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CROP PRODUCTION

Base temperature, cycle duration, and thermal constant for yacon culture

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ABSTRACT. Yacon is a perennial herbaceous plant that naturally occurs in South America at altitudes ranging from 2,000 m to 3,100 m above sea level. The yacon culture has recently grown in popularity as it has high productive potential in mild climates and multiple benefits to human health. This study aimed to determine the lower and upper base temperatures, cycle duration, and thermal constant for the yacon culture, based on phenological data from field experiments that were carried out during three growing seasons (fall, winter, and spring) in 2013. The experiments were conducted in the municipality of Ibatiba in the state of Espírito Santo, Brazil, in a randomized block design with four replicates. The lower base temperature was determined using methods of the lowest standard deviation in days and degree-days, relative development, and variation coefficient in degree-days for two subperiods: emergence to maturation, and onset of tuberization to maturation. The upper base temperature was determined by the standard deviation and coefficient of variation methods, both in degrees-days. The relationship between meteorological elements and the onset of tuberization was also investigated. The lower base temperature values determined for yacon were 12.5°C in the two subperiods studied with a base temperature above 34.0°C. The productivity of these tuberous roots was higher in the fall because of the longer cycle, lower temperature, and lower photoperiod. In turn, a higher thermal sum was needed to initiate tuberization with the delay of planting.

Keywords: *Smallanthus sonchifolius*; phenology; degree days; photoperiod.

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Introduction

Belonging to the Asteraceae family and originating from the Andean Valleys in South America at altitudes ranging from 2,000 to 3,100 m above sea level (Paula, Abranches, & Ferreira, 2015), the culture of yacon (*Smallanthus sonchifolius*) has great potential in folk medicine, because its root offers several benefits to human health. Among the benefits, we can mention its ability to lower cholesterol and blood glucose levels (Gusso, Mattanna, & Richards, 2015), immunostimulating properties (Vaz-Tostes et al., 2014), diabetes or renal disorder (Paula et al., 2015), weight management, and obesity prevention in overweight adults (Silva et al., 2017; Machado, Silva, Chaves, & Alfenas, 2019).

The main characteristics of the yacon culture include its adaptability to edaphoclimatic differences, ease of use in cultural methods, and good productivity. It is a tuberous culture capable of tolerating minimum temperatures of 4-5°C, but its optimum development occurs between 18 and 25°C (Grau & Rea, 1997).

These characteristics make yacon an important crop in agriculture. Moreover, yacon has achieved worldwide notoriety because it is a great source of bioactive components, including fructooligosaccharides (FOS) and phenolic compounds (Silva et al., 2018a; Kamp, Hartung, Mast, & Graeff-Hönninger, 2019), which led to a significant increase in its consumption since the mid-2000s (Erlacher, Oliveira, Fialho, Silva, & Carvalho, 2016).

In Brazil, cultivation started in 1989 in the Capão Bonito region of São Paulo State by Japanese immigrants. As of late, cultivation has been limited planting cycles in the mountainous areas located in the states of Espírito Santo and Rio de Janeiro (Moscatto, Prudêncio-Ferreira, & Hauly, 2004; Santana & Cardoso, 2008). For this reason, studies in the country are restricted, which shows the importance of searching for information to assist in the productive development of this culture. Among the several necessary ecophysiological information, the effect of air temperature on the development of yacon can adequately explain the development of this species, as well as its adaptation to new areas of cultivation and its physiological processes, moderating the biochemical reactions of photosynthesis and photorespiration (Souza & Martins, 2014; Freitas, Martins, & Abreu, 2017).

One way to evaluate the effect of air temperature and the degree of development of a species is to use the thermal sum or degree day (DD), assuming that base temperatures control the growth and development of the crop (Posse et al., 2018). The concept of a DD is a simple way to quantify the energy available to the plant assuming there are minimum and maximum temperatures capable to cease development and may even cause disturbances to plant tissues.

After the base temperatures are determined, the thermal sum of the cycle is obtained. This information is necessary for agricultural planning (Pilau, Battisti, Somavilla, & Schwerz, 2011). There is currently no information regarding the thermal sum required for the yacon culture, nor the effect of the growing season temperature that can offer insight to improving productivity or understanding its relationship with meteorological elements (air temperature and photoperiod) during the growing period.

Thus, given the increasing importance of yacon in Brazilian agricultural production and the scarcity of climatic and phenological parameters that assist in crop planning and management, this study aims to determine the lower base temperature (Bt) for the subperiods of emergence-maturation and onset of tuberization-maturation and the upper base temperature (BT) for emergence-maturation, as well as the cycle duration and thermal constant for the yacon culture.

Material and methods

Climatic characteristics and location of the experiment

Field experiments were conducted in the agricultural area of the municipality of Ibatiba (20°17’ S 41°37’ W, 837 m in altitude) located in the state of Espírito Santo, Brazil (Figure 1), in a randomized block design, with four replicates. The experiments consisted of three seasons of yacon planting in 2013: fall (April 20), winter (July 20), and spring (September 20). For climate monitoring, a meteorological station belonging to the Capixaba Institute for Research, Technical Assistance and Rural Extension (Incaper) located 10 km away from the experimental area at an altitude of 758 m, was used.

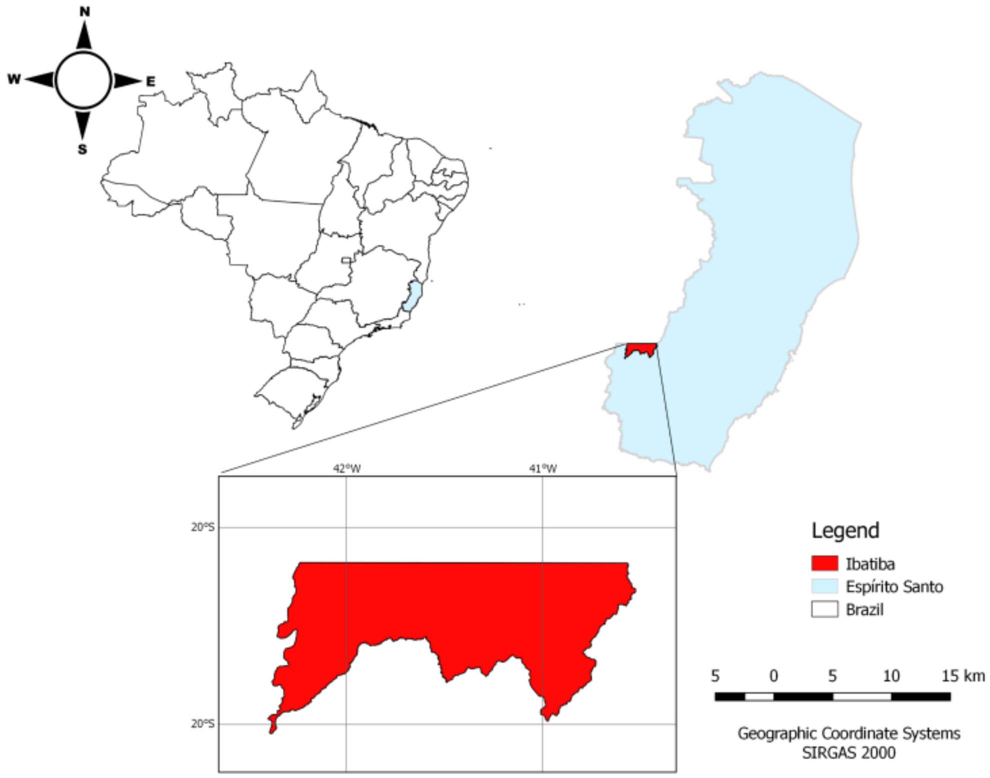

Figure 1. Study area. Geographic location of the state of Espírito Santo, Brazil, with an emphasis on the municipality of Ibatiba.

Cultivation practices

The soil was prepared by plowing 30 cm deep and then harrowing. The planting system was manual, performed in furrows using rhizomes of approximately 35 g at a depth of 10 cm following the desired spacing, and 180 g of cattle manure per plant were used. The manure contained the following nutrients: 14.21 g kg^{-1} of N, 4.75 g kg^{-1} of P, 5.28 g kg^{-1} of K, 4.29 g kg^{-1} of Ca, and 1.92 g kg^{-1} of Mg. During the growing cycle, a conventional sprinkler irrigation supplied 30 mm of water weekly. The local soil is a red-yellow latosol of medium texture (*Empresa Brasileira de Pesquisa Agropecuária* [Embrapa], 2014), and a sample was submitted to the soil laboratory of Ccae/Ufes for chemical and physical analyses. A sample was gathered from a depth range 0-20 cm and through analyzation was determined to have the following characteristics: pH (water) - 6.20, phosphorus mehlich 1 - 53.99 mg dm^{-3}, potassium - 80.00 mg dm^{-3}, calcium - 2.12 $cmol_c$ dm^{-3}, magnesium - 0.87 $cmol_c$ dm^{-3}, aluminum - 0.0 $cmol_c$ dm^{-3}, sum of bases - 3.24 $cmol_c$ dm^{-3}, CTC effective - 3.24 $cmol_c$ dm^{-3}, total organic carbon - 1,83%, and total nitrogen - 0.15%.

The experiment consisted of five 8 m rows of crops spaced 1.0 m apart with 0.5 m between each plant, totaling 16 yacon plants per row. The root dry matter mass data were obtained in a greenhouse with forced air circulation at 70 ± 5°C until constant mass, and were converted to biomass per land area, considering the plant density of each plot (2 plants m^{-2}).

Calculation of lower basal temperature

The base temperatures of yacon were determined in two phenological phases, assuming the emergence time (EME) to be the moment when 50% of the plants broke through the soil, the onset of tuberization (OT) to be when the tuber began to form, and the physiological maturation (MAT) to be the end of the experiment. To estimate the Bt, one must first calculate the DDs (°C day), using the method proposed by Arnold (1960) as described in Equation 1:

$$\mathrm{DD}_i = \left(\frac{(\mathrm{Tmax}+\mathrm{Tmin})}{2}\right)\text{-Bt}$$

where:
DD_i is the degree days (°C day);
Tmax is the maximum daily air temperature (°C);
Tmin is the minimum daily air temperature (°C); and
Bt is the lower base temperature of the cultivar.

To calculate the DD, a series of Bts ranging from 5 to 15°C were used in intervals of 0.5°C. The accumulated DDs sum were obtained from the emergence of each season using the sum of DD_i as follows (Equation 2):

$$\mathrm{DD} = \sum_{i=1}^{n} \mathrm{DD}_i$$

Methodologies proposed by Arnold (1959) and Yang, Logan, and Coffey (1995) were used to estimate the Bt by four methods:
standard deviation in DD (SD_{dd});
standard deviation in days (SD_d);
coefficient of variation in degree days (CV_{dd}); and
relative development (RD).

In the SD_{dd} method, the Bt of each plant is the one that results in the lowest standard deviation in DD using different growing seasons (Yang et al., 1995), as described in Equation 3 as follows:

$$\mathrm{SD_{dd}} = \sqrt{\frac{\sum_{i=1}^{n}(\mathrm{DD}_i - \mathrm{MDD})^2}{\text{n-1}}}$$

where:
SD_{dd} is standard deviation in degree days;
DD_i is degree days accumulated in the i-th growing season using a series of Bt;
MDD is mean degree days accumulated for all the i-th growing times; and
n is the number of growing seasons.

For the method SD_d, the indicated Bt values were previously selected, identical to those of the previous method, in which Arnold (1959) suggested that the determination of the base temperature by SD_d method between the different growing seasons (Equation 4) was:

$$SD_d = \frac{SD_{dd}}{\bar{\chi}\text{-Bt}}$$

where:
SD_d is the standard deviation in a day;
SD_{dd} is the SD_{dd} standard deviation in degree days using a series of Bt;
$\bar{\chi}$ is the mean air temperature of all *i* seasons (°C); and
Bt is the lower base temperature (°C).

The CV_{dd} is the relationship between the SD_{dd} and the MDD. It considers the value of Bt as one that presents the lowest coefficient of variation in relation to the DDs required to reach a certain phase of development, following Equation 5, which was adapted by Yang et al. (1995):

$$CV_{dd} = \left(\frac{SD_{dd}}{MDD}\right)100$$

Finally, the RD method is based on the linear relationship between mean temperature (MT) during the studied development phase and the RD values of the species/cultivar. To determine the RD, the following equation is used (Equation 6):

$$RD = a*MT + b, \text{ being } RD = \frac{100}{N}$$

where:
the angular coefficient of the linear regression;
b is the linear coefficient, 100 is an arbitrary weighting value; and
N is the number of days in the development phase in each growing season. Using RD, Bt is the result of a null relative development from the prolongation of the simple linear regression between the RD of the cultivar and the MT, i.e., Bt = −b/a.

Calculation of upper basal temperature

The maximum base temperature (BT) was determined in a similar way to Bt. Using the methods of SD_d and CV_{dd}, both in degree days, being considered as BT when Tb became constant. The temperatures of a 1-in-1-degree variation were used for this estimation, from 21 to 35°C. The characterization of the thermal requirements were made using the methodology proposed by Ometto (1981), whose variations are presented as:

Case 1: BT > Tmax > Tmin > Bt, according Equation 7:

$$DD = \left(\frac{(Tmax\text{-}Tmin)}{2}\right) + (Tmin\text{-}Bt)$$

Case 2: BT > Tmax > Bt ⩾ Tmin, according Equation 8:

$$DD = \left(\frac{(Tmax\text{-}Bt)^2}{2(Tmax\text{-}Tmin)}\right)$$

Case 3: BT > Bt > Tmax > Tmin, according Equation 9:

$$DD=0$$

Case 4: Tmax > BT > Tmin > Bt, according Equation 10:

$$DD=2\left(\frac{(Tmax\text{-}Tmin)(Tmin\text{-}Bt)+(Tmax\text{-}Tmin)^2\text{-}(Tmax\text{-}BT)}{2(Tmax\text{-}Tmin)}\right)$$

Case 5: Tmax > BT > Bt > Tmin, according Equation 11:

$$DD=0.5\left(\frac{(Tmax\text{-}Bt)^2\text{-}(Tmax\text{-}BT)}{(Tmax\text{-}Tmin)}\right)$$

where:
Tmax is maximum temperature of the day;
Tmin is minimum temperature of the day; and
Bt is lower base temperature and BT is the upper base temperature.

After determining the Bt through different methods, the arithmetic mean was used between them to determine the BT, which was subsequently used for the thermal sum. The equations were adjusted to determine which meteorological factors most interfered in the duration of the cycle and in the emergence-onset of tuberization subperiod, using Excel and the open source program R for data organization and processing.

Results and discussion

The cultivation of yacon in different growing seasons in the field allowed the plants to develop in distinct meteorological conditions during their cycle, making it possible to estimate their Bt. During the corresponding period between the emergence of plants until maturation, the highest temperature observed occurred in the fall and winter crops, with a value of 33.2°C on September 23, 2013 (Table 1). However, evaluating the mean maximum temperatures during the cycle, the spring crop presented a higher mean maximum temperature, with a value of 28.4°C, followed by the winter and fall crops, with 27.7 and 25.5°C, respectively.

Therefore, it was determined that the mean daily maximum temperature for each growing season existed above the ideal temperature range of yacon production (18-25°C) as determined by Grau and Rea (1997), with the spring crop 3.4°C higher than the ideal temperature.

Regarding the minimum temperatures, the lowest occurred in the fall crop at 6.5°C on July 6, 2013. This same growing season presented lowest mean minimum temperatures from the emergence to the maturation period, with 15.5°C. According to Grau and Rea (1997), when subjected to high solar radiation and temperatures below 10-12°C, yacon presents cooling damage in the leaves. In this experiment, such damage was not observed. According to Grau and Rea (1997), when subjected to high solar radiation and temperatures below 10-12°C, yacon presents cooling damage in the leaves. In this experiment, such damage was not observed.

The mean temperatures during the yacon cycle in the three growing seasons were 20.5, 22.6, and 23.2°C for the fall, winter, and spring crops, respectively. The differences between the meteorological conditions prevailing during these growing seasons also affected the duration of the crop development phase, which showed a tendency to decrease the duration with the advance of the growing season (Figure 7). During the experiment, the accumulated precipitations of 776.8 mm, 915.4 mm, and 915.4 mm were recorded for the fall, winter, and spring, respectively.

Small variations in the Bt values were observed between the four methods used (Figure 2 and 3), which was also verified by Luz et al. (2012) for *Brassica napus* L., and by Souza and Martins (2014) for two olive cultivars. Figure 2a and b show that the values obtained for the relationship of RD and mean air temperature during the cycle of each sowing season resulted in a linear coefficient ‘a’ equal to -0.821 and the angular coefficient ‘b’ equal to 0.0628, with ‘R^2’ as 0.84 for the EME – MAT subperiod. Meanwhile, the OT – MAT subperiod presented an ‘a’ of -0.7842 and a ‘b’ of 0.0600, where ‘R^2’ equaled 0.79.

Applying the Bt equation (-b/a), the value of 13.1°C was obtained for both the EME – MAT and OT – MAT subperiods. In the SD_{dd} method, the Bt value found for the subperiods was 13.5ºC (Figure 2c and d). Knowing the Bt is important because the cultures have their development compromised when subjected to temperatures below the Bt. Therefore, these results can contribute to agricultural planning as well as to the climatic knowledge of each region.

The results obtained in this experiment are very similar to those found by Douglas et al. (2007), who, when determining the base temperature of yacon in New Zealand, obtained an R^2 value of 0.81 with a base temperature of 12°C. The values of the Bt by the RD method present values slightly different from those obtained by the SD_{dd} method, indicating that the estimation methods have a similar efficiency for determining the Bt of yacon as their differences were lower than 0.5°C. Determining the Bt for two olive cultivars, based on the same methods adopted in this study, Souza and Martins (2014) also obtained close Bt values, with a low variation of 0.5°C.

The SD_d method, shown in Figure 3, resulted in lower Bt values than those obtained by the SD_{dd} and RD methods, with a value of 12.0°C for each subperiod (Figure 3a and b). According to Streck et al. (2005), it is important to determine the Bt throughout the cycle by determining its subperiods. However, differences in the subperiods were only observed when Bt was determined by the CV_{dd} method, with a variation of 0.5ºC. Plants may present different Bt values for each developmental subperiod, which are observed in the most varied species and genetic materials (Pilau et al., 2011; Farias, Costa, Souza, Takaki, & Lima, 2015). However, based on these results, yacon presented little variation between its phases.

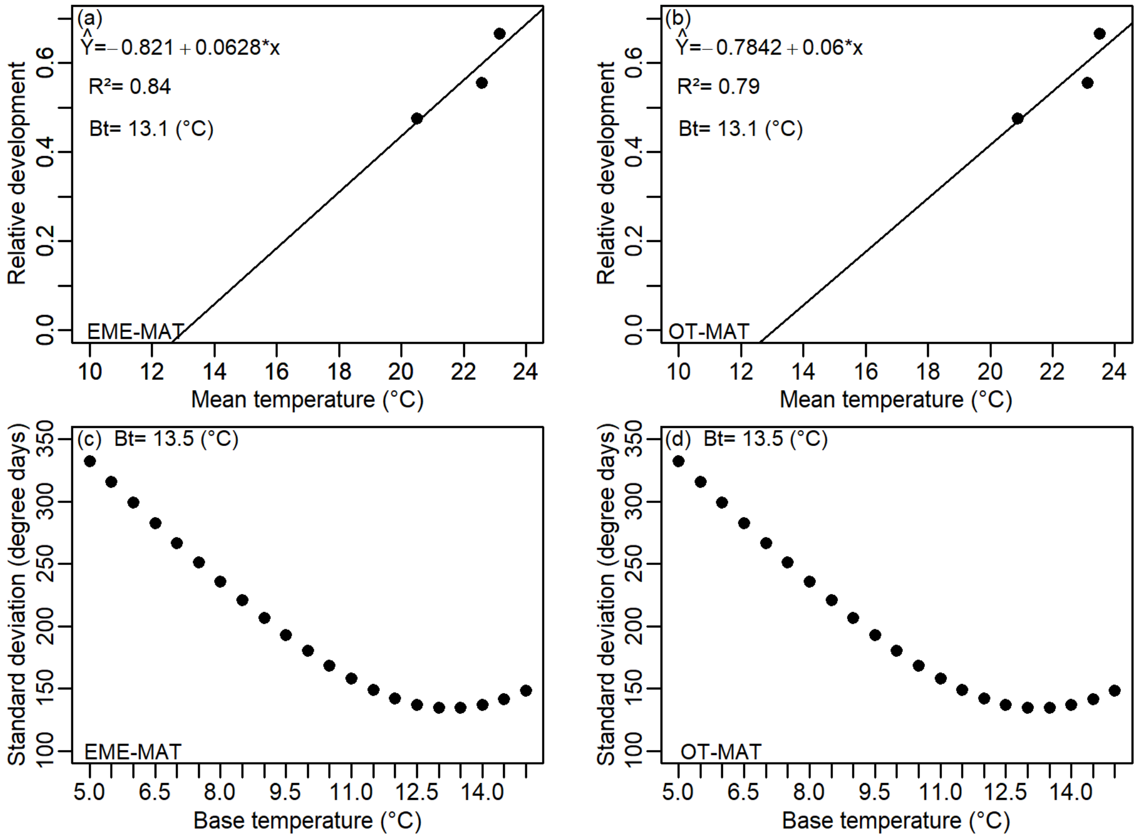

Figure 2. Lower base temperature for the development phases of emergence to maturation (EME – MAT) and onset of tuberization to maturation (OT – MAT) obtained by the methods relative development (a – b) and standard deviation (c – d) for the yacon culture.

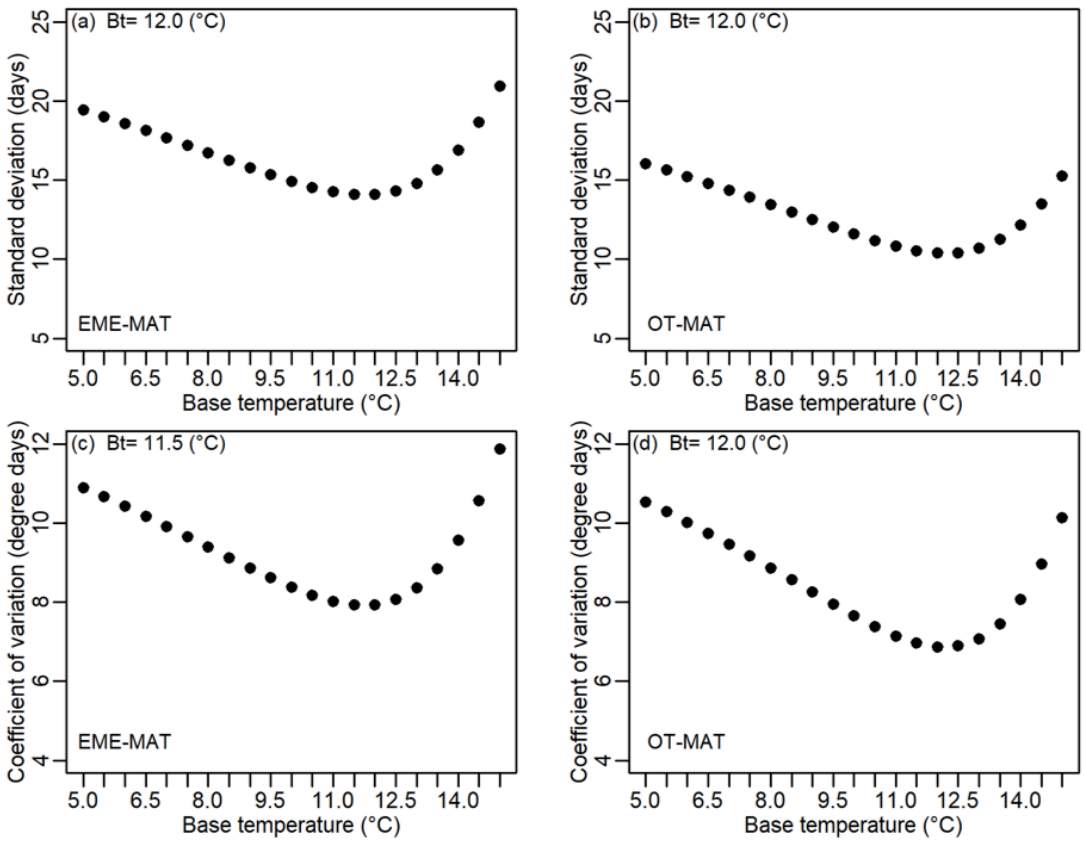

Figure 3. Lower base temperature for the development phases of emergence to maturation (EME – MAT) and onset of tuberization to maturation (OT – MAT) obtained by the methods standard deviation (a – b) and coefficient of variation (c – d) for the yacon culture.

The literature has several studies on lower base temperature, because they are conducted in places where the upper base temperature (BT) is hardly reached (Farias et al., 2015). However, the BT provides important information regarding the culture because temperatures above the BT can cause disturbances to plants, such as damaging the plant tissue by burns and thus leading to its death. In the climatic conditions of the study region, the BT by the SD_{dd} and CV_{dd} showed estimated values of 34.0°C (Figure 4).

These values are below the absolute maximum temperatures found in the three growing seasons (Table 1). Basic information about plant development, such as the estimation of Bt and BT, is important for the yacon culture because it allows one to know the adaptability of the culture to certain climatic conditions as well as its needs regarding meteorological conditions, which are essential for the planning, management, and cultivation of the crop under field conditions (Martins, Reis, & Pinheiro, 2012; Souza & Martins, 2014).

Figure 5 shows the relationship of the thermal sum with the mean air temperature and the photoperiod in the EME – OT subperiod. A Bt 12.5°C was used for the calculation of the thermal sum, and the arithmetic mean was obtained between the different methods used for the entire yacon cycle because there was little variation between each analyzed phases.

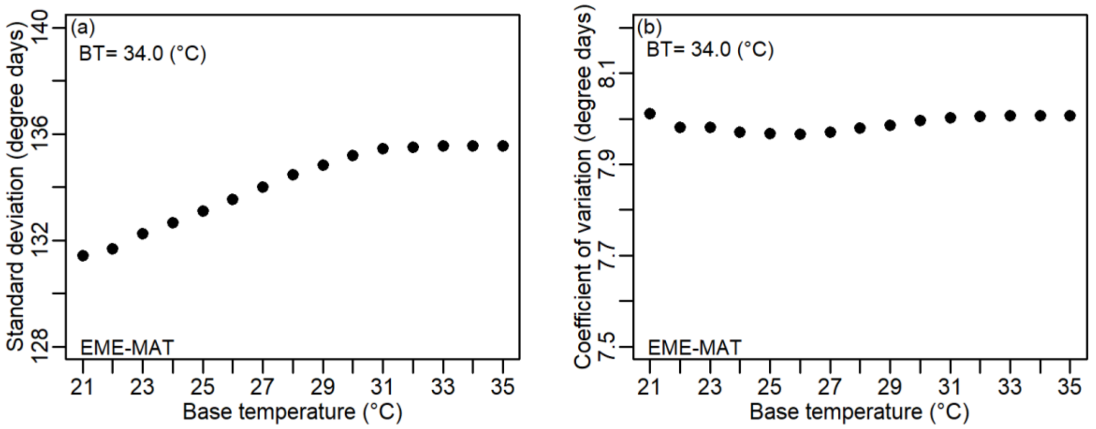

Figure 4. Determination of the upper base temperature during the period of emergence to maturation (EME – MAT) obtained by the methods standard deviation (a) and coefficient of variation methods (b), both in degree days, for the yacon culture.

Table 1. Values of the maximum, minimum, and mean temperatures as well as the accumulated precipitation from the emergence to the maturation period in the different growing seasons of yacon in Ibatiba, Espírito Santo[1].

Growing season	Absolut Maximum T.	Mean Maximum T.	Absolute Minimum T.	Mean Minimum T.	Mean T.	Precipitation
	(°C)					(mm)
Fall	33.2	25.5	6.5	15.5	20.5	776.8
Winter	33.2	27.7	10.3	17.5	22.6	915.4
Spring	32.8	28.4	13.0	17.9	23.2	859.8

[1]Fall (planted on April 20, 2013; emergence after 60 days), Winter (planted on July 20, 2013; emergence after 60 days), and Spring (planted on September 20, 2013; emergence after 30 days).

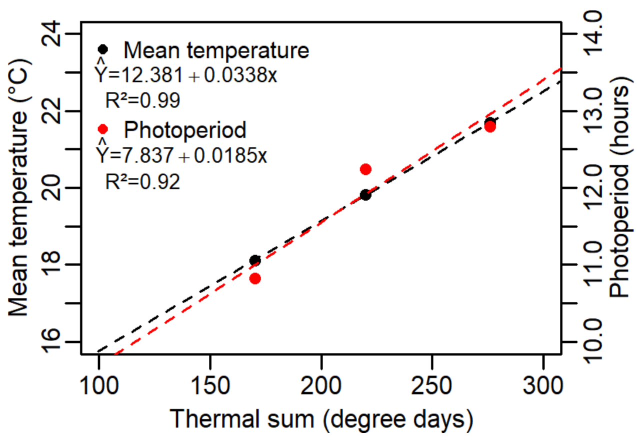

Figure 5. Relationship between the thermal with the mean temperature and photoperiod during the emergence to onset of tuberization (EME – OT) phase in the three growing seasons of yacon.

As can be seen by the coefficient of determination (Figure 5), 92% of the variance of the corresponding EME – OT period can be explained by the photoperiod variance, while 99% of the variance in this period is explained by the mean temperature. According to Araldi et al. (2011), temperature is an important environmental factor in the tuberization process as high temperatures inhibit tuber formation while low temperatures promote its growth.

Many researchers have reported the effect of photoperiods on the production of tuberous roots (Abelenda et al., 2019; Natarajan, Kondhare, Hannapel, & Banerjee, 2019). Short days induce the movement and accumulation of StBEL5 RNA, that has been consistently associated with tuberization (Dutt et al., 2017). Although the EME – OT period responded to the photoperiod, some researchers have reported that yacon tubers are indifferent to the photoperiod and that temperature is the main environmental factor affecting yacon the tuberization (Itaya, Carvalho, & Figueiredo-Ribeiro, 2002; Silva, Oliveira, Cavatte, Quaresma, & Christo, 2018b). Thus, more in-depth research is required to determine whether the yacon tuber responds to the length of the day because the photoperiod presented the same behavior of the mean air temperature in this subperiod.

The duration of the EME – OT phase in accumulated DDs (Figure 6) varied between the planting dates. Specifically, the duration was higher in the spring crop, with 276 accumulated DDs, and lower in the winter and fall, with only 220 and 170 DDs, respectively. One reason for this could be that the mean photoperiod, which ranged from 10.82 to 12.8 between the seasons, showed a positive linear relationship with the accumulated thermal sum (R^2 = 0.92) (Figure 5). That is, the longer the photoperiod, the higher the thermal sum needed to reach the onset of tuberization. This result is similar to that obtained by Erpen, Streck, Uhlmann, Freitas, and Andriolo (2013) for the sweet potato crop.

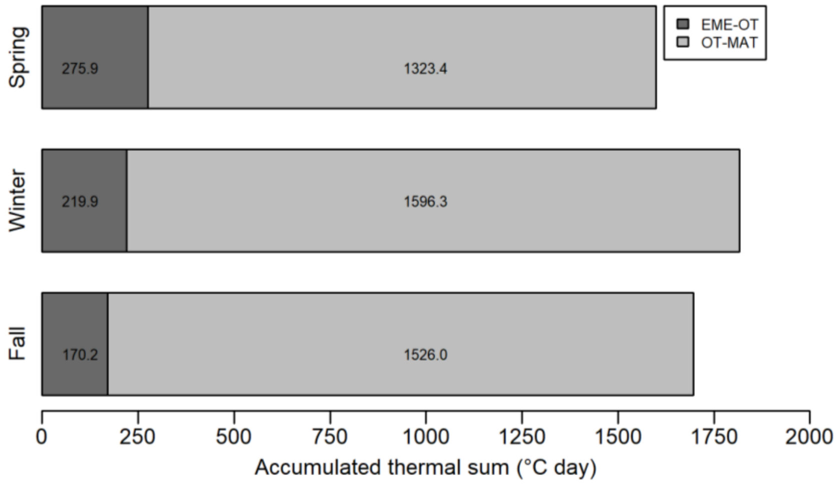

Figure 6. Duration of the emergence to onset of tuberization (EME – OT) and onset of tuberization to maturation (OT – MAT) phases in accumulated degree days in the three growing seasons of yacon (April 20, 2013 – Fall; July 20, 2013 – Winter; and September 20, 2013 – Spring).

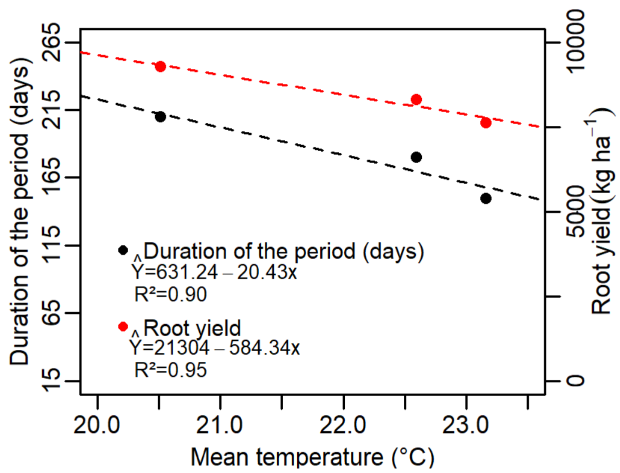

Figure 7. Relationship of the mean air temperature with the duration of the period and the root yield in dry matter (kg ha^{-1}) from emergence to maturation in the three growing seasons of yacon.

Another possible cause for the variation in accumulated DDs required for initiate tuberization in the spring crop could be linked to the increased mean temperature in the EME – OT subperiod (Figure 5) as this increase in mean temperature led to an increase in the thermal sum, while the inverse was observed in the fall crop. However, while the yacon requires a higher accumulated thermal sum to initiate tuberization, the same effect was not observed in the OT – MAT subperiod, in which the winter crop presented the highest thermal sum for the physiological maturation of yacon at 1,596 DDs, followed by the fall and spring crops, with respective values of 1,526 and 1,323 accumulated DDs.

Figure 6 shows the relationship of mean air temperature with the duration of the period (days) and root yield (dry matter) from emergence to maturation (EME – MAT). A decreasing linear equation is observed for the duration of the plant cycle, showing that 90% of the variance of the period from planting to crop is explained by the air temperature, that is, as the mean air temperature increased during the crop cycle, the time required for maturation to occur decreased.

The same is observed for root yield, which decreased with increasing air temperature during the aforementioned period. Note that this result was unfavorable to the growth and development of yacon. According to Araldi et al. (2011), the increase in air temperature promotes the inhibition of tubers, while low temperatures promote their growth. However, the temperatures that occurred during the three yacon crop seasons were sufficient for tuberization to occur, even though the increase in temperature led to an increase in the thermal sum required for its onset.

Thus, the increased mean temperature during the yacon cycle promoted a decrease in the time spent (days) to complete its cycle and caused a reduced root yield. Conversely, more mild temperatures throughout the cycle seemed to favor root yield, despite the need for more days to complete its cycle. Note also that with the increase in cycle time, the higher the root yield will be because the increase in the development cycle results in an increase in the duration of green leaf area, contributing to increased photosynthesis and ensuring a greater production of photoassimilates that will be directed to the tubers.

Conclusion

The values of lower base temperatures determined using the methods of SD_{dd}, SD_d, CV_{dd}, and RD for the analyzed subperiods were similar, with a Bt of 12.5°C for the respective phases of EME – MAT and OT – MAT, and a upper basal temperature of 34°C during EME – MAT. In a tropical climate, yacon presented a longer cycle duration with the increase in photoperiod and mean air temperature.

The thermal sum for the OT – MAT phase showed values from 170 to 275 DDs, and a higher thermal sum was required to initiate tuberization with the increase in air temperature.

Both temperature and photoperiod conditions modified the duration of the EME – OT phase in each growing season, indicating that short photoperiods and lower temperatures accelerate initiate tuberization.

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