Revista Facultad Nacional de Agronomía Medellín
ISSN: 0304-2847
ISSN: 2248-7026
Facultad de Ciencias Agrarias - Universidad Nacional de Colombia

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Revista Facultad Nacional de Agronomía Medellín, vol. 72, no. 1, 2019, January-April, pp. 8699-8706
Facultad de Ciencias Agrarias - Universidad Nacional de Colombia

DOI: https://doi.org/10.15446/rfnam.v72n1.72076

Research article

http://www.revistas.unal.edu.co/index.php/refame

Revista Facultad Nacional de Agronomía

Identification of climatic and physiological variables associated with rice (*Oryza sativa* L.) yield under tropical conditions

Identificación de variables climáticas y fisiológicas asociadas al rendimiento del arroz (*Oryza sativa* L.) en condiciones tropicales

doi: 10.15446/rfnam.v72n1.72076

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ABSTRACT

Rice crop productivity is influenced by climatic conditions such as solar radiation, temperature, and water availability during its vegetative and reproductive stage. In Colombia, rice cultivation is carried out throughout the year; so, it is necessary to identify the sowing dates where high yields are obtained, and which physiologic and climatic factors significantly influence them. Therefore, this research aimed to identify the key climatic and physiological factors that allow maximizing the yield and maintaining good productivity in sowing dates with optimal and deficient environmental conditions, respectively. The experiment was carried out in a rice producing region in northern of Tolima, Colombia from 2015 to 2016. Ten sowing dates were established, with a randomized complete block design in a divided strips arrangement. For each sowing date, climatic conditions were tracked, and growth, development, and yield of rice plant were evaluated. Also, the photosynthetic rate was assessed on five sowing dates. Results showed that physiologic factors that have more relation with crop yield are plant height, leaf area index and dry mass accumulation between phenological stages 37 and 49; whereas the unique climatic factor, that was highly related to yield, was solar radiation between phenological stages 51 to 77. Furthermore, when the optimum values of each variable were reached, a yield higher than 9,500 kg ha^{-1} was achieved. No relation was observed between the photosynthesis rate of at leaf level and yield.

Keywords:
Crop yield
cv. *Oryzica* 1
Photosynthesis
Solar radiation
Sowing date

RESUMEN

La productividad del cultivo del arroz está influenciada por las condiciones climáticas, como la radiación solar, temperatura y disponibilidad de agua, durante la etapa vegetativa y reproductiva. En Colombia se realizan siembras de arroz durante todo el año, por lo que es necesario identificar las fechas de siembra donde se obtenga alto rendimiento, y qué factores fisiológicos y climáticos influyen de forma significativa en este. Por lo tanto, esta investigación tuvo como objetivo identificar los factores climáticos y fisiológicos clave, que permitan maximizar el rendimiento y mantener una buena productividad en fechas de siembra con condiciones ambiental óptimas y deficientes, respectivamente. El experimento se realizó en una región productora de arroz en el norte de Tolima, Colombia durante los años 2015 y 2016. Se establecieron diez fechas de siembra, con un diseño en bloques completos al azar en un arreglo de franjas divididas. En cada fecha de siembra se hizo seguimiento a las condiciones climáticas y se evaluó el crecimiento, desarrollo y rendimiento de las plantas de arroz. Además, la tasa fotosintética se evaluó en cuatro fechas de siembra. Se encontró que los factores fisiológicos que más relación tienen con el rendimiento son la altura de la planta, el índice de área foliar y la acumulación de masa seca entre los estados fenológicos 37 y 49, mientras que, un único factor abiótico que estuvo altamente relacionado con el rendimiento fue la radiación solar entre los estados fenológicos 51 a 77. Cuando se alcanzaron los valores óptimos de cada una de estas variables se alcanza un rendimiento superior a los 9.500 kg ha^{-1}. No se observó relación entre la tasa de fotosíntesis a nivel de hoja y el rendimiento.

Palabras clave:
Rendimiento de cultivos
cv. *Oryzica* 1
Fotosíntesis
Radiación solar
Fecha de siembra

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Received: May 8, 2018; Accepted: November 5, 2018
Rev. Fac. Nac. Agron. Medellín 72(1): 8699-8706. 2019
ISSN 0304-2847 / e-ISSN 2248-7026

Rice (*Oryza sativa* L.) is an essential food grain for about half of humanity, being a basic component in political, economic and social stability, and to a certain degree, in our survival (Degiovanni *et al*., 2010). Rice is the second most cultivated cereal in the world after corn reaching a world production of 740 billion t in 2014; in Colombia production reached 2.2 million t the same year (FAO, 2017).

Climatic conditions directly affect crop physiology and yield (Chen *et al*., 2004; Jarma *et al*., 2012). Currently, climate change has generated climatic alterations as a higher frequency of extreme weather events (Delerce *et al*., 2016). Climate change effects on different zones vary depending on the magnitude and seasonal characteristics (Ko *et al*., 2014). In Colombia, according to the IPCC (2014), these events will occur in higher frequency and magnitude, which, according to simulation models, will generate a temperature increase from 5 to 7 °C and an approximate decrease of 10% in precipitation during 2005-2100 period. In this context, there will be variability in rice cultivation productivity between 5 and 29% (Iizumi *et al*., 2014), which represents a threat at the socioeconomic level for rice producers (Delerce *et al*., 2016).

Rice productivity is influenced by climatic conditions such as Solar Radiation (SR), temperature and water availability during the vegetative and reproductive stages (Fageria, 2007). For example, high night temperature (>30 °C) reduces crop yield; it causes an increase in respiratory rate, subsequently, reduces photosynthesis rate, amount of dry matter (DM), and leaf area (Alvarado *et al*., 2017). Another climatic variable that negatively affects rice cultivation is high daytime temperature (>40 °C), as this generates an increase in respiratory rate, and therefore, a reduction in photosynthesis rate by non-stomatal limitations (Sánchez *et al*., 2014). DM production and harvest index are positively related to yield (Yoshida, 1981). Accumulation of DM is determined by SR interception by the canopy, which is influenced by the amount of incident SR and characteristics such as Leaf Area Index (LAI) and insertion angle and orientation (Ying *et al*., 1998; De Costa *et al*., 2006; Zhang *et al*., 2009). The LAI has a direct correlation with yield because it determines the ability to intercept a more considerable amount of photosynthetically active radiation (Ahmad *et al*., 2009; Aschonitis *et al*., 2014). Therefore, SR is the limiting factor of productivity (Delerce *et al*., 2016).

In the department of Tolima, Colombia, agronomic management practices as sowing dates (SD) are not carried out in accordance with the region's climatology. Producers are sowing throughout the year due to water access rotation imposed by irrigation districts, so the two SD with the highest solar radiation peaks are being misapplied. Thus, there is a high yield variability in different SD (Castilla *et al*., 2010; Delerce *et al*., 2016). Nonetheless, because of climate change, the SD that is considered ideal for crop establishment may have suffered changes.

Availability of climatic information and plant characteristics help understand yield variability and its determinant factors (Huang *et al*., 2016). Consequently, for this production area, it is necessary to estimate the physiologic and climatic factors that are highly related to yield, with the objective of using them as variables for crop monitoring or defining management practices to maintain these key variables within optimal ranges.

In the department of Tolima, the effect of three SD on crop growth and yield have been studied (Garcés and Restrepo, 2015). Besides, some authors have carried out studies with secondary information to estimate the relationship between climatic variables and yield (Delerce *et al*., 2016). Previous investigations were developed in the municipality of Saldaña in the south of the department, but this production area is very different in climate, soil characteristics, and management practices applied to productive rice systems compared to the north of Tolima. There is a necessity in development studies that evaluate how the physiological and climatic factors affect rice crop in this region. Therefore, this research aimed to identify the key climatic and physiological factors that allow maximizing the yield and maintaining good productivity in sowing dates with optimal and deficient environmental conditions, respectively. In the experiment, 10 SD were evaluated to identify which time of the year presented the best environmental conditions that allow maximizing the crop yield and establishing a relationship through automatic learning techniques between physiologic and climatic factors and the yield.

MATERIALS AND METHODS

Study site and plant material

This research was carried out during the period 2015-2016 in the municipality of Armero-Guayabal, located in the northern region of Tolima, Colombia. Ten sowing dates (SD), a SD per month, were established on November, December, January, February, March, April, May, June, July, and August. The cultivar used was *Oryzica* 1, this cultivar was selected because it has been sown for 34 years in this region due to its good productivity and high grain quality.

Experimental design and evaluated variables

The experiment was carried out in soil formed by volcanic flows with a sandy loam texture. Plots were established in a completely randomized block design in a divided strips arrangement, where the stripes corresponded to the sowing dates. Each strip comprised 2500 m^2 divided into three blocks. Similar agronomic management was carried out for the ten sowing dates, where irrigation was provided by gravity with a frequency of two days per week. The control of pests, diseases, and weeds were carried out according to weekly sampling, using chemical synthesis products. The nutritional supply was made using five edaphic fertilizations, during the different phenological stages according to the nutritional requirements for the extraction of potential yield of 10,000 kg ha^{-1}.

Growth variables and trends were estimated, as follows: Leaf area index (LAI) and dry matter (DM) above the soil was determined following the methodology described by Degiovanni *et al.* (2010) and Garcés and Restrepo (2015), respectively. Phenology stages were characterized according to the BBCH scale (Lancashire *et al.*, 1991), and plant height was also measured. These variables were evaluated in all the plants that were in an area of 625 cm^2, from the phenological stage 11 to 99. Once the phenological stage 99 was reached, harvest index and plant components were estimated. Moreover, with data obtained from the panicle number per square meter, weight of 1,000 grains, the percentage and weight of filled grains, green paddy yield in kg ha^{-1} was calculated according to Garcés and Restrepo (2015). The yield was estimated with a grain humidity of 22%.

Climatological variables were collected using a weather station (Davis Vantage Pro 2, San Francisco, California) located 500 meters far from the study area. These data were divided into 12 parts according to the BBCH scale, and the following variables were obtained: maximum diurnal temperature, maximum night temperature, minimum night temperature, accumulated solar radiation (SR), accumulated precipitation and average relative humidity according to each of the 12 parts considered.

In the SD of April, May, June, July, and August, photosynthesis rate, stomatal conductance and transpiration, in the phenological stages 49 (i.e., first awns visible), 65 (i.e., 50% of flowers), and 75 (i.e., milky ripe) were estimated in the youngest completely expanded leaf, using a portable open photosynthesis-meter system (LI-6400 XT Li-Cor Lincoln, Nebraska, U.S.A.). The photosynthetic photon flux density of 1600 µmol photons m^{-2} s^{-1}, the concentration of CO_2 inside the chamber was set at 400 µmol CO_2 mol^{-1}, and the vapor pressure deficit remained between 1.5 and 1.7 kPa; data were taken after reaching stable state equilibrium (~10 min). The area of the leaf inside the chamber was measured in order to correct with the real data area.

Growth trends, as well as growth, development, yield components and, climatic variables, were analyzed with the automatic learning methodology using tree decision algorithms (Delerce *et al.*, 2016). In order to use this technique, it is necessary to previously filter the variables considering their correlation with predictors (Hastie *et al.*, 2009); therefore, these variables were filtered by partial least squares regression using the NIPALS model (Geladi and Kowalski, 1986). Furthermore, the criteria considered were the variables of importance that presented a coefficient >0.8 and a correlation with the predictor variable. Once important variables were identified through the trees and photosynthesis analysis, contour plots were made with yield as a response variable. This analysis was done with the objective of identifying optimal points where performance is maximum (Figueroa, 2003). Besides, a multivariate analysis of variance with a Hotelling's significance test was performed with yield component data. Data analyzes were carried out with the software RStudio Inc., version 3.5.1.

RESULTS AND DISCUSSION

Identification of sowing dates

The SD of December and May presented the highest yields (Table 1), agreeing with the results found by various authors (Datt *et al.*, 2012; Sameera *et al.*, 2016; Dong *et al.*, 2017). Moreover, the number of panicles and the percentage of full grains have a high correlation with yield (Table 2) where a significant correlation is observed between these variables. This correlation explains the high yields found in the SD of December and May, the results obtained were similar to those reported by Thippani *et al.* (2017). However, no relationship was observed between the weight of 1,000 grains and the number of grains per panicle with yield (Table 2), what differs from what was found by Díaz *et al.* (2000), where they stated that these are variables that significantly influence yield and are closely related to grain length. Possibly this correlation was not observed because only one variety was evaluated, and it is probable that no variability in this character would occur, so in future studies, this variable should be considered.

Table 1. Yield components and harvest index of rice in ten sowing dates in Armero-Guayabal.

Sowing date	Harvest index	Number of panicles (m^2)	Yield (kg ha^{-1})	Weight of 1000 grain (g)	Filled grains (%)	Number grains per panicles	Hotelling grouping
July	0.42	260.00	6,247.46	24.53	65.14	85.59	a
May	0.37	509.67	9,964.31	21.74	77.31	78.60	b
December	0.30	569.67	10,831.3	24.70	78.62	59.23	c
November	0.43	347.17	5,658.62	24.85	78.69	50.74	d
April	0.38	359.17	9,609.48	20.93	79.54	62.83	e
March	0.28	353.33	7,992.42	24.63	71.92	76.78	fg
August	0.36	298.33	6,948.08	23.75	59.92	85.98	fhi
June	0.37	336.00	8,150.35	25.08	73.31	66.08	g
February	0.49	337.00	7,223.23	25.50	64.78	76.71	h
January	0.42	432.33	6,355.61	23.85	65.87	51.50	i

Treatments with a different letter indicate significant differences ($P \leq 0.05$).

Table 2. Pearson correlation between crop yield and yield components evaluated on ten sowing dates in Armero-Guayabal.

Response Variable 1	Response Variable 2	Pearson	*P*-value
Yield	Number of panicles	0.57687	0.0001
	Weight of 1,000 grains	-0.17424	0.28225
	Filled grains (%)	0.59497	0.00005
	Number of grain per panicle	0.19518	0.22746

Identification of physiologic and climatic factors associated with rice yield

According to the tree method, the LAI variable in the stage 49 (i.e. maximum panicle swelling stage), plant height in the phenological stage 41 (i.e. beginning of panicle swelling), and accumulated DM in the stage 37 (i.e. elongation of the stem), are the variables that are mostly associated with rice yield, moreover, together they explain this with an R^2 of 0.92 (Figure 1A). Maximum yield is reached when the LAI is between 10 and 11 (Figure 2A), which are similar to values found by Mae *et al.* (2006), who observed a linear relationship between LAI and yield, finding the maximum crop yield with a LAI between 10 and 12. Garcés and Restrepo

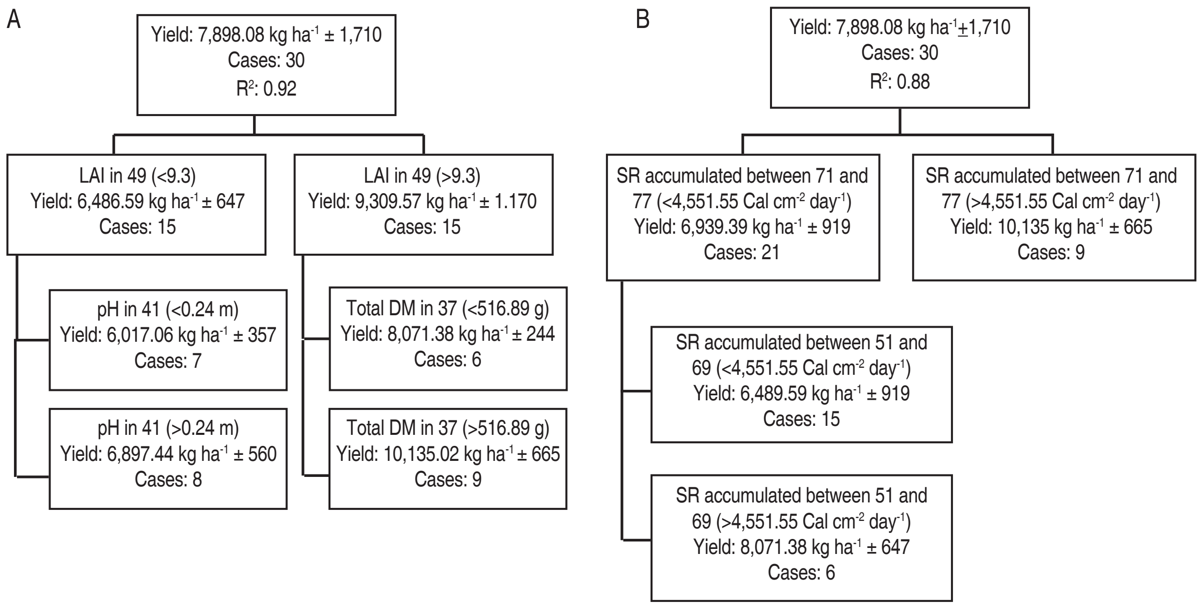

Figure 1. A. Tree for physiologic factors associated with rice yield; B. Tree for climatic factors associated with rice yield. LAI: leaf area index; PH: plant height; DM: dry matter; SR: solar radiation.

(2015) conducted a similar study in the southern area of Tolima, where they found that maximum yield was reached with a LAI of 7; this difference can be attributed to the fact that different varieties were used. The highest yield is reached with a plant height between 0.30 and 0.40 m, while yield is significantly reduced when it is less than 0.30 m (Figure 2A). These differences are present because higher plants allow better ventilation and better location of the leaves inside the canopy. On the contrary, plants with lower height generate lower ventilation and wrong leaf location, which generate a reduction in the photosynthesis rate of the canopy in 60 to 80%, and yield is reduced by approximately 2,000 kg ha^{-1} (Setter, 1997; Peng *et al*., 2008). Therefore, to obtain a high yield, it is necessary to reach a LAI between 10 and 11 and a plant height between 0.30 and 0.40 m, both between plant development stages 41 and 49, which allows the plant to have a better solar radiation uptake.

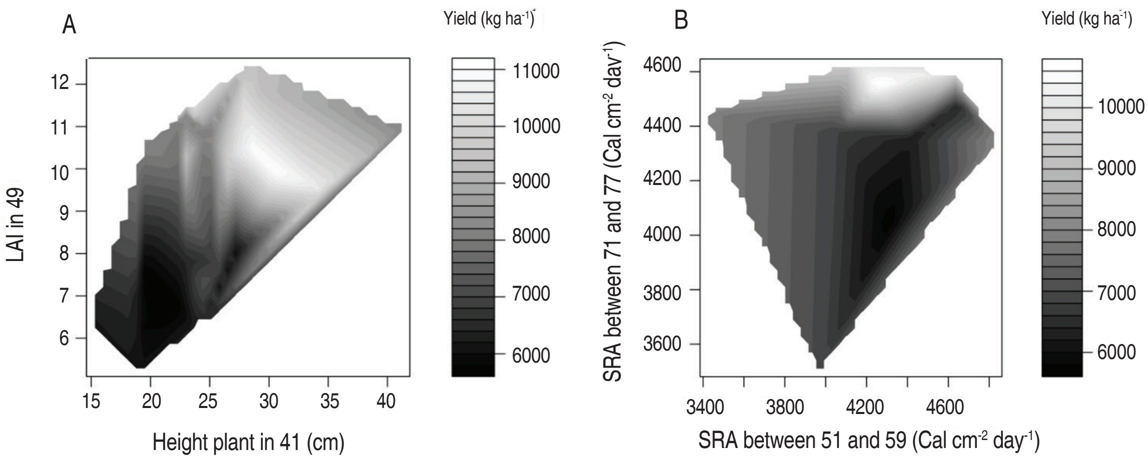

Figure 2. A. Physiologic contour plot associated with rice yield; B. Climatic factor contour plot associated with rice yield; LAI: leaf area index; SR: solar radiation.

SR that is received by crops from stages 30 to 89 has a decisive influence on crop yield (Yoshida and Parao, 1976). According to the tree methodology, the climatic factors that are the most associated with yield is SR in the phenological stage 51 to the 77, with an R^2 of 0.88 (Figure 1B). Maximum yield is reached when SR presented values between 4,000 and 4,500 cal cm^{-2} d^{-1} between stages 51 to 59 (i.e., inflorescence emergence), and greater than 4,500 cal cm^{-2} d^{-1} between stages 71 and 77 (i.e., development of fruit) (Figure 2B). The relationship found between SR and yield is due to a direct relationship between global and intercepted SR and accumulation of DM; and therefore, with yield (Garcés and Restrepo, 2015; Huang *et al*., 2016).

However, for SR to be converted into DM, it must be intercepted, and this is defined by plant LAI and architecture (Ying *et al*., 1998; De Costa *et al*., 2006; Zhang *et al*., 2009). These physiological factors are decisive because it allows SR, that cannot be absorbed by the leaves of the upper third, to penetrate and be intercepted by the middle and lower third leaves, where 70% of the leaf area is found, which contributes to a photosynthetic rate of approximately ~47% of the canopy (Song *et al*., 2013). Furthermore, to have a high efficiency in the conversion of SR into carbon skeletons, it is necessary that the photosynthetic apparatus does not show climatic stress limitations, which can be generated by high diurnal (>40 °C) and nocturnal (>30 °C) temperatures (Sánchez *et al*., 2014; Alvarado *et al*., 2017). However, these temperatures were not found in any sowing date (data not shown).

The photosynthesis rate has a close relationship with yield because as it increases, photosynthate supply increases from leaves to grains (Fu and Lee, 2008). However, no clear relationship was found between yield and this variable. SD with the highest yield does not coincide with a high photosynthesis rate in any of the three phenological stages evaluated (Figure 3). This lack of relationship is contradictory to the direct relationship between photosynthesis rate and yield found by other authors (Hidayati *et al*., 2016). This result is explained because the photosynthesis rate was not evaluated at the canopy level but on a single leaf, and it was also estimated at the saturation point and not the real photosynthesis rate on different phenological moments. Therefore, the influence of SD in the photosynthesis rate of the canopy should be studied further in depth, through daily curves, which allow seeing the real capacity of carbon fixation and its relationship with the yield.

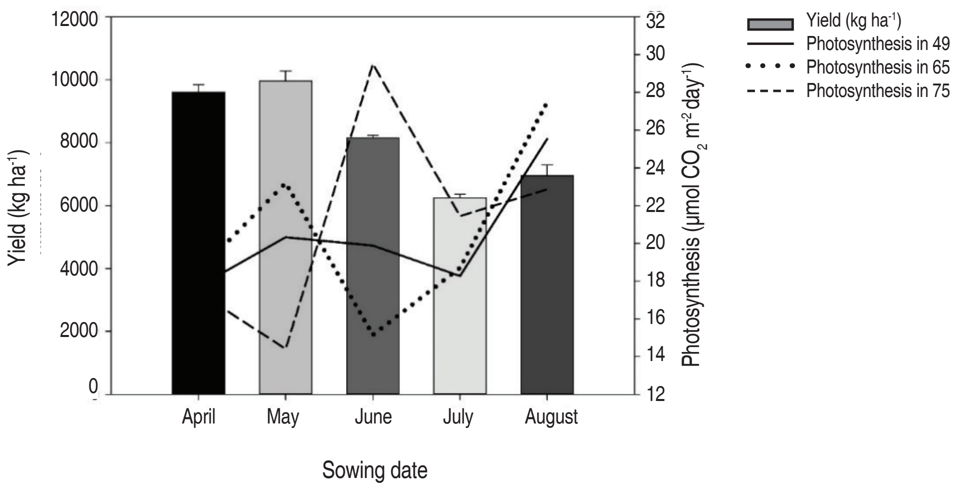

Figure 3. Behavior of yield and the photosynthetic rate in different phenological stages of the rice plant.

CONCLUSIONS

The physiological parameters that influenced the rice yield are leaf area index, plant height and dry matter in rice phenological stages 37 to 49. The climatic factor that had a significant relationship with yield was solar radiation in plant phenological stages between 51 and 77, corresponding to the sowing days of December and May. Since solar radiation was optimal for only these sowing dates, more practices and studies should be developed to maximize solar radiation uptake along the year, focusing on the increase of photosynthesis rate of the canopy, and subsequently, rice yield.

ACKNOWLEDGEMENTS

The Authors thank to Corporación Colombiana de Investigación Agropecuaria (Agrosavia), and the Government of the Republic of Colombia for financing this study. The authors also thank to Gonzalo Sarmiento and his work team for their valuable collaboration that was essential to complete this research.

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