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ORIGINAL PAPER

A method to determine agro-climatic zones based on correlation and cluster analyses

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Abstract
Determining agro-climatic zones (ACZs) is traditionally made by cross-comparing meteorological elements such as air temperature, rainfall, and water deficit (DEF). This study proposes a new method based on correlations between monthly DEFs during the crop cycle and annual yield and performs a multivariate cluster analysis on these correlations. This 'correlation method' was applied to all municipalities in the state of São Paulo to determine ACZs for coffee plantations. A traditional ACZ method for coffee, which is based on temperature and DEF ranges (Evangelista et al.; RBEAA, 6:445–452, 2002), was applied to the study area to compare against the correlation method. The traditional ACZ classified the "Alta Mogina," "Média Mogiana," and "Garça and Marília" regions as traditional coffee regions that were either suitable or even restricted for coffee plantations. These traditional regions have produced coffee since 1800 and should not be classified as restricted. The correlation method classified those areas as high-producing regions and expanded them into other areas. The proposed method is innovative, because it is more detailed than common ACZ methods. Each developmental crop phase was analyzed based on correlations between the monthly DEF and yield, improving the importance of crop physiology in relation to climate.

Keywords Crop zoning · Water deficit · Multivariate analysis · Coffee

1 Introduction

Bounding areas that have similar weather patterns allows the identification of appropriate regions for crop growing, known as agro-climatic zones (ACZs). According to Aggarwal (1993), a literature review showed that ACZs were exercised with the following objectives: data inventory of environmental resources, spatial and temporal data analysis for demarcation of regions, technology transfer within a region of great diversity, planning for regional development, identification of research priorities, and the impact of climate variability on agricultural production.

The development of ACZ methods is valuable, as it provides a concise inventory of climatic potential and constraints for crop production (Araya et al. 2010). In agriculture and forestry, air temperature and rainfall are the main factors that define crop zoning, sowing dates, and expected yield levels (Alvares et al. 2013). Van Wart et al. (2013) proposed the use of ACZs to upscale simulated crop yield potential and compared six ACZ schemes but did not use water deficit (DEF) in the calculations. The same study separated ACZ methods into a matrix and used cluster methodologies. These matrix methodologies were based on classes and subclasses of meteorological element values. The cluster methodologies relied on multivariate statistical analyses to separate similar regions.

The main concern with ACZ methods is that they are based only on meteorological elements, with few variables relating climate, phenology, and crop yield. They have a stronger climatological focus rather than an agro-meteorological approach. Van Wart et al. (2013) stated that many of the ACZs are simply too coarse for estimating and developing a yield gap analysis, because the climate heterogeneity within zones is too large. The need for new methods to determine ACZs is described in some papers. Pinto et al. (2001) noted that few studies account for the probability of weather extreme occurrences in different moments of the crop cycle.

The forefront of studies analyzing coffee ACZs were conducted by Camargo (1977) and Pinto et al. (1979), where they

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rated regions of Brazil as either suitable, marginal, or restricted. Recently, Evangelista et al. (2002) conducted a climatic zoning study associated with the yield potential for coffee in the state of Minas Gerais. However, all these studies were based on general ranges of temperature and DEF.

The variation of coffee production in Brazil is directly correlated with climatic variability (Sá Junior et al. 2012). However, the correlation is very complex, because environmental factors affect the growth and development of coffee plants differently during each phase of cultivation (Camargo 2010). The DEF was the main factor responsible for lower coffee yields (Carvalho et al. 2011), followed by solar radiation (Aparecido et al. 2016). The effects of DEF depended on its duration and intensity, as well as the phenological phase of the plants.

The introduction of new agricultural practices to mitigate DEF problems, or even to verify the impact of droughts in coffee plantations, will require quantifying the effects of DEFs on production (Melo et al. 2014) in diverse ACZs. The purpose of this study is to develop a new agro-climatic zoning method based on a cluster analysis correlating monthly DEFs during phenological phases and crop yields.

2 Materials and methods

Daily meteorological data consisting of air temperature and precipitation from 1998 to 2014 were obtained for 32 counties from the Integrated Center for Agrometeorology (CIIAGRO/IAC-APTA). These counties were selected to represent their Regional Development Offices (RDOs) and for their importance in coffee production. São Paulo has 43 RDOs, averaging 15 counties each. Annual coffee yield data (60 kg sacks ha^{-1}) for all counties in São Paulo were provided by the Agricultural Economics Institute (IEA-APTA) from 2001 to 2014 and were organized by the RDO. Meteorological and yield data began in 1998 and 2001, respectively, because the coffee cycle requires a 24-month period. A period of 30 years should be used to characterize the relationship between climate and crop yields (Thornthwaite 1948). However, it was very difficult to find crop yield experiments or datasets of this length. Due to a lack of coffee yield data, a new method was exemplified with a shorter period (17 years). The effect of this shorter period was analyzed in the paper.

The actual evapotranspiration (AET) and DEFs (Eq. 1) were estimated by the monthly sequential water-balance model proposed by Thornthwaite and Mather (1955). Equations 2, 3, 4, and 5 used the available water capacity (AWC; 100 mm), because according to Meireles et al. (2009), this value represents most of the soil found in the coffee regions. The monthly potential evapotranspiration (PET) was calculated using Camargo's model (1971) (Eq. 6). This model was adapted for the state of São Paulo, as suggested by Camargo and Camargo (2000). PET estimates only consider meteorological factors, whereas AET also considers the water condition of the soil. DEFs are a consequence of the interactions in the soil-plant-atmosphere system.

$$DEF = PET - AET \quad (1)$$

$$AET = P + |SC| \quad if \quad SC < 0 \quad (2)$$

$$AET = PET \quad if \quad SC \leq 0 \quad (3)$$

$$SC = \Delta STO \quad (4)$$

$$STO = AWC \cdot e^{\left(\frac{ACN}{AWC}\right)} \quad (5)$$

$$PET = F \cdot \left(\frac{Q_0}{2.45}\right) \cdot Tm \cdot ND \quad (6)$$

where P is precipitation, SC is the storage change, STO is water storage, AWC is the available water capacity, CAN is the accumulated negative, F is the adjustment factor that varies with mean annual temperature ($Ta < 23.5$ °C, $F = 0.01$), Q_0 is the extraterrestrial solar radiation (MJ m^{-2} day^{-1}), Tm is the mean air temperature and ND is the number of days.

The average yield of an RDO over several years indicates the climatic adaptability of a crop. If this value is high, the crop is well adapted to that region. The standard deviation (SD) is a measure of data dispersion indicating the climatic risk of cultivation in a particular environment. A high SD indicates a highly variable yield annually due to adverse meteorological conditions, which are therefore at greater risk.

The proposed method for ACZs consisted of two stages: the first analysis used correlations (e.g., r and linear Pearson) between the monthly DEF in the crop cycle and the annual yield of each RDO. These correlations quantified the monthly physiological behavior of the crop towards the DEF. Coffee has a cycle from September (first physiological year) to August (second physiological year), totaling 24 DEFs to be analyzed. In the second stage, we carried out a grouping analysis of correlations for each RDO based on a multivariate cluster analysis. Groups of ACZs were determined by using Euclidean distances, adapted from the Ward method (1963).

These groups indicated regions with similar physiological behaviors for coffee. The defined groups allowed the mapping of the ACZs. A multivariate principal component analysis (PCA) identified monthly DEFs with the highest influence on yield levels within each group. A traditional ACZ, based on ranges of air temperature and DEF (proposed by Evangelista et al. 2002) (Table 1), was applied to the state in order to verify the effectiveness of the new correlation method proposed.

We analyzed the lowest and highest average annual yields in the state to determine the importance of the highest monthly DEF. The year with the highest number of RDOs and the highest yields and the year with the highest number of

Table 1 Parameters of coffee zoning as proposed by Evangelista et al. (2002) based on annual air temperature and water deficit

Region	Average annual Air temperature (T, °C)	Water deficit (DEF, mm)
Suitable	$19 \leq T < 22$	DEF < 200
Restricted	$22 \leq T < 24$	$200 \leq$ DEF < 400
Unsuitable	$T < 19$ or $T \geq 24$	DEF ≥ 400

RDOs and the lowest yields were identified. Months with larger differences in DEF between years with high and low yields were thus identified.

3 Results and discussion

São Paulo has large climatic diversity, which complicated this study (Alvares et al. 2013). Only a few studies have identified coffee ACZs. The most important studies, such as those by Pinto et al. (1979) and Camargo (1977), have rated regions as suitable, marginal, or adverse but did not consider variations in DEFs during the coffee phenological development phases.

Climate has a strong influence on coffee yields, which causes a high variation on each 2-year production (biennially). Assimilated photons in one phenological cycle were used to increase the leaf area index, length of branches, and root development but not the grain filling, which thereby produced a low yield. In the next phenological cycle, when the vegetative development was limited, photoassimilates were used for bud and grain production, producing a high yield (DaMatta et al. 2007).

Coffee crops were highly sensitive to climate, generating a high variability among the RDOs. The high average yields indicated that the main coffee regions of the state usually had high climatic adaptabilities. The average yields were 25.33 and 25.07 sacks ha^{-1} for the Mogi Mirim and São João da Boa Vista RDOs, respectively, in the region of Média Mogiana. The average yields were 21.15 and 19.30 sacks ha^{-1} for the RDOs in Ourinhos and Tupã, respectively. The region of Alta Mogiana in Franca had an average yield of 17.88 sacks ha^{-1}. Frequent pruning in many areas can contribute to lower average yields (Conab 2016). Climatic risk was higher for Barretos, where the biennial yields produced a standard deviation (SD) of 5.76 sacks ha^{-1}. Bauru's RDO was influenced the least by climate, with a SD of 1.16 sacks ha^{-1}.

Average yields for coffee in the state of São Paulo were lowest in 2005 and highest in 2012, at 13.36 and 19.14 sacks ha^{-1}, respectively. During those cycles, the total amount of DEFs were 452 and 496 mm cycle^{-1}, respectively. Therefore, the difference between the highest and lowest yields was close to 4 sacks ha^{-1}. The state contains approximately 215,132.6 ha of coffee plantations, of which 203,490.6 ha are in production and 11,642 ha are in preparation (Conab 2016). Thus, this decrease in yields would represent a decrease of 813,960 sacks in the state. The 2005 data presented a downward asymmetry of 0.14, and the 2012 data presented an upward asymmetry of 0.50.

The difference in DEFs between the 2 years was 44 mm. Some variables, however, should be considered when ideal conditions are evaluated, such as the timing and intensity of the DEF, water surpluses, and physical soil properties (Camargo 2010). For the 2003–2005 crop yield, the cycle began with a DEF significantly higher than the crop DEF from September to November in 2010–2012 2 years before harvest

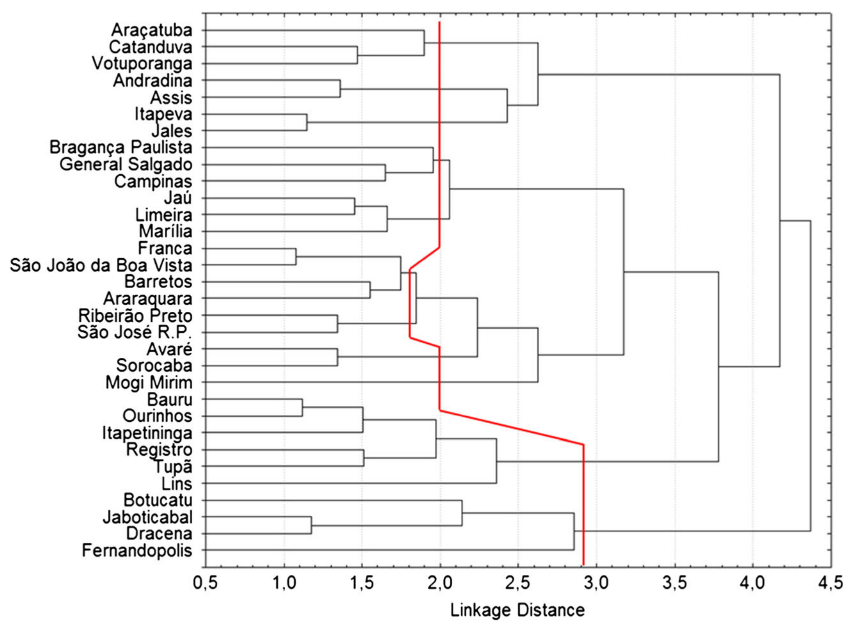


Fig. 1 Grouping of regional development offices (RDOs) in a cluster analysis, regarding the correlations between water stress and yield

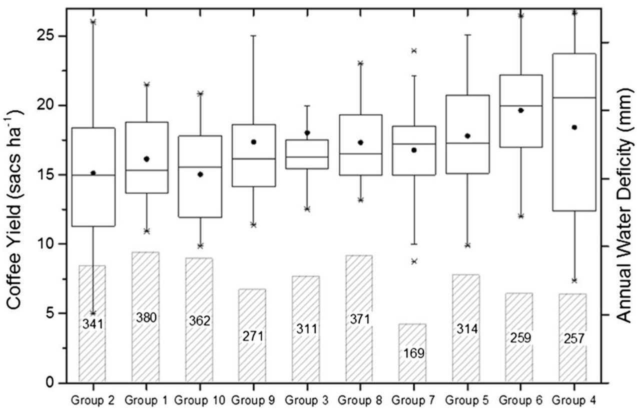


Fig. 2 Coffee yield and annual water deficit for each group obtained in the cluster analysis that represents the agro-climatic zones. The box plot represents coffee yield, and the bars represent annual water deficit (mm)

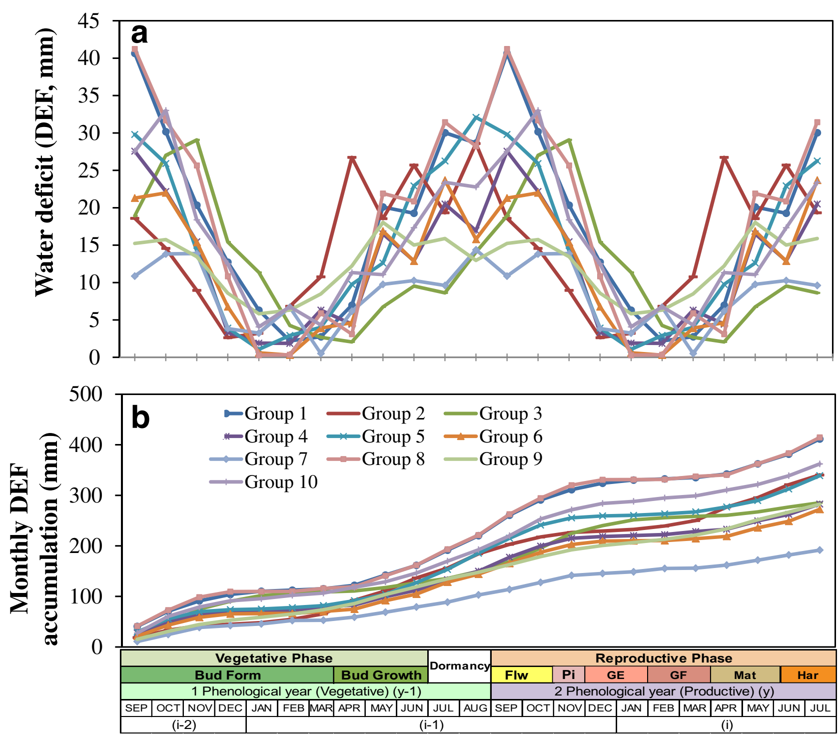
(SEP_{i-2} and NOV_{i-2}, respectively), which corresponded to a vegetative growth phase. A DEF during this phase will decrease the growth of branches and may affect the formation of buds in DEC_{i-2} (DaMatta et al. 2007; Camargo 2010).

The DEF between MAY_{i-1} and JUL_{i-1} (where $_{i-1}$ is 1 year before harvest) was lower in the year with the lowest yield (2005) than the year with the highest yield (2012). When the dormancy period is not well defined due to occasional rain or low temperatures, the coffee yield can be lower due to multiple and uneven flowering, extending the period of harvest (DaMatta et al. 2007). A DEF between AUG_{i-1} and OCT_{i-1} was also important, because this period corresponds to the beginning of the flowering phase. A peak of 55 mm in SEP_{i-1} of the 2003–2005 cycle, which was higher than the peak in the 2010–2012 cycle, likely had a negative influence on yield. DEFs and high temperatures during flowering can greatly affect fertilization of the ovary, thereby limiting production (Carvalho et al. 2011).

The cluster analysis grouped similar RDOs by correlating the monthly DEF with the yield (Fig. 1), producing 10 groups for the state. For example, group 4 included Campinas, Bragança Paulista, and General Salgado. This group corresponds to a traditional coffee region called "Média Mogiana." The first two regions had a similar monthly DEF. Bragança Paulista was hotter, with the highest DEFs in APR_{i-1} and between the January (JAN_i) and MAR_i year harvest, but had a similar correlation in monthly DEF compared to yield (Fig. 6). Group 2 had a higher annual DEF and a lower yield (15 sacks ha^{-1}), and group 4 had a lower annual DEF and a higher yield (17.5 sacks ha^{-1}) (Fig. 6).

The grouping of similar RDOs by correlating monthly DEF and yield (Fig. 2) indicated that regions such as the Araçatuba RDO were similar to the Catanduva and Votuporanga RDOs, which formed group 1. Another similar group, group 8, included the Ribeirão Preto and the São José do Rio Preto RDOs. The distribution of the DEF throughout the coffee cycle was similar in these two groups (Fig. 3a), with an accumulated DEF of 400 mm cycle^{-1}. A comparative data analysis

Fig. 3 Monthly water deficit **a** and cumulative water deficit **b** of the groups obtained in the cluster analysis that represents the agro-climatic zones



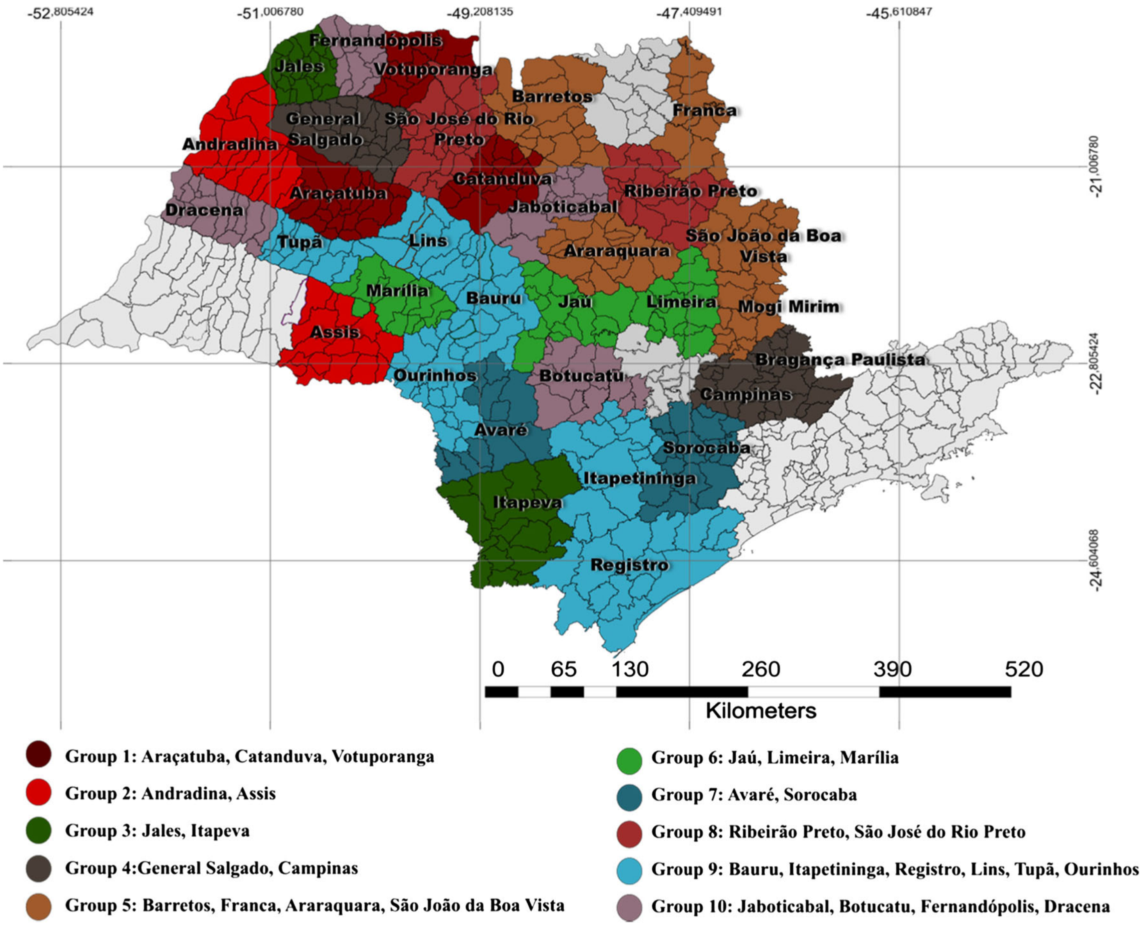


Fig. 4 A map of agro-climatic zones, according to a cluster analysis, using the correlation water deficit during the monthly coffee and yield cycles. Each group indicated similarities in climate and crop yield

of the water balance in several Brazilian coffee regions (Camargo 1977) found that coffee could support a maximum DEF of 150 mm year^{-1}, especially if this period did not extend into September, but only if the phases were restricted to bud formation and dormancy. Under these conditions, groups 2, 5, 10, and 8 had DEFs exceeding 150 mm during the same period (Fig. 3b). These groups comprised regions with higher average temperatures. The growth of Arabica coffee generally exhibits a periodicity accompanying the distribution of precipitation if the temperature is favorable (Maestri and Barros 1977; Rena et al. 1994). A return to growth in some coffee regions, however, may precede the onset of rain, as in southern India and Santa Tecla, El Salvador (DaMatta et al. 2007). The growing frequency in other regions, with regularly distributed precipitation and mild temperatures (i.e., Costa Rica and Colombia), may be determined by small variations in solar radiation (Alvim 1964).

The mapping of ACZs divided the north and south portions of the state. The northern portion contained regions with warmer and drier climates. The southern portion contained regions with milder and more humid climates (Fig. 4).

The groups had specific ranges of monthly DEFs. Group 1 (Araçatuba, Votuporanga, and Catanduva) had minimum and maximum DEFs of 27 and 35 mm month^{-1}, respectively. The maximum DEF in AUG_{i-1} of 45 mm was the most interesting feature in this group. Monthly variations were similar between groups 1, 4, and 5 and groups 7, 9, and 10, which were more variable (Fig. 5).

A DEF can decrease the coffee yield, although its effects depend on the duration and intensity of the deficit and the phenological phase in each climate region. Monthly DEFs and yields were negatively correlated in all vegetative phases, except maturation and dormancy. That is, DEF was associated with a decrease in yield (Fig. 6). DaMatta et al. (2007) reported that DEFs during dormancy from JUL_{i-1} to AUG_{i-1}, the phase prior to the anthesis could be beneficial and favor a more uniform flowering with the first rains in September. DEF is not a determining factor for flowering in coffee, but it is necessary for a more uniform flowering (Crisosto et al. 1991). DEFs and yields were negatively correlated during the pinhead and fruit expansion phases, according to DaMatta et al. (2007), who reported that severe droughts in these phases may hinder fruit growth and produce small grains.

Groups 4, 9, and 10 may be more affected by DEFs because the negative correlation between DEF and yield was dominant throughout the cycle. The monthly DEF was

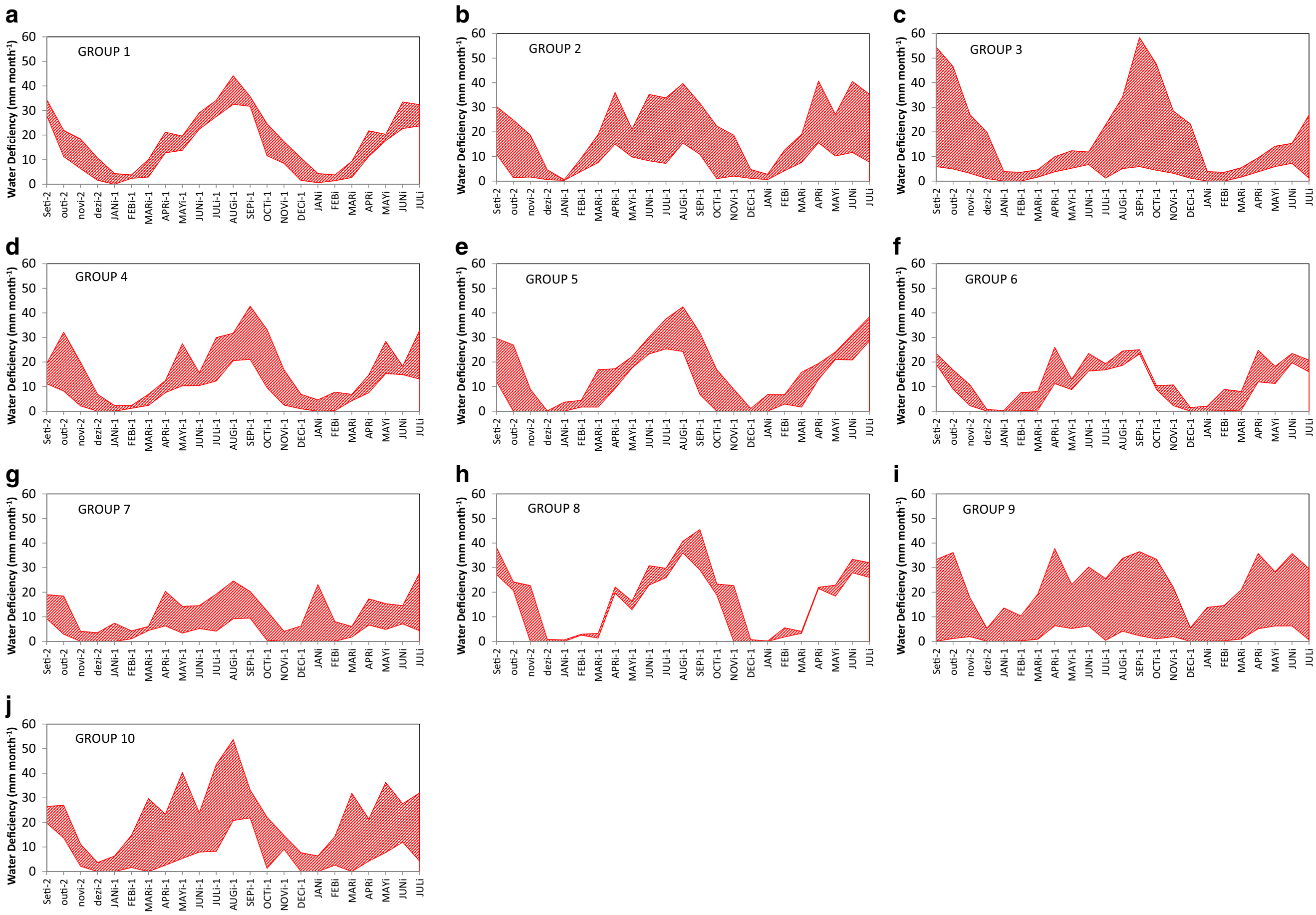


Fig. 5 Maximum and minimum monthly water deficits for each agro-climatic zone in the state of São Paulo during an average crop cycle

significantly, positively correlated with the yield in groups 6 and 7 (Fig. 7). These regions were more humid, where DEF was beneficial in several phenological phases, mainly in the vegetative and flower bud formation phases, perhaps due to the tendency for climate to be milder in more humid regions. The occurrence of DEFs throughout the cycle, due to an increase in average temperature and degree-days, will consequently increase the rate of photosynthesis.

The traditional Alta Mogiana coffee region in group 5 stood out for its positive correlation between DEF and yield from JAN_i to JUL_i. Regions with milder temperatures at higher altitudes have longer cycles (i.e., the period between flowering and full maturity), such as northeast São Paulo where Alta Mogiana is located (Bardin-Camparotto et al. 2012). The positive correlation may have been due to a longer cycle, causing the DEF to provide a more uniform flowering and harvest. The northwestern and southwestern traditional regions, such as Marília and Garça (group 6), had shorter cycles and an anticipated harvest due to higher temperatures. These regions were extended to Jaú and Limeira; despite being cooler, they also had rain at harvest that lowered the quality and yield of the coffee. The "correlation method" applied to coffee suggests that it is possible to utilize a minimum period of 17 years to determine agro-climatic zones for coffee in the state, because the method identified all known traditional coffee-producing regions (e.g., Alta Mogiana, Média Mogiana, and the regions of Garça and Marilia).

To compare and verify the efficiency of the new proposed method, a traditional ACZ method was performed using the criteria proposed by Evangelista et al. (2002) (Fig. 8). The traditional ACZ method made more errors than the new one. The traditional regions of coffee production in São Paulo State were proven to be suitable climatic regions, because production in these regions dated back to 1800. The Alta and Média Mogiana regions were classified as suitable and restricted areas. The region of Garça and Marília was classified as suitable and restricted. It is known that these regions (Garça and Marilia) have problems with the quality of beans due to precipitation during harvest, but classifying them as restrictive for yield was not adequate. The traditional method limits these regions only in terms of annual air temperature and water stress. The new method found that these regions hold the highest yields. The correlation method identified these regions and even expanded their classification, as was the case for Alta

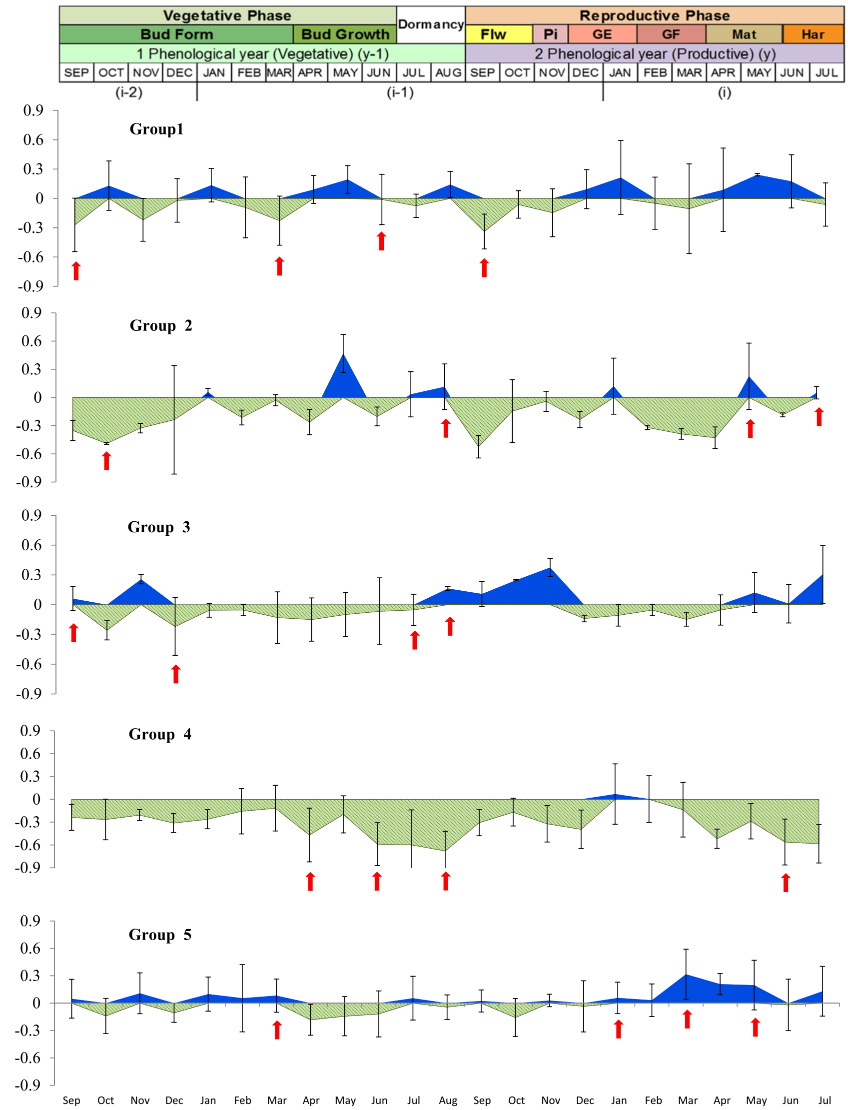


Fig. 6 Correlations between water deficit and yield for groups 1 to 5. The arrows mean the most important monthly DEFs which were determined by a principal component analysis

Mogina where the Araraquara and Barretos RDOs were added. Other relevant results indicated that the correlation method found 10 groups, which was different than the three found from the traditional ACZ method.

The analysis of what monthly DEFs were the most important for coffee yields was made by the principal component analysis (PCA). The PCA identified the most important DEF in the coffee cycle as SEP_{i-1}, MAR_{i-1}, SEP_{i-2}, and JUN_{i-1} for group 1; JUL_i, OCT_{i-2}, JUL_{i-1}, and APR_i for group 2; SEP_{i-2}, SEP_{i-1}, AUG_{i-1}, and APR_{i-1} for group 3; JUN_{i-1}, JUN_i, AUG_{i-1}, and APR_{i-1} for group 4; JAN_i, MAR_{i-1}, MAY_i, and APR_i for group 5; JUN_i, APR_i, MAR_{i-1}, and JUN_{i-1} for group 6; JAN_i, JUN_{i-1}, JAN_{i-1}, and May_{i-1} for group 7; JUL_{i-1}, MAR_i, JAN_i, and JUN_{i-1} for group 8; DEC_{i-1}, JAN_i, DEC_{i-2}, and AUG_{i-1} for group 9; and DEC_{i-2}, JAN_{i-1}, JAN_i, and FEB_i for group 10.

SEP_{i-2}, JAN_{i-1}, MAY_{i-1}, and APR_{i-1} were the most important months during the growing period for all groups. JUN_{i-1} and AUG_{i-1}, which included dormancy and the beginning of flowering, were the most important months during the reproductive stage. Maturation occurred unevenly in natural conditions; coffee in regions such as south-central Brazil flowered at different times. For example, crops have two to four flowerings from August to November in the main coffee-producing regions in Brazil (Barros et al. 1978; DaMatta et al. 2007).

DEFs were managed in irrigated plantations to obtain uniform harvests, which can lead to the loss of seed endosperm and could have a long-term negative impact on crop performance. For example, the cv. “Caturra” has several blooms in Colombia and Costa Rica but not in Brazil, where the decline and sometimes death of the plant are common after four or five harvests (DaMatta et al. 2007).

Fruit filling and maturation occurred in JAN_i and APR_i, respectively. A DEF during these phases can be harmful (DaMatta et al. 2007), where less fruit produced and poorly formed grains

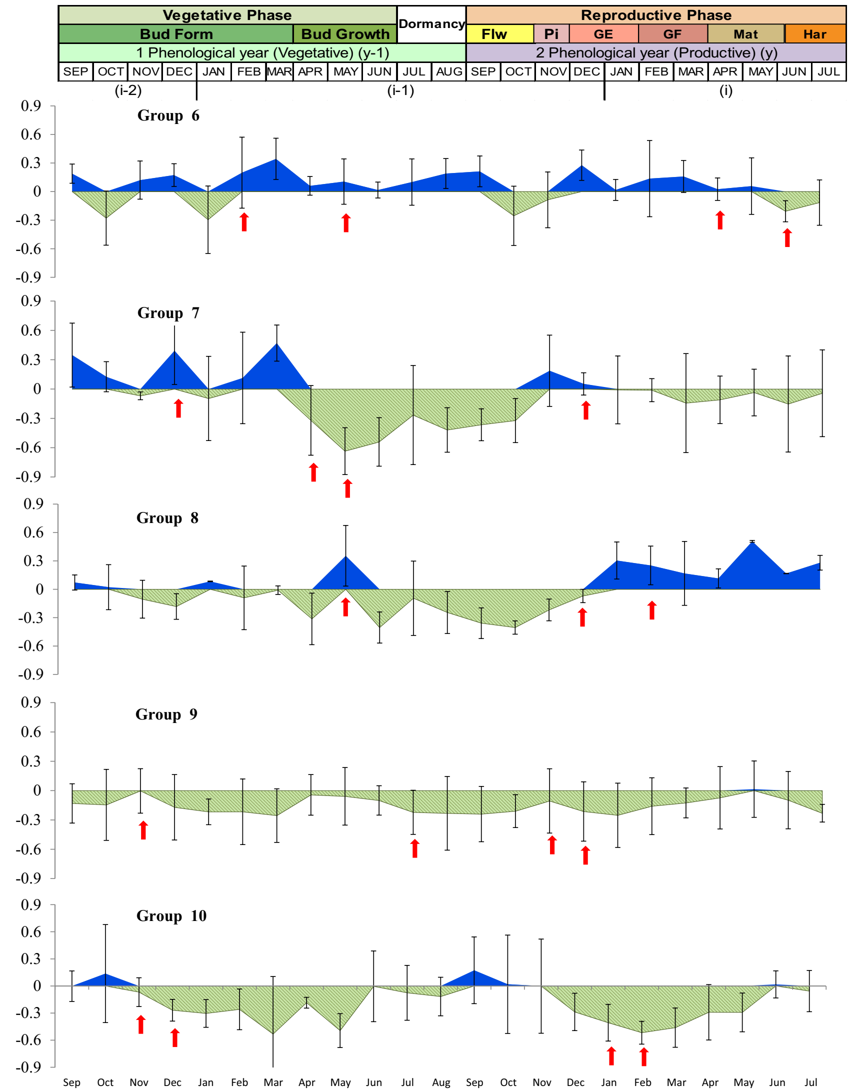


Fig. 7 Correlations of water deficit and yield for groups 6 to 10. The arrows mean the most important monthly DEFs which were determined by a principal component analysis

cause black, green, and burn defects. Seasonal rain was a relevant factor in determining the ecological interval between flowering and grain maturation (DaMatta et al. 2007). This interval is very short in many species that are adapted to dry regions, only about 3 months for some species in eastern Africa, such as *Coffea racemosa* (Charier and Berthaud 1985). The opposite extreme (12–13 months) occurs for *C. liberica* in India (Ahmad 1980). The interval between flowering and complete fruit maturation is usually 8–12 months for most coffee species.

4 Conclusions

Coffee crops are highly sensitive to climate and generate high variability among RDOs. Climatic risk was higher for Barretos, with a standard deviation of 5.76 sacks ha^{-1} for yields. Bauru's RDO was influenced least by climate, with a standard deviation of 1.16 sacks ha^{-1}.

The cluster analysis grouped similar RDOs by correlating monthly DEFs and yields, producing 10 ACZs for the state. ACZ mapping divided the state into northern and southern regions. The northern part of the state contained regions with warmer and drier climates, and the southern part of the state contained regions with milder and more humid climates.

Groups 4, 9, and 10 were most affected by DEF, because the negative correlation between the DEF and the yield was dominant throughout the cycle. The monthly DEF was significantly and positively correlated with the yield in groups 6 and 7. The traditional coffee region of Alta Mogiana in group 5 stood out for its positive correlation between DEF and yield from JAN_i to JUL_i. The northwestern and southwestern traditional regions, such as Marília and Garça, had shorter cycles and anticipated harvests due to higher temperatures.

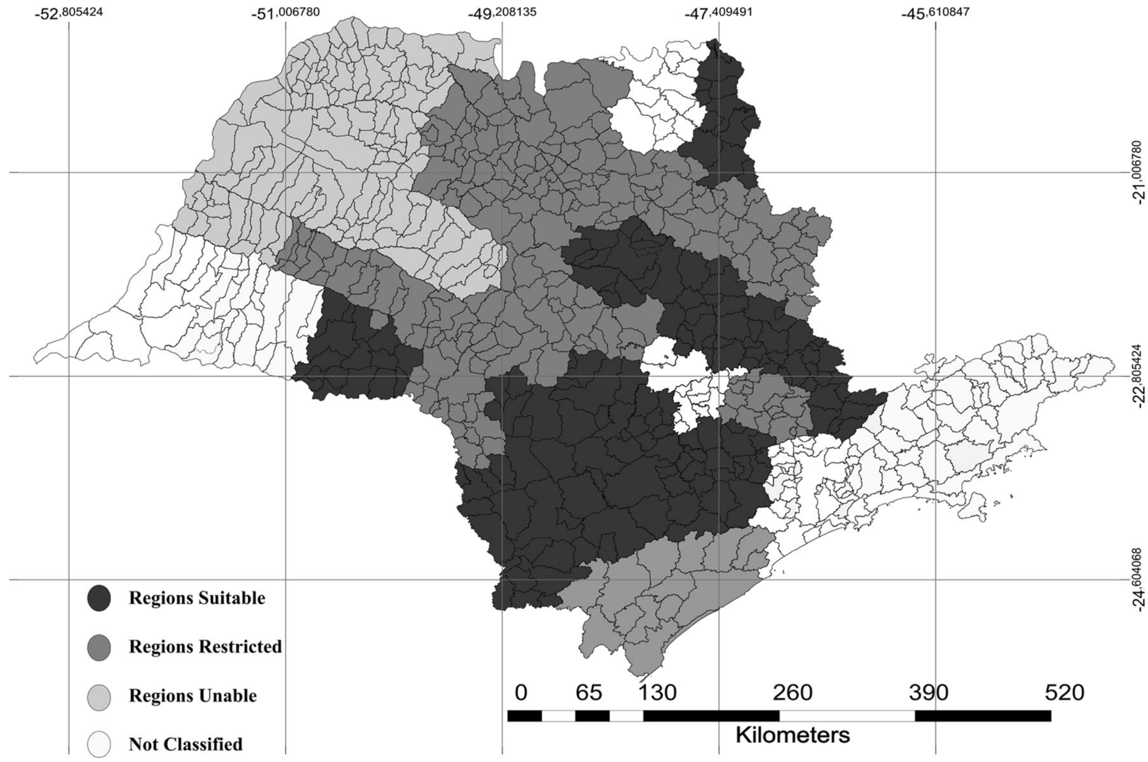


Fig. 8 Agro-climatic zone for *Coffea Arabica* L. using criteria from Evangelista et al. (2012) for the state of São Paulo

The PCA identified the most important months during the growing period for all groups, which were SEP_{i-2}, JAN_{i-1}, MAY_{i-1}, APR_{i-1}, JUN_{i-1}, and AUG_{i-1}. They all contained dormancy and the beginning of flowering and were the most important months during the reproductive stage.

The new method, called the "correlation method," determined agro-climatic zones with more efficiency than a traditional agro-climatic zone based the range of meteorological elements. The "correlation method" identified all known traditional coffee regions in the state of São Paulo and expanded them to new potentials. This method allowed for the identification of correlated monthly DEFs with yield levels within each agro-climatic zone.

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