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Energy conversion efficiency in sugarcane under two row spacings in northeast of Brazil

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Key words:
soil cover
specific heat of combustion
radiation use efficiency

A B S T R A C T
The study aimed to evaluate growth and physical environment of cultivation to determine the efficiency in which the sugarcane, cultivated in two row spacing configurations, converts solar radiation into biomass in Alagoas state - Northeastern of Brazil. For this purpose, the sugarcane variety RB98710 was cultivated, in plot with a single spacing and other with combined spacing. Biometric and solarimetric measurements were performed to evaluate plant growth and net radiation inside the canopy. The extinction coefficient (k), radiation use efficiency (RUE), specific heat of combustion, energy stored in dry matter (DM) and energy conversion efficiency (ECE) were determined for both row spacings. Plants of cultivated with single spacing had k value equal to 0.48 (± 0.03) and value of k with combined spacing was 0.51 (± 0.02). The RUE of sugarcane plants were 2.73 (± 0.09) and 2.78 (± 0.25) g MJ^{-1} of intercepted photonsynthetically active radiation (R^2 = 0.96 and 0.83) in single and combined spacing, respectively. The average specific heat of combustion of the different sugarcane parts was equal to 16,300 J g^{-1} of DM, but the DM value of stalks was equal to 15,600 J g^{-1}. Thus, the ECE values were 4.4 and 4.5% respectively for crops with single and combined row spacings.

Palavras-chave:
cobertura do solo
calor específico de combustão
eficiência do uso da radiação

Eficiência de conversão de energia em cana-de-açúcar sob dois espaçamentos entrelinhas no Nordeste do Brasil

R E S U M O
O estudo objetivou avaliar o crescimento e o ambiente físico de cultivo para determinar a eficiência com que a cana-de-açúcar, cultivada em duas configurações de espaçamentos entrelinhas, converte a radiação solar em biomassa no estado de Alagoas - Nordeste do Brasil; para este fim, a variedade RB98710 de cana foi cultivada em uma parcela com um único espaçamento e outra com espaçamento combinado. Medidas biométricas e solarimétricas foram realizadas para avaliar o crescimento da planta e o balanço de radiação dentro do dossel. O coeficiente de extinção (k), a eficiência do uso da radiação (RUE), calor de combustão específico, energia armazenada na matéria seca (MS) e a eficiência de conversão de energia (ECE) foram determinados para ambos os espaçamentos de plantio. Plantas cultivadas com espaçamento simples proporcionaram valor k igual a 0,48 (± 0,03) e o valor de k no espaçamento combinado foi de 0,51 (± 0,02). A RUE das plantas de cana foi 2,73 (± 0,09) e 2,78 (± 0,25) g MJ^{-1} de radiação fotossinteticamente ativa interceptada (R^2 = 0,96 e 0,83), em espaçamento simples e combinado, respectivamente. O calor específico de combustão médio das diferentes partes da cana foi igual a 16.300 J g^{-1} de MS, mas o valor da MS dos colmos foi igual a 15.600 J g^{-1}. Assim, os valores de ECE foram 4,4 e 4,5%, respectivamente, para os cultivos no espaçamento simples e combinado.

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Introduction

Biomass produced by plants through photosynthesis, uses solar energy, water and carbon dioxide (CO_2). This energy is called Photosynthetically Active Radiation (PAR), and is distributed in the wavelength (λ) range of 400 - 700 nm. The biomass has currently attracted great interest in the global energy scenario, especially for the production of biofuels and the generation of electricity through combustion. In Brazil, for the year 2011, biomass represented 7% of the electricity supply. However, considering the production of primary energy, biomass accounted for 27% (17% of sugarcane products and 10% of fuelwood). Among the crops of importance in the national energy sector, sugarcane (*Saccharums sp.*) stands out from the others because its cultivation is traditional in several regions of Brazil. Approximately 40% of sugarcane is used for ethanol production in Brazil (Steduto et al., 2012). In addition to these products, the generation of electricity by burning sugarcane bagasse and straw left after harvest is a reality. In the near future, all mills will supply electricity to the public energy network. Thus, the development of technologies in the agricultural sector leads to increased productivity.

In this sense, row spacing (RS) is a that factor that still to be adjusted in sugarcane crops, as practices such as drip irrigation and mechanized harvesting require alternative row spacing. Thus, the solar radiation balance in the plant canopy in these different agricultural management is fundamental to understanding the growth and development processes (Sinclair & Muchow, 1999; Ferreira Junior et al., 2014b; Wang et al., 2015) and the application of models that use components of this balance as input variable (Liu & Bull, 2001; Marin & Jones, 2014). Solar radiation intercepted (or absorbed) by the plant canopy is the most important component for growth analysis, but to estimate this radiation, it is necessary to know the leaf area index (LAI) and the extinction coefficient (k) (Silva & Costa, 2012).

In this context and considering the lack of information for sugarcane crops, this study aimed to evaluate growth and physical environment of cultivation to determine the efficiency in which the sugarcane crop, cultivated in two row spacing configurations, converts solar radiation into biomass in the Alagoas state in Northeast of Brazil. The aim was also to determine: 1) fraction of soil coverage, 2) radiation use efficiency, 3) biomass energy and 4) energy conversion efficiency.

Material and Methods

The field research was conducted with sugarcane crop (*Saccharum sp.*), variety RB98710 at Rio Largo (09º 28' 02" S, 35º 49' 43" W, 127 m), Alagoas state, Northeastern of Brazil. The climate of this region is classified, according to the Thornthwaite method as humid, megathermal, with moderate water deficiency in the summer and large water surplus in the winter. The annual climatological averages (1972-2010) of rainfall, average air temperature, relative humidity and cloudiness fraction are 1789.5 mm, 25.4 °C, 82 and 42%, respectively. The local soil was classified as distrocohesive Yellow Latosol, intermediate/clayey texture, in which the physical properties of the profile at the depth of 0.60 m was on average: 57% sand, 13% silt, 30% clay, and soil density of 1.32 kg dm^{-3}. Information about the crop management (soil preparation, fertilization, weed control and irrigation) are found in Ferreira Junior et al. (2014a).

Planting was completed on August 11, 2011 in an area of 480 m^2 divided into two plots, consisting of 12 planting rows of 20 m in length, one plot with a single row spacing (1 m) and the other with combined row spacing (0.6 and 1.4 m between rows alternately). The sugarcane variety (RB98710) used in the present study is characterized by great tillering, upright position, good row spacing closing, high sugar content and high agricultural productivity. It is part of the new generation of varieties developed by the Sugarcane Genetic Improvement Program (PMGCA) of Department of Agrarian Sciences, Federal University of Alagoas, which is included in the Interuniversity Network for the Development of the Sugar-Energy Industry (RIDESA) (Barbosa et al., 2012).

The meteorological data (air temperature, relative humidity, rainfall, global solar irradiance and wind speed) used in this study were obtained from the automatic agrometeorological station (Campbell Scientific, Logan, Utah) located next to the field area. The growth measurements in ten plants randomly chosen from each crop were submitted to the following monthly measurements. The leaf area index (LAI) was adjusted for thermal time (TT, °C day) accumulation through empirical equation (Ferreira Junior et al., 2014a). This adjustment allowed estimating the LAI evolution (daily) throughout of the cycle, which is an important variable for calculating the radiation balance of plants. TT was calculated with basal temperature (Tb) equal to 10 °C (Inman-Bamber, 1995; Sinclair et al., 2004; Smit & Singels, 2006).

Dry matter (DM) mass was determined in five samples along the growth cycle (169, 244, 308, 364 and 439 days after planting - DAP). In each sampling, 10 plants were randomly cut at ground level in each plot. The plants were separated into green leaves and sheaths, developed stalks, stalk tip and straw. The specific heat of combustion of the different plant parts was determined (at 169 days after planting) using a calorimeter IKA C 200 (ASTM D-2382). Each sample with approximately 0.5 g was placed inside the calorimetric pump. After the end of the burning process, the equipment displays the value of the specific heat of combustion in J g^{-1}. For each plant part, the procedure was performed twice and averages between results were made.

The PAR irradiance (W m^{-2}) was estimated as 43% of the global solar irradiance (Rg, W m^{-2}). This fraction was determined for the region of study by the relationship of these components, which were measured with standard sensors (CMP21, Kipp & Zonen and LI - 190SA, Li -COR, respectively for Rg and PAR) used only for calibration. The CMP 21 sensor is a secondary standard pyranometer from Kipp & Zonen that presents spectral range from 285 to 2800 nm and response time of five seconds.

Throughout cultivation, Rg data were measured by an Eppley pyranometer (model 848, B & W) located in the agrometeorological station, and the daily global solar irradiation (Hg, MJ m^{-2}) was obtained by integration Rg. Eppley pyranometer was calibrated with the same standard sensor (CMP21) used for determining the PAR versus Rg ratio. The PAR transmitted (PAR_T, W m^{-2}) by the canopy was measured by 18 photometers (LI-210SL, Li-COR) arranged into three bars with 1 m in length (each bar was composed of six sensors 20 cm away from each other) and a linear Quantum sensor (LI-191SA), all of them (the three bars and the linear sensors) were diagonally arranged on the soil surface between the planting rows (Monteith, 1993).

In each type of crop (row spacing configurations), five campaigns (monthly time interval) to measure the PAR_T were performed in the period from 85 to 204 DAP in order to represent the leaf area variation (LAI between 1 and 6) during crop development. The observations were always performed at the same time (from 10:00 a.m. to 02:00 p.m.). Photometers were scheduled to perform measurements every 30 s and store averages every 5 min. Averages of measurements of sensors were performed on the same bar and then the average measurement time was calculated (from 10:00 a.m. to 02:00 p.m.). All sensors used in PAR_T measurements through the canopy were calibrated against a Quantum sensor (LI-190SA, the same sensor used to determine the PAR versus Rg ratio) to obtain the densities of photosynthetic photon flux, μmol s^{-1} m^{-2}, and for the conversion of PAR correspondents, W m^{-2}, factor of 4.6 was used (McCree, 1972).

The fraction of PAR_T ($fPAR_T$) was calculated by the ratio of PAR_T and PAR from 10:00 a.m. to 02:00 p.m. on days 85, 112, 140, 173 and 204 DAP. The extinction coefficient (k) through plant canopy:

$$k = \left[\frac{-\text{Ln}\left(\text{fPAR}_T\right)}{\text{LAI}}\right] \tag{1}$$

where:

LAI corresponding to the days in which PAR_T was measured. The k medium, which is the value for the cycle, was determined by linear regression ($\beta_0 = 0$) between the negative of the natural logarithm of $fPAR_T$ and the LAI.

The soil cover (SC) along the crop cycle was considered equal to the estimated fraction of intercepted PAR (PAR_I), according to equation (1 - exp(-k LAI)) (Adams & Arkin, 1977). The length of the initial growth stage was determined through information from the SC estimate. According to Allen et al. (1998), the end of the initial growth stage (S1) is determined when plants take up 10% of the SC. The length of S1 was close to the tabulated value (50 days) for the plant crop (crop established by planting stalk is called "plant crop", after harvest, the other cycles are called "rattoon cane") cultivated in the tropics (Allen et al., 1998). The end of the development stage (S2) occurs with the full canopy closure. The same authors mentioned that the end of this stage is equivalent to SC value from 70 to 80% (in this study, it was considered to be equal to 80%).

To calculate Radiation Use Efficiency (RUE), the PAR_I was determined in daily scale (PAR_I^d, MJ m^{-2}) by multiplying the PAR in daily scale ($PAR^d = 0.43$ Hg) with the estimated $fPAR_I$, considering the k value constant for the cycle and previously determined (as described above). Later, RUE was estimated by linear regression, forced to pass through the origin ($\beta_0 = 0$), between the DM of shoots (except for dry leaves) and accumulated PAR_I^d (ΣPAR_I^d). A relationship only with the first two DM samplings was also adjusted, including dry leaves.

Energy Conversion Efficiency (ECE) expresses the energy stored in the biomass accumulated in one cycle (or period) compared to the solar energy flux during this period. In the present study, ECE was calculated as the ratio between energy stored in the accumulated DM (Biomass Energy - $E_{DM,}$ Joules m^{-2}) and the ΣPAR_I^d (MJ m^{-2}) in the same period. The latter was measured using a calorimeter, as previously described.

Cane yield (t cane ha^{-1}) was determined with the aid of a digital scale with capacity of 100 kg. Samplings were performed in the two central rows of each plot (5 linear m). Sugar yield (t ha^{-1} of sugar) was obtained by analyses of agroindustrial characteristics (quality of raw material) of stalks performed at the Laboratory of the Santa Clotilde Mill, located in Rio Largo City.

Results and Discussion

During the crop cycle, the daily average air temperature (Tm) ranged from 21.1 to 27.3 °C, averaging 24.2 °C (Figure 1A). These values were below the optimal range (28-30 °C) for the two sugarcane varieties evaluated by Liu et al. (1998). In research with controlled temperature, Inman-Bamber et al.

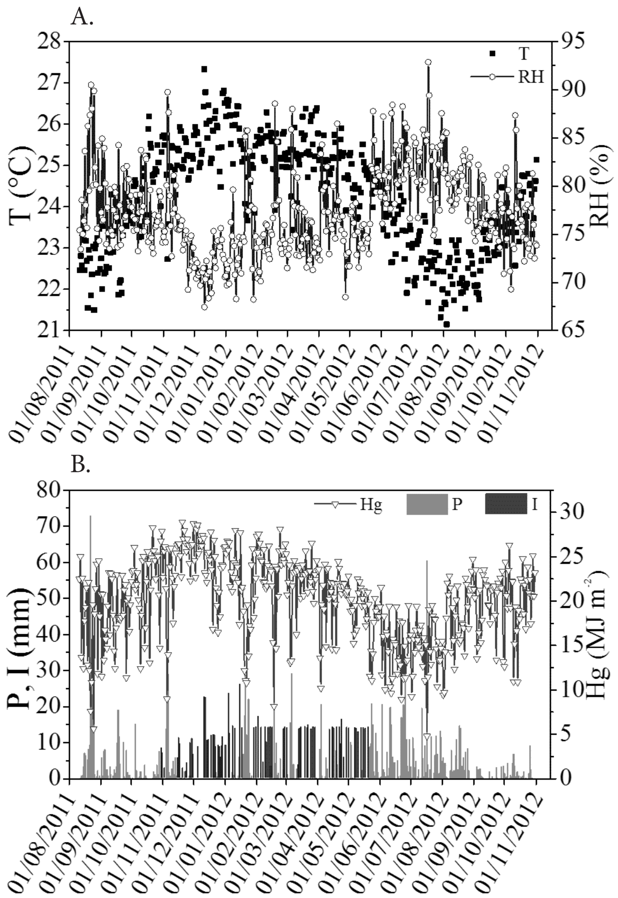

Figure 1. Main daily meteorological elements: (A) average air temperature (T) and average relative air humidity (RH), (B) precipitation (P), irrigation (I) and global solar irradiation (Hg). Planting date: August 11, 2011

(2010) mentioned that the cane internode length was reduced when the temperature was reduced from a daily average of 26.6 to 25.2 °C and concluded that the optimum temperature (daily average) for the elongation of cane internodes is between 26 and 31 °C. During the crop cycle of this research, the daily Tm was below 26 °C in 413 days (approximately 94% of the cycle days). The average daily relative humidity (RHm) in the cycle ranged from 67.4 to 92.3%, averaging 77.4%.

Rainfall during 440 days of crop cycle was 1415.3 mm, with magnitude (average rainfall per event) of 5.3 mm and average frequency of one rain event at every 1.6 day. However, there is a period of the year in the region between April and August that shows the largest amount of rain (72% of the annual total), which characterizes the rainy season; the other months (September to March) were considered less rainy (Souza et al., 2004; Carvalho et al., 2013). Thus, the magnitude and frequency of rainfall events (~14 months) do not satisfactorily represent the rainfall characteristics of the region, because these parameters are the mean values of two periods with different rainfall conditions. The water applied through irrigation amounted 900 mm (for both crops) between the months of November 2011 and May 2012, which supplied part of the crop water demand in the less rainy period.

The daily average Hg during the crop cycle was equal to 19.9 MJ m^{-2}, with maximum value of 28.9 MJ m^{-2} and minimum value of 4.8 MJ m^{-2}. The months of June and July 2012 showed the lowest daily averages (14.7 MJ m^{-2}) (Figure 1B) mainly due to the high cloudiness observed at this time of year. In the less rainy season (October to April), the global solar irradiation was higher than the other months of the crop cycle, with daily average of 22.0 MJ m^{-2}.

Meteorological elements have different behaviors between crop growth stages, mainly because sugarcane is a crop with long cycle (440 days in this study). Thus, the effects of seasonality on the environmental elements are observed between crop growth stages. In Stage 1 (initial growth stage, August 11 to October 07, 2011) of the crop cycle, Tm was 23.1 °C, on average, RHm around 78.8%, the accumulated rainfall was 309.4 mm (magnitude = 6.3 mm frequency of one event every 1.2 day) and Hg approximately 18.5 MJ m^{-2}. In Stage 2 (crop development stage; October 08 to December 07, 2011), Tm was greater than the previous growth stage (25.0 °C), which associated with reduced accumulated rainfall (total = 123.2 mm; magnitude = 3.7 mm and frequency of one event every 1.8 day), led to lower RHm (76.1%) compared to Stage 1, with Hg of 23.4 MJ m^{-2}. In this growth stage, 90 mm of water were applied through irrigation. Stage 3 (mid-season stage; December 08, 2011 to July 17, 2012), due to its greatest length (223 days), showed great amplitude of meteorological elements, as it initiated within the driest season (December) and extended until near the end of the rainy season (July), with Tm (24.8 °C), RHm (76.9%), P (734.3 mm) and Hg (19.9 MJ m^{-2}). Rainfall in this stage had magnitude of 6.1 mm and average frequency of one event every 1.8 day. The largest volume of water applied by irrigation was at this phase, which totaled 810 mm. During Stage 4 (late season stage, July 18 to October 24, 2012), the average Tm was 23.0 °C, RHm of 78.7%, accumulated P of 248.4 mm (magnitude = 3.8 mm and average frequency of one event every 1.5 days) and Hg of 18.6 MJ m^{-2}.

The DM mass of plants ranged from 2.3 to 7.9 kg m^{-2} in single RS and from 2.1 to 9.3 kg m^{-2} in combined RS from 169 to 439 DAP. At 169 DAP, the stalk had less DM mass (39%) than the other plant parts (leaves and stalk tips) because the number of internodes was lower than five per plant. On this day, the crop was within the mid-season stage (S3), where the canopy closure is effective (GC > 80%), the crop coefficient (Kc) value is maximal and LAI is much higher than 5.5. The fresh matter (FM) mass of whole plants (average of both RS) that day had water content exceeding 75%, being higher than 80% in stalks. Along the other samples, the DM mass values of stalks increased until reaching maximum values of 6.8 (single RS) and 8 kg m^{-2} (combined RS) at harvest time. At this time, the water content in the FM mass of stalks was approximately 50% of the total. Unlike the mass gain that occurred in stalks, the mass of green leaves and stalk tips was almost constant throughout the samplings, because the mass lost by senescence of older leaves is compensated by the appearance of new ones, maintaining the number of green leaves around five.

The ΣPAR_I^d (MJ m^{-2}) by the plant canopy during the cycle of both RS were similar, being equal to 2770.8 MJ m^{-2} in single RS and 2776.5 MJ m^{-2} in combined row spacing. The period between 170 and 244 DAP was the period that plants most accumulated PAR_I^d (9.1 MJ m^{-2} in both row spacing configurations), resulting from the combination of high LAI at the beginning of the period, which was equal to 5.9 (single row spacing) and 5.7 (combined row spacing), and PAR^d with daily average of 9.5 MJ m^{-2} (Hg = 22.2 MJ m^{-2}). The period from 309 to 364 DAP (June 14 to August 09, 2012) showed the lowest daily average PAR_I^d (5.8 and 5.7 MJ m^{-2}, respectively, for single and combined row spacing). This value is because the daily average PAR^d of the period is relatively low, which was 6.5 MJ m^{-2} (Hg = 15.0 MJ m^{-2}), since it is within the rainy season of the region.

The average RUE of sugarcane plants were 2.73 (± 0.09) and 2.78 (± 0.25) g MJ^{-1} of PAR_I^d (R^2 = 0.96 and 0.83) in single and combined row spacing, respectively (Figure 2). These values are similar when one considers the standard error of estimate. In plants with single spacing, the accumulated intercepted Hg was 2762.8 MJ m^{-2}, with DM productivity by the model equal to 7542.4 g m^{-2}. Plants with combined row spacing accumulated 2268.3 MJ m^{-2} and had DM mass equal to 7723.6 g m^{-2} (estimated by the model). In a review by Heerden et al. (2010), the authors reported RUE values of 1.7 (Robertson et al., 1996) and 2.0 g MJ^{-1} (Muchow et al., 1997) as the highest found in literature for sugarcane crops using measures based on global solar radiation. These studies included straws (dry leaves) in the DM mass of plants. Using the conversion factor (0.55) suggested by Bonhomme (2000) to convert RUE on the basis of global solar radiation into RUE on the basis of photosynthetically active radiation, these values would be equivalent to 3.1 and 3.6 g MJ^{-1} of PAR_I^d, i.e., efficiencies greater than those found in the present study. However, in this study, the DM mass of leaves was not included in the total DM of shoots. Only for the first two samples, the DM of dry leaves were quantified. In relation to this period, the relationship between the DM mass (including dry leaves) and ΣPAR_I^d was close to those reported as maximum and with value equal to 3.56 g MJ^{-1} of PAR_I^d (1.96 g MJ^{-1} of intercepted Hg) for plants

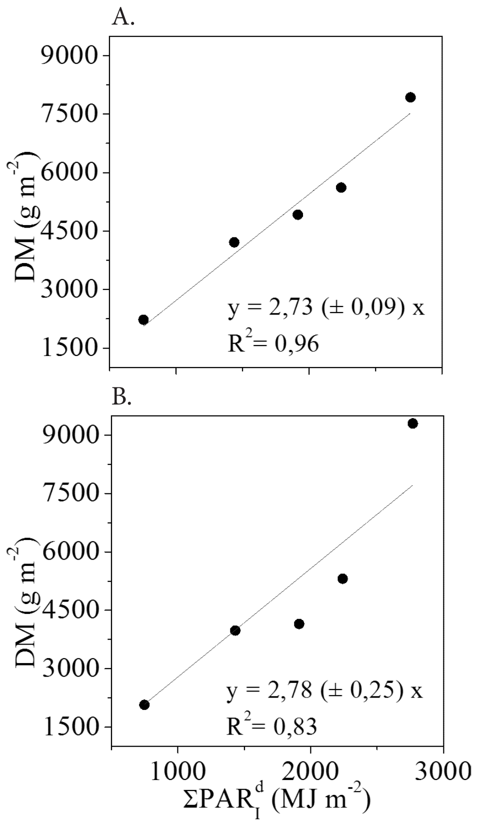

Figure. 2. Relationship between dry matter (DM) of shoots and accumulated intercepted photosynthetically active radiation (ΣPAR_I^d) for irrigated sugarcane: (A) single row spacing. (B) combined row spacing

with single row spacing and 3.38 g MJ^{-1} of PAR_I^d (1.86 g MJ^{-1} of intercepted Hg) for plants with combined row spacing.

The lodging of plants causes crushing and breaking of stalks, resulting in their death (Heerden et al., 2010). Thus, this factor along with the low air temperatures occurred during the rainy season (mainly from June to August), most likely caused a decrease in mass accumulation and consequently decreased RUE. However, the cane yield were high when compared with the national average (in the 2012/13 season, it was equal to 69.8 Mg ha^{-1}). The crops of this study reached cane and sugar yields of 100.9 Mg ha^{-1} and 17.8 Mg ha^{-1}, respectively, for both row spacing configurations.

The average specific heat of combustion of the different sugarcane parts (variety RB98710) was equal to 16,300 J g^{-1} of DM, but the DM value of stalks was equal to 15,600 J g^{-1}. Ripoli et al. (2000) found values of 18,000 J g^{-1} for sugarcane cultivated in Brazil. In sugarcane, the biomass composition consists mainly of carbohydrates, which has specific heat of combustion of ± 15,900 J g^{-1} (Waclawovsky et al., 2010). By determining the specific heat of combustion, it was possible to estimate the efficiency in which plants store the flux of intercepted solar energy in the usable range by the photosynthetic process. Figure 3 shows these efficiencies on different days after the start of the cycle. The biomass energy accumulated at the end of the crop cycle were 129.26 and 151.65 MJ m^{-2}, respectively, for single and combined row spacing. These stored energy are the result of an efficiency of 4.9 and 5.8%, respectively. When these efficiencies were found by the RUE curve, the values were, respectively, 4.4 and 4.5%. However, these efficiencies are determined with the intercepted PAR; when determined based on the intercepted Hg, their values are 2.4 and 2.5%. Monteith (1977), working with various crops, found ECE value equal to 2.4% as equivalent to RUE of 1.4 g MJ^{-1}, with specific heat of combustion of 17,500 J g^{-1}. Using RUE value of 2.0 g MJ^{-1} of global solar irradiation, considered as maximum in literature for sugarcane crop (Heerden et al., 2010) and the specific heat of combustion used in the present study, the maximum efficiency for sugarcane would be equivalent to 3.3%. Ramanujam & Venkataramana (1999), in a study conducted in India, reported ECE (using PAR) of 4.9% in the plant formation phase.

The ECE was lower in the initial phase of cultivation (germination up to the first sampling at 169 DAP), this is due to the fact that in this period, the solar incidence is the highest in the region and the leaf apparatus is still not the maximum, then the biomass production in the shoots is relatively lower. Another factor that probably influenced this lower efficiency was that in this period, the formation of the root system consumes energy from the shoot.

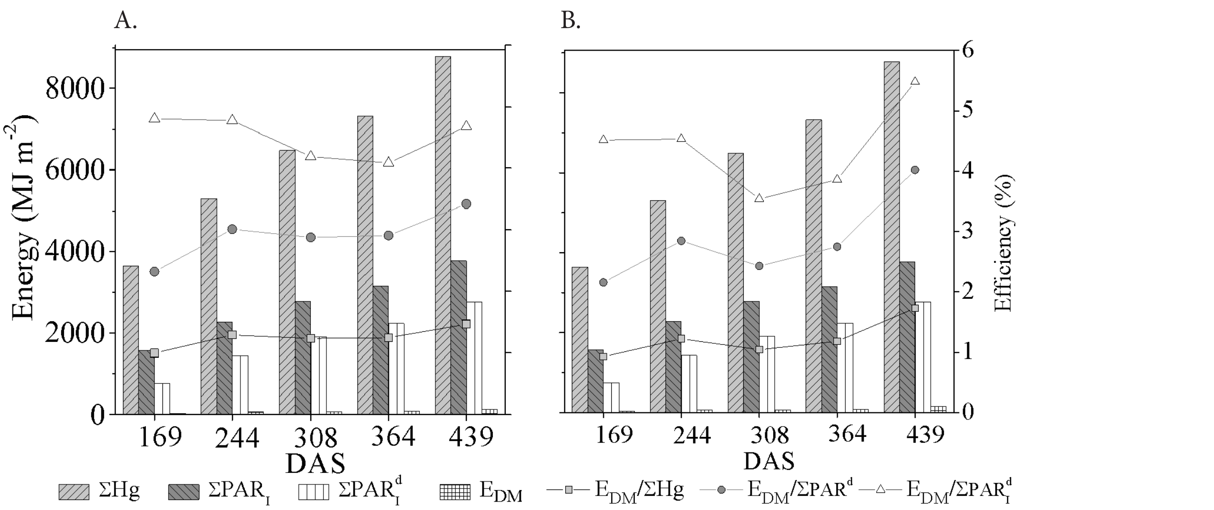

Figure 3. Global solar irradiation (ΣHg), daily photosynthetically active radiation (ΣPAR^d), intercepted photosynthetically active radiation (ΣPAR_I^d), biomass energy (E_{DM}) accumulated and energy use efficiency as a function of days after planting (DAP) of irrigated sugarcane: (A) single row spacing. (B) combined row spacing

Conclusions

1. The yield of irrigated sugarcane cultivated in Rio Largo - Alagoas, northeastern of Brazil, is not influenced by the use of different row spacing (single and combined). Other parameters determined in the study reinforces that the use of combined spacing suffers no loss of production compared to single spacing such as leaf area index, extinction coefficient, and thus soil cover (intercepted solar radiation).

2. The RUE and the ECE are similar in both types of row spacing (single and combined spacing). It was also concluded that the fraction of soil cover in both crops relative to the leaf area index had satisfactorily adjusted equations.

Literature Cited

Adams, J. E.; Arkin, G. F. A light interception method for measuring row crop ground cover. Soil Science Society of America Journal, v.41, p.789-792, 1977. http://dx.doi.org/10.2136/sssaj1977.03615995004100040037x

Allen, R. G.; Pereira, L. S.; Raes, D.; Smith, M.; Crop evapotranspiration - Guidelines for computing crop water requirements. Rome: Food and Agriculture Organization of the United Nations, 1998. 300p. Report nr 56,

Carvalho, A. L; Souza, J. L.; Lyra, G. B.; Porfirio, A. C. S. Ocorrência de períodos secos na região de Rio Largo, Alagoas. Revista Brasileira de Meteorologia, v.28, p.173-180, 2013.

Barbosa, M. H. P.; Resende, M. D. V.; Dias, L. A. S.; Barbosa, G. V. D. S.; Oliveira, R. A. D.; Peternelli, L. A.; Daros, E. Genetic improvement of sugar cane for bioenergy: the Brazilian experience in network research with RIDESA. Crop Breeding and Applied Biotechnology, v.12, p.87-98, 2012. http://dx.doi.org/10.1590/s1984-70332012000500010

Bonhomme, R. Beware of comparing RUE values calculated from PAR vs solar radiation or absorbed vs intercepted radiation. Field Crops Research, v.68, p.247-252, 2000. http://dx.doi.org/10.1016/S0378-4290(00)00120-9

Ferreira Junior, A. F.; Souza, J. L.; Escobedo, J. F.; Teodoro, I.; Lyra, G. B.; Araújo Neto, R. A. Cana-de-açúcar com irrigação por gotejamento em dois espaçamentos entrelinhas de plantio. Revista Brasileira de Engenharia Agrícola e Ambiental, v.18, p.798-804, 2014a. http://dx.doi.org/10.1590/1807-1929/agriambi.v18n08p798-804

Ferreira Junior, A.F.; Souza, J. L.; Teodoro, I, Lyra, G. B.; Souza, R. C.; Araújo Neto, R. A. Eficiência do uso da radiação em cultivos de milho em Alagoas. Revista Brasileira de Engenharia Agrícola e Ambiental, v.18, p.322-328, 2014b. http://dx.doi.org/10.1590/S1415-43662014000300012

Heerden, P. D. R. van; Donaldson, R. A.; Watt, D. A.; Singels, A. Biomass accumulation in sugarcane: unravelling the factors underpinning reduced growth phenomena. Journal of Experimental Botany, v.61, p.877-887, 2010. http://dx.doi.org/10.1093/jxb/erq144

Inman-Bamber, N. G. Climate and water as constraints to production in the South African Sugar Industry. Proceedings of The Annual Congress of The South African Sugar Technologists Association, v.69, p.55-59, 1995.

Inman-Bamber, N. G.; Bonnett, G. D.; Spillman, M. F.; Hewitt, M. H.; Glassop, D. Sucrose accumulation in sugarcane is influenced by temperature and genotype through the carbon source-sink balance. Crop & Pasture Science, v.61, p.111-121, 2010. http://dx.doi.org/10.1071/CP09262

Liu, D. L,; Bull, T. A. Simulation of biomass and sugar accumulation in sugarcane using a process-based model. Ecological Modelling, v.144, p.181-211, 2001. http://dx.doi.org/10.1016/S0304-3800(01)00372-6

Liu, D. L.; Kingston, G.; Bull, T. A. A new technique for determining the thermal parameters of phonological development in sugarcane, including sub optimum and supra-optimum temperature regimes. Agricultural and Forest Meteorology, v.90, p.119-139, 1998. http://dx.doi.org/10.1016/S0168-1923(97)00087-7

McCree, K. J. Test of current definitions of photosynthetically active radiation against actual leaf photosynthesis data. Agricultural and Forest Meteorology, v.10, p.443-453, 1972. http://dx.doi.org/10.1016/0002-1571(72)90045-3

Marin, F. R.; Jones, J. W. Process-based simple model for simulating sugarcane growth and production. Scientia Agricola, v.71, p.1-16, 2014. http://dx.doi.org/10.1590/S0103-90162014000100001

Monteith, J. L. Climate and the efficiency of crop production in Britain. Philosophical Transactions of the Royal Society, v.281, p.277-294, 1977. http://dx.doi.org/10.1098/rstb.1977.0140

Monteith, J. L. Using tube solarimeters to measure radiation interception by crop canopies and to analyse stand growth. Pub. Delta-T Devies, doc. code TSL-AW-4-1, 1993.

Muchow, R. C.; Evensen, C. I.; Osgood, R. V.; Robertson, M. J. Yield accumulation in irrigated sugarcane. II. Utilization of intercepted radiation. Agronomy Journal, v.89, p.646-652, 1997. http://dx.doi.org/10.2134/agronj1997.00021962008900040017x

Ramanujam, T.; Venkataramana, S. Radiation interception and utilization at different growth stages of sugarcane and their influence on yield. Indian Journal of Plant Physiology, v.4, p.85-89, 1999.

Ripoli, T. C. C.; Molina, J. R.; Ripoli, M. L. C. Energy potential of sugar cane biomass in Brazil. Scientia. Agricola, v.57, p.677-681, 2000. http://dx.doi.org/10.1590/S0103-90162000000400013

Robertson, M. J.; Wood, A. W.; Muchow, R. C. Growth of sugarcane under high input conditions in tropical Australia: I. radiation use, biomass accumulation and partitioning. Field Crops Research, v.48, p.11-25, 1996. http://dx.doi.org/10.1016/0378-4290(96)00041-X

Silva, A. L. C.; Costa, W. A. J. M. de. Growth and radiation use efficiency of sugarcane under irrigated and rain-fed conditions in Sri Lanka. Sugar Tech, v.14, p.247-254, 2012. http://dx.doi.org/10.1007/s12355-012-0148-y

Sinclair, T. R.; Gilbert, R. A.; Perdomo, R. E.; Shine Jr, J. M.; Powell, G.; Montes, G. Sugarcane leaf area development under field conditions in Florida, USA. Field Crops Research, v.88, p.171-178, 2004. http://dx.doi.org/10.1016/j.fcr.2003.12.005

Sinclair, T. R.; Muchow, R. C. Radiation use efficiency. Advances in Agronomy, v.65, p.215-265, 1999. http://dx.doi.org/10.1016/s0065-2113(08)60914-1

Smit, M. A.; Singels, A. The response of sugarcane canopy development to water stress. Field Crops Research, v.98, p.91-97, 2006. http://dx.doi.org/10.1016/j.fcr.2005.12.009

Souza, J. L,; Moura Filho, G.; Lyra, R. F. F.; Teodoro, I.; Santos, E. A.; Silva, J. L.; Silva, P. R. T.; Cardim, A. H.; Amorim, E. C. An assessment of the rainfall and air temperature in the region of Tabuleiro Costeiro of Maceió, AL, Brazil, during the 1972-2001 period. Revista Brasileira Agrometeorologia, v.12, p.131-141, 2004.

Steduto, P.; Hsiao, T. C.; Fereres, E.Crop yield response to water. Irrigation and drainage. Rome: Food and Agriculture Organization of the United Nations, 2012. 503p. Report nr 66.

Waclawovsky, A. J.; Sato, P. M.; Lembke, C. G.; Moore, P. H.; Souza, G. M. Sugarcane for bioenergy production: an assessment of yield and regulation of sucrose content. Plant Biotechnology Journal, v.8, p.263-27 6, 2010.

Wang, Z.; Zhao, X.; Wu, P.; He, J.; Chen, X.; Gao, Y.; Cao, X. Radiation interception and utilization by wheat/maize strip intercropping systems. Agricultural and Forest Meteorology, v.204, p.58-66, 2015. http://dx.doi.org/10.1016/j.agrformet.2015.02.004