RESEARCH ARTICLE

Recommendations for the Regionalizing of Coffee Cultivation in Colombia: A Methodological Proposal Based on Agro-Climatic Indices

Juan Carlos García L. 1,2*, Húver Posada-Suárez3, Peter Läderach4

1. Production and Productivity Program, National Center for Coffee Research (CENICAFÉ), Manizales, Colombia, 2. Agricultural Sciences Faculty, Universidad de Caldas, Manizales, Colombia, 3. Technical Division, National Federation of Coffee Growers of Colombia (FNC), Santafé de Bogotá, Colombia, 4. Decision and Policy Analysis (DAPA), International Center for Tropical Agriculture (CIAT), Cali, Colombia

* juan.garcia@cafedecolombia.com.co

Abstract

The Colombian National Federation of Coffee Growers (FNC) conducted an agro-ecological zoning study based on climate, soil, and terrain of the Colombian coffee-growing regions (CCGR) located in the tropics, between 1° and 11.5° N, in areas of complex topography. To support this study, a climate baseline was constructed at a spatial resolution of 5 km. Twenty-one bioclimatic indicators were drawn from this baseline data and from yield data for different coffee genotypes evaluated under conditions at eight experimental stations (ESs) belonging to the National Center for Coffee Research (CENICAFÉ). Three topographic indicators were obtained from a digital elevation model (DEM). Zoning at a national level resulted in the differentiation of 12 agro-climatic zones. Altitude notably influenced zone differentiation, however other factors such as large air currents, low-pressure atmospheric systems, valleys of the great rivers, and physiography also played an important role. The strategy of zoning according to coffee-growing conditions will enable areas with the greatest potential for the development of coffee cultivation to be identified, criteria for future research to be generated, and the level of technology implementation to be assessed.

Introduction

Coffee is one of the most important commodities in the international agricultural market and a source of income for many countries in Asia, Africa and Latin
America. In the period from 1965 to 1995, Colombia contributed to an average of 13.5% of world production, and between 2000 and 2011 to 7.6% [1]. The coffee crop (*Coffea arabica*) represents 17% of Colombia’s agricultural gross domestic product and constitutes 9% of its agricultural output. About 2.2 million people depend directly on coffee for their livelihoods, this figure is equivalent to 25% of Colombia’s rural population and 31% of its national labour force employed in agriculture [2]. Much of this employment is seasonal, part-time and informal [1], with jobs directly generated by the coffee industry distributed among the following activities: investment (3.9%); management (65.2%); harvest (29.5%); and postharvest (1.4%) [3].

The Colombian coffee-growing regions, lie between 1° and 11.5° N, and 72° and 78° E, encompassing the Western, Central, and Eastern Andean Ranges, as well as the mountain system of the Sierra Nevada of Santa Marta in northern Colombia [4]. Coffee plantations are found at altitudes between 800 and 2000 masl.

CENICAfe has experimental stations (ESs) located in important coffee-growing areas, in the states of Caldas, Antioquia, Tolima, Risaralda, Cauca, Cundinamarca, Cesar and Quindío. These highly technological coffee farms include the Central Experimental Station Naranjal, ES Rosario, ES La Trinidad, ES La Catalina, ES El Tambo, ES Santa Bárbara, ES Pueblo Bello and ES Paraguacuítio.

In Colombia, the intertropical convergence zone is responsible for the existence of two dry and two wet seasons per year [4, 5, 6]. These seasons determine the two coffee harvesting periods, with variations in the northern and southern extremes of the CCGR where a mono-modal rainfall distribution results in a concentrated harvest [4, 5, 6, 7]. The relative intensity of the dry season (1 to 2 months) has repercussions on the production cycle, from flowering to harvesting, with variability observed between 215 to 240 days at 5° N and 11° N, respectively [5].

Colombia is characterized by climatic complexity, with temporal variability rendering the association of a pattern of reaction to an agronomic variable with given climatic elements, as difficult. The country’s climate was first classified by Hurtado into seven groups using Thornthwaite’s classification criteria [8]. Later, Baldión and Hurtado [9] proposed five groups based on agro-climatic indices derived from hydric balances obtained through Palmer’s method [10] which collected climate information over a period of 10 years. More recently, Malagón et al. introduced the concept of bioclimatic factors related to soil formation, emphasizing the importance of temperature and soil moisture in soil evolution [11].

The FNC studied soils, climates, and terrains in the coffee-growing regions defined by the 1980–1981 Coffee Plantations Census. In total, 86 agro-ecological zones known as *ecotopes* were identified where coffee trees responded to their environment in similar ways and where geographic area was homogenous and continuous [4].

In several studies in Brazil, the use of indicators for coffee has permitted the following activities:

- Estimation of the length of different phenological periods [12, 13, 14]
• Development of agro-climatic models for estimating productivity [15, 16]

• Construction of agro-climatic zones for delimiting homogeneous areas by their performance and defining their limitations, advantages, and risks [17, 18]

• Design of frost-alert systems [19]

In Colombia, indices have been constructed taking into account the crop’s physiological periods, in particular, flowering [20, 21], fruit development [7], and the entire cycle from planting to harvest [22]. These indices help to establish criteria for season planning [23, 24, 25].

This research aims to identify coffee-growing areas with similar agro-climatic characteristics and determine if the scope of current research is sufficiently regional in terms of its coverage. This will contribute to important future decision-making processes by coffee growers in the diverse regions of the country.

Materials and Methods

The methodology consisted of defining and acquiring the baseline and the bioclimatic indicators, and then incorporating field attributes of the coffee-growing regions. This methodology was adopted following previous analysis which used climatic elements such as annual precipitation and temperature. The results of the agro-climatic groups (ACGs) obtained are presented in a later section of this paper.

2.1. Physiological data

2.1.1. Information on harvesting patterns

Based on Arcila et al. [23], a harvest raster adjusted to the Colombian coffee-growing regions was generated using two criteria: the main harvest predominating in the first semester (between January and June) and the main harvest predominating in the second semester (between July and December). These criteria were used to construct the coffee tree’s physiological stages (detailed below), with their corresponding peak harvesting months for the zones with first and second semester harvests (May and October, respectively).

2.1.2. Consolidation periods and physiological phases

Three physiological phases were defined as occurring before the main harvest, relating to the bioclimatic indices described above:

a. *Four months before maximum flowering* (which defines the principal harvest): hereafter referred to as stage 1. This phase begins with the flowering induction, followed by the appearance of latent floral buds, and finally the occurrence of flowering after a rainfall. [20, 26].

b. *First four months of berry development* (towards the principal harvest): hereafter referred to as stage 2. In this phase, the completion of the early phases of coffee berries development towards final seed size take place. [7, 26].
c. *Four months before the principal harvest:* hereafter referred to as stage 3. In this phase coffee berries acquire their uniformity and final weight. [7, 26].

2.2. Environmental data

2.2.1. Climate information
More than 20 years of historical information on precipitation, temperatures (minimum, mean, and maximum), and solar brightness from 80 meteorological stations of the FNC’s coffee climate network was used for this study. Daily information from the coffee-growing regions was modelled using Hutchinson’s methodology [27] together with the ANUSPLIN interpolator, version 4.3 (which uses geographic coordinates and terrain elevation as independent variables). This procedure has been used in global studies undertaken by Hutchinson [28] and others [29, 30, 31, 32, 33, 34]. Usually, the strategy of generating daily data requires the adaptation of programming routines in the R Platform [35, 36].

2.2.2. Information on the water retention capacity of soil
Soil water retention (SWR), also known as maximum storage in hydric balance, is defined in terms of field capacity (fc), permanent wilting point (pwp), apparent density (ad), and depth of the coffee tree’s root zone (d). The formula is as follows:

\[
SWR = \frac{(fc - pwp) \times ad \times d}{10} \quad [37]
\]

Information on the shape of soil units (digitized from findings in FNC’s framework study on coffee ecotopes [4]) was crossed with the results of the physical characterization (fc, pwp, ad, d) carried out by Suárez [38] on some of these units. A raster with information on soil water retention was generated. To assure the zone’s continuity, in areas not covered by Suárez’s study [38] a theoretical daily retention capacity of 50 mm was assigned, based on test results from hydric balances of CENICAFE’s Agroclimatology Research Group.

2.2.3. Generating buffer zones adjusted to CCGR
Following the delimitation of coffee-growing plantations or farms, additional bordering areas or buffer zones of 3 km wide were generated to cover the edges of coffee-growing regions and facilitate generation of daily information on bioclimatic indices. Through this information, 5789 pixels or centroids across CCGR were obtained.

2.2.4. Constructing the bioclimatic indices
Twenty one bioclimatic indices were obtained and classified into 3 groups: 9 moisture indices, 6 solar brightness indices and 6 thermal indices. Most bioclimatic indicators were developed on a point basis, given that they were associated with, for example, meteorological stations collecting largely pluviometric information together with historical information.
**Moisture indices:** To calculate the daily hydric balance, a routine was generated in R Platform [35], according to the methodology described and adapted by Jaramillo et al. [39, 37]. At the end of the routine, the soil water index (SWI) was obtained (i.e. the difference between real evapotranspiration \( [ET_r] \) and potential evapotranspiration \( [ET_p] \)). Its values are expressed between 0 and 1, where 0 corresponds to completely dry soil, and 1 to all the porous spaces being filled. Moderate hydric deficit (MHD) falls in the range \( 0.5 \leq SWI \leq 0.8 \), while severe hydric deficit (SHD) is established at \( SWI < 0.5 \). For each stage, the number of days, and the accumulated daily rainfall (ppt) observed satisfied the criteria for one of the two indices. The following bioclimatic indicators were generated:

\[
\begin{align*}
\text{ppt1} &= \text{accumulated rainfall, stage 1} \\
\text{ppt2} &= \text{accumulated rainfall, stage 2} \\
\text{ppt3} &= \text{accumulated rainfall, stage 3} \\
\text{md1} &= \text{number of days with MHD, stage 1} \\
\text{md2} &= \text{number of days with MHD, stage 2} \\
\text{md3} &= \text{number of days with MHD, stage 3} \\
\text{sd1} &= \text{number of days with SHD, stage 1} \\
\text{sd2} &= \text{number of days with SHD, stage 2} \\
\text{sd3} &= \text{number of days with SHD, stage 3}
\end{align*}
\]

**Solar brightness indices:** An R Platform routine was generated to calculate solar radiation (SR), using Campbell and Donatelli’s methodology as described by Meza and Varas [40] and Rivington et al. [41, 42]. Solar brightness (SB) is calculated from SR, based on (a) coefficients \( a \) and \( b \) obtained by Gómez and Guzmán [43], using the Ángström formula, and (b) the methodology presented in Appendix C of the *Atlas de Radiación Solar de Colombia* [44]. The difference between the duration of the astronomical day in hours and SB gives the solar brightness deficit (SBD). For each of the physiological stages established, the hours of SB were counted, together with days where SBD was \(<7.2 \) [21], to generate the following bioclimatic indicators:

\[
\begin{align*}
\text{sb1} &= \text{accumulated SB, stage 1} \\
\text{sb2} &= \text{accumulated SB, stage 2} \\
\text{sb3} &= \text{accumulated SB, stage 3} \\
\text{bd1} &= \text{number of days with SBD at } <7.2, \text{ stage 1} \\
\text{bd2} &= \text{number of days with SBD at } <7.2, \text{ stage 2} \\
\text{bd3} &= \text{number of days with SBD at } <7.2, \text{ stage 3}
\end{align*}
\]

**Thermal indices:** The indices for Thermal Amplitude (TA) or thermal gradient \( (T_{\text{max}} - T_{\text{min}}) \) and Thermal Time (TT) or degree days \( (T_{\text{mean}} - T_{\text{base}}) \) were generated from information on maximum \( (T_{\text{max}}) \), minimum \( (T_{\text{min}}) \), and mean \( (T_{\text{mean}}) \) temperatures, and with the lowest base temperature \( (T_{\text{base}}) \) of 10°C, as determined for coffee trees in Colombia by Jaramillo and Guzmán [22]. For each
of the three physiological stages proposed, the TT and the number of days with TA at<10 were accumulated [21]. The following bioclimatic indices were generated:

\[ 
\begin{align*}
\text{tt1} & = \text{accumulated TT, stage 1} \\
\text{tt2} & = \text{accumulated TT, stage 2} \\
\text{tt3} & = \text{accumulated TT, stage 3} \\
\text{ta1} & = \text{number of days with TA at <10, stage 1} \\
\text{ta2} & = \text{number of days with TA at <10, stage 2} \\
\text{ta3} & = \text{number of days with TA at <10, stage 3}
\end{align*}
\]

### 2.2.5. Incorporating the bioclimatic indices to the geo data base

As well as constructing the 21 bioclimatic indices, each of the 5789 centroids was associated with the physiographic components of aspect, shade, and slope, thus incorporating 24 attributes per pixel. This also served to geo-reference the pixels.

### 2.2.6. Topographic information

Terrain attributes such as elevation, slope, hillside shade, and aspect were generated from the DEM of the Shuttle Radar Topography Mission [45]. A resolution of 5 km was used for national zoning, taking into consideration only pixels where the area covered by coffee was more than 30%.

### 2.3. Statistical methodology

#### 2.3.1. Multivariate analysis

The multivariate analysis described by Peña and Díaz [46, 47], and the statistical package “ade4” [48] in the R platform were used. The selection of synthetic variables was based on the maximum degree of variability that was explained by the PCA, where the eigenvalues were equal to or greater than 1. Due to the fact that the original variables were standardized before the PCA was performed, the means of the standardized variables were zero and the variances were equal to one.

A cluster analysis was also undertaken, using PCAs from the previous analysis. Two aspects were considered: similarity measures and clustering methods [46, 47]. For the first aspect, according to the method, the proximity of observations must be measured; in this case, the Euclidean distance was used. For the second aspect, clusters were formed, whereby observations were selected to be as similar and as different as possible within and between clusters, respectively. K-means clustering, a partitioning method that assumes the existence of an Euclidean distance between the members comprising the cluster, was used to construct this time series [49, 50]. Indices of similarity and quality as proposed by Liao [49] were assumed as criteria for evaluating and deciding on cluster formation. The R routine was adapted to the needs of the current research, using the statistical package “cclust” from R Platform [51].
Results

3.1. Forming agroclimatic groups for the CCGR

Six principal components represented 86% of the variability attributable to the original 24 variables (21 bioclimatic and 4 topographic indices). The first component explained 34% of total variation, comprising most of the bioclimatic indicators; except sd2, sb2, ppt1, ta3, sb3, bd3, md1, and sd1, which were not significant. The second component explained 21.5% of the variation and was composed of six bioclimatic indicators: sb2, sb3, bd3, ta3, ppt1, and sd1. Components 3 to 6 explained 11.7, 7.5, 6.6, and 5.0% of the variation respectively. Component 5 was represented by the topographic indicators of aspect and shade. Slope showed a relationship with component 6 (Table 1).

The six components were taken into account in the cluster analysis. The clustering test considered 40 combinations for 39 possible groups with 100 iterative processes for each one. The cluster for agroclimatic group 12 (ACG 12) showed three situations of interest: (a) a similarity index mean value of 75% and the least fluctuation on the range of all the groups, even though the extreme values were 64 and 90%; (b) a quality index mean value of 2.47 with minimum variation; and, (c) 78.9% of variability explained, with a fluctuation between 77.5 and 79.5% (Figure 1).

The above-mentioned results show the need to subject the indices to increased control when deciding on the number of groups to be formed.

The process focused on seeking, within each of the 12 ACGs, the particular conditions that differentiated them. Table 2 lists, for each ACG, the mean values of the 21 bioclimatic and 4 topographic indices (including altitude obtained from a DEM with a resolution of 90 m).

3.1.1. Distribution of experimental stations and the coffee climate network in the setting of agro-climatic groups

The red dots in Figure 2 show the distribution of CENICAFÉ’s ESs throughout the ACGs. Four ESs — El Rosario, Naranjal, La Trinidad, and La Catalina — lie within ACG 9, whereas ESs El Tambo and Santa Bárbara lie within ACG 12. The two remaining ESs are situated in different ACGs, namely, ES Pueblo Bello in ACG 6 and ES Paraguaicito in ACG 4. The main stations in the coffee climate network, totaling 74 and forming part of CENICAFÉ’s ESs, are represented in Figure 2 by yellow dots. Aside from ACG 2, they are distributed throughout all the ACGs, cover different types of areas.

3.1.2. Description of the agro-climatic groups

Tables 2 and 3 characterize the ACGs, showing bioclimatic and topographic differences, and other characteristics such as varieties and luminosity. The last column of Table 3 provides the ranges of the most noteworthy bioclimatic and topographic indicators. In particular, the ACGs present variable ranges of altitude, from the predominantly low as in ACGs 6 and 10, in which sd1 is accentuated with more than 59% of its coffee-growing area under shade, to ACGs found mostly in high zones (ACGs 2, 3, and 12), where thermal time values between flowering and harvest are predominantly less than 2500 hours (Figure 2).
Discussion

4.1. Agro-climatic groups

The cluster analysis describes relevant characteristics that either contribute to, or limit coffee production. The methodology is based on factors that occur before the crop’s principal harvest, over the three stages of the reproductive period, that is, the physiological events of pre-flowering, flowering, and fruit growth until

| Principal Component | Eigenvalues | Explication of the Variability |
|---------------------|-------------|--------------------------------|
| 1                   | 8.13        | 33.90%                         |
| 2                   | 5.15        | 55.40%                         |
| 3                   | 2.81        | 67.10%                         |
| 4                   | 1.81        | 74.60%                         |
| 5                   | 1.58        | 81.20%                         |
| 6                   | 1.2         | 86.10%                         |

doi:10.1371/journal.pone.0113510.t001

Figure 1. Boxplot from three indexes, Quality of Elbow and Similarity and Quality of Liao, built to determine the best decision criteria for groups, in an analysis of k-means clustering in the ACG. The axis “x” represents the k group level and the axis “y” the value of each index, the first and last values are expressed from 0–1, with 1 being the perfect fit. The red box highlights the group with best fit.

doi:10.1371/journal.pone.0113510.g001
Table 2. Mean values that discriminate, using 21 bioclimatic and 4 topographic indices, among 12 agro-climatic groups (ACGs) resulting from cluster analysis for the Colombian coffee-growing regions.

| ACG | Bioclimatic Indicator | Topographic Indicator |
|-----|-----------------------|-----------------------|
|     | sb1 | sb2 | sb3 | sd1 | sd2 | sd3 | md1 | md2 | md3 | bd1 | bd2 | bd3 | ta1 | ta2 | ta3 | pp1 | pp2 | pp3 | tr1 | tr2 | tr3 | hs | asp | slp | elev |
| 1   | 510 | 626 | 575 | 1   | 0   | 0   | 43  | 14  | 0   | 54  | 53  | 42  | 43  | 72  | 66  | 537 | 868 | 886 | 1194| 1236| 1163| 175| 124 | 4.66| 1698 |
| 2   | 598 | 482 | 588 | 0   | 0   | 0   | 11  | 1   | 3   | 55  | 30  | 63  | 33  | 59  | 42  | 598 | 772 | 771 | 916 | 982 | 967 | 181 | 167 | 4.81| 1824 |
| 3   | 575 | 656 | 526 | 0   | 0   | 0   | 25  | 6   | 0   | 78  | 57  | 20  | 21  | 37  | 53  | 597 | 1048| 1116| 1039| 1046| 897 | 176 | 135 | 4.93| 1815 |
| 4   | 667 | 363 | 431 | 96  | 1   | 0   | 22  | 16  | 34  | 75  | 2   | 0   | 61  | 123 | 120 | 304 | 749 | 674 | 1327| 1288| 1288| 185 | 279 | 4.14| 1512 |
| 5   | 585 | 708 | 715 | 5   | 0   | 0   | 46  | 14  | 2   | 84  | 111 | 104 | 14  | 15  | 7   | 506 | 832 | 820 | 1135| 1196| 1131| 183 | 223 | 3.00| 1660 |
| 6   | 666 | 732 | 643 | 51  | 29  | 0   | 24  | 18  | 18  | 92  | 103 | 73  | 16  | 28  | 34  | 398 | 729 | 1033| 1299| 1450| 1437| 187 | 254 | 5.48| 1207 |
| 7   | 483 | 627 | 644 | 1   | 0   | 0   | 48  | 28  | 45  | 34  | 59  | 77  | 67  | 95  | 52  | 561 | 771 | 714 | 1284| 1343| 1329| 179 | 176 | 4.02| 1536 |
| 8   | 244 | 420 | 636 | 1   | 23  | 81  | 12  | 31  | 15  | 0   | 75  | 120 | 122 | 58  | 726 | 603 | 395 | 1260| 1314| 1363| 177 | 140 | 3.30| 1410 |
| 9   | 378 | 544 | 619 | 1   | 19  | 38  | 29  | 39  | 0   | 6   | 68  | 120 | 122 | 89  | 660 | 782 | 689 | 1368| 1447| 1484| 176 | 128 | 2.99| 1362 |
| 10  | 390 | 569 | 712 | 7   | 20  | 45  | 43  | 41  | 29  | 0   | 6   | 101 | 119 | 107 | 30  | 623 | 673 | 668 | 1375| 1502| 1567| 188 | 277 | 4.27| 1187 |
| 11  | 387 | 517 | 643 | 1   | 7   | 54  | 24  | 31  | 33  | 0   | 2   | 84  | 118 | 122 | 45  | 622 | 650 | 476 | 1122| 1142| 1119| 178 | 121 | 3.36| 1646 |
| 12  | 688 | 452 | 562 | 51  | 1   | 0   | 56  | 16  | 28  | 92  | 12  | 40  | 43  | 105 | 94  | 398 | 702 | 675 | 1135| 1158| 1174| 184 | 277 | 3.33| 1715 |

*This symbol and the next within the same row, refer to indices, where sb1 = accumulated solar brightness (SB), stage 1; sb2 = accumulated SB, stage 2; sb3 = accumulated SB, stage 3; sd1 = number of days with severe hydric deficit (SHD), stage 1; sd2 = number of days with SHD, stage 2; sd3 = number of days with SHD, stage 3; md1 = number of days with moderate hydric deficit (MHD), stage 1; md2 = number of days with MHD, stage 2; md3 = number of days with MHD, stage 3; bd1 = number of days with solar brightness deficit (SBD) at <7.2, stage 1; bd2 = number of days with SBD at <7.2, stage 2; bd3 = number of days with SBD at <7.2, stage 3; ta1 = number of days with thermal amplitude (TA) at <10, stage 1; ta2 = number of days with TA at <10, stage 2; ta3 = number of days with TA at <10, stage 3; pp1 = accumulated rainfall, stage 1; pp2 = accumulated rainfall, stage 2; pp3 = accumulated rainfall, stage 3; tt1 = accumulated thermal time (TT), stage 1; tt2 = accumulated TT, stage 2; tt3 = accumulated TT, stage 3; hs = hillshade; asp = aspect; slp = slope; and elev = elevation.

doi:10.1371/journal.pone.0113510.t002
harvest. Seasonal analysis is determined through the way in which the baseline is obtained - daily history for an average year - whereby the goal is to analyze the performance of the climatic indices.

Table 4 presents advantages and disadvantages of the ACGs according to their agro-ecological suitability for the coffee crop in Colombia. This information is based on agro-climatic indices values drawn from the literature and based on research on the coffee crop in Colombia and Brazil.

In general, planting time dates determines crop development. At high elevations, the reproductive stage is reached later than at lower altitudes. In some
Table 3. Characteristics associated with the groups that conform the agro-climatic zones proposed for the Colombian coffee-growing regions.

| Agro-climatic zone or group (ACG) | Coffee area and lands | Departments and representation within the ACG | Proportion by Andean range within the ACG | Proportion by latitudinal zone and luminosity within the ACG | Proportion by variety within the ACG | Bioclimatic indicators (range for 80% of coffee farms) |
|----------------------------------|-----------------------|---------------------------------------------|------------------------------------------|----------------------------------------------------------|----------------------------------|----------------------------------------------------|
|                                  |                       | Dep’            | Range      | Flank | Propr. (%) | Latitudinal zone/ Luminosity | Propr. (%) | Variety | Propr. (%) | Indicator | Range      |
| 1                                | 121,400 ha            | Antioquia       | Occidental | East   | 58        | Central-northern             | 80.4      | Caturra | 44.8      | Altitude (masl) | 1400–1940 |
|                                  |                       | Caldas          | Central    | West   | 14.4      | Central-southern             | 15.7      | Colombia | 33.6      | Solar brightness (h/yr) | 1660–1760 |
|                                  |                       | Risaralda       | West       | 10.1   | 20.8      | Sun                          | 68.2      | Castillo | 18.3      | Annual rainfall (mm) | 2110–2470 |
|                                  |                       | Valle del Cauca | East       | 8.2    | 19        | Semi-shade                   | 22.9      | Typica  | 3.2       | MHD, stage 1 (days) | 32–46     |
|                                  |                       | Tolima          |            | 7.7    |           | Shade                        | 8.8       |          |            | TA, stage 1 (days) | 30–60     |
| 2                                | 34,000 ha             | Tolima          | Central    | East   | 30.6      | Central-southern             | 52.9      | Caturra | 53.4      | Altitude (masl) | 1600–2050 |
|                                  |                       | Cauca           | West       | 16.6   | 30.2      | Southern                     | 41.1      | Castillo | 19.5      | Solar brightness (h/yr) | 1620–1750 |
|                                  |                       | Huila           | Oriental   | West   | 15.9      | Central-northern             | 6.1       | Colombia | 16.7      | Annual rainfall (mm) | 2010–2400 |
|                                  |                       | Nariño          | East       | 12.4   | 2         | Typica                       | 10.3      |          |            | MHD, stage 1 (days) | <32       |
|                                  |                       | Cundinamarca   | Occidental | East   | 8.6       | Sun                          | 60.2      |          |            | TA, stage 1 (days) | 18–52     |
|                                  |                       | Valle del Cauca | West       | 6      | 1.1       | Semi-shade                   | 30.2      |          |            | TT (accumulated, stages 2 and 3) | 1730–2080 |
| 3                                | 20,300 ha             | Antioquia       | Central    | West   | 51.7      | Central-northern             | 72.2      | Caturra | 50.9      | Altitude (masl) | 1540–2060 |
|                                  |                       | Caldas          | East       | 13.5   | 14.1      | Northern                     | 26        | Colombia | 20.5      | Solar brightness (h/yr) | 1700–1900 |
|                                  |                       | Cesar           | Occidental | East   | 10.7      | Northern                     | 26        | Colombia | 20.5      | Annual rainfall (mm) | 2570–3100 |
|                                  |                       | Risaralda       | West       | 5.7    | 5.7       | Sun                          | 59.4      | Typica  | 9.8       | MHD, stage 1 (days) | 11–35     |
|                                  |                       | Norte de Santander | Oriental  | West   | 5.1       | Semi-shade                   | 28.2      |          |            | TA, stage 1 (days) | 10–28     |
| Agro-climatic zone or group (ACG) | Coffee area and lands | Departments and representation within the ACG | Proportion by Andean range within the ACG | Proportion by latitudinal zone and luminosity within the ACG | Proportion by variety within the ACG | Bioclimatic indicators (range for 80% of coffee farms) |
|----------------------------------|-----------------------|---------------------------------------------|-------------------------------------------|------------------------------------------------------------|----------------------------------|----------------------------------------------------------|
| Magdalena                        | 4.4                   | East                                        | 5.2                                       | Shade                                                      | 12.4                             | TT (accumulated, stages 2 and 3) 1680–2160                |
| Santander                        | 3.3                   | Sierra Nevada                               | 6.8                                       |                                                            |                                  |                                                          |
| Tolima                           | 3                     | Central                                     | West                                      | Central-southern                                           | 56.4                             | Caturra 35.8 Altitude (masl) 1200–1780                     |
| 4 114,700 ha                      | 26.2                  | East                                        | West                                      | South                                                      | 34                               | Castillo 20.6 Solar brightness (h/yr) 1160–1590           |
| 105,200 farms                    | 22                    | East                                        | West                                      | Southern                                                   | 42                               | Colombia 29 Annual rainfall (mm) 1600–1920                |
| Cundinamarca                     | 16                    | Oriental                                    | West                                      | Semi-shade                                                 | 44.9                             | Castillo 14.6 SHD, stage 1 (days) 80–100                  |
| Hula                             | 14.8                  | Occidental                                  | East                                      | Semi-shade                                                 | 44.9                             | Typica 14.6 SHD, stage 1 (days) 33–120                    |
| Nariño                           | 11.8                  | West                                        | East                                      | Sun                                                        | 39.8                             | TA, stage 1 (days) 2440–2800                              |
| Valle del Cauca                  | 6.6                   | Shade                                       |                                            |                                                            | 15.3                             | TT (accumulated, stages 2 and 3)                          |
| 5 54,300 ha                      | 48.6                  | Oriental                                    | West                                      | Central-northern                                           | 55.3                             | Colombia 34.4 Altitude (masl) 1370–1880                   |
| Norte de Santander               | 25                    | East                                        | Northern                                  | 44.7                                                       | Caturra 28.1 Solar brightness (h/yr) 1940–2060            |
| Boyacá                           | 10.5                  | Sierra Nevada                               |                                            | Typica                                                     | 21.1                             | Annual rainfall (mm) 2020–2400                            |
| Cesar                            | 9.7                   | Semi-shade                                  |                                            |                                                            | 52                               | Castillo 16.4 MHD, stage 1 (days) 32–57                  |
| Magdalena                        | 3.3                   | Shade                                       |                                            |                                                            | 38.2                             | TT (accumulated, stages 2 and 3)                          |
| 6 39,500 ha                      | 2.8                   | Sun                                         | 9.7                                       |                                                            |                                  |                                                          |
| Cesar                            | 43.9                  | Sierra Nevada                               | 63.2                                      | Northern                                                   | 100                              | Typica 43.9 Altitude (masl) 840–1600                      |
| 10,900 farms                     | 42.9                  | Oriental                                    | West                                      | Caturra                                                    | 28.8                             | Solar brightness (h/yr) 1980–2210                         |
| La Guajira                       | 10.2                  | East                                        | 1.5                                       | Semi-shade                                                 | 63                               | Castillo 14.2 Annual rainfall (mm) 2020–2400              |
| Agro-climatic zone or group (ACG) | Coffee area and lands | Departments and representation within the ACG | Proportion by Andean range within the ACG | Proportion by latitudinal zone and luminosity within the ACG | Proportion by variety within the ACG | Bioclimatic indicators (range for 80% of coffee farms) |
|----------------------------------|-----------------------|---------------------------------------------|------------------------------------------|-------------------------------------------------|-----------------------------------|------------------------------------------------|
| **Table 3. Cont.**               |                       |                                             |                                          |                                                 |                                   |                                                   |
| **Norte de Santander**           | 2.9                   | Shade                                       | 29.4                                     | Colombia                                        | 12.9                              | MHD, stage 1 (days) 19–29                        |
|                                  |                       | Sun                                         | 7.5                                      |                                                 |                                   | SHD, stage 1 (days) 39–59                       |
| **Risaralda**                    | 20.9                  | Occidental East                             | 34.5                                     | Central-northern                                | 55.1                              | Altitude (masl) 1270–1800                       |
|                                  | 85,000 farms          |                                             |                                          |                                                 |                                   |                                                   |
| **Caldas**                       | 19.7                  | West                                        | 7.4                                      | Central-southern                                | 36.6                              | Solar brightness (h/yr) 1670–1870                |
|                                  |                       |                                             |                                          |                                                 |                                   |                                                   |
| **Valle del Cauca**              | 19.6                  | Central West                                | 32.7                                     | Northern                                        | 8.3                               | Annual rainfall (mm) 1940–2200                   |
|                                  |                       |                                             |                                          |                                                 |                                   |                                                   |
| **Antioquia**                    | 17.9                  | East                                        | 8.8                                      | Typica                                          | 6.9                               | MHD, stage 1 (days) 42–55                       |
|                                  |                       |                                             |                                          |                                                 |                                   |                                                   |
| **Santander**                    | 7.9                   | Oriental West                               | 9.5                                      | Sun                                             | 56.9                              | SHD, stage 3 (days) 26–57                       |
|                                  | 150,700 ha            |                                             |                                          |                                                 |                                   |                                                   |
| **Norte de Santander**           | 6.3                   | East                                        | 7.2                                      | Semi-shade                                      | 29.9                              | TT (accumulated, stages 2 and 3) 2480–2870      |
|                                  | 8 80,600 ha           |                                             |                                          |                                                 |                                   |                                                   |
| **Tolima**                       | 2.7                   | Shade                                       | 13.1                                     |                                                 |                                   |                                                   |
| **Quindío**                      | 2.5                   |                                             |                                          |                                                 |                                   |                                                   |
| **Boyacá**                       | 1.1                   |                                             |                                          |                                                 |                                   |                                                   |
| **Huila**                        | 70.9                  | Oriental West                               | 56.6                                     | Southern                                        | 76.5                              | Altitude (masl) 1110–1680                       |
|                                  | 80,600 ha             |                                             |                                          |                                                 |                                   |                                                   |
| **Tolima**                       | 15.8                  | East                                        | 9.2                                      | Central-southern                                | 18.6                              | Solar brightness (h/yr) 1640–2080               |
|                                  | 59,900 farms          |                                             |                                          |                                                 |                                   |                                                   |
| **Caquetá**                      | 3.5                   | Central East                                | 33.7                                     | Central-northern                                | 4.9                               | Annual rainfall (mm) 1140–1400                  |
|                                  |                       |                                             |                                          |                                                 |                                   |                                                   |
| **Meta**                         | 3.1                   |                                             |                                          | Typica                                          | 3.7                               | MHD, stage 2 (days) 20–40                       |
|                                  |                       |                                             |                                          |                                                 |                                   |                                                   |
| **Casanare**                     | 2.4                   | Sun                                         | 76                                       |                                                 |                                   | SHD, stage 3 (days) 60–80                       |
|                                  |                       |                                             |                                          |                                                 |                                   |                                                   |
| **Cauca**                        | 2.1                   | Semi-shade                                  | 19                                       |                                                 |                                   | TT (accumulated, stages 2 and 3) 2430–3050      |
|                                  |                       |                                             |                                          |                                                 |                                   |                                                   |
| Shade                            | 5                     |                                             |                                          |                                                 |                                   |                                                   |
Table 3. Cont.

| Agro-climatic zone or group (ACG) | Coffee area and lands | Departments and representation within the ACG | Proportion by Andean range within the ACG | Proportion by latitudinal zone and luminosity within the ACG | Proportion by variety within the ACG | Bioclimatic indicators (range for 80% of coffee farms) |
|----------------------------------|-----------------------|---------------------------------------------|-----------------------------------------|-------------------------------------------------|---------------------------------|--------------------------------------------------|
| 9                               | 95,700 ha             | Dep’t | Proportion (%) | Range | Flank | Proportion (%) | Latitudinal zone/ Luminosity | Proportion (%) | Variety | Proportion (%) | Indicator | Range     |
| Caldas                          | 29.8                  | Central | West | 34.5 | Central-northern | 69.6 | Colombia | 40 | Altitude (masl) | 1080–1660 |
| Antioquia                       | 24.9                  | East | 33.2 | Central-southern | 29.1 | Caturra | 38.6 | Solar brightness (h/yr) | 1360–1660 |
| Tolima                          | 14                    | Occidental | East | 21.8 | Northern | 1.3 | Castillo | 18.8 | Annual rainfall (mm) | 2010–2300 |
| Quindío                         | 9.7                   | West | 3    |          |         |         |         | Typica | 2.6 | MHD, stage 1 (days) | 26–46 |
| Risaralda                       | 8.2                   | Oriental | West | 7.4 | Sun | 69.6 | MHD, stage 3 (days) | 31–51 |
| Cundinamarca                    | 6.2                   | Semi-shade |          | 22 |          |         |         |         |         | TT (accumulated, stages 2 and 3) | 2690–3210 |
| Valle del Cauca                 | 6                     | Shade |          | 8.3 |         |         |         |         |         |         |         |         |
| Norte de Santander              | 35.3                  | Oriental | West | 42.4 | Northern | 53.4 | Colombia | 36.5 | Altitude (masl) | 820–1520 |
| Santander                       | 30                    | East | 33.5 | Central-southern | 23.9 | Caturra | 28.7 | Solar brightness (h/yr) | 1510–1770 |
| Valle del Cauca                 | 23.9                  | Central | West | 23.6 | Central-northern | 22.7 | Typica | 20.2 | Annual rainfall (mm) | 1830–2140 |
| Cesar                           | 7.1                   | Central | West | 3.1 | Central-southern | 30 | Castillo | 14.6 | MHD, stage 1 (days) | 33–53 |
|                                |                       | Semi-shade |          | 59 |         |         |         |         |         | SHD, stage 3 (days) | 26–56 |
|                                |                       | Shade |          | 24.6 |         |         |         |         |         | TT (accumulated, stages 2 and 3) | 2830–3390 |
|                                |                       | Sun |          | 16.4 |         |         |         |         |         |         |         |
| 10                              | 21,100 ha             | 69.700 ha | Tolima | 24.2 | West | 3.1 | Central-southern | 30 | Castillo | 18.9 | Solar brightness (h/yr) | 1450–1660 |
|                                |                       | 52,000 ha | Cauca | 5.4 | Oriental | West | 31.2 | Central-northern | 3.2 | Colombia | 15.5 | Annual rainfall (mm) | 1640–1900 |
|                                |                       | 69,700 ha | Valle del Cauca | 4.9 | East | 4.8 |          |         |         |         | MHD, stage 3 (days) | 19–62 |
### Table 3. Cont.

| Agro-climatic zone or group (ACG) | Coffee area and lands | Departments and representation within the ACG | Proportion by Andean range within the ACG | Proportion by latitudinal zone and luminosity within the ACG | Proportion by variety within the ACG | Bioclimatic indicators (range for 80% of coffee farms) |
|----------------------------------|----------------------|---------------------------------------------|------------------------------------------|----------------------------------------------------------|----------------------------------|--------------------------------------------------|
| Boyacá                           | 2.3                  | Occidental West                             | 1.3 Sun                                  | 76                                                       | SHD, stage 3 (days)              | 14–75                                           |
|                                  |                      |                                             |                                          |                                                          | East 0.5 Semi-shade 18.6         | TT (accumulated, stages 2 and 3) 2060–2580     |
| Cauca                            | 36                   | Central West                               | 56.5 Shade                               | 5.3                                                      | SHD, stage 3 (days)              | 14–75                                           |
|                                 | 124,100              |                                             |                                          |                                                          | Central-southern 41.9            | Castillo 20.1 Solar brightness (h/yr) 1590–1750 |
|                                  |                      |                                             |                                          |                                                          | Central-northern 2.8             | Colombia 19.9 Annual rainfall (mm) 1690–1900   |
| Narino                           | 14.3                 | East                                       | 13.2 Central-southern                    | 41.9                                                     | Castillo 20.1 Solar brightness (h/yr) 1590–1750 |
|                                 | 130,600 farms        |                                             |                                          |                                                          | Colombia 19.9 Annual rainfall (mm) 1690–1900   |
| Tolima                           | 10.8                 | Oriental West                              | 16.8 Central-northern                    | 2.8                                                      | Colombia 19.9 Annual rainfall (mm) 1690–1900   |
|                                 | 10.7                 | Occidental East                            | 10.1 Typica                               | 10.2                                                     | MHD, stage 1 (days)              | 38–76                                           |
| Cundinamarca                     | 10.7                 |                                             |                                          |                                                          | MHD, stage 3 (days)              | 14–39                                           |
|                                 |                      |                                             |                                          |                                                          | Sun 43.2                         | SHD, stage 1 (days)                 | 8–75                                             |
| Quindio                          | 10.6                 | West                                       | 3.3 Semi-shade                            | 43.6                                                     | MHD, stage 3 (days)              | 14–39                                           |
|                                 | 10.6                 |                                             |                                          |                                                          | MHD, stage 3 (days)              | 14–39                                           |
| Valle del Cauca                  | 9.2                  |                                             |                                          |                                                          | SHD, stage 1 (days)              | 8–75                                             |
| Hula                             | 8.6                  |                                             |                                          |                                                          | TT (accumulated, stages 2 and 3) 2140–2470            |

doi:10.1371/journal.pone.0113510.t003
| Agroclimatic zone | Limitations | Advantages | Recommendations |
|------------------|-------------|------------|-----------------|
| 1 and 4          | -Slow vegetative and reproductive growth in high areas. | -Zones are suitable for the crop. | -Management with mulch. |
|                  |             | -Flowering tends to be concentrated in two periods. |         |
|                  |             | -Longer renovation cycles. |         |
| 2 and 3          | -Zones are affected by the La Niña phenomenon. | -Zones can become suitable for cultivation under conditions of the El Niño phenomenon. | -Management with mulch and semishade. |
|                  |             | -Excess humidity does not permit concentration of flowering. |         |
|                  |             | -Risk of diseases such as rots caused by Phoma spp., especially at higher altitudes. |         |
|                  |             | -Slow vegetative and reproductive growth. |         |
| 5 and 6          | -In both zones, shaded conditions may limit production. | -Concentrated flowering and harvesting times. | -Planting at the beginning of the rainy season. |
|                  | -Risk of hydric deficit in the middle phase of fruit development in zone 6. | -Longer renovation cycles. | -Regulating shading so that it is no more than 50%. |
|                  | -Slow vegetative and reproductive growth at higher altitudes, principally in zone 5. | -Conservation practices with mulching in the dry season. |         |
| 7, 8, and 9      | -Risk of hydric deficit in the late phases of fruit development. | -Flowering frequently concentrates into one semester. | -Management with mulch or transitory shading that favor humidity in stage 3. |
|                  | -These zones can lose their suitability for coffee cultivation under conditions of the El Niño phenomenon. | -Sufficient thermal availability. | -Planting at the beginning of the two rainy seasons. |
|                  | -Shorter renovation cycles. | -Optimal distribution in coffee border lands. |         |
| 10               | -Cropping in agroforestal systems because of the temporariness of rainy seasons. | -Flowering frequently concentrates into one semester. | -Management with mulch to favor humidity in stages 2 and 3. |
|                  | -This zone can lose its suitability for cultivation during conditions of the El Niño phenomenon. | -Regulating shading so that it is no more than 60% |         |
|                  | -Shade can diminish thermal availability. | |         |
|                  | -Shady conditions can limit production. | -Medium to high planting densities and arranged in wide alleys. | -Planting at the beginning of the rainy season. |
| 11 and 12        | -Slow vegetative and reproductive growth. | -Flowering frequently concentrates into one semester. | -Management with mulch to favor humidity in stage 3. |
|                  | -Risk of hydric deficit in the late phases of fruit development. | -Longer renovation cycles. | -Regulating shading so that it is no more than 45%. |
|                  | -Zones may lose suitability for cropping under conditions of the El Niño phenomenon. | -Management with mulch to favor humidity in stage 3. |         |
|                  | -Thermal availability diminishes under cloudy conditions. | |         |
|                  | -Risk of diseases such as rots caused by Phoma spp. | |         |

doi:10.1371/journal.pone.0113510.t004
ACGs, hydric deficit during the last phases of fruit development could be improved by adopting management practices such as mulching and establishing live barriers on steep hillsides [52, 53]. In other ACGs, high humidity prevailing throughout most of the crop’s reproductive development may favour the appearance of diseases such as those caused by *Phoma* sp. (dieback) and *Erithricium salmonicolor* (pink disease). During flowering, star flower or other abnormalities and attacks from fungi such as *Colletotrichum* sp. (anthracnose) may also appear [52, 54, 55, 56].

As growing coffee under shade may also limit yield [57], practices through the dry period such as regulating shade, sanitary harvesting, and pruning the crop, reduce the potential effects of pests and diseases [58, 59]. Agronomic management of the crop, such as fertilizer application, weed control, mulching, and shade management, reinforces the conditions for a suitable crop [58, 59, 60, 61].

### 4.2. General considerations on agro-climatic group formation

In Colombian coffee cultivation, the concept of latitudinal zoning has been used in agronomical management. In this context, such differentiation results in at least four zones, which are related to flowering patterns [5, 23, 62, 63]: (a) southern zone, delimited between 1° and 3° north; (b) central-southern zone, between 3° and 4° north [5] and 4° in the west, 5° in the north, and 6° in the east; (c) central-northern zone, between 5° and 8° north; and (d) northern zone, between 9° and 11° north.

As indicated above in the description of ACG formation, altitude exerts a strong influence on agro-ecological suitability of areas for coffee cultivation. The four latitudinal zones are associated with the ACGs as follows: the northern zone with ACGs 5, 6, and 10; the southern zone with ACGs 4, 11, and 12; the central-southern zone (the piedmont of the plains and south of Huila) with ACG 8; and the central-northern zone with ACGs 1, 7, and 9. For the northern, southern, and central-southern zones, these associations with the ACGs clearly delineate the influence of the great northeastern air currents and the atmospheric systems of the Pacific Ocean and the Amazon Basin, respectively [6, 64]. The broad valleys forming the Magdalena River’s central watershed and the Cauca River watershed noticeably influence the formation of ACGs 1, 7, and 9. Only ACGs 2 and 3 are primarily governed by altitude, which averages at 1800 m above sea level.

These findings present a dimension beyond the geographic, orographic concept or historical development when involving the level of detail such as water retention, solar brightness, degree days, and certain topographic conditions. These aspects brought together, delimit the crop agro-climatically, defining its potential.

Depending on the extent to which information is available for association with a given farm or region, future work will approximate the concept of site-specific agriculture, similar to what was developed for Colombia by CENICAN [65, 66], integrating environmental concepts with management concepts. Pilot studies for coffee such as those undertaken by Cock et al. [66], Läderach et al. [67] and Oberthür et al. [68] to obtain the “denomination of origin” for Nariño and
Cauca, will determine the future for coffee growers and the FNC, safeguarding farmers from variability in terms of both climate and prices, and enabling progress to be made towards guaranteeing a quality product.

**Recommendations**

Spatial resolution at 5 km used to obtain the indices is limited, especially for climatic elements such as precipitation and for topographical features such as slope and altitude. In steep zones, where slopes are more than 25°, the changes associated with altitude, precipitation, and solar radiation within a cell of 5 km are large. Assuming only one class for each element will consequently distort these extreme conditions. The advantages of using this resolution are (a) an association of large surfaces in a continuous manner incorporating data into each cell; (b) efficient use of hardware and software resources; and (c) improved level of precision of information generated.

Although the objective of establishing the potential scope of research results generated by the ESs was achieved, the level of dispersion of the coffee climate network did not allow a higher level of precision. An option to consider is to incorporate more historical series type of information from weather stations, both within and outside the coffee-growing regions, as administered by national agencies such as the Institute of Hydrology, Meteorology, and Environmental Studies (IDEAM) or private companies such as sugar mills. This would result in benefits in terms of consistency of information, the possibility of increasing the level of resolution and therefore the level of detail, and the possibility of exploring other methodologies based on functional geo-statistics, functional regression, and other tools of interpolation to obtain a greater coverage with improved level of confidence.

One factor that limited the process of obtaining bioclimatic indicators was the restricted scope of soil studies. Another factor was the scarcity of associated digital information as attributes in each unit, such as in the case of water retention capacity for which only a small part (40 units out of 800) could be related.

Yield information on coffee genotypes evaluated in the ESs and related to bioclimatic indices, other variables of interest related to vegetative growth, flowering, and quality, and molecular markers should be included in new research. Research should not be limited to the ESs, but should have wider national application, incorporating new research sites that this study identified as having potential strategic importance and therefore as being worthy of inclusion in the FNC’s investigation plan.

**Conclusions**

The coffee-growing regions in Colombia, based on bioclimatic indicators, can be classified into 12 large zones in which the coffee tree’s responses are conditioned by the constraints or suitabilities of the environment, soils, and management. This
information is valuable to the Colombian National Coffee Federation to guide their research and extension and will benefit the farmers of Colombia. The methodology and approach developed here can be used in other coffee-growing countries across the world.

**Acknowledgments**

The authors acknowledge: the National Federation of Coffee Growers of Colombia, who provided information and sponsored Juan Carlos García’s doctoral formation in this fieldwork; the CENICAFE’s Agroclimatology Research Group, headed by Álvaro Jaramillo and Andrés Peña, for consolidating and facilitating historical information on the coffee climate network and for participating in the review of the baseline generated; the CGIAR research program on Climate Change, Agriculture and Food Security (CCAFS) and specifically the Decision and Policy Analysis (DAPA) at the International Center For Tropical Agriculture (CIAT), for training and supervising Juan Carlos García during his internship, allowing him to develop the methodology presented in this article. This manuscript represents a portion of a PhD thesis submitted by the first author to a Doctoral Program of the Universidad de Caldas, Colombia.

**Author Contributions**

Performed the experiments: JCGL HPS PL. Analyzed the data: JCGL HPS PL. Contributed reagents/materials/analysis tools: JCGL HPS PL. Wrote the paper: JCGL HPS PL. Participated in study design and coordination and revised the manuscript: JCGL HPS PL. Acquired data, participated in data analysis and interpretation, and drafted the manuscript: JCGL HPS PL. Read and approved the final manuscript: JCGL HPS PL.

**References**

1. Cano C, Vallejo C, Caicedo E, Amador J, Tique E (2012) El mercado mundial del café y su impacto en Colombia. Borradores de Economía: 1–56.
2. Federación Nacional de Cafeteros de Colombia (FNC) (2012) Caficultura sostenible. Informe del Gerente General. LXXVII Congreso Nacional de Cafeteros 2012. Accedida Septiembre, 2013. Available: http://www.federaciondecafeteros.org/static/files/IGG2012.pdf. Federación Nacional de Cafeteros de Colombia.
3. Leibovich J, Botello S (2008) Análisis de los cambios demográficos en los municipios cafeteros y su relación con los cambios en la caficultura colombiana (1993–2005). Ensayos sobre economía cafetera 21: 67–87.
4. Gómez L, Caballero A, Baldión J (1991) Ecotopos cafeteros de Colombia. Bogotá: Federación Nacional de Cafeteros de Colombia. pp.131.
5. Trojer H (1968) The phenological equator for coffee planting in Colombia. In: Unesco editor, París. pp. 107–117.
6. Jaramillo A (2005) Clima andino y café en Colombia. Chinchiná: FNC - Cenicafé. 195 p.
7. Arcila J, Jaramillo A (2003) Relación entre la humedad del suelo, la floración y el desarrollo del fruto del cafeto. Avances Técnicos Cenicafé 311: 1–8.
8. Hurtado G (1988) Caracterización agroclimática de Colombia. Santafé de Bogotá, D.C.: Instituto colombiano de hidrología, meteorología y adecuación de tierras. 112 p.

9. Baldión J, Hurtado G (1992) Estudio agroclimático del trópico húmedo de Colombia. Santafé de Bogotá, D.C.: Instituto colombiano de hidrología, meteorología y adecuación de tierras. 187 p.

10. Palmer WC (1965) Meteorological Drought. Research Paper No. 45. U.S. Department of Commerce. Washington, D.C.

11. Malagón D, Pulido C, Llinás R, Chamorro C (1995) Factores bioclimáticos de formación del suelo. Suelos de Colombia. Santafé de Bogotá, D. C.: Instituto Geográfico Agustín Codazzi. pp. 221–286.

12. Pezzopane J, Pedro JM, Camargo M, Fazuoli L (2008) Exigencia térmica del café arábica CV. Mundo Novo no subperíodo florescimento - colheita. Cienc agrotec, Lavras 32: 1781–1786.

13. Nunes F, Camargo M, Fazuoli L, Rolim G, Pezzopane J (2010) Modelos agrometeorológicos de estimativa de la duración del estádio floración-maturación para tres cultivares de café arábica. Bragantia, Campinas 69: 1011–1018.

14. Carvalho H, Melo B, Rabelo P, Silva C, Camargo R (2011) Índices bioclimáticos para a cultura de café. Revista Brasileira de Engenharia Agrícola e Ambiental 15: 601–606.

15. Santos M, Camargo M (2006) Parametrização de modelo agrometeorológico de estimativa de produtividade do cafeeiro. Bragantia, Campinas 65: 173–183.

16. Camargo M, Rolim G, Santos M (2007) Modelagem agroclimatológica do café: estimativa e mapeamento das produtividades. Informe Agropecuário, Belo Horizonte 28: 58–65.

17. Silva F, Santos E, Evangelista B, Assad E, Pinto H, et al. (2000) Delimitacao das áreas aptas para o ponto de vista agroclimático para o plantio da cultura do café (Coffea arábica) no estado de Goiás. I Simpósio de Pesquisa dos Cafés do Brasil: Embrapa. pp. 123–125.

18. Meireles E, Volpato M, Alves H, Vieira T (2007) Zoneamento agroclimático: Um estudo de caso para o café. Informe Agropecuário, Belo Horizonte 28: 50–57.

19. Caramori P, Filho A, Morais H, Filho F, Duquia C (2007) Sistema de aleta pars geadas na cafeicultura do Paraná. Informe Agropecuário, Belo Horizonte 28: 66–71.

20. Camayo G, Chaves B, Arcila J, Jaramillo A (2003) Desarrollo floral del cafeto y su relación con las condiciones climáticas de Chinchiná, Caldas. Revista Cenicafé 54: 35–49.

21. Ramírez V, Arcila J, Jaramillo A, Rendón J, Cuesta G, et al. (2010) Floración del café en Colombia y su relación con la disponibilidad hídrica, térmica y de brillo solar. Revista Cenicafé 61: 132–158.

22. Jaramillo A, Guzmán O (1984) Relación entre la temperatura y el crecimiento en Coffea arabica L., variedad catuara. Revista Cenicafé 35: 57–65.

23. Arcila J, Jaramillo A, Baldión J, Bustillo A (1993) La floración del cafeto y su relación con el control de la broca. Avances Técnicos Cenicafé 193: 1–6.

24. Jaramillo A, Arcila J (1996) Épocas recomendables para la siembra de los cafetos. Avances Técnicos Cenicafé 229: 8p.

25. Jaramillo A, Ramírez V, Arcila J (2011) Distribución de la lluvia, clave para planificar las labores en el cultivo del café en Colombia. Avances Técnicos Cenicafé 411: 1–8.

26. Arcila J, Buhr L, Bleiholder H, Hack H, Wicke H (2001) Application of the "Extended BBCH - Scale" for the description of the growth stages of coffee (Coffea sp.). Cenicafé. pp. 32.

27. Hutchinson M (2006) Anusplin version 4.36 User Guide. 4.36 ed., Canberra, Australia: Centre for Resource and Environmental Studies at the Australian National University. pp. 54.

28. Hutchinson M (1998) Interpolation of Rainfall Data with Thin Plate Smoothing Splines - Part I: Two Dimensional Smoothing of Data with Short Range Correlation. Journal of Geographic Information and Decision Analysis 2: 139–151.

29. Hijmans R, Cameron S, Parra J, Jones P, Jarvis A (2005) Very high resolution interpolated climate surfaces for global land areas. Int J Climatol 25: 1965–1978.

30. McAlpine J, Pedlar J, Papadopol P, Hutchinson M (2006) The development of 1901–2000 historical monthly climate models for Canada and the United States. Agricultural and Forest Meteorology 138: 69–81.
31. Hutchinson M, McKenney D, Lawrence K, Pedlar J, Hopkinson R, et al. (2009) Development and Testing of Canada-Wide Interpolated Spatial Models of Daily Minimum–Maximum Temperature and Precipitation for 1961–2003. Journal of Applied Meteorology and Climatology 48: 725–740.

32. Ramírez J, Jarvis A (2010) Downscaling Global Circulation Model Outputs: The Delta Method Decision and Policy Analysis Working Paper No. 1. Cali, Colombia: CIAT. 17p p.

33. Niekerk A, Joubert S (2011) Input variable selection for interpolating high-resolution climate surfaces for the Western Cape. Water SA 37.

34. Láderach P, Zelaya C, Ovalle O, García S, Eltzeinger A, et al. (2012) Escenarios del Impacto del Clima Futuro en Areas de Cultivo de Café en Nicaragua. Cali, colombia; Managua, Nicaragua: CIAT. 32 p.

35. Team RDC (2008) R: A language and environment for statistical computing. R Foundation Statistical Computing.

36. Hijmans R (2010) Introduction to the ‘raster’ package (Version1.6–19). R package ‘raster’.

37. Jaramillo A, Gómez O (2002) Desarrollo de una aplicación de cómputo para el cálculo de balance hídrico en cafetales. Chinchiná, Caldas: Cenicafé.

38. Suárez S (2000) Características físicas de los suelos de la zona cafetera de Colombia relacionadas con el uso, manejo y conservación. Simposio sobre suelos de la zona cafetera Colombiana, Cenicafé. pp. 17p.

39. Jaramillo A (1983) Balance hídrico de la zona cafetera colombiana. Revista Cenicafé 33: 15–28.

40. Meza F, Varas E (2000) Estimation of mean monthly solar global radiation as a function of temperature. Agricultural and Forest Meteorology 100: 231–241.

41. Rivington M, Matthews B, Buchan K (2005) A Comparison of Methods for Providing Solar Radiation Data to Crop Models and Decision Support Systems. Proc Int Environmental Modelling and Software Society 3: 193–198.

42. Rivington M, Bellocchi G, Matthews B, Buchan K (2005) Evaluation of three model estimations of solar radiation at 24 UK stations. Agricultural and Forest Meteorology 132: 228–243.

43. Gómez L, Guzmán O (1995) Relación empírica entre la radiación solar global y el brillo solar en el área de Cenicafé, Chinchiná, Caldas. Revista Cenicafé 46: 205–218.

44. UPME, IDEAM (2005) Atlas de Radiación solar de Colombia. Santafe de Bogotá D.C.: Unidad de Planeación Minero Energética, Ministerio de Minas y Energía; Instituto de Hidrología, Meteorología y Estudios Ambientales, Ministerio de Ambiente, Vivienda y Desarrollo Rural. 176 p.

45. Reymondin L, Nelson A, Jarvis A (2007) An evaluation of void-filling interpolation methods for SRTM data. International Journal of Geographical Information 21: 983–1008.

46. Peña D (2002) Análisis datos multivariantes: McGraw Hill. 539 p.

47. Díaz L (2007) Estadística multivariada: inferencia y métodos. Santafé de Bogotá D. C.: Universidad Nacional de Colombia. Facultad de Ciencias, Departamento de Estadística. 487 p.

48. Chessel D, Dufour A (2012) Analysis of Ecological Data: Exploratory and Euclidean methods in Environmental sciences. Package ade4: dudipca Principal Component Analysis. 1.5–1 ed.

49. Liao T (2005) Clustering of time series data—a survey. Pattern Recognition 38: 1857–1874.

50. Reymondin L (2011) Near-real time pan-tropical monitoring system for natural habitat conversion detection. Strand, London: King’s College London. 53 p.

51. Dimitriadou E (2012) Convex Clustering Methods and Clustering Indexes. R package version 2.15.2 (2012-10-26). R-project.org/package= cclust.

52. Ramírez V, Jaramillo A, Peña A (2013) Gestión del riesgo agroclimático. Vulnerabilidad y capacidad de adaptación del sistema de producción de café. Manual del cafetero colombiano Investigación y tecnología para la sostenibilidad de la caficultura. Chinchiná, Caldas. Colombia: FNC-Cenicafé. pp. 91–114.

53. Salazar L, Hincapié E (2013) Conservación de suelos y aguas. Manual del cafetero colombiano Investigación y tecnología para la sostenibilidad de la caficultura. Chinchiná, Caldas. Colombia: FNC-Cenicafé. pp. 287–320.
54. Jaramillo A, Arcila J (2009) Variabilidad climática en la zona cafetera colombiana asociada al evento de El Niño y su efecto en la caficultura. Avances Técnicos Cenicafé 390: 1–8.

55. Jaramillo A, Arcila J (2009) Variabilidad climática en la zona cafetera colombiana asociada al evento de La Niña y su efecto en la caficultura. Avances Técnicos Cenicafé 389: 1–8.

56. Flórez C, Ibarra L, Gómez L, Carmona C, Castaño A, et al. (2013) Estructura y funcionamiento de la planta de café. Manual del cafetero colombiano Investigación y tecnología para la sostenibilidad de la caficultura. Chinchiná. Caldas. Colombia: FNC-Cenicafé. pp. 123–168.

57. Farfán F, Jaramillo A (2009) Sombrio para el cultivo del café según la nubosidad de la región. Avances Técnicos Cenicafé 379: 1–8.

58. Farfán F (2013) Establecimiento de sistemas agroforestales con café. Manual del cafetero colombiano Investigación y tecnología para la sostenibilidad de la caficultura. Chinchiná. Caldas. Colombia: FNC-Cenicafé. pp. 44–63.

59. Ramírez V (2013) Establecimiento de cafetales al sol. Manual del cafetero colombiano Investigación y tecnología para la sostenibilidad de la caficultura. Chinchiná. Caldas. Colombia: FNC-Cenicafé. pp. 28–43.

60. Sadeghian S (2013) Nutrición de cafetales. Manual del cafetero colombiano Investigación y tecnología para la sostenibilidad de la caficultura. Chinchiná. Caldas. Colombia: FNC-Cenicafé. pp. 85–116.

61. Salazar L, Hincapié E (2013) Manejo integrado de arvenses. Manual del cafetero colombiano Investigación y tecnología para la sostenibilidad de la caficultura. Chinchiná. Caldas. Colombia: FNC-Cenicafé. pp. 117–142.

62. Trojer H (1954) El ambiente climatológico y el cultivo del café en Colombia: problemas, conocimientos actuales y perspectivas. Revista Cenicafé 5: 22–37.

63. Arcila J (2007) Factores que determinan la productividad del cafetal. In: Cenicafé-FNC, editor. Sistemas de producción de café en Colombia. Chinchiná. pp. 61–86.

64. Trojer H (1959) Fundamentos para una zonificación meteorológica y climatológica del tropico y especialmente de Colombia. Revista Cenicafé 10: 287–373.

65. Carbonell J, Quintero R, Torres J, Osorio C, Isaacs C, et al. (2011) Zonificación agroecológica para el cultivo del caña de azúcar en el valle del río Cauca (cuarta aproximación). Principios metodológicos y aplicaciones. Cenicaña. pp. 119.

66. Cock J, Oberthur T, Isaacs C, Läderach P, Palma P, et al. (2011) Crop management based on field observations: Case studies in sugarcane and coffee. Agricultural Systems 104: 755–769.

67. Läderach P, Haggar J, Lau C, Eitzinger A, Ovalle O, et al. (2011) Café Mesoamericano: Desarrollo de una estrategia de adaptación al cambio climático. CIAT Políticas en Síntesis: 4p.

68. Oberthür T, Läderach P, Posada H, Fisher M, Samper L, et al. (2011) Regional relationships between inherent coffee quality and growing environment for denomination of origin labels in Narino and Cauca, Colombia. Food Policy 36: 783–794.