

# Modeling the productive potential of coffee trees in the Cerrado of Minas Gerais through hierarchical landscape analysis and remote sensing data

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Editor: Samuel Pereira de Carvalho

Received in January 13, 2026 and approved in August 11, 2026

## ABSTRACT

Brazil stands out as the world's largest producer and exporter of Arabica coffee, one of the world's most important commodities, which plays a crucial role in the country's economy. In this context, this study develops a model to classify the productive potential of coffee trees based on hierarchical landscape analysis and coffee plant metrics, applied to different farms in the Córrego Feio watershed, Patrocínio, Minas Gerais. We employed a model based on landscape metrics (slope, water flow, vegetation, and slope shape), inspired by Ross's (1994) proposal for Environmental Fragility. Each variable was reclassified according to hierarchical levels from the literature and empirical observations of the area. The data were integrated to generate two products: Factor T, which represents the potential of the area based on static soil and relief variables, and Calculated Potential, which combines Factor T with the NDVI vegetation index for a dynamic assessment. The application of the model demonstrated a strong capacity to interpret the qualitative hierarchy of productive potential, supporting the delineation of differentiated management zones. The results indicated that productive potential is more strongly associated with soil and topographic factors than with the vegetation index. It is concluded that the proposed method is a valuable tool for precision agriculture, allowing the delineation of management zones for the application of inputs in a more efficient and sustainable manner, contributing to resource conservation and environmental protection.

**Key words:** Arabica coffee; environmental fragility; hierarchical analysis; vegetation index; watershed.

## 1 INTRODUCTION

The coffee culture is sensitive to environmental factors and conditions, such as temperature, water availability and altitude (Petek, Sera & Fonseca, 2009). This implies that changes in these factors can lead to damage and losses, as well as it is possible to infer that natural variations in edaphoclimatic factors will influence the productive factors of the crop (Ovalle-Rivera et al., 2015; Petek, Sera & Fonseca, 2009; Reay, 2019; Sediyaama et al., 2001). These facts lead us to the need to understand the behavior of the coffee plant regarding environmental variations, as well as the creation of models that allow to determine and/or predict the response of the coffee plant regarding the environment. This demand is accentuated in view of the need for the execution of an increasingly sustainable agriculture with the scenario of climate change and global warming (Läderach et al., 2017; Saito, 2004).

Arabica coffee (*Coffea arabica* L.) is one of the most important agricultural commodities in the world, playing a major role within the world economy (Talbot, 2011). In this scenario, Brazil stands out as the largest producer and exporter of the grain in the world, highlighting the importance of this crop for the country. Even more specifically, the municipality of Patrocínio, Minas Gerais, is the largest national producer, with approximately 60,000 hectares planted in the 2020/21 harvest (Emater, 2022). The municipality is part of the Cerrado

Mineiro Designation of Origin in the state of Minas Gerais. In 2025, the state's estimated production was 25,170.90 thousand bags, while the total national production reached 35,763.10 thousand bags, accounting for approximately 70% of all Arabica coffee in Brazil (Companhia Nacional de Abastecimento - CONAB, 2025). Both in the municipality of Patrocínio, and within the Cerrado Mineiro region, coffee farming, along with the production of annual grains such as soybeans and corn, is one of the main agricultural products responsible for the economy.

In this regard, a model that allows predicting the productive potential of areas, as well as the variations of this potential within plots would allow farmers to make better decisions regarding the management of fertilization and soil correction, resulting in a better direction and rational use of these inputs, and consequently, monetary savings and less aggressiveness to the environment, both by saving the extraction process of these inputs (mining) and by avoiding soil and groundwater contamination.

In order to exist the management of agricultural areas in a more rational way, it is necessary to understand the variations that occur in the areas spatially, enabling the management to be done in a balanced way for each area reality and its due agricultural potential (Bongiovanni & Lowenberg-Deboer, 2004; Li et al., 2013), which generates the rational consumption of inputs in crops, saves money, boosts productivity, and

preserves the environment, both by reducing contamination by inputs, less damage to the soil due to less machine traffic, and by the greater possibility of preserving native vegetation areas (Bongiovanni & Lowenberg-Deboer, 2004; Gardezi & Stock, 2021; Zhang, Wang & Wang, 2002). This concept of farm management executed according to variability is Precision Agriculture (PA) (Zhang, Wang & Wang, 2002).

The creation of models of wide use for coffee farming is an undeniably difficult task because there are several factors that influence the productivity of the crop. These factors are related to the genetics of the plant, the cropping system and management used, the age of the crop combined with its vigor (genetics), and the chemical, physical and biological properties of the soil (Cunha et al., 2023; Faria et al., 2024; Kouadio et al., 2018; Salgado et al., 2014). Besides this, the biennial nature of the crop is another factor to be observed when we create a crop prediction model for the coffee crop (Manoel, Rosa & Queiroz, 2024; Brunsell, Pontes & Lamparelli, 2009). Within the same property, or more specifically, within the same plot, the cultivation system, climate, management and genetics of the plant are practically constant, and thus the definition of productivity would be a combination of the influence of soil variations, as well as plant vigor, which can be inferred from remote sensing products, such as digital elevation models (DEM) and multispectral images, facilitating the process.

In parallel, the concept of environmental fragility, in the model proposed by Ross (1994), treats environmental fragility in two different stages, namely: Potential environmental fragility, which is based on short-term immutable factors related to relief and soil formation, such as slope, soil classification and slope shapes, and therefore deals with the natural fragility relative to preserved environments, without anthropic interference. The emerging environmental fragility, on the other hand, deals with the interaction between the factors previously mentioned with the changes in land use and occupation caused by human as he uses the environmental resources available (Manfré et al., 2013; Ross, 2012).

Similar to the behavior of environmental fragility, the dynamics of productivity of agricultural areas occurs, which is initially influenced by climatic factors, which can be considered constant comparing the same region at the same time, factors related to the plant itself and its genetics, and also those arising from the formation of soils, which relate directly to the relief (Schaefer, 2013; Vidal Torrado, Lepsch & Castro, 2005), these being the chemical properties, such as Cation Exchange Capacity (CEC) and Buffer Power, physical properties, such as soil porosity and aggregation, and organic properties, such as the amount of humus. Combining these factors, the fourth and last pillar of productivity would be the management, which interacts with the soil factors generating the productivity of an area. Along this line of thought, we could adapt the model proposed by Ross (1994) in order to predict the

productive dynamics of coffee by dividing the productivity of an area in a similar way to environmental fragility: in potential productivity (or productive potential), based on the factors that influence soil properties, such as relief and soil orders (formation factors); and in emergent productivity (or response to productive potential), which would be the interaction of potential productivity with the level or quality of vegetation of the plantation in each location.

Our work then seeks answers to the questions: Is it possible to identify and hierarchically classify the factors that influence soil properties and relate them to changes in the productivity potential of a coffee area? Can we relate these factors together, seeking to quantify this potential? Finally, is it possible to use remote sensing means to define the variations of vegetative qualities and estimate what would be the emerging productivity? How does this process influence the conservation of native vegetation areas and improve the creation of a more sustainable coffee production?

Thus, the general objective of this study is to develop and test a model based on hierarchical landscape analysis to classify the productive potential of coffee plants using environmental and vegetation metrics.

## 2 MATERIAL AND METHODS

### 2.1 Study Area

The study area, with a total of approximately 9.400 hectare is a watershed, belonging to the Córrego Feio, and is located on the northeast bank of the urban area of the municipality of Patrocínio, Minas Gerais, Brazil. Figure 1 illustrates the location context, as well as the study area. Four rural coffee producing farms were used for the study, these being named here farms A, B C and D.

Farm A, located in the eastern portion of the watershed, of medium-low potential and emerging environmental fragility, is a small farm consisting of 8 plots. The coffee trees on this property are generally old and with failure problems in some plots, however, some trees have been replanted. It is interesting to note that this is a farm with common management of the plots and that has been on an organic coffee farming system for 7 years.

Farm B has the highest level of environmental fragility among the studied farms, located in the central portion of the watershed, in a lower area, with higher declivity and shallower soils. It is a small property with 5 plots, of common management under traditional system of bush management (clean road).

Farm C is located in the area of least environmental fragility among those studied, in the northern portion of the watershed. It is an area of high altitude, flat terrain and predominance of latosols. There is less uniformity in the

management of the areas, with pruning scheduled according to vigor, and scheduled replanting, which implies younger crops, as well as variations in fertilization. Also, there is a management using animal waste. It is a medium-sized farm with a high technological management level.

Farm D is in the transition zone between the northern area, of less environmental fragility, and the central area of the watershed, of high fragility. It is a small property composed of 4 plots, 2 of which are young coffee trees (5 years old) and 2 of older ones. As for management, it is similar to farm C.

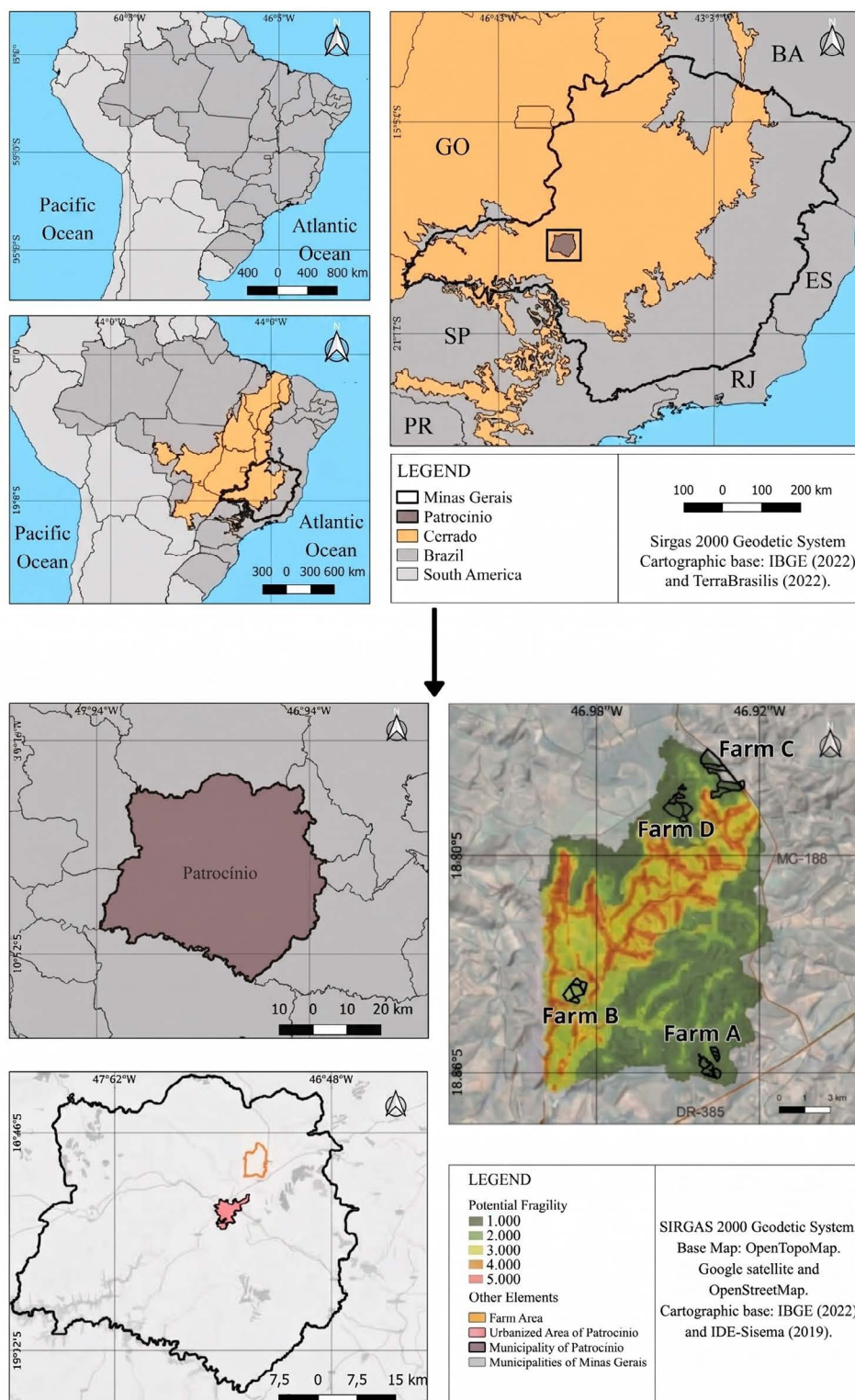


**Figure 1:** Context of the Study Area/Farms location on the Potential Environmental Fragility map.

Source: The authors (2023).

## 2.2 Method

The flowchart in Figure 2 describes the steps of the method used to generate the products that allowed us to analyze the relationship between the fragility of areas with the productivity of coffee trees in the Córrego Feio watershed.

In this work we adopted the method proposed by Ross (1994) adapted to meet the reality of the study area for parameters associated with coffee productivity. Originally, the method proposed by Ross (1994) uses as parameters that influence the environmental fragility of an area the slope, the type of soil and the use and occupation of the area, and the combination of fragility generated by each of these factors results in environmental fragility classes. Our adaptation of the model relies on the addition of the variables of water flow power, surface temperature, and slope shape (Valeriano, 2008). Considering that in our application of this model there is no difference between land use and land occupation, we performed the substitution of this variable by coffee tree vegetation levels, measured from the Normalized Difference Vegetation Index (NDVI). It is worth noting that the method proposed by Ross (1994) was used because it is widely applied in environmental research. In addition, the adaptations proposed by Valeriano (2008) allowed the incorporation of new variables, expanding the analytical capacity of the model.

In addition to the analysis presented in this study, with parameter variations according to our contribution, this study also used as a general reference, at the watershed level, the results

obtained by Cunha and Bravo (2022) regarding the survey and analysis of the watershed's environmental fragility, as well as the conservation levels of reserve and permanent preservation areas. A comparison between the maps obtained in the present work and the levels of conservation was carried out to allow an understanding of the relationship between the products generated.

The delimitation of coffee plantation plots was based on interviews with rural producers, who helped in the delimitation and provided historical productivity data for each plot. In the case of lack of actual quantitative data in the form of bags processed per hectare, a ranking of the areas was performed with the producer, creating a hierarchy of the most productive area, following to the least productive, according to the producer's perception. Each farm was separated in its own vector file, and these vectors were used ahead as delimiters for data extraction used in the analyses.

More specifically, a survey of the agricultural potential of the coffee areas was carried out, here called T Factor, based on the method proposed by Cunha et al. (2023), which considers in its calculation classes calculated from slope parameters, surface temperature, water flow power and slope shape (Table 1). The interval values for the formation of the classes were defined based on empirical observation and a survey of the literature regarding the relationship of each variable in relation to the coffee production capacity. After defining the T Factor, the NDVI was added to the model, aiming to adapt the potential to the current dynamics of the plantation. It is important to emphasize that this analysis was performed internally to the farm data, comparing

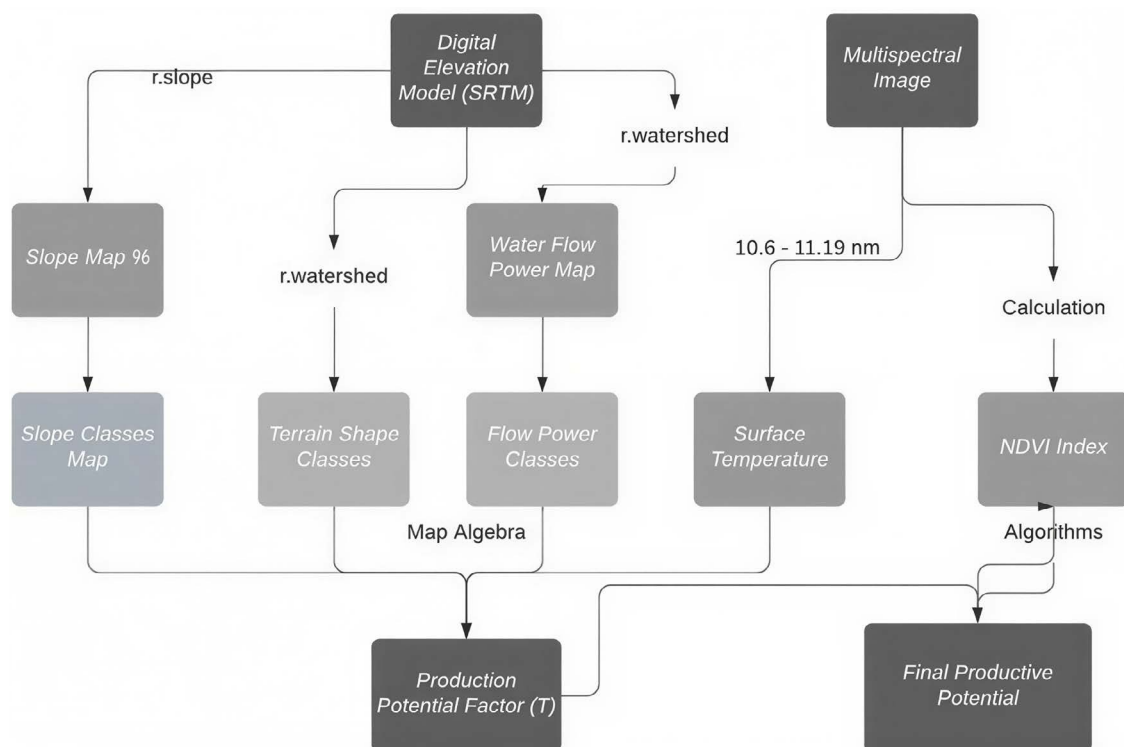


**Figure 2:** Flowchart of the processes used in the method.

Source: The authors (2023).

different plots of the same farm, without comparing different farms. This choice is due to the heterogeneity observed between the technological and management levels between different farms, which would certainly lead to errors in reading the results if the data were compared in only one set.

As materials, for the confection of the slope, flow power and slope shape maps, the SRTM digital elevation model and the available map of slope shape classification, available in the Topodata-INPE initiative index map (Valeriano, 2008), were used. The MDE was processed by the *r.watershed* tool, resulting also in the flow power maps. As for the NDVI and the surface temperature map, images obtained by the OLI and MIRS sensors respectively were used, both are on-board sensors of the Landsat-8 satellite. It is worth noting that the temporal treatment of NDVI was established for the end of April and the beginning of May, as this is a period of high physiological activity in coffee plants, resulting in higher NDVI values. The images were obtained and pre-processed from the Semi-automatic Classification Plugin, generating the corrected maps of bands 5 and 4, for NDVI and the corrected map for Celsius, in the case of band 10. All products obtained in these processes were reclassified according to the parameters in Table 1 from the *r.reclass* tool.

After defining the potential environmental fragility of the coffee areas of the watershed, considering the parameters soils, slope, distance from drainage and slope shape, and considering that the use and occupation is in this case a constant (Coffee Plantations), for the classification of the level and quality of land cover a classification was used, defined by us, through the classification of the NDVI index values, which was calculated at this time from images captured by the MSI sensor (Multispectral Instrument) of the Sentinel 2 satellite (ESA) during the 4 years of study (2017, 2018, 2019 and 2020). The acquisition of the images was done on the EarthExplorer platform (US, 2020).

The images used in this work were preprocessed within QGIS (Semi-automatic Classification Plugin (SCP), based on the corresponding MTL file data. In addition to

atmospheric corrections, this step was used to transform the raw data to percentage reflectance values. Subsequently the images were registered from the Georeferencer plugin to obtain perfect overlap.

For the classification of slope parameters, as well as slope shapes, the product offered for download from the Topodata catalog (Valeriano, 2008) was used, which has products in .TIFF format processed from the digital elevation model SRTM (Shuttle Radar Topographic Mission). The data obtained were extracted for the contour of the coffee areas under study and reclassified according to Table 1 for slope and according to the empirical analysis of the slope forms, afterwards. The drainage distance map used was obtained from the *r.grow.distance* tool, based on the drainage raster of the watershed. The entire reclassification process was carried out using the *r.reclass* tool.

We then used the class values in the calculation of the T-Factor, which was defined by us as being a ratio between the sum of the increasing ranking factors (slope and temperature) and the sum of the decreasing ranking factors (flow power and terrain shape), as shown in Equation 1.

$$T = \frac{\text{Slope} + \text{Temperature}}{\text{Flow} + \text{Shape}} \quad (1)$$

It should be noted that, to obtain the NDVI index, Equation 2 was used.

$$NDVI = \frac{NIR - RED}{NIR + RED} \quad (2)$$

To obtain the final value of estimated calculated potential (CP) the sum of the NDVI value obtained with the T factor was performed, as shown in Equation 3.

$$CP = T \text{ Factor} + NDVI \quad (3)$$

**Table 1:** Hierarchical categories for coffee productivity in view of the factors slope, flow power and terrain shape, adapted from the proposition of Ross (1994).

| Hierarchical Categories | Slope (%)           | Flow Power (W/m) | Terrain Shape (Topodata Classes) | Temperature (Kelvin – B10 transformed) |
|-------------------------|---------------------|------------------|----------------------------------|----------------------------------------|
| Very Bad                | >25<br>(1)          | >8<br>(5)        | 8 and 9<br>(5)                   | >20.13 (1)                             |
| Bad                     | 16-25<br>(2)        | 6-8<br>(4)       | 6 and 7<br>(4)                   | 19.9-20.13 (2)                         |
| Medium                  | 12-16<br>(3)        | 4-6<br>(3)       | 4 and 5<br>(3)                   | 19.67-19.9 (3)                         |
| Good                    | 6-12 and 0-3<br>(4) | 2-4<br>(2)       | 1 and 3<br>(2)                   | 19.44-19.67 (4)                        |
| Very good               | 3-6<br>(5)          | 2-4<br>(1)       | 2<br>(1)                         | 19-19.44 (5)                           |

Source: The authors, adapted from Ross (1994).

Another product used in the present work was the zoning based on the soil map, in order to compare the quality and productivity between different areas and farms that are contained in different zones of environmental fragility. In this case, there are two zones of low fragility and two zones of high fragility, as reported by Cunha and Bravo (2022).

### 2.3 Analysis of the results

Initially, we analyzed the interaction between slope forms and areas of highest productivity, in order to create the hierarchy of this parameter. We analyzed the existing relation between the occurrence of potential fragility classes and the level of productivity, among different coffee areas. We also analyzed if in a situation of the same potential environmental fragility, the NDVI value directly influenced productivity, that is, if in the same area, the emerging environmental fragility is directly proportional to productivity.

The statistics used for the analysis of different farms varied according to the level of data available regarding the productivity of the plots in each case. For farms A and B, only a qualitative hierarchy of the productivity level of the plots was provided, and in this case, we conducted the discussion based on descriptive statistics of the data for each plot. For farm C, with data available in a quantitative manner, analysis was performed using simple linear regression and RMSE, in addition to the discussion of the data.

## 3 RESULTS

For farm A, we observed that the averages of the calculated levels of factor T corresponded to the productive levels indicated by the data, except for plot 4, which although classified by factor T as having the highest productive potential, in practice, showed itself as seventh in the productive hierarchy of the farm. In order, the production hierarchy of the fields according to the field data would be Fields 3, 5, 8, 7, 2, 4, 6, and 1, respectively. The hierarchy observed according to factor T was: 4, 3, 5, 8, 7, 2, 4, 6, and 1.

It is worth noting that this plot is planted with the oldest coffee tree on the farm, and has many planting failures, resulting in a much smaller population compared to the others, which may be the justification for the error observed in the classification. Here, once again, we emphasize the need for some homogeneity in the farm management practices for this type of modeling to be effective, with similar cultivars, management systems, and age of crops. In the case of farm A, the plots are old coffee trees and management is common to all areas, and organic agriculture has been practiced for 5 years. Field 1 was replanted in the 2019/20 crop year.

We also observed that, in this specific case, there was a closer approximation to the reality of plot 4 when corrected

according to the NDVI value for the final productive potential. However, for the other areas, the final classification showed more errors than the one according to the T factor.

Here we emphasize the idea that the T factor is an estimate of the potential of an area to productivity and that the response or not of its potential is due to the specific management of those areas, which shows the potential of the method mainly for the formation of management zones according to the topography. Another point to be highlighted is that the NDVI, as expected based on literature (REF), shows no direct relationship with productivity for coffee culture, except in the case of plot 4, where the response is mainly due to the stand, and this in turn, is decisive in the production levels of this plot. Figure 3 represents the values of the T factor and the final potential calculated following the productivity hierarchy according to the data. The maps representing the spatial distribution of each class in each of the variables analyzed for Farm A are shown in Figure 4.

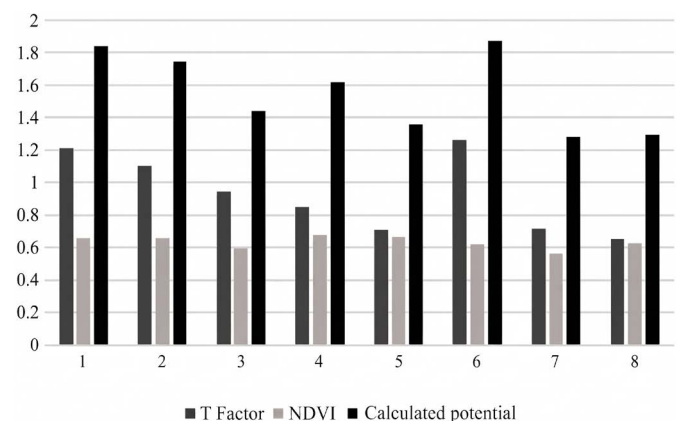


**Figure 3:** T-factor, NDVI and Calculated Potential for Farm A according to productivity hierarchy in the year 2020.

Source: The authors (2023).

For Farm B we observed a good fit in the model in estimating the potential of the plots, being that for factor T there was a failure in the hierarchy between plots 2 and 3, which were inverted in the ranking order. In this case, the addition of NDVI to the model adjusted in a way to correct the hierarchy, and the final calculation of potential was more appropriate to what was observed in the field. In order, the productive hierarchy of plots according to field data would be: Plots 4, 3, 2, 1, and 5, respectively. The hierarchy observed according to the T factor was: 4, 2, 3, 1 and 5, and for the final calculated potential the hierarchy was adjusted to be identical to that of the field data. Figure 5 shows the graphical representation of the values of the T-factor parameters, NDVI and calculated potential according to the productive hierarchy on the X-axis, while Figure 6 shows the spatial representation of the class distribution of these parameters, for Farm B.

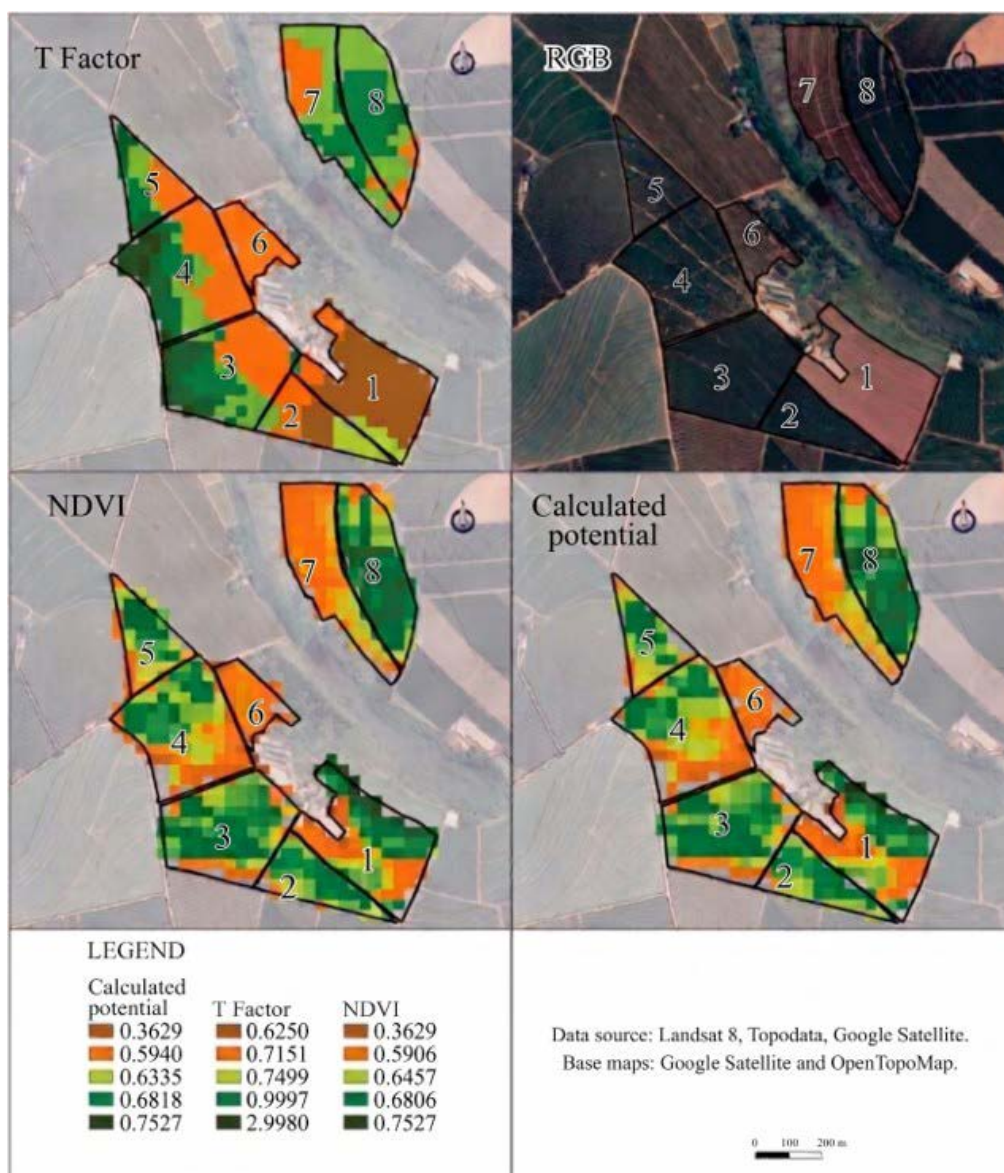


**Figure 4:** Visualization of T factor (A), RGB (B), NDVI (C) and Calculated Potential (D) for Farm A in the year 2020.  
Source: The authors (2023).

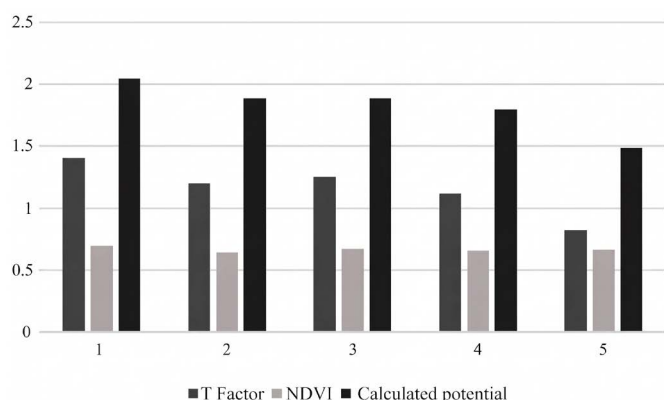


**Figure 5:** T-factor, Calculated Potential and NDVI for Farm B according to productivity hierarchy in the year 2020.  
Source: The authors (2023).

It is important to note that for this farm there is a good uniformity of management, with crops of similar ages, common bienniality and similar cultural treatments between different plots. Another interesting point to note is the possibility that, in cases such as farm B, the model points to the limitation of the potential of certain areas, where there is probably a waste of inputs, especially fertilizers, which could generate responses in terms of productivity if reallocated to areas with greater potential.

For farm C, the level of correlation between T-factor variables and calculated Potential was lower than that observed in farms A and B. This behavior is probably due to the greater heterogeneity of management and age among the plots. When we observe the graph in Figure 7, we can see that especially for

#### 4 DISCUSSION

plots 2 (70.23) and 4 (28.94) there is a break in the behavior of the relationship. It is important to note that in this case, plot 2 is a young plot, of second harvest, and therefore at the peak of its productive potential and vigor, and plot 4 is the oldest, with the observed productivity data appearing in the average of two harvests after pruning (drastic pruning), which justifies its low productivity in view of its probable potential. The other plots, used later in the regression analysis have greater homogeneity among themselves in terms of age and spacing used.

Based on these observations, plots 2 and 4 were left out of the quantitative correlation analysis. We observed a polynomial fit of degree 2 with  $R^2$  of 0.8629 for the relationship between factor T and productivity, but with a rather low correlation value with NDVI, which provided a decrease in the  $R^2$  value when adjusted for calculated potential to 0.668. The RMSE values were 29.7 and 31.5 bags per hectare for T factor and calculated potential, respectively. The graph in Figure 8 shows the regression relationship between the variables observed by average productivity (bags / hectare) and factor T.

Thus, in this research it is understood that the model has great potential for final adjustments where there is similarity in management, age, and spacing, which does not occur on Farm C. There is great diversity in ages, management techniques, and spacing, resulting in low correlation, especially in relation to NDVI, compromising the result obtained by the model. In any case, it is possible to observe again that the classification of the terrain according to topographic and climatic parameters allows the formation of management zones according to the potential of the areas.

Considering the management levels and behaviors observed in the relationship between the reading of adapted environmental fragility parameters and actual productivity, whether classificatory or quantitative, a greater correlation was found between production levels and factors related to topography than to vegetative index readings, in this case NDVI, for coffee cultivation.

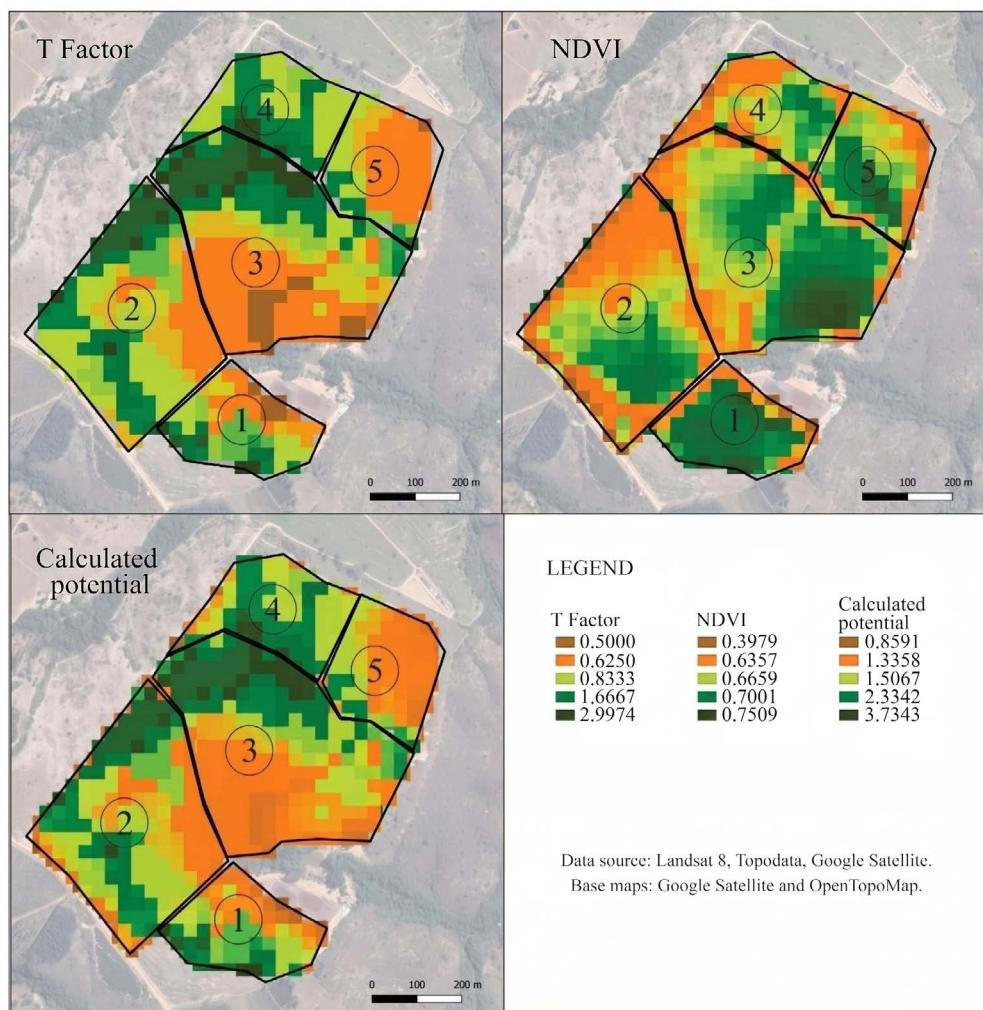


**Figure 6:** Visualization of T-factor, NDVI and Calculated Potential for Farm B in the year 2020.

Source: The authors (2023).

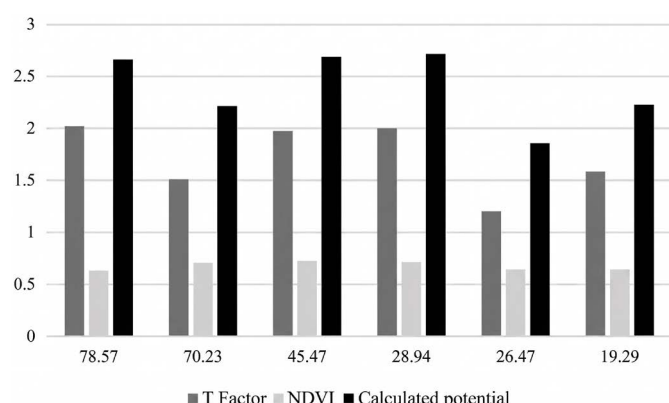


**Figure 7:** T-factor, Calculated Potential and NDVI for Farm C according to yield hierarchy in year 2020.

Source: The authors (2023).

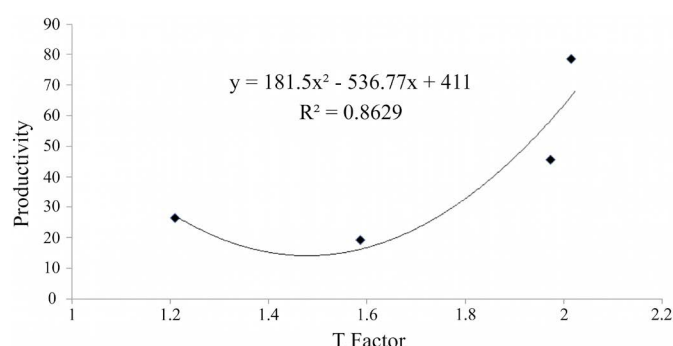


**Figure 8:** Graph of the Regression Analysis between T-Factor and Productivity for farm C.

Source: The authors (2023).

These results corroborate the literature that points to the difficulty of reading coffee productivity from the NDVI due to issues of age, phenology, biennially, pruning, and different cultivars (Hunt et al., 2020; Vieira Júnior et al., 2019).

On the other hand, we emphasize that topography and the variables directly influenced by it, such as surface temperature and water flow power, have a decisive influence on the productive potential of a given area, as these are determining factors in soil formation (Rossi & Queiroz Neto, 2001; Sanchez et al., 2005; Vidal Torrado, Lepsch & Castro, 2005).

Although it is complicated to develop models that allow for estimating coffee productivity, we emphasize the possibility of using the parameters mentioned here to establish management zones and rational soil use according to its potential.

Thus, the study demonstrates the possibility of identifying and hierarchically classifying environmental parameters according to their influence on coffee productivity, allowing different locations to be qualified based on their potential. This highlights the potential use of the method we propose for the delineation of management zones for coffee cultivation, which may serve as a tool to support more sustainable production.

As for quantifying potential, based on the data collected here, we cannot broadly affirm this possibility, although Cunha et al. (2023) successfully demonstrated its use for the case study. The quantification or estimation of coffee production is a delicate subject, considering the nuances of the crop in terms of its phenology and the direction of physiological drains, which makes the task at hand difficult. Directly, we did not find here, or in the work of Cunha et al. (2023), a direct relationship between production levels and NDVI.

It should be noted, this study has enabled us to understand that there are spatial variations in productivity at different levels caused by soil variations, which in turn can be estimated by reading landscape features, as proposed by Ross (1994), which is a useful tool, especially in Precision Agriculture.

From this point on, it would be important to compare the results of the pixel-by-pixel models for the purpose of their final validation. In any case, we emphasize the possibility of using landscape reading to create specific management zones for coffee cultivation.

## 5 CONCLUSIONS

This research concludes that the productive potential of areas is more related to soil and topography factors (Factor T) than to vegetative vigor measured by satellite (NDVI). In addition, the method is a useful tool for Precision Agriculture, as it allows the creation of “management zones,” which helps producers apply inputs in a more rational and sustainable manner, saving resources and preserving the environment. It should be noted that the next step in this study would be an even more detailed validation, with a “pixel-by-pixel” comparison of the data.

## 6 AUTHORS' CONTRIBUTIONS

Conceptual idea: Cunha, J.E.F.; Martins, G.D.; Bravo, J.V.M. Data collection: Cunha, J.E.F. Methodology design: Cunha, J.E.F.; Martins, G.D.; Bravo, J.V.M. Data collection: Cunha, J.E.F. Data analysis and interpretation: Cunha, J.E.F.; Segismundo, M.D. and Writing and editing: Cunha, J.E.F.; Segismundo, M.D.

## 7 DATA AVAILABILITY STATEMENT

Data available upon request to authors.

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