latitude and the meridians $39°41'18''$ to $41°52'45''$ west longitude (Figure 1).

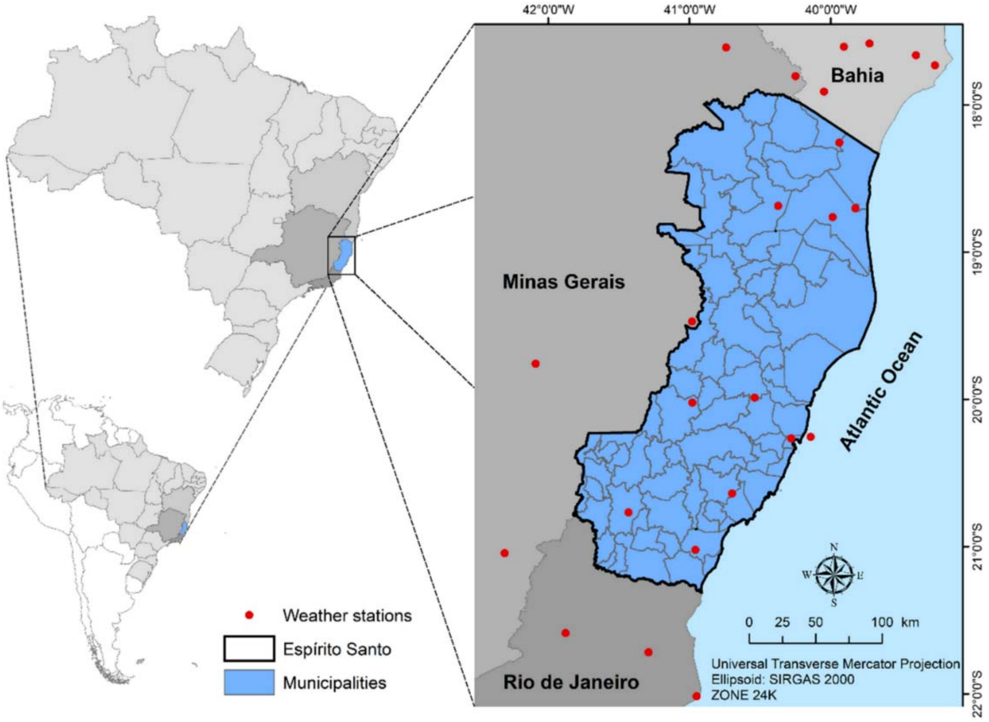

Figure 1. Study area and automatic meteorological stations are located in the state and neighboring areas.

2.1.1. Step 01-Punctual Vector Spatialization of Automatic Weather Stations

A series of hourly meteorological data for the period from 2006 to 2013 were used; the period established from the date of the installation of the meteorological stations, originating from 24 automatic stations located in the state of Espírito Santo and areas bordering the state, in order to favor the interpolation data statistics (Figure 1).

From the data of the meteorological variables, maximum temperature and leaf wetness, obtained from the automated stations monthly (series of 8 years), and annual average infection indexes, with respect to each season, were calculated, based on the model of [11], presented in the following equation (Equation (1)):

$$II = -32.2626 + 3.6999 \times T + 0.4613 \times H - 0.0018 \times T \times H - 0.0903 \times T^2 - 0.0068 \times H^2 \quad (1)$$

where II is the infection index; T is the maximum temperature (°C), and H is the length of leaf wetting period (hours).

Before applying the variables in Equation (1), the correlation between them was calculated, using Pearson's correlation coefficient (r) (Equation (2)), with the objective of verifying a possible overfit of the model if there is a high degree of correlation between the variables. The value obtained was equal to 0.115, indicating a weak positive correlation, allowing the application of the variables in Equation (1) proposed by [11].

When the association between two variables that are measured on an interval/ratio (continuous) scale is sought, the appropriate measure of association is Pearson's correlation coefficient. Pearson's correlation coefficient r for a sample is defined by the following equation (Equation (2)):

$$r = \frac{COV(X,Y)}{s_x, s_y} \quad (2)$$

where $COV(X,Y)$ is the sample covariance between two random variables X and Y that are normally distributed with means $\overline{x}$ and $\overline{y}$, and standard deviations s_x and s_y, respectively. To calculate the population correlation coefficient, the sample means $\overline{x}$ and $\overline{y}$ are replaced by population means μ_x and μ_y, and the sample standard deviations s_x and s_y are replaced by population standard deviations σ_x and $\sigma_y zf$, respectively.

After estimating the infection index for each weather station, an electronic spreadsheet was built. Using ArcGIS® software (Environmental Systems Research Institute, Redlands, CA, USA), the electronic spreadsheet was imported, specifically the field representing the infection index variable, culminating in the punctual spatial vectoring of the referred weather stations.

2.1.2. Step 02—Spatial Interpolation by Polynomial Kernel

With the field of the infection index variable of the point vector image representative of the weather stations, the geostatistical technique of polynomial kernel interpolation was applied [23–25], generating the matrix image of the infection index for each month, and for the annual average in the state. Kernel interpolation is a variant of a first-order local polynomial interpolation in which instability in the calculations is prevented using a method similar to the one used in the ridge regression to estimate the regression coefficients. When the estimate has only a small bias and is much more precise than an unbiased estimator, it may well be the preferred estimator [25]. The raster resolution used throughout the research was 90 m.

2.1.3. Step 03—Fuzzy Standardization of the Infection Index, Generating the Risk Index

The fuzzy standardization considers that, although the infection indexes are in different locations within the study area, there is a need to classify them on the same scale of values for comparison purposes, so that they do not lose their unique spatial character, that is, their absolute location. For this, fuzzy standardization was performed using a decreasing linear equation, with an interval from 0 to 1. Thus, a rescheduling of the infection indexes was carried out for each month and for the annual average. For this, the minimum values were inserted and the maximum of each factor of the infection index, so that the limits of each Euclidean map were not exceeded, with a continuous scale, with 0 being the lowest index and 1 the highest calculated infection index (Figure 2).

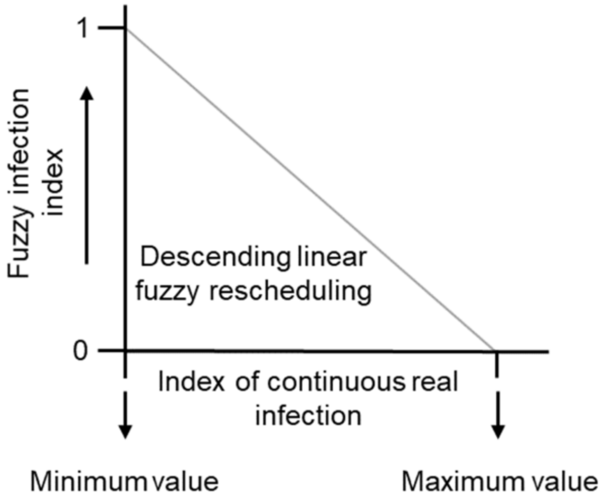

Figure 2. Fuzzy function for monolithically decreasing linear standardization of the infection index.

With these data in hand, continuous maps of the risk index were prepared for each month and for the annual average in the state of Espírito Santo. Later, a single image representing the average risk index was generated, having as input data, the 12 monthly images of risk index.

2.1.4. Step 04—Spatial Reclassification of the Risk Index

After the generation of continuous maps of the risk index based on the fuzzy standardization, spatial reclassification was performed at defined intervals of 0.333 (Table 1), from 0 to 1, generating the discrete reclassified matrix image representing the risk indexes of occurrence of rust, based on the fuzzy methodology. Additionally, after making the discrete maps, the percentage of each risk index class was calculated using fuzzy standardization for the state of Espírito Santo.

Table 1. Matrix table for discrete reclassification representing the risk indexes for the occurrence of eucalyptus rust (*Austropuccinia psidii*) in the state of Espírito Santo.

Range	Class	Risk	Color
0–0.333	1	Low	🟩
0.333–0.666	2	Medium	🟨
0.666–1	3	High	🟥

The following is a methodological flowchart containing the four steps necessary for development of eucalyptus rust zoning based on the calculation of the risk index (Figure 3).

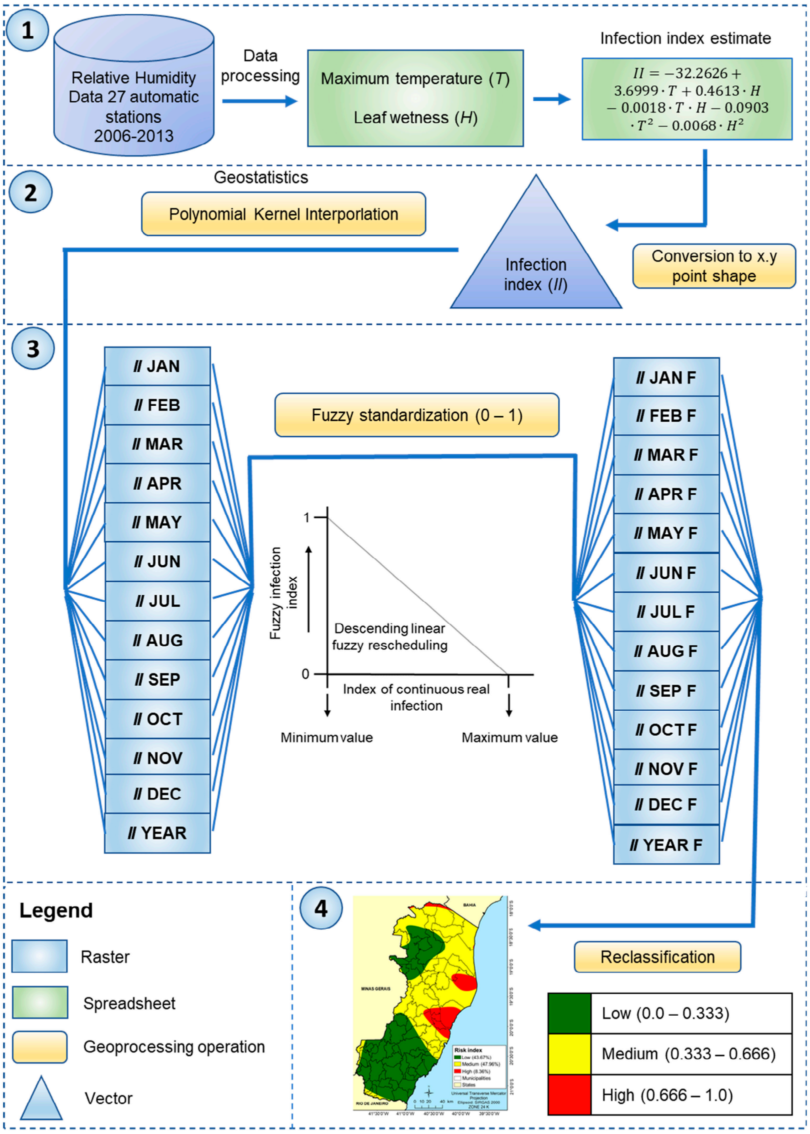

Figure 3. Methodological flowchart containing the four steps necessary to prepare the zoning of the risk index for the occurrence of eucalyptus rust (*Austropuccinia psidii*) based on the fuzzy methodology.

2.2. Phase 2—Monthly Rust Assessment in Three Different Areas, and Data Analysis Based on the Infection Index and Fuzzy Standardization

2.2.1. Step 01—Pilot Study

The experiments were carried out in three stands of commercial eucalyptus plantations owned by the company Fibria Celulose S.A., located in the municipalities of Joeirana, Nova Viçosa, and Santo Antônio in the extreme south of the state of Bahia, Brazil, from September 2008 to August 2009, using a clone susceptible to rust. The experimental plot consisted of six planting lines with 10 plants, with 3.0 × 1.5 m spacing. The plants were always kept in growth to guarantee the presence of new leaves, with three lines being maintained for evaluation and three others kept as a source of inoculum.

The severity of the disease was quantified monthly in the plant using a specific diagrammatic scale [26]. The evaluation started after the appearance of the first symptoms. Once severity for each leaf of the plant was quantified, the average percentage of injured leaf area of the plant and the plot was calculated.

2.2.2. Step 02—Data Analysis

The disease severity data were used to plot the rust progress curves [18]. The infection index was calculated based on the equation proposed by [11] (Equation (1)), using meteorological data recorded at three automated meteorological stations located in the southern region of Bahia (Figure 1). From the determination of the infection index, the risk index was calculated using the fuzzy methodology [27,28].

3. Results

3.1. Phase 1—Mapping of Areas of Risk to Rust in the State of Espírito Santo

Eucalyptus rust zoning for Espírito Santo was performed based on the fuzzy methodology for each calendar month and for the annual average. The risk index calculated from the fuzzy methodology is hereafter referred to as the "fuzzy risk index". The fuzzy methodology was selected for the present study because it has already been applied broadly across the agricultural sciences [4,29–32].

Regarding the temporal dynamics of the disease, the months between May and November (Figure 4) were the ones that presented the most favorable climatic conditions for the occurrence of rust. The greatest risk factors for rust during this period are temperatures in the range of 19 to 25 °C, and a leaf wetness period always greater than 6 h, conditions favorable for rust occurrence [11]. On the other hand, in December, the risk of disease occurrence decreased and the months from January to March were those that presented the most unfavorable climatic conditions for rust occurrence.

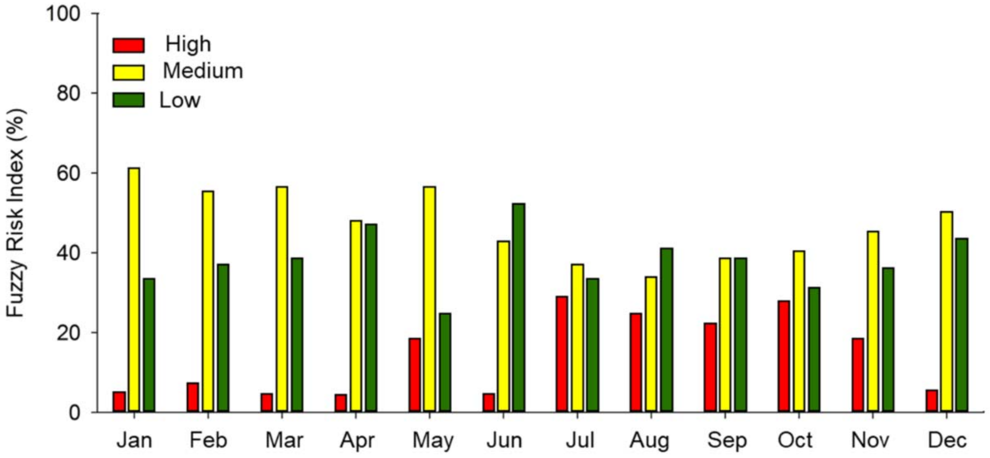

Figure 4. Fuzzy risk index classes (high, medium, and low) to the occurrence of eucalyptus rust (*Austropuccinia psidii*) in the state of Espírito Santo, Brazil, over the months of January to December (2006–2013).

Throughout the year, it is observed that there was a predominance of areas classified as low and medium fuzzy risk index, which may vary, for the low-risk class, from 25% to 50% in the months of October and June, respectively, and from 25 to 60% for the months of August and January, respectively, in the medium-risk class (Figure 4).

The southern region of the state had the largest areas of low disease occurrence across the year, except for the Caparaó region, which presented medium to high risk of disease occurrence, probably because the region has a cool, humid climate. Additionally, a transition from the favorable to the unfavorable season for rust occurrence occurs in November, probably because of increasing temperatures during this month (Figure 5).

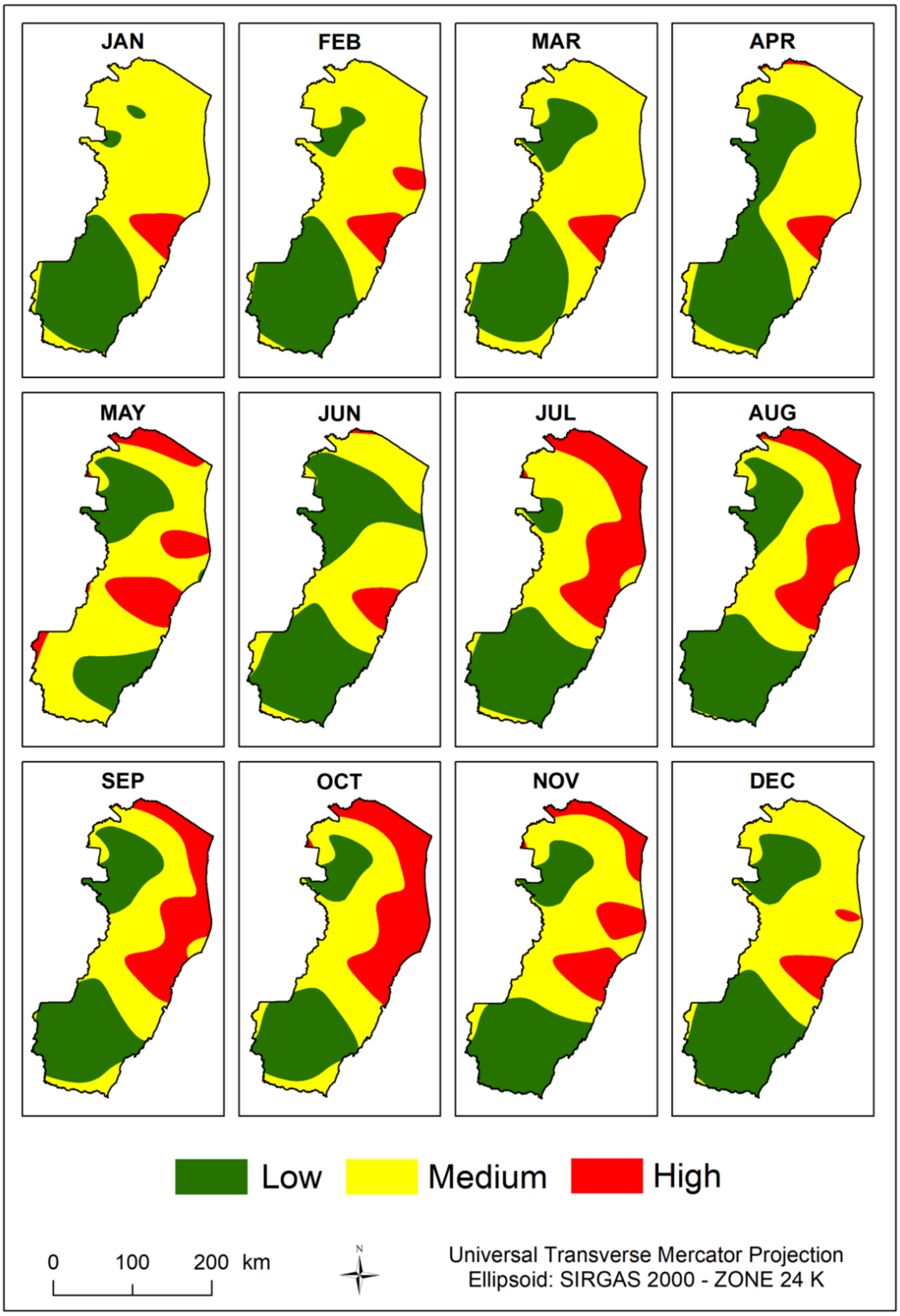

Figure 5. Spatiotemporal dynamics of the fuzzy risk index for eucalyptus rust (*Austropuccinia psidii*) in the state of Espírito Santo, Brazil, over the months from January to December (2006–2013).

When risk was calculated as an annual average, most areas of the state were found to be at medium risk of rust (Figure 6). The southern region of the state is characterized by a low risk of rust occurrence, while regions of Aracruz, Linhares, and the extreme north of the state are at high risk, a fact of great importance because these regions have large eucalyptus plantations.

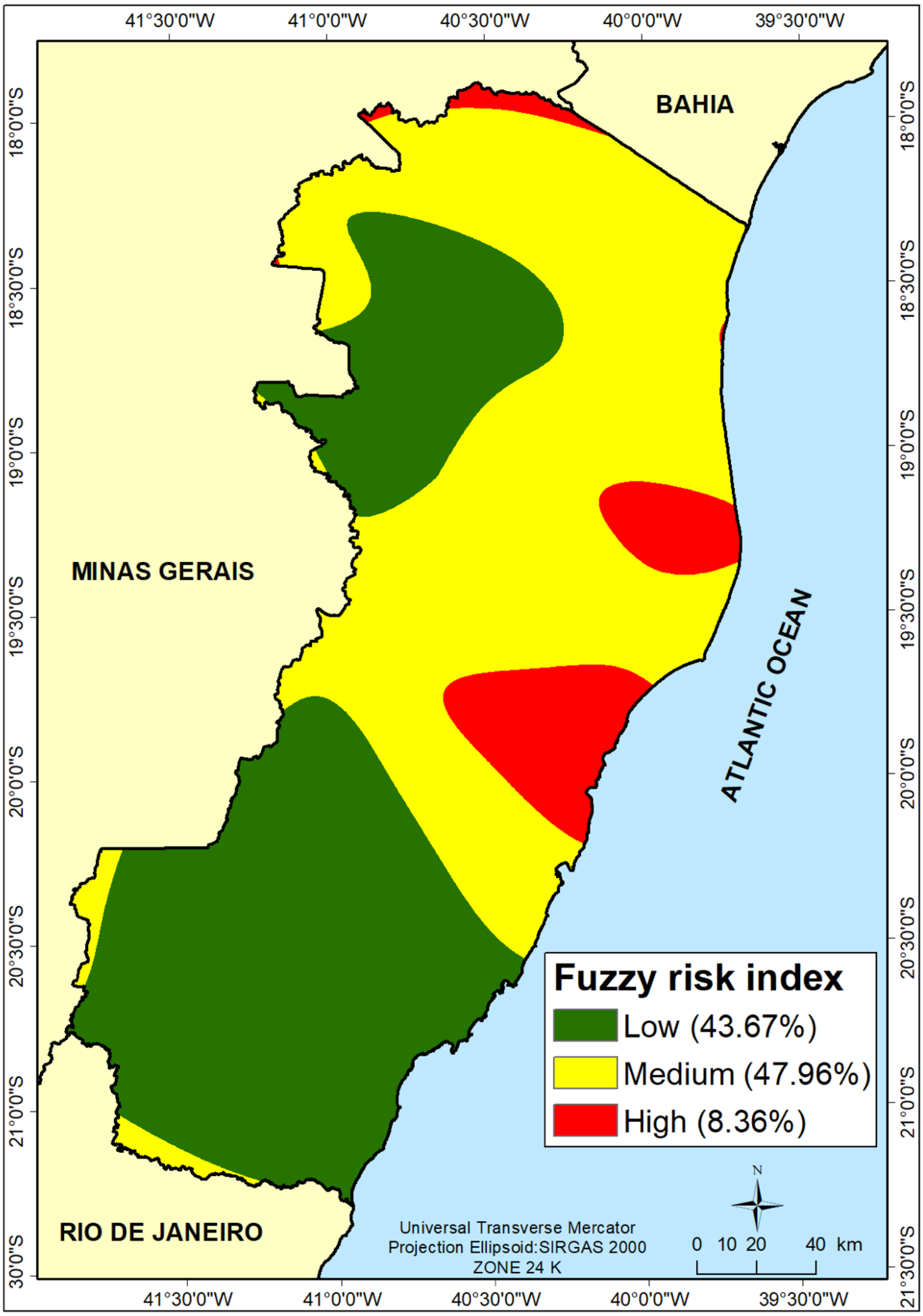

Figure 6. Average fuzzy risk index for eucalyptus rust (*Austropuccinia psidii*) for the state of Espírito Santo, Brazil.

3.2. Phase 2—Monthly Rust Assessment in Three Different Areas, and Data Analysis Based on the Infection Index and Fuzzy Standardization

Eucalyptus rust was detected in all field sites during the experimental evaluation period (Figure 7).

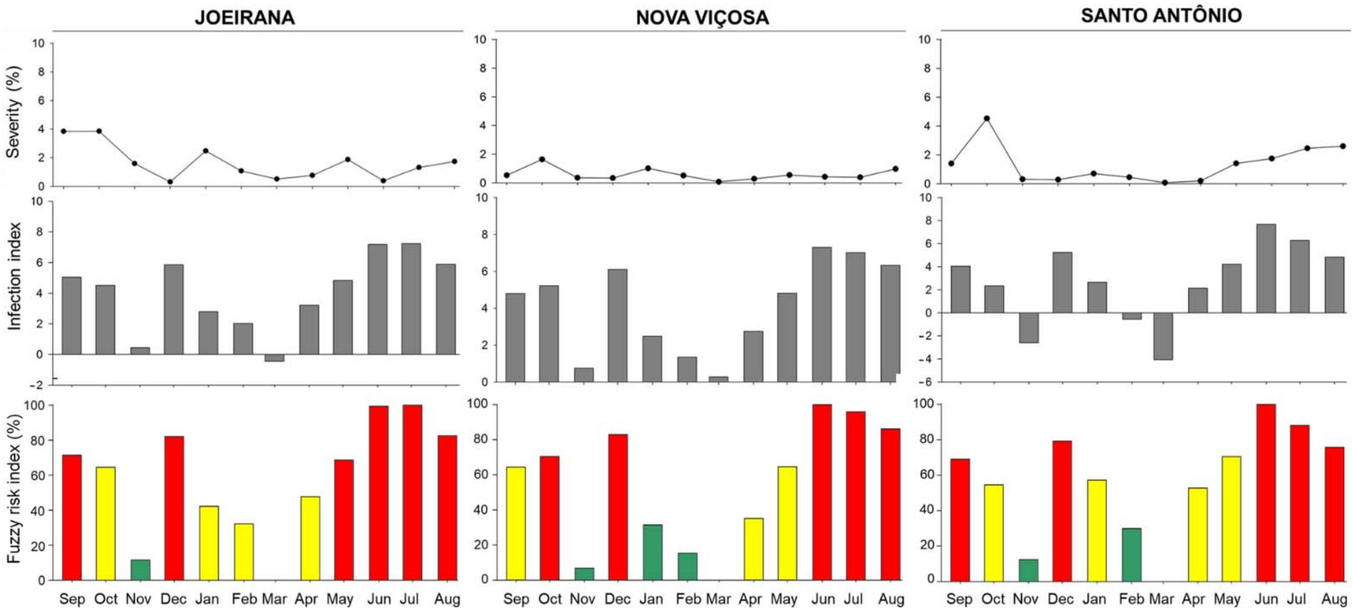

Figure 7. Severity of eucalyptus rust (%), infection index according to the equation of [11], and fuzzy risk index for the period from October 2008 to August 2009, under field conditions, in the municipalities of Joeirana, Nova Viçosa, and Santo Antônio, located in the extreme south of Bahia, Brazil.

Analysis of the monthly infection index revealed that, for the 15 days before the assessment, only 3 months had infection index above 0, as observed in November in Joeirana, noted above. The disease severity in the same month was similar to the severity observed in the months of September and October, which showed infection index values between 1.36 to 8.27 in the 15 days prior to evaluation (Figure 8).

In Nova Viçosa and Santo Antônio, the opposite situation was documented for the month of December, in which low disease intensity was observed (0.33% and 0.28%, respectively), but the infection index values were high in the 15-day period prior to our monthly field evaluations, reaching up to 10.9. However, for both areas, in the same month, negative indexes were also observed (−5 and −6), suggesting that the model for estimating the infection index lacks sufficient precision for studying disease intensity under natural conditions of infection (Figures 9 and 10).

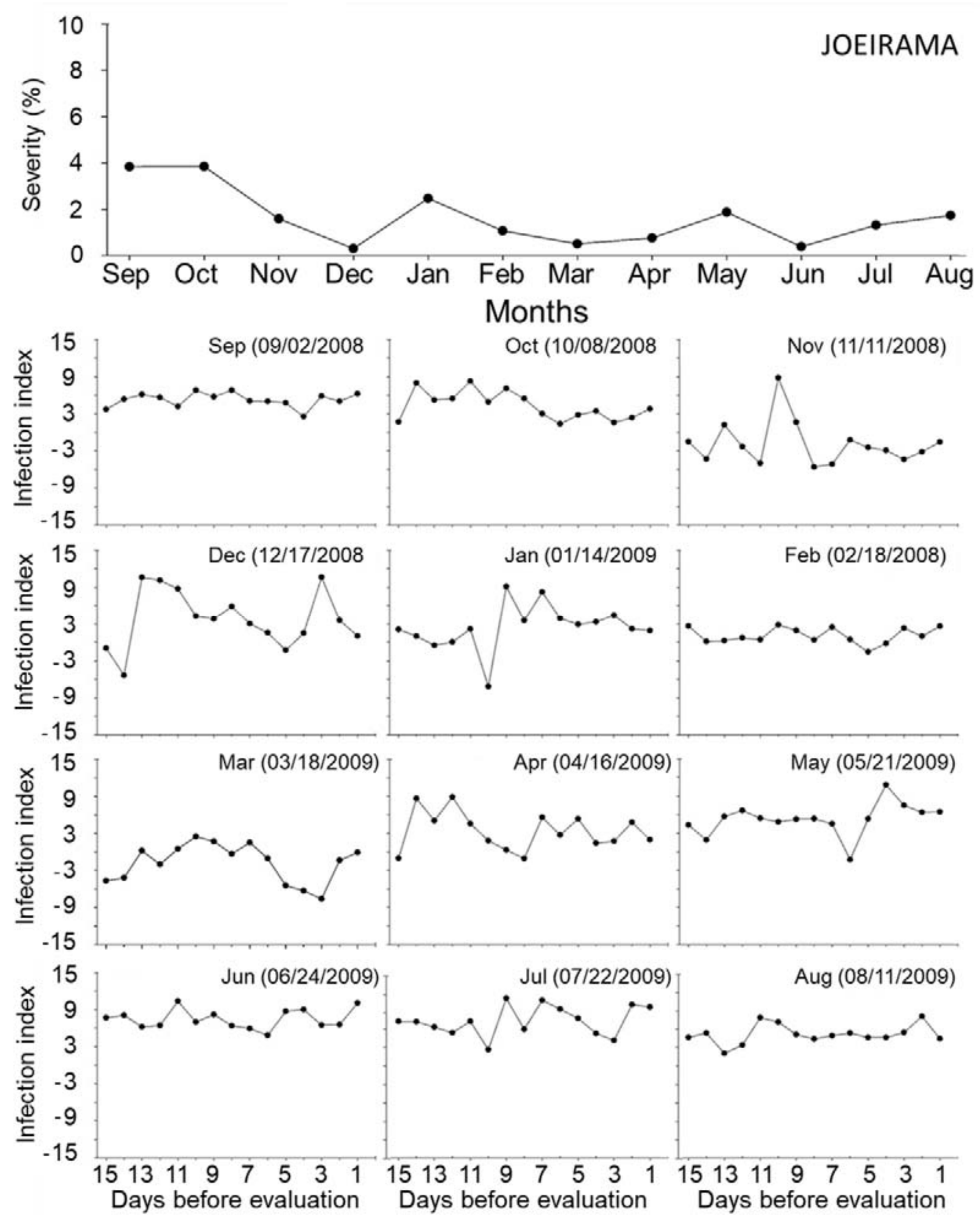

Figure 8. The severity of eucalyptus rust (%) and infection index were evaluated under field conditions and used to calculate the infection index according to the equation of [11], for the 15-day period prior to the monthly evaluations conducted in September 2008 through August 2009, in the municipality of Joeirana, located in the extreme south of Bahia, Brazil.

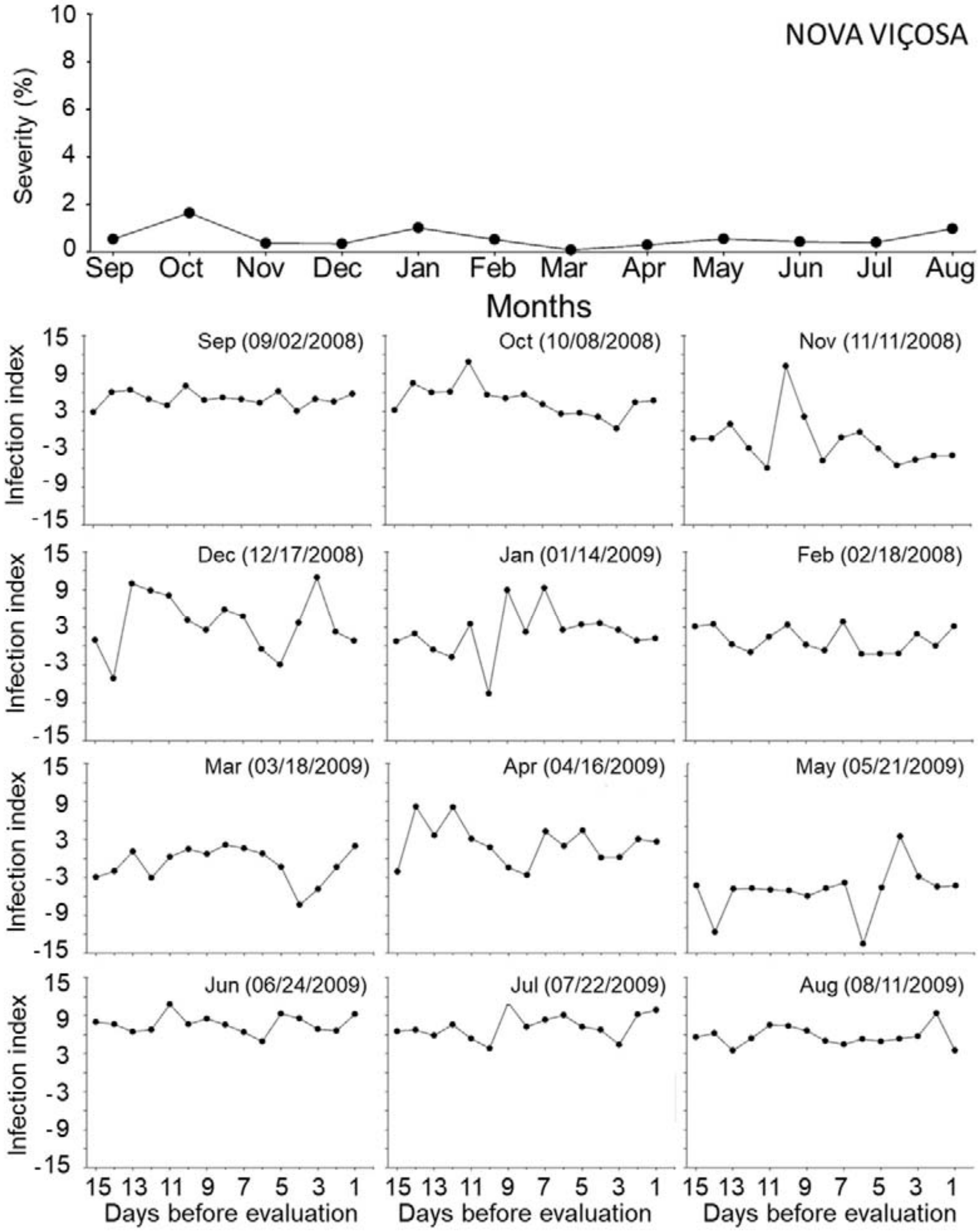

Figure 9. The severity (%) and infection index of eucalyptus rust were evaluated under field conditions and used to calculate the infection index according to the equation of [11], for the 15-day period prior to our monthly evaluations conducted from September 2008 through August 2009, in the municipality of Nova Viçosa, located in the extreme south of Bahia, Brazil.

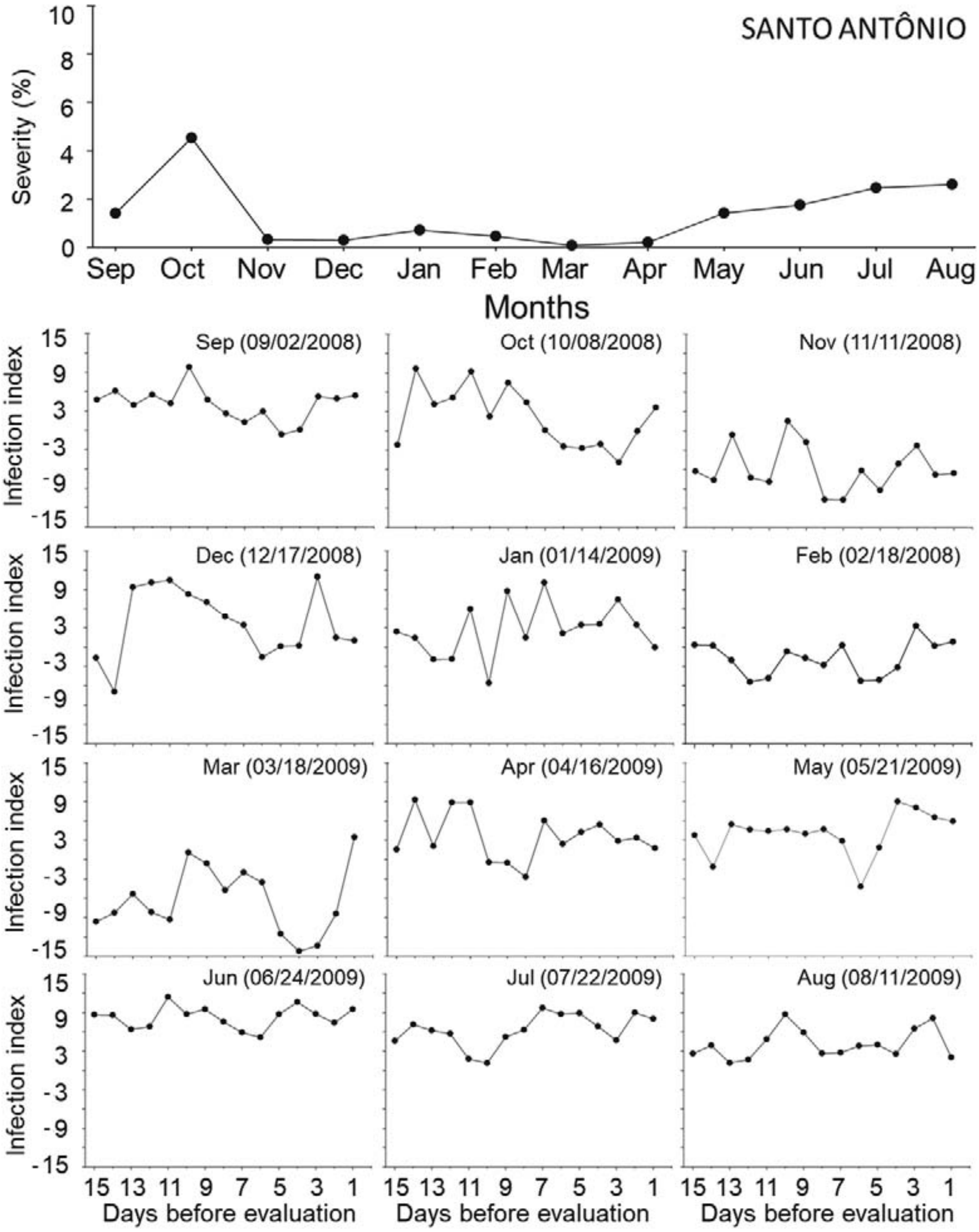

Figure 10. Eucalyptus rust severity (%) and infection index was evaluated under field conditions and used to calculate the infection according to the equation by [11], for the 15-day period prior to our monthly evaluations conducted from September 2008 through August 2009, in the municipality of Santo Antônio, located in the extreme south of Bahia, Brazil.

4. Discussion

In field studies by [33] in the Teixeira de Freitas region, BA, Brazil, it was observed that disease incidence was higher in the months from March to November. Likewise, study [34] for the Luiz Antônio, SP, Brazil region, observed that the months with the highest incidence of the disease occurred between May and December, mainly due to the conditions of high relative humidity and temperature in the range of 15 to 25 °C.

According to our results for the spatiotemporal disease distribution in Espírito Santo (Figures 4 and 5), the months from July to October presented the largest areas classified as having a high fuzzy risk index, with an index varying from 20% to 30%, while for the months of December to April, the high index class did not exceed 5%. In general, there was a high fuzzy risk index for the occurrence of rust in the central and northern regions of the state, regions of great importance due to their productive potential.

The results obtained in this study corroborate those observed by [35], who observed that the period between May and November was the most favorable for the occurrence of rust in the region of Aracruz, ES. This can be explained by the period of leaf wetness and maximum temperatures close to 23 °C in this region.

For the month of May, a transition from the unfavorable to the favorable season for rust occurrence was observed. This transition is probably related to declining temperatures during this month. According to the fuzzy risk index zoning for rust (Figure 5), a large part of the state is at medium risk for rust occurrence nearly year-round. The extreme north and central regions were classified as "medium to high risk" throughout the year, even during warmer periods. Due to this, it was necessary to adopt complementary control measures, mainly the planting of resistant clones in the most favorable areas, but also planting at times which were unfavorable for rust and evasion. All of these management strategies are beneficial as long as these are conducted in a timely manner, taking into account the pathogen-host-environment relationship.

In studies carried out by [35] for the regions of Aracruz and São Mateus, ES, and Teixeira de Freitas, BA, the highest risk indexes for eucalyptus rust were found to occur between May and November, mainly because temperatures remain in the range of 19 to 25 °C, with a leaf wetting period of exceeding 6 h [11].

In field observations in southeastern Brazil, teliospores of myrtle (i.e., Myrtaceae) rust, were easily found during the hottest time of the year (i.e., from December to March). At this same time of year, *A. psidii* teliospores can be found in *Syzygium jambos* (L.) Alston and, less frequently, in *Plinia cauliflora* (Mart.) Kausel. These are found mainly in leaf pustules, mixed with urediniospores [36]. The study in [37] reported an analogous situation with rust in *Eucalyptus cloeziana* during the hottest months of the year. Under controlled conditions, abundant teliospores were produced by rust occurring on eucalyptus plants that were inoculated with urediniospores (isolated from *Eucalyptus sp.* or *S. jambos*) during the hottest time of the year [36].

In zoning carried out by [29] for eucalyptus rust, considering current and future scenarios for Brazil, the states of Bahia, Espírito Santo, Minas Gerais, and São Paulo, and those in the south of the country, where most eucalyptus plantations are located [2], are favorable to the development of the disease, especially in the winter months. This result corroborates those obtained in the present study since, according to our analysis, more than 50% of the state is favorable for the occurrence of rust (i.e., was classified as medium to high risk).

In the areas of escape from disease present in the state, planting moderately susceptible clones may be acceptable, but for the areas that are most vulnerable to rust occurrence, which is equivalent to most of the state, it is necessary to plant resistant clones. In general, planting and re-sprouting should be carried out in these regions from August to October, in order to avoid favorable host conditions for pathogen infection [7,38,39].

For the future use of zoning in the management of rust, it is necessary to use climatic variables related to the infection and, if possible, a mapping, with geoprocessing tools, of commercially planted eucalyptus species, because the eucalyptus species behave differently in terms of genetic resistance to the fungus *A. psidii* [36]. Furthermore, eucalyptus species behave differently in terms of phenology in the production of susceptible young tissues throughout the year, an important factor for infection.

The crossing of this information can assist in selecting planting areas suitable for existing eucalyptus strains, as well as assist in the continuous monitoring of forest diseases as a way of anticipating control or mitigation measures, so that control strategies can be used before the disease reaches epidemic proportions.

The highest intensities of *A. psidii* occurred in the same months in all areas, but with varying intensity by location. The experiment in Nova Viçosa showed the least severity of the disease, with intensity values less than 2%. On the other hand, the Santo Antônio area had the highest disease severity, with intensity values close to 5%.

Although the optimal temperature range for the pathogen is 18 to 23 °C, even during months that we anticipated being unfavorable for the disease, such as October through January, the rust intensity was high in the three plots studied. The opposite was also observed; that is, the severity of the disease was low in those months we had considered likely to be favorable to rust (e.g., June) (Figure 7). Thus, we hypothesize that periods unfavorable to the disease are compensated for by short periods that are extremely favorable to the pathogen, thus guaranteeing conditions of infection and, consequently, greater intensities of the disease.

Some contradictions became apparent when comparing the progress of the disease in the field relative to the infection index. In Joeirana, for example, the severity of the disease was less than 2% in the months of December and June, but the infection index was high (5.8 and 7.2, respectively) during the same time periods. The opposite fact was true in November; that is, despite the November severity value being similar to those of December and June (2%), the infection index for November was low (0.44). Such contradictions were also seen in the areas assessed in Nova Viçosa and Santo Antônio (Figure 7).

The infection index can be useful for temporal disease assessments; however, for spatial assessments, it has some limitations. Such inconsistencies may indicate that other variables influence disease development; these other variables may include nighttime temperature, periods of leaf wetness, and the daily frequency of occurrence of leaf wetness and precipitation, since the latter variable can prolong the duration of the leaf wetness period caused by dew [35]. None of these factors are considered in the model proposed by [11], which considers only the maximum temperature and leaf wetness, and even then, constantly, and under controlled conditions.

Thus, if the climatic variables used do not represent disease development, such methodology would be limited for both temporal and spatial analyses of the disease in the field. This is because climate, which is considered a key factor in the epidemiology of eucalyptus rust, presents more intense variation in the field than in experiments under controlled conditions, since environmental variables influenced by the macro, meso, or microclimate can affect different processes in the disease life cycle, reducing the probability of infection [40]. In this way, a factor that is held stable under controlled conditions may be influenced by numerous other variables under field conditions, which likely explains the observed discrepancy between rust progression in our three study areas and their respective infection index values.

When comparing the development of the disease in the field with the risk index calculated with fuzzy methodology, the obtained field results were similar to those predicted by the infection index. However, the fuzzy methodology softens the infection index estimates, making the estimates align more closely with the actual infection index measured in the field (Figure 7). The fuzzy methodology has been applied broadly across different areas of science; however, there are still few works cited in the phytopathology literature that apply this technique [28,30,41], particularly for diseases of forest species.

5. Conclusions

The fuzzy methodology is suitable for mapping the risk of occurrence of eucalyptus rust in the state of Espírito Santo, considering the space-time distribution. Contradictions were detected between the intensity of eucalyptus rust observed in the field and the infection index calculated using the equation of [12]. Such contradictions may indicate that other variables influence disease development, such as nighttime temperature, periods of leaf wetness, and daily frequency of occurrence of leaf wetness and precipitation.

Most areas in Espírito Santo presented a medium to high risk of rust, which requires complementary measures to manage the disease, including the selection and planting of resistant clones. Although presented results serve as a subsidy for decision making, new models must add other variables to estimate the infection index and, consequently, the risk of infection, aiming to obtain a result even closer to the field data.

The application of geotechnologies in large-scale environmental studies has opened space for more complex and low-cost research. The combination of tools and concepts of environmental management has provided an increasingly broad exploration of problems related to the management of anthropized areas. Finally, the methodology employed can be expanded and applied in other areas, aiming to generate significantly accurate information.

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