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Proposal of an empirical model to estimate the productivity of 'Valencia' orange (Citrus *sinensis* L. Osbeck) in the Colombian low tropics

Propuesta de un modelo empírico para estimar la productividad de naranja var. Valencia (*Citrus sinensis* L. Osbeck) en el trópico bajo colombiano

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Adult cultivation of var. Valencia orange (*Citrus sinensis* L. Osbeck). Photo: J.A. Cleves-Leguízamo

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ABSTRACT

The response of the citrus crop to environmental supply largely determines the speed and intensity of the plant's ecophysiological processes, which affect the development and production of the crop. The main objective was to analyze the effects of climatic conditions on the productivity of the 'Valencia' orange agroecosystems (*Citrus sinensis* L. Osbeck) previously typified in the department of Meta, Colombia. The climatological variables precipitation (PPT), maximum and minimum temperatures (Tmax and Tmin), wind speed, relative humidity and solar brightness were analyzed in an observation window spanning the years 2013 to 2015. Using the FAO CropWat model, the crop reference evapotranspiration (ETo) was obtained to applied agroclimatic indices. Using the statistical software STATGRAPHICS Centurion XVI v. 16.2.04, an empirical model was proposed that relates productivity according to agroclimatic indices, for the vegetative and reproductive phenological phases. It was found that the proposed empirical model explains 49% (P=0.0233) of the oscillation of productivity in study area agroecosystems. The model, based on agroclimatic indices associated with PPT, ETo, Tmax and Tmin, found that the relationship between productivity and agroclimatic indices is non-linear. It was established that productivity variation is mainly influenced by PPT, the occurrence and magnitude of which determines the volume of production and quality of the fruit. On the other hand, whereas increases in air temperature and the occurrence of water deficits in the pre-flowering and flowering phases positively favor crop production, the same factors produce a negative effect in the setting phase.

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Additional key words: low tropics; citriculture; productivity; empirical models; climatic data.

RESUMEN

La respuesta del cultivo de cítricos a la oferta ambiental determina en gran medida, la velocidad e intensidad de los procesos ecofisiológicos de la planta, que inciden en el desarrollo y producción del cultivo. Como objetivo principal se propuso analizar los efectos de las condiciones climáticas en la productividad de los agroecosistemas citrícolas de naranja 'Valencia' (*Citrus sinensis* (L.) Osbeck) previamente tipificados en el departamento del Meta-Colombia. En una ventana de observación (años 2013-2015) se analizaron las variables climatológicas precipitación (PPT), temperatura máxima (Tmáx) y mínima (Tmín), velocidad del viento, humedad relativa y brillo solar. Utilizando el modelo CropWat de FAO, se obtuvo la evapotranspiración de referencia del cultivo (ETo), aplicando índices agroclimáticos. Utilizando el software estadístico STATGRAPHICS Centurión XVI v 16.2.04, se propuso un modelo empírico que relaciona la productividad en función de índices agroclimáticos, para las fases fenológicas vegetativa y reproductiva. Se constató que el modelo empírico propuesto explica el 49% (P=0,0233) de la oscilación de la productividad en los agroecosistemas analizados en la zona de estudio en función de los índices agroclimáticos asociados con la PPT, ETo, Tmáx y Tmín, encontrando que dicha relación es de carácter no lineal. Se estableció que la variación de la productividad está principalmente influenciada por la PPT, cuya ocurrencia y magnitud determina el volúmen de la producción y calidad del fruto, en un segundo plano se encontró que los incrementos en la temperatura del aire y la ocurrencia de déficit hídricos en fase de pre-floración y floración favorecen positivamente la producción del cultivo, pero incrementos de la temperatura en la fase de cuajamiento afectan negativamente la producción.

Palabras claves adicionales: trópico bajo; citricultura; productividad; modelos empíricos; datos climatológicos.

INTRODUCTION

Among the varieties of orange cultivated in the world, the orange var. Valencia belongs to the group of the most important ones, reaching 80% of the volume in producing countries such as Brazil, in the Colombian Orinoquia reaches 90% (Auler *et al*., 2008; Cunha *et al*., 2019).

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Environmental conditions, especially the agroclimatic ones, affect the ecophysiology of the plant, being this influence specific for each crop and even for each variety of the same species, the plant has adaptive strategies that help to adapt quickly to environmental change (Mooney *et al.,* 2001; Agustí, 2003; Abdelghany, 2015; Cleves-Leguízamo, 2018a; Nissi et al., 2021).

The level of connectivity between the minor agroecosystems (lots) and the larger ones (farms), and between these and the landscape, determine an articulated Main Agroecological Structure (MAS) (Cleves-Leguízamo *et al*., 2020), giving the productive systems greater response capacity (resilience) against the occurrence of disturbances of different nature, including microclimatic regulations, with an increase in functional biodiversity that is expressed in a direct relationship with productivity, and in inverse relationship with the number of phytosanitary controls per year (Cleves-Leguízamo *et al*., 2017; León *et al*., 2018; Cleves-Leguízamo, 2018b).

According to studies by Granda *et al.* (2009) and Montgomery and Peck (2002) and Cleves-Leguízamo and Jarma (2014) by means of using Multivariate Analysis techniques (Principal Components), they identified a strong relationship and influence of the meteorological conditions on citrus crop production, finding that the lowest degree of maturity of the fruits (high content of acidity, low index of maturity and percentage of juice) was related to the meteorological conditions that had to do with high temperatures (maximum and average), increases in reference evapotranspiration, strong wind speed, low precipitation volumes, as well as with low relative humidity and insolation (solar brightness).

The hydrophysical parameter evaluations carried out by Orduz and Fischer (2007), in Oxisol soils in the Piedemonte Llanero, indicated that the water that is usable by plants (difference between field capacity and permanent wilting point), corresponds to about 3.5% of the water that is contained in the first twenty centimeters of the soil, volume that can only supply up to three days of the water requirements of the citrus crop.

Since Oxisols are the order of soils that are predominant in the study area, citrus cultivars need to be permanently supplied with water. Oxisols are characterized by their low moisture retention, as well as a high toxicity due to the iron, aluminium, the deficiencies of phosphorus, and the calcium that limit the root development and therefore, the adsorption of water and nutrients (Cleves-Leguízamo *et al*., 2019).

Fischer *et al*. (2016), point out that the environmental modifications influenced by climate change act upon the physiological processes of fruit plants, affecting the growth, development, yield, and quality of fruits in a different manner. The excess of solar radiation together with higher temperatures can cause photoinhibition and burn injury in those parts of the plant that are exposed the most during drought events.

The increase in temperature could accelerate the crop, and plant or seed cycle of cultivars at higher altitudes, but it would also increase the harmful effects of water stress, high radiation, and it would modify the behavior of pests, diseases, and weeds (Cleves-Leguízamo *et al*., 2016).

The citrus agroecosystems that are present in the production area of the foothill in the department of Meta (Colombia), have an adequate water supply, in terms of volume and quality of the resource, during a large part of the year (Cleves-Leguízamo *et al*., 2018b).

These conditions have made the design and implementation of irrigation systems not necessary in adult plants, taking into account that during the annual water deficit it is necessary for the induction of flowering (Nissi et al., 2021); while with the onset of rains the flowering takes place and the crops receive enough rainfall until the harvest season (Orduz and Fischer, 2007; Orduz *et al*., 2010).

In spite of the conditions described above, the objective was to analyze the incidence of the most important climatological variables (temperature and precipitation) on the productivity of the 'Valencia' orange agroecosystem (*Citrus sinensis* L. Osbeck), in the conditions of the Colombian low tropics, to optimize cultural management practices through an empirical model.

MATERIALS AND METHODS

In the present study, we used climatic information that was collected between the years 2013 and 2015, of the precipitation variables (PPT) in millimeters (mm), maximum temperature (Tmax) and minimum temperature (Tmin) in degrees Celsius (°C), relative humidity (RH) in percentage (%), solar brightness (S.Br) in light hours per day (h d^{-1}), on a monthly time scale, registered in meteorological stations of the Colombian national network, administered by the *Instituto de Hidrología, Meteorología y Medio Ambiente* of Colombia (IDEAM) and located in the study area (Tab. 1).

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Table 1. Climatological stations located in the study area

Code	Type of station	Station	Municipality	Latitude (°) N	Longitude (°) W	Altitude m a.s.l.
3502502	CP*	Libertad La	Villavicencio	4°3'26.5"	73°28'4.5"	336
3207504	CO**	Holanda La	Granada	3°30'58.8"	73°42'57.7"	360
3501004	PM***	Caño Hondo	Guamal	3°55'.0"	73°48'.0"	800
3501007	PM***	Guamal	Guamal	3°52'.0"	73°45'.0"	525
3206501	CO**	Lejanías	Lejanías	3°31'46.3"	74°1'38.5"	680

*CP: Main climatological station; **CO: Ordinary climatological station; ***PM: Pluviographic gauge station. Source: IDEAM.

It is by means of using the FAO Penman Monteith method (Allen *et al.,* 2006) and from the climatic variables of Tmáx, Tmin, HR, and S.Br, on a monthly scale, with the variable of wind speed, taken constantly with a value of 2 m s^{-1}, that the evapotranspiration of the crop in reference (ETo) in mm $month^{-1}$ was estimated.

Under the climatic conditions of the foothills of the Meta department, Colombia, the flowering that occurs in the last week of March or the first of April is the one that originates the main harvest, which begins in December for the Valencia variety (nine months after anthesis).

During the years 2013, 2014 and 2015, semi-structured interviews were carried out with citrus farmers, identifying the months when the phenological phases of fruit formation, fruit setting and development normally occur. This information was corroborated by the work of Orduz and Garzón (2012). The results indicate that floral induction occurs during the hydrological deficit that begins in December and lasts until the first fortnight of March (Orduz, 2007).

The open flowers appear in the first week of April and the stages of anthesis, fruit set and fruit growth occur from this date until the months of September to October, depending on the incidence of climatic variability towards the beginning of flowering. The orange becomes ripe for consumption in the first week of December when it reaches a ratio of 9 (° Brix / % acidity).

It is from the variables of PPT, ETo, Tmax, and Tmin, that the agroclimatic indices are constructed for the periods in each phase of the formation and development of the 'Valencia' orange fruit (*Citrus sinensis* L. Osbeck). The agroclimatic indices that were generated are presented below.

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Moisture content

It allows to determine the deficit or total excess of water that is available for the citrus crop in the phenological phases of fruit growth (DNP and IDB, 2014) (Eq. 1).

$$IH = \sum_{j}^{n} \frac{PPT_i}{ETo_i} \quad (1)$$

where, $\sum_{j}^{n}$ was summation of the months included in each of the phases that were analysed; i was takes values between 1 to 12, corresponding to the month of the year; PPT was monthly precipitation in mm*month^{-1} and ETo was evapotranspiration of reference in mm month^{-1}.

Index of degrees of accumulated days

It is a calculated index considering that the development of the fruit is dependent upon temperature.

In order to build this index, we used the method of Owens and Moore (1974):

$$IGDA = \sum_{j}^{n} \frac{n_i * (T_m - T_b)_i}{2526} \quad (2)$$

where, T_m was average monthly temperature in ºC; n_i was number of days in the month; T_b was core temperature of the citrus crop (12.5 ºC) (Orduz and Fischer, 2007).

The value of 2526 is constant and represents the annual cumulative degrees (ºC) on an annual average in the study area.

Anomaly of the 'Valencia' orange crop yield

ΔY was estimated using the yield data from the crop under study, collected in 50 citrus agroecosystems between the years 2013 and 2015, located within a radius of 30 km of influence of the study stations (Tab. 1). This index was estimated with the following expression (Eq. 3).

$$\Delta Y = \frac{Y_x + Y_p}{Y_p} \tag{3}$$

Where, Y_x was yield of a farm in one year and Y_p was average yield of citrus farms.

The empirical model (Eq. 4), developed according to Penning de Vries *et al*. (1989) is also called a descriptive or black box model, since it reflects the causal mechanisms of the behavior of a system. This type of model allows for a diagnosis between the relationship of climatic variables and the variation in yield of the 'Valencia' orange crop. The agroclimatic indices described above (Eq. 1, 2 and 3) were used for the development of the model.

Prior to modeling, the data was analyzed and processed for quality control. The statistical software STATGRAPHICS Centurion XVI v. 16.2.04 was used to build the model and to perform multiple regression analysis with non-linear adjustment, using the non-linear least squares method (Rivas *et al*., 1993; Díaz, 2012).

The coefficient of determination (R^2) was used to explain the variability of the adjusted model of agricultural performance based on the agroclimatic variables under study. In addition, an analysis of variance (ANOVA) was performed to estimate the statistical relationships of significance between the analyzed variables at a 95% confidence interval, which rejects the null hypothesis at a probability greater than P>0.05.

Additionally, other statistical indicators were calculated to evaluate the developed model. These included the standard error of the estimate, which shows the standard deviation of the residuals; the mean absolute error (MAE), which is the average value of the residuals; and the Durbin-Watson statistic (DW), which examines the residuals to determine if there is any significant correlation based on the order in which the data is presented. The DW indicates the absence of serial autocorrelation in the residuals with P<0.05, at the 95% confidence level (Díaz, 2012).

RESULTS AND DISCUSSION

As a result of the relationship between the agroclimatic indices (Eq. 1 and 2) and the anomaly index of the 'Valencia' orange crop yield (Eq. 3), we obtain the model of equation 4, which

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shows a significant non-linear relationship (P<0.05), based on the climatic variables of PPT, ETo, Tmax, and Tmin as presented below (Eq. 4).

$$\Delta Y = 0.891359 * \varphi(IH, IGDA) \quad (4)$$

Where,

$$\varphi(IH, IGDA) = 1.02383 * \gamma(IH) + 0.246129 * \beta(IGDA);$$

$$\gamma(IH) = 4409.3 f(IH_k)^4 - 534.17 f(IH_k)^3 + 25.924 * f(IH_k)^2 + 3.5044 * f(IH_k) + 0.128;$$

$$f(IH_k) = 0.221891 - 0.233548 * IH_1 - 0.0824495 * IH_2;$$

$$\beta(IGDA) = -5.52 * g(IGDA_k)^3 + 2.1253 * g(IGDA_k)^2 + 0.914 * g(IGDA_k) - 0.0054; \text{ and}$$

$$g(IGDA_k) = 0.0579598 + 3.24518 * IGDA_1 + 4.8082 * IGDA_2 - 4.58485 * IGDA_3$$

It should be noted that k takes values of 1 in the pre-flowering phase between the months of January and February, of 2 during flowering in the months of March and April, and of 3 in the phase of fruit growth in the period from May to August.

The model of equation 4 (Fig. 1) explains 49% (P=0.0233) the variability of the ‘Valencia’ orange crop yield in the study area, according to the agroclimatic indexes (Eq. 1 and 2), which at the same time depend on the precipitation, ETo, and air temperature on a monthly time scale. This model has a standard error of the estimated or standard deviation of the residuals of 7%.

Figure 1 shows the anomalies or variations with regard to the average value between the period of 2013 and 2015, and the simulated (Eq. 4) for the same period. It can be seen that the simulated values have a similarity and concordance with the values that were observed or measured in the field and are between the limit of ±10% with respect to those that were observed.

According to the perception of 92% of the farmers queried in the study area, they indicate that there have been changes in the climate during the last 10 years. These changes have been reflected in increases in the air temperature, mainly in the season of low rainfall (January-February, and part of March), and variations in the distribution and volume of rainfall. These changes in the climate have had negative effects in the cultivation of citrus (in the opinion of the producers), associated to the occurrence of erratic rainfall in dry periods, which coincides with the period of floral induction and differentiation.

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The presence of untimely rains promotes anticipated blooms that, followed by water deficit, cause excessive and premature fall of flower buds, affecting the main crop in the years that these events occur. The main decrease in yield takes place in crops with low levels of technology, in particular with low levels of corrective and fertilizer, and in which there are low leaf area indexes (LAI) and deficiencies in mineral nutrition (Orduz and Abella, 2008; Cleves-Leguízamo *et al*., 2012).

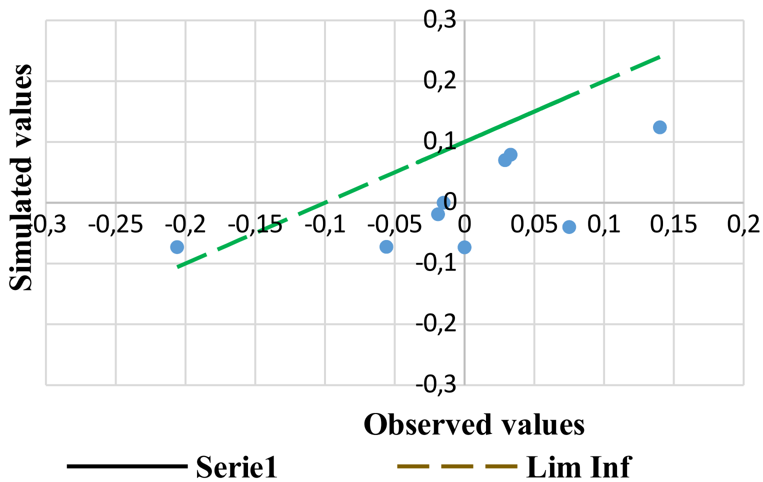

Figure 1. **Anomaly of the ‘Valencia’ orange crop yield observed in the field and simulated with the empirical model (Eq. 4).**

This perception of local farmers is corroborated by the results of the model in equation 4, which indicates that increases in rainfall in the pre-flowering and flowering phases has an impact on the decrease in the volume of production. This is confirmed in the studies that were carried out by Southwick *et al*. (1995) and Davenport (1990), who found that in order to induce floral differentiation, citrus crops require between 60 and 90 days with deficit water conditions. Works by Fischer *et al*. (2016), indicate that extreme climatic conditions associated with climate change and variability can cause negative impacts on the crop, depending on the phenological phase that may be found. In the equatorial zone, the main climatic factor that influences the growth and development of the citrus fruit is the occurrence, volume, and distribution of rainfall (Orduz, 2007).

In figures 2 and 3 it is evident that in conditions of deficient rainfall (<10 mm) in the pre-flowering and flowering phases, precipitation determines the intensity, duration and distribution of flowering, conditions that are favorable for the yield of ‘Valencia’ oranges. These results are

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concordant with reports by Reuther and Ríos (1969), Stover *et al*. (2002) and Aguilar *et al*. (2010).

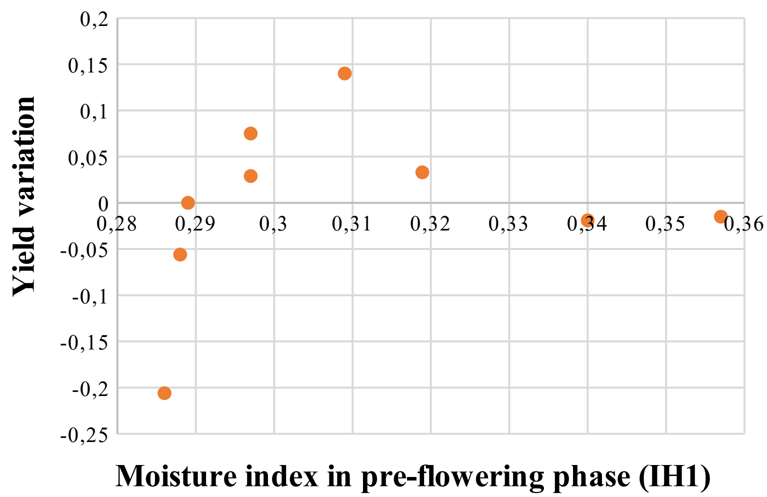

Figure 2. Variation in yield of the 'Valencia' orange (Citrus *sinensis* L. Osbeck) crop, versus the moisture index in the pre-flowering phase (january and february).

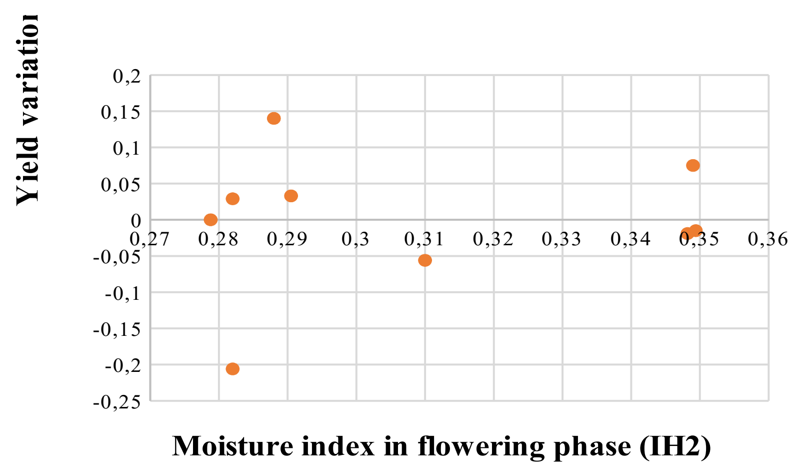

Figure 3. Variation in yield of the 'Valencia' orange (Citrus *sinensis* L. Osbeck) crop, versus the moisture index in the flowering phase (march and april).

It should be noted that during the period of evaluation, favorable water conditions were present in the fruit set-growth phase. That is, there were no variations in the soil moisture regime, which consequently did not affect the average yield of the area under study (Fig. 4 and 5).

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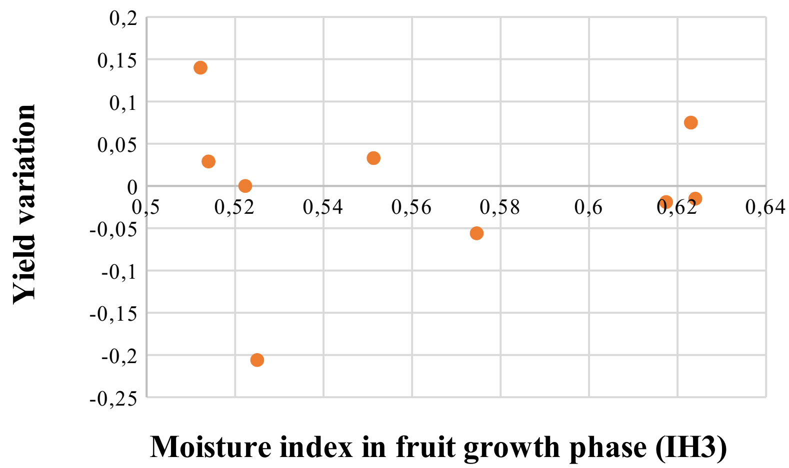

Figure 4. Yield variation of the 'Valencia' orange (Citrus *sinensis* L. Osbeck) crop, versus the moisture index in the fruit growth phase (may and august).

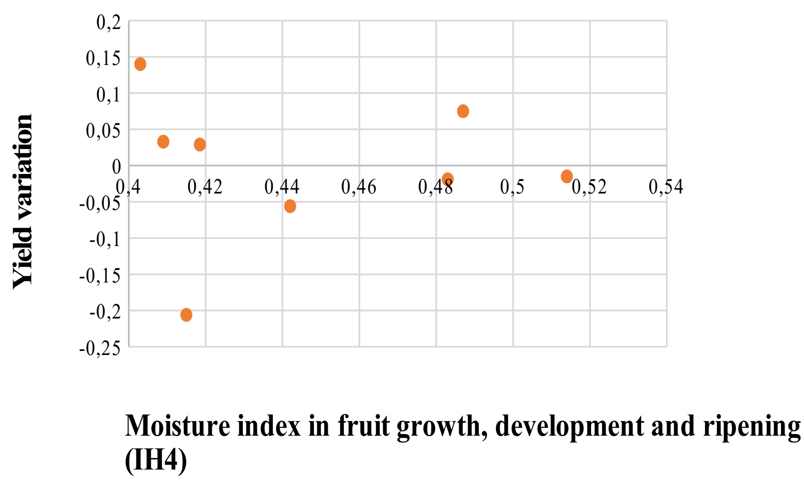

Figure 5. Yield variation of the 'Valencia' orange (*Citrus sinensis* L. Osbeck) crop, versus moisture index in the fruit growth, development, and ripening phase (september and december).

According to Orduz and Fischer (2007), in the Foothills of the Meta department, citrus fruits demand 1,046 mm/year, (typical requirement for the region), equivalent to 77% of the evapotranspiration of the annual crop, which is 1,357 mm year^{-1}. The above shows the broad adaptation of the citrus species to the environmental conditions expressed in the efficient use of the water resource.

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It is evident that in the study area there is no water deficit in the soil; therefore there are no limitations for fruit development. The water deficit in this stage is linked to the decrease in the yield components (number of fruits and size), in accordance with what was reported by Garzón *et al*. (2013), Orduz and Fischer (2007) and Nissi *et al*. (2021).

The greatest demand for water resources takes place in the phases of flowering, fruit set, and fruit growth; being the fall of petals (anthesis) until the end of the stage of fruit growth the critical phase; period in which there was sufficient rainfall for the crops in the years evaluated, which is shown in the previous graphics. On the other hand, hydric deficit is required in the phase of floral differentiation.

The annual average temperature in the study area oscillates between 26 and 27ºC, which allows to reach 4,948 units of heat/year (HU). In equation 4, it can be seen that temperature increase in the flowering and pre-flowering phases favors the crop yield, but if the increase appears in the fruit setting phase and with water deficit, it could affect negatively the production of the fruit, particularly in crops with nutritional or sanitary management deficiencies.

However, the average temperature in the phase of development of the fruit during the study period (September to November) ranged between 25 and 26ºC, with thermal gradients (difference between day and night temperatures) of less than 10ºC on average, therefore, no significant influence was seen in the yield variation, aligned with the studies by Orduz (2007) and Orduz and Avella (2008).

It is important to keep in mind that, what happened during the years of study in this work can be discussed and analysed. In order to analyse the influence of climate change on the frequency, duration, and intensity of the maximum, minimum and average extreme temperatures, and their impact on the crop, other methodologies that are more complex should be used.

The studies developed by Reuther (1973), indicate that the average temperature in the growth phase of the fruit accelerates the physiological process of the fruit, increasing its volume and reducing the time that is required until harvest. Although the above supports that there is a relationship between the temperature and the growth phase of the fruit, the results of this work support this statement and additionally find that this relationship is non-linear.

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CONCLUSIONS

Variation in the performance of the 'Valencia' orange crop (*Citrus sinensis* L. Osbeck) in the department of Meta is highly influenced by climatic conditions, mainly to the ones related to the occurrence and volume of precipitation. Increases in average air temperature and water deficits in the pre-flowering and flowering phase positively favor the floral induction and therefore the productivity of the citrus crop. Increases in temperature in the flowering-curd phase negatively affect production.

The proposed model takes into account the agroecological attributes (ecosystem and cultural) implemented by the citrus growers. The model that has been developed explains the variability of the 'Valencia' orange crop yield, depending on the availability of water in the soil and the occurrence of temperatures for the months matching the critical phases of the crop (pre-flowering, flowering, and curd of the fruit).

The design and implementation of adaptive measures are recommended to help reduce the negative effects on the cultivation of the 'Valencia' orange, due to the threat of drought, excess rain, or inadequate distribution of rain with respect to crop needs, which are associated with both variability and climate change. Adaptive measures must include adaptation of local irrigation infrastructures, adequate management of water resources, use of materials with tolerance to conditions of water and/or thermal stress. It is important to note that in the study area, especially in the municipality of Lejanías, irrigation systems have been implemented, mainly in the Tangelo Minneola (C. *reticulata* Blanco×C. *paradisi* Macf) technical crops. These systems seek to modify the date of flowering and harvest of this high-value fruit.

Conflict of interests: The manuscript was prepared and reviewed with the participation of the authors, who declare that there exists no conflict of interest that puts at risk the validity of the presented results.

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