Interception of photosynthetically active radiation, growth and yield of grains in sunflower under doses of nitrogen

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ABSTRACT

The objective of the work was to evaluate the response of growth and production, the interception efficiency of photosynthetically active radiation, the extinction coefficient, and the productivity components of sunflower in with the use of cover nitrogen doses in subtropical environments. The experiment was conducted at Santa Maria-RS, Brazil, where they were evaluated the leaf area index (LAI), interception efficiency (εi), and extinction coefficient (k) of photosynthetically active radiation (PAR), plant height (PH), chapter diameter (CPD), stem diameter (SD), the mass of one thousand achenes (MTA), and grain productivity (PROD) were evaluated. Nitrogen doses influenced the LAI only at 52 and 65 DAE, while the canopy interception efficiency (CIE) was influenced at 36, 42, 52, and 86 DAE. Therefore , for growth and production doses of cover N positively influence stem diameter and grain productivity. The application of cover nitrogen fertilizer linearly and positively affects the sunflower crop, and 160 kg ha^{-1} N. Interception efficiency of photosynthetically active radiation by the canopy and the leaf area index are positively influenced by the doses of nitrogen in the canopy. The extinction coefficient of the photosynthetically active radiation in sunflower decreases with the increasing dose of cover N.

Keywords: *Heliantus annus* L.; nutritional management; grain productivity; leaf area index; extinction coefficient.

INTRODUCTION

Sunflower (*Heliantus annus* L.) is an oilseed known for its versatile characteristics, the great edafoclimatic adaptation, and good resistance to cold, heat, and drought. Its grain production is little influenced by latitude, altitude, and photoperiod (Embrapa, 1997; Ungaro *et al.*, 2009). On the other hand, nitrogen fertilization is one of the practices that greatly affects sunflower productivity, and the interception of photosynthetically active radiation (Valeriano *et al.*, 2020; Soleymani, 2017; Schwerz *et al.,* 2016). Air temperature and absorbed solar radiation are related to the production and number of achenes per chapter (Barni *et al.*, 1995; Ungaro *et al.*, 2009). The plant was initially used as fodder and later as oilseed due to the insertion of cultivars with good oil yield (Pelegrini, 1985).

In Brazil, sunflower cultivation represents an area of 62.1 thousand hectares and productivity in the 2020/2021 harvest of 1,143 kg ha^{-1} (Conab, 2021) is very far from the potential of the culture. One of the points for improving management in sunflower crops is the adjustment of nitrogen (N) fertilization (Valeriano *et al.*, 2020; Soleymani, 2017; Schwerz *et al.,* 2016). N is the most limiting nutrient for sunflower crops and is the most exported by grain harvesting (Gazzola *et al.*, 2012). Its N deficiency causes nutritional disorder, which reduces plant development, the number of leaves, plant height, stem diameter, and leaf area (Oliveira *et al.*, 2014).

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Nitrogen plays an important role in the physiology of sunflower culture. It can significantly change the expression of leaf area index (LAI) and greatly limits grain production in sunflower (Soleymani, 2017), with observed in soybean (Casaroli *et al.*, 2007), wheat (Elli *et al.*, 2015), maize (França *et al.*, 2011), and canola (Dalmago *et al.*, 2018). Its cover application is subject to various nutrient loss processes, which can result in bad use by the culture. Additionally, with the change in the LAI caused by N management, a different interaction dynamic between the canopy leaves and the photosynthetically active radiation (PAR) can occur, significantly changing the extinction coefficient of PAR in the canopy (Dalmago *et al.*, 2018). These data support decision-making both in fertilizing management and in crop growth and development models.

Global solar radiation (GSR) can be used to estimate the maximum yield per rice plant at a given location (De Castro *et al.*, 2018). GSR absorption per unit of leaf area depends on the sowing date (Barni *et al.*, 1995). However, the PAR represents only a portion of the GSR. Since the leaves absorb PAR for the photosynthetic process more than the GSR, a greater extinction occurs in the PAR canopy than with the GSR. This indicates that the solar radiation interaction dynamics in the sunflower canopy are relevant to understanding the crop's performance when subjected to the effect of nitrogen fertilization doses. Schwerz *et al.* (2016) identified that the dose of 100 kg ha^{-1} N was the most indicated for morphological variables, radiation interception, and grain productivity under low water deficiency.

Water availability affects the adjustment of nitrogen fertilization and crop development. This implies changes in the intensities of physiological and morphological processes that can determine different levels for nitrogen fertilization dose, implying both photosynthetically active radiation transmitted by the canopy and grain productivity, as in other characters. Under conditions of lower water availability and with possible losses, it is necessary to verify the hypotheses that the dose of cover N applied is greater than 100 kg ha^{-1} N and substantially changes the PAR's extinction coefficient. In this context, the objective of the work was to evaluate the response of growth and production, the interception efficiency of photosynthetically active radiation, the extinction coefficient, and the productivity components of sunflower in with the use of cover nitrogen doses in subtropical environments.

MATERIAL AND METHODS

The experiment was carried out in 2019/20 in the experimental area of the Department of Phytotechnics of the Universidade Federal de Santa Maria, Santa Maria, Rio Grande do Sul, Brazil. The site is located in the central region of the state of Rio Grande do Sul, with coordinates of 29°42' S and 53°42' W, and an altitude of 103m. The soil of the experimental area is classified as a Sandy Dystrophic Red Argisol (Santos *et al.*, 2018). The climate is classified as Cfa, humid subtropical, according to Köppen (Alvares *et al.*, 2013). The meteorological data regarding the experimental period were provided by the station and database of INMET of Santa Maria - RS. The experimental period presented average temperature of 22.9 °C. According to the methodology described by Allen *et al.* (1998), the sequential water balance was elaborated based on the meteorological data.

The predecessor crop to the experiment was barley (*Hordeum vulgare*), used as a cover crop. The area was desiccated with glyphosate at a concentration of 890 g ha^{-1}, 15 days before sowing. Previously, the soil analysis of the site was performed, presenting the following values: clay = 31%, organic matter = 2.3%, pH = 4.8, P (Melich) = 5.0 mg. dm^{-3}, K = 0.102 cmolc dm^{-3}, H + Al = 19.4 cmolc dm^{-3}, Ca+2 = 3.3 cmolc dm^{-3}, and Mg = 1.5 $cmol_c$ dm^{-3}, thirty days before sowing was limestone application for acidity correction, at a dose of 5 Mg ha^{-1} with a correction capacity of 70%.

The area was prepared with the opening of lines for sowing using a fertilizing sower and the application of 300 kg ha^{-1} N of fertilizer formula 5-20-20. The total area of the experiment was 212.5 m², and each plot was composed of 10 lines, oriented from East to West, spaced in 0.5 m with 2.5 m of length, totaling 12.5 m². The experimental design used was that of randomized blocks with three replicates. The treatments consisted of nitrogen doses (0, 40, 80, 120, 160 kg ha^{-1} N) in the form of urea (45%) applied as a cover when the plants were in development stage V_8, identifying the phenological stages of the crop according to the scale described by Castilioni *et al.* (1997). At the time of nitrogen application there was no water restriction in the area, the same was applied after the occurrence of precipitation.

The sunflower cultivar used in the experiment was ADVANTA 5504, early material, which was chosen because it is well accepted by farmers and the oil industry, one of the most used by farmers in the state. Sowing was carried out manually after fertilizing the lines with the sower on October 7th, 2019, with the distribution of three seeds per pit. Thinning was carried out, leaving only one plant per pit, resulting in 40,000 plants ha^{-1}. The treatments were manually applied 22 days after the emergency (DAE), after precipitation when the plants had six true leaves. Mechanical control of the weeds present at the experiment site was performed during plant development until the canopy closure.

The canopy's leaf area and radiation interception were evaluated at 36, 42, 52, 65, and 86 DAE. Leaf area (LA) was evaluated using three plants per plot, marked. The length and width of three leaves of the lower, middle, and upper third of the canopy of each plant were measured using a ruler graduated in millimeters. The length was measured along the main vein and the width perpendicular to the insertion of the petiole in the widest part of the leaf, according Aquino *et al.* (2011). Thus, it was possible to calculate the leaf area index (LAI) by the expression LAI = LA SA^{-1}, with SA a soil area occupied.

Furthermore, the LAI was estimated based on the thermal sum accumulated during the experimental period. The thermal sum (degrees-day) was calculated by the residual method (ST, GD):

$$ST = \left(\frac{Tx + Tm}{2}\right) - Tb \qquad (1)$$

where Tb is a lower basal temperature of 8.5 °C (Sadras & Hall, 1988), Tx is as maximum temperature (°C), and Tm is as the minimum temperature (°C) of the air.

The LAI was estimated by:

$$LAI = a\,e^{-0,5\left[\frac{Ln\frac{ST}{b}}{c}\right]^2} \qquad (2)$$

where *a* is the parameter expressing the maximum LAI, *b* is the thermal requirement for maximum LAI (in GD), and *c* is the longevity of the LAI.

A bar with five photosynthetically active radiation sensors (PAR) connected in parallel was used to evaluate the canopy radiation interception (CRI), previously calibrated with a Li-Cor® Quantum sensor. The voltage (mV) readings generated by the amorphous silicon photocells were performed using a portable dt830-G digital multimeter. Subsequently, the readings were converted with the calibration coefficient to µmol m^{-2} day^{-1}. Each portion was sampled in four points, constituting 20 samples per experimental unit in each evaluation. The PAR measurements were carried out in three levels, the incident above the canopy (INC), transmitted by the upper extract of the canopy at one meter high (T1M), and by the canopy, that is, at 5 cm from the ground surface (TC). The canopy interception efficiency (εi_c), extracts superior (εi_s) and inferior (εi_i) to 1 m high, expressed in %, were calculated by the expressions:

$$\varepsilon i_c = (INC–TC)/INC.\ 100$$
$$\varepsilon i_s = (INC-T1M)/INC\ .\ 100 \qquad (3)$$
$$\varepsilon i_i = \varepsilon i_c - \varepsilon i_s$$

Additionally, the chapter diameter, stem diameter, and plant height were evaluated. These evaluations occurred at 102 DAE, after the physiological maturation stage. A tape measure was used to measure the chapter diameter (CPD) from one edge to the other by the center of each chapter. A caliper was used at the height of 1 m from the ground to measure the SD. Plant height (PH) was determined by measuring from the base of the plant at ground level until the insertion of the chapter using a measuring tape.

The harvest of the useful area of the plots, of 6 m^2, was performed at 106 DAE after the chapters reached maturation, collecting the eight central lines of the plots and excluding the borders. The chapters were tracked manually and, after the achenes, subjected to a pre-cleaning under forced ventilation with the aid of a fan to remove impurities. Subsequently, the mass of 1000 achenes (M1000) was determined and, later, grain productivity (PROD, kg ha^{-1} N) and moisture content were inferred to correct the values. The achene productivity and mass data were corrected to 13% moisture on a moist basis.

The collected data were submitted to analysis of variance and regression through the computer program SISVAR version 5.6 (Ferreira, 2019), considering 5% of error probability ($p < 0.05$).

RESULTS AND DISCUSSION

The verified cumulative rainfall from sowing to sunflower maturation was 698.4 mm (Figure 1). This precipitation was poorly distributed, and 55% occurred 30 days before the flowering of the crop and 25% in the eight days before maturation. Only 20% of the rainfall occurred in the period with the highest leaf area index, including flowering, determining frequent and significant water deficiencies. This situation may have affected fertilization and the beginning of grain development, although 400 to 600 mm of rainfall well distributed throughout the crop cycle is sufficient to result in good yields (Gazzola *et al.*, 2012; Ungaro *et al.*, 2009).

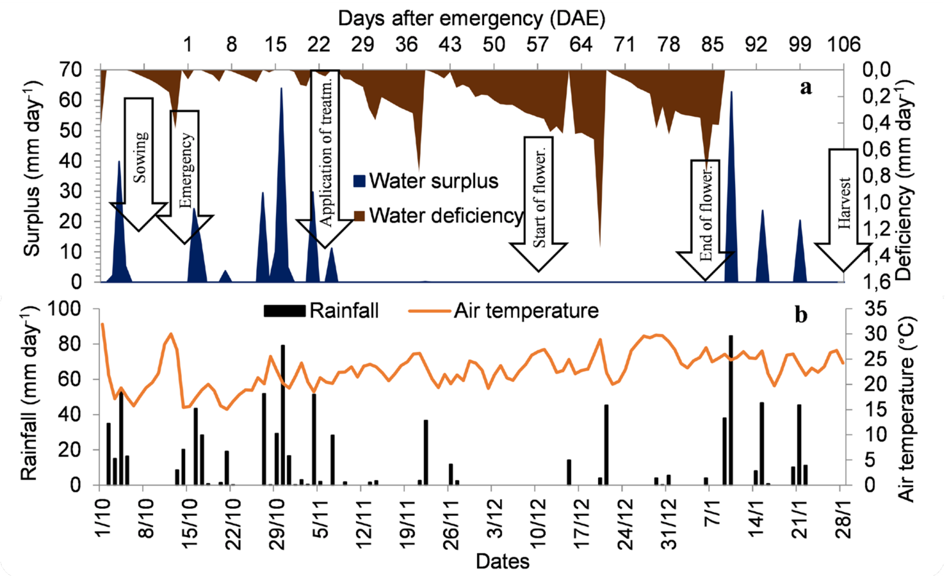

Figure 1: Deficiency and excess extracted from the daily sequential water balance for the grassy surface, with the available water content of 75 mm (a), rainfall, and average daily air temperature (b) between October 2019 and January 2020 in Santa Maria, Rio Grande do Sul, Brazil.

The average thermal condition in the experimental period (Figure 1) was favorable for crop development, although close to the upper thermal limit, which is influenced by lower water availability. According to Castilioni *et al.* (1997), the optimal development temperature range for sunflower crops is between 27 °C and 28 °C, but temperatures between 10 °C and 34 °C are tolerated without significantly reducing the production.

Nitrogen (N) doses did not influence the LAI at 36, 42, and 86 days after emergence (DAE). However, there was a significant effect at 52 and 65 DAE. Given the linear and positive effect of nitrogen doses, the highest values of LAI were found at the dose of 160 kg ha^{-1} N (Figure 2). The effect of N doses can be quadratic on the number of leaves (Biscaro *et al.*, 2008) and leaf area index (Schwerz *et al.*, 2016) in other cultivation environments. However, a restriction in expression at maximum levels of LAI in intermediate treatments should be determined with the intensification of environmental rain reduction, determinant for water deficiency after the application of cover N. The self-shading with overlapping leaves was less intense with the increase in the dose of N due to the lower water availability.

Nitrogen doses significantly influenced canopy interception efficiency (CIE) at 36, 42, 52, and 86 DAE. However, the influence was not significant only at 65 DAE (Figure 2). With the advancement of the cycle, there was a progressive increase in the efficiency of solar radiation interception by the culture, reaching the maximum values of 88.44% at 52 DAE at the dose of 26.86 kg ha^{-1} N . According to Schwerz *et al.* (2016), who evaluated the effect of nitrogen doses and sources on morphological variables, radiation interception, and productivity, radiation interception behaved in a quadratic form with the increase in nitrogen doses, having increased radiation interception where the highest values were found at the dose of 100 kg ha^{-1} N.

Compared to the determination of LAI, the measure of PAR interception efficiency allowed a better demonstration of the effects of N doses in most evaluations, except when the mean LAI of all treatments exceeds 5.0 (5.16) at 72 DAS (65 DAE). Greater self-shading of the leaves in the canopy occurs under higher LAI. In other words, although N doses significantly affect LAI, higher LAI values do not result in greater PAR interception. This suggests that in addition to being more practical for determinations than the LAI, the PAR interception efficiency measures also make it possible to better demonstrate significant effects of N doses in sunflower.

This finding was related to the lower variability obtained with interception efficiency measures (εi_c) than LAI. The mean coefficient of variation (CV) between the different evaluations was 19.9 and 0.4% in the LAI and εi evaluations, respectively. Thus, the CV is an important indicator of greater experimental accuracy. Thus, it can be

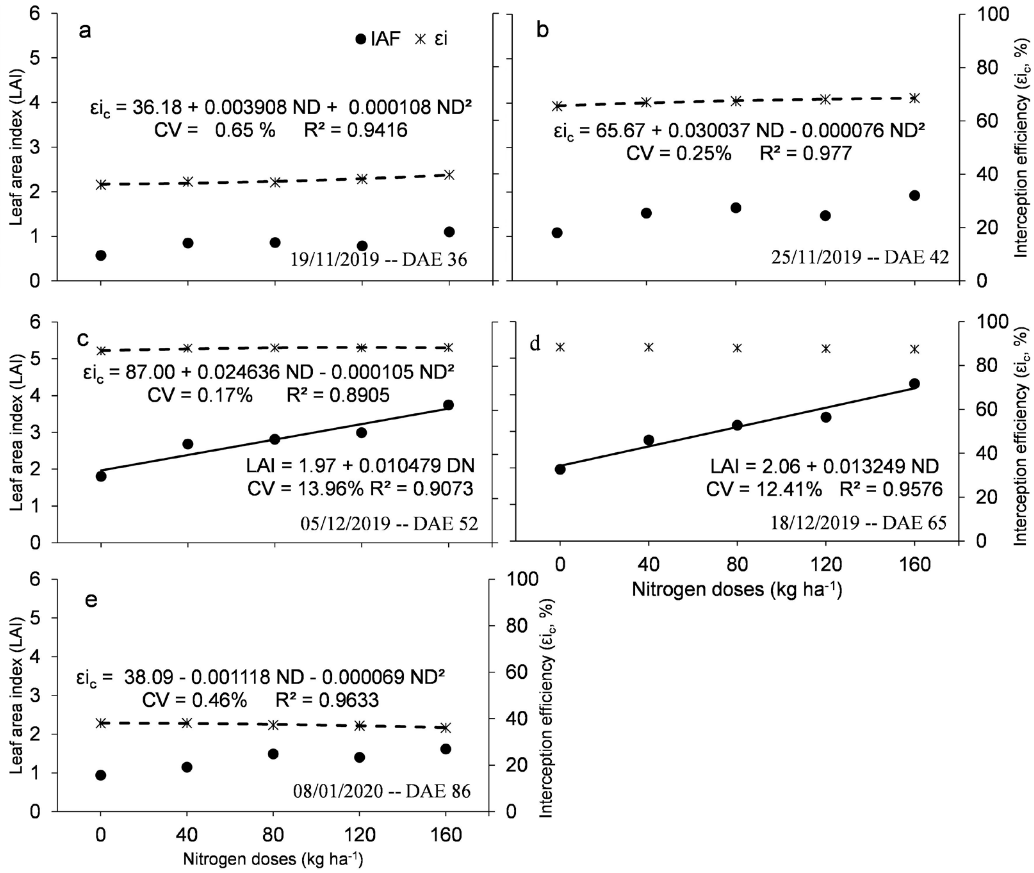

Figure 2: Leaf area index (LAI), canopy radiation interception efficiency (εi_c, %) by the Sunflower at 36 (a), 42 (b), 52 (c), 65 (d), and 86 (e) days after emergence (DAE) under cover nitrogen doses (ND) in the agricultural year 2019/2020 in Santa Maria, Rio Grande do Sul, Brazil.

inferred that the εi_c is a precision variable that should be used in sunflower experiments that imply changes in the LAI. Although the measure of the LAI is fundamental in growth analysis, the εi_c can be determined more often since this variable is faster and easier to be determined if sensors are available.

Nitrogen doses negatively influenced the interception of the PAR in the canopy extract less than 1 m high, only at 86 DAE (Figure 3). This indicates the possibility of a smaller leaf area in the lower extract of the sunflower canopy at the highest doses of N. This result was probably influenced both by environment water deficiency and by the greater intraspecific competition for the PAR at higher doses of N, given the greater number of leaves at higher doses and larger leaves (Figures 3b, 3c, and 3d). This can determine greater leaf senescence in the extract smaller than 1m, with greater availability of N to plants, especially near the end of flowering (Figure 1). There was no effect of the doses at the other evaluation date and the interception of PAR by the upper canopy extract.

The LAI modeling based on thermal requirements (GD) showed that the highest LAI was 4.37, at 819.2 GD, and the lowest of 2.08, at 818.4 GD, at the highest and lowest nitrogen dose, respectively (Figure 4). In an experiment on the growth, development, and retardation of leaf senescence in sunflower with nitrogen sources and doses in Santa Maria carried out by Fagundes *et al.* (2007), it was verified that the nitrogen dose positively affected the leaf area (LA), as observed in the LAI (Figure 2c and 2d) and number of leaves per plant (Figure 3b). According to these authors, nitrogen influences both cell division and leaf expansion. This affects the final size of the leaves, as verified in the area per leaf (Figures 3c and 3d) and, consequently, the LAI.

One of the possibilities of representing the interaction of the PAR with the canopy can be by the extinction coefficient (k) of the PAR. The k decreased as the dose of N increased (Figure 4), ranging from 0.5135 to 1.0645 at the doses of 160 and 0 kg ha^{-1} N , respectively. Although the N doses significantly affected the canopy εi_c (Figure 2), the LAI models

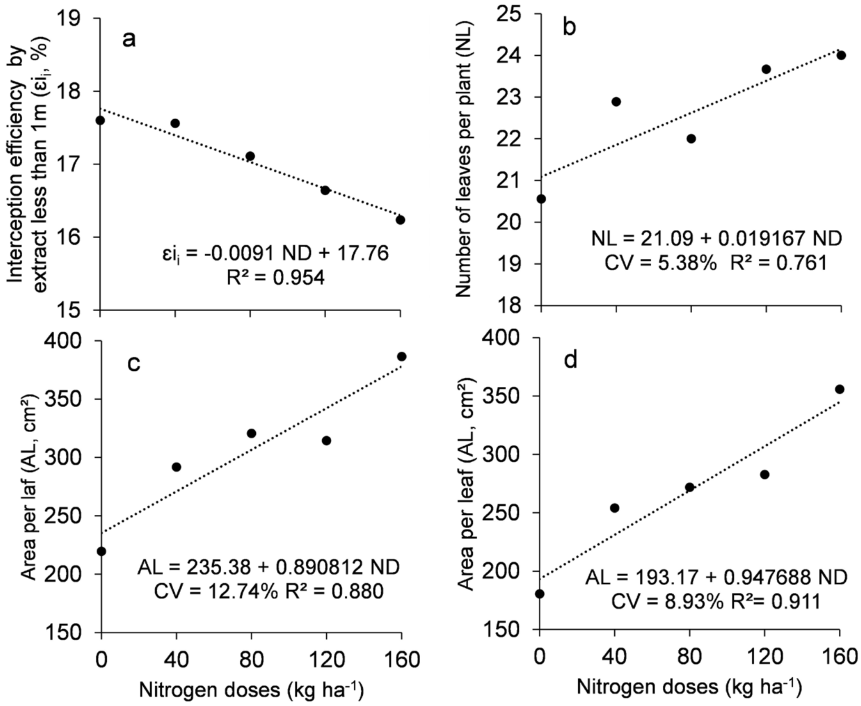

Figure 3: Efficiency of interception of photosynthetically active radiation by canopy extract less than 1 m high (εi_i) at 86 days after emergency (DAE) (a), number of leaves per plant (NL) at 52 DAE (b) and average area per leaf (AL) at 52 DAE (c) and 65 DAE (d) in sunflower as a function of nitrogen doses in the agricultural year 2019/2020 in Santa Maria, Rio Grande do Sul, Brazil.

showed a very significant increase in LAI with the increase in N dose, with maximum LAI at the dose of 160 kg ha^{-1} N exceeding by 116.3% the LAI value obtained with 0 kg ha^{-1} N . Given the high precision in the εi measurement.

According to Hernández (2010), the sunflower has its largest leaves in the middle and lower third of the plant, where even the leaf limbo presents an erectophilic form, mainly in the lower third of the plant. Additionally, the insertion of the leaves into the sunflower stem occurs in a spiral in the middle and upper third. Erectotile leaves and the spiral phyllotaxis insertion indicate that, although there was a higher LAI (116.3%) in relation to the lower dose of N, a very similar interception efficiency occurred, as seen in Figure 2d. Thus, the effect of overlapping leaves becomes small with the increase in LAI due to the dose of cover N, both by the largest number (Figure 3b) and by larger leaves (Figure 3c and Figure 3d), in a way that the growth and development modeling of the crop requires considering the variation in k as a function of the management of cover N fertilization.

Soleymani (2017) verified that, under irrigated conditions, k presented values of 0.648 and 0.707 with 8 and 14 plants per m^2, respectively. Notwithstanding the differences in plant densities, the k results of this work follow those observed in other works. The decrease in k with the increase in the dose of cover N may result, in part, according to Hernández (2010), from the variation of the insertion angles of the petioles and leaf limbo as a function of the position of the leaves in the plant since these present a positive linear dependence with the PAR incident fraction of the top of the plants. In canola, the change in k in the canopy with the N dose in top dressing was smaller (Dalmago *et al.*, 2018) than that observed in sunflower, probably due to differences in plant architecture between the two species.

The doses of N did not influence plant height (PH) and chapter diameter (CPD). PH presented an average value of 1.85 m, and the mean CPD was of 0.19 m. In the experiment conducted by Castro *et al.* (1999) using doses and methods of nitrogen application in sunflower, the highest value found for the variable PH was of 1.84 m, similar to the results found in this work. Biscaro *et al.* (2008) observed a significant effect on CPD, with a maximum value of 11.9 cm at the dose of 44.9 kg ha^{-1} of cover nitrogen fertilizing in sunflowers under irrigation, using cultivar Helio 358 with a density 56% higher than in the present study.

The stem diameter (SD) was linear positive influenced by nitrogen doses (Figure 5). This variable is essential for the plant as it is related to the resistance to lodging

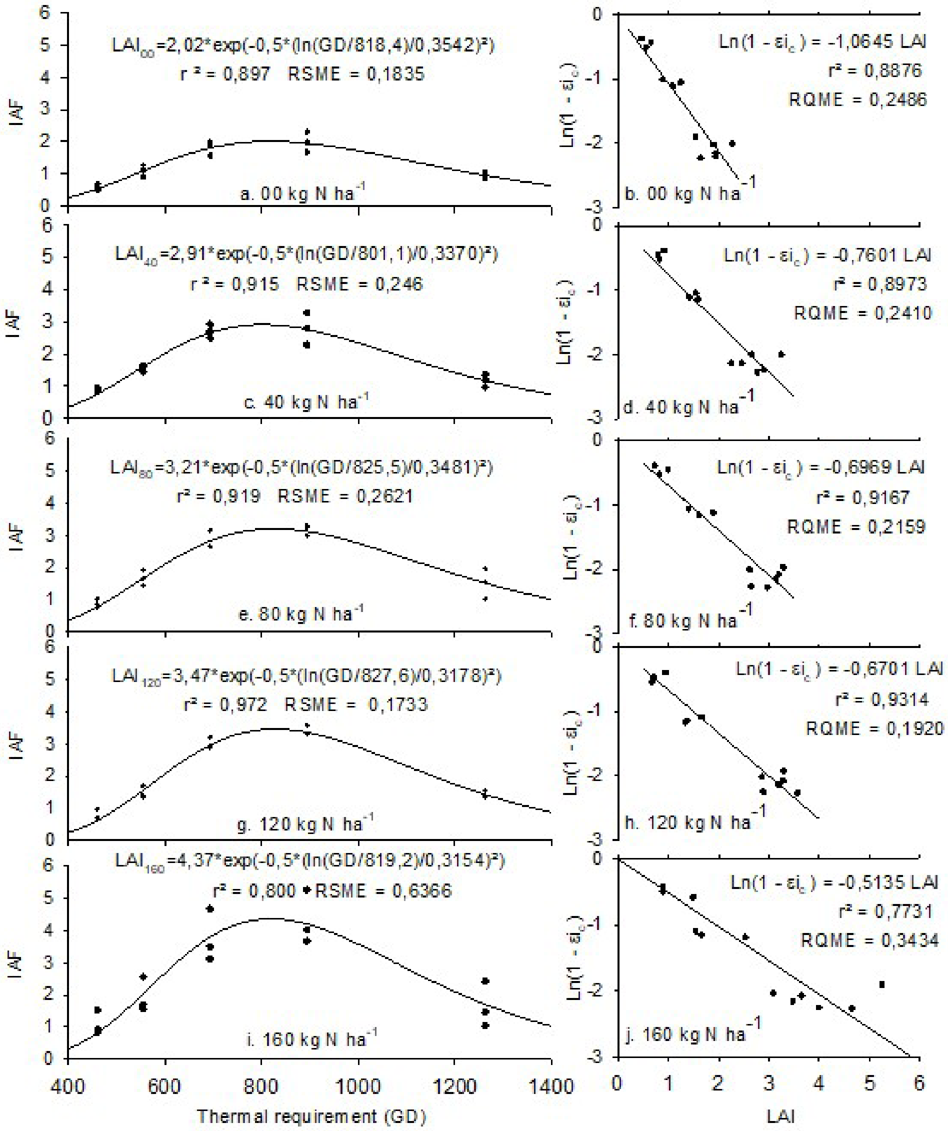

Figure 4: Estimate of sunflower leaf area index (a, c, e, g, i) based on the thermal requirement (GD, °C day) and of the extinction coefficient (k) of the PAR (b, d, f, h, j) in the cover nitrogen doses of 0 (a, b), 40 (c, d), 80 (e, f), 120 (g, h), and 160 kg ha^{-1} (i, j) in the agricultural year 2019/2020 in Santa Maria, Rio Grande do Sul, Brazil.

(Castro *et al.*, 1999). Analyzing the angular coefficient of the linear equation, it can be inferred that the SD increases by 0.045 mm for each kg ha^{-1} of nitrogen applied (Figure 5), which may decrease the risk of lodging.

According to Castro *et al.* (1999), a maximum SD value of 26.8 mm was found in the experiment of doses and nitrogen application methods in sunflower. Valeriano *et al.* (2020) worked with nitrogen doses for the crop of irrigated sunflower in a soil classified as dystrophic Red Latosol, at an altitude of 800 m, and verified a trend of linear increase of stem diameter with nitrogen doses. The doses of N did not influence the mass of one thousand achenes (MTA), with an average value of 61.80 g. Biscaro *et al.* (2008) found a maximum value of MTA of 71.9 g. Valeriano *et al.* (2020) also found no significant effect of nitrogen doses on the mass of achenes.

The nitrogen doses positively influenced productivity (PROD), ranging between 3.543 kg ha^{-1} in the witness and 4.789 kg ha^{-1} at a dose of 160 kg ha^{-1}, occurring a linear trend (Figure 5b). These results disagree, in part, with those found by Valeriano *et al.* (2020), who obtained productivity of 7004 kg ha^{-1} at the maximum dose of 120 kg ha^{-1}. This difference in productivity at maximum doses can be justified by the fact that the year of the experiment of this

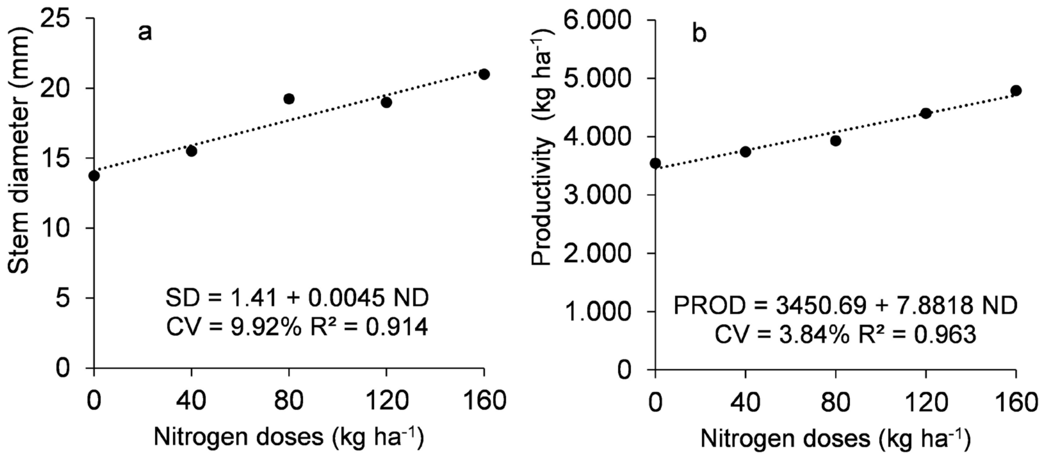

Figure 5: Stem diameter (a) and productivity of achenes (b) as a function of cover nitrogen doses applied in the agricultural year 2019/2020 in Santa Maria, Rio Grande do Sul, Brazil.

work presented a water deficiency at critical moments for the development of sunflower crops, as is the case of the anthesis period (Figure 1a).

Lobo *et al.* (2011) indicate that the maximum sunflower production can be achieved with nitrogen doses between 80 and 90 kg ha^{-1}. However, it is possible to obtain an approximate production of 90% in relation to maximum productivity with an application of N ranging between 40 and 50 kg ha^{-1}, with soil organic matter content of 0.8%. Valeriano *et al.* (2020) also observed a linear increase in productivity in relation to the increase in nitrogen doses. Still, the productivity values were higher than in this study, reaching 7004.03 kg ha^{-1} at the highest dose of 120 kg ha^{-1} of N. However, the results of this study are similar to that of Zarzicki *et al.* (2019) and Loose *et al.* (2019), with a maximum values of 5,542 and 5,192 kg ha^{-1}, respectively.

The application of cover N allowed a better availability of the nutrient to the plants, given the positive linear effect of productivity. However, the lower productivity found in this study compared to those in the literature can be explained by the environmental rain reduction, determinant for water deficiency throughout the experimental period, especially between the beginning and end of the flowering period (Figure 1a). Nonetheless, the productivity results of this work were high, ranged from 3,543 kg ha^{-1} in the witness to 4,789 kg ha^{-1} at the maximum dose, compared with the mean Brazilian productivity in the 2020/2021 harvest of 1,143 kg ha^{-1} (Conab, 2021).

According to Lobo *et al.* (2011), who experimented on the effect of nitrogen on sunflower nutrition, one should consider the N losses that occur in the production system both by nitrate leaching and by ammonia volatilization and denitrification. Thus, it cannot be guaranteed that all the N supplied was absorbed by the sunflower crop, especially due to the limitation in water availability that occurred (Figure 1). Above all, based on the results, it was verified that the dose of nitrogen in coverage can be higher than 100 kg ha^{-1}, even under conditions of limited water availability in a subtropical environment.

CONCLUSION

Therefore, for growth and production doses of cover N positively influence stem diameter and grain productivity. The application of cover nitrogen fertilizer linearly and positively affects the sunflower crop, and 160 kg ha^{-1} N.

Interception efficiency of photosynthetically active radiation by the canopy and the leaf area index are positively influenced by the doses of nitrogen in the canopy.

The extinction coefficient of the photosynthetically active radiation in sunflower decreases with the increasing dose of cover N.

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The authors declare no conflicts of interest.

REFERENCES

Allen RG, Pereira LS, Raes D & Smith M (1998) Crop evapotranspiration - Guidelines for computing crop water requirements. Available at: <http://www.fao.org/tempref/SD/Reserved/Agromet/PET/FAO_Irrigation_Drainage_Paper_56.pdf>. Accessed on: August 18th, 2020.

Alvares CA, Stape JL, Sentelhas PC, Gonçalves JL de M & Sparovek G (2013) Köppen's climate classification map for Brazil. Meteorologische Zeitschrift, 22:711-728.

Aquino LA, dos Santos Júnior V, Guerra JVS & Costa MM (2011) Estimativa da área foliar do girassol por método não destrutivo. Bragantia, 70:832-836.

Barni NA, Berlato MA, Bergamaschi H & Riboldi J (1995) Rendimento máximo do girassol com base na radiação solar e temperatura: ii. Produção de fitomassa e rendimento de grãos. Pesquisa Agropecuária Gaúcha, 1:201-216.

Casaroli D, Fagan EB, Simon J, Medeiros SP, Manfron PA, Neto DD, van Lier Q de J, Müller L & Martin TN (2007) Radiação solar e aspectos fisiológicos na cultura de soja. Revista da Faculdade de Zootecnia, Veterinária e Agronomia, 14:102-120.

Castilioni VBR, Balla A, de Castro C & Silveira JM (1997) Fases de Desenvolvimento da Planta de Girassol. Londrina, Embrapa. 26p.

Castro CD, Balla A, Castiglioni VBR & Sfredo GJ (1999) Doses e métodos de aplicação de nitrogênio em girassol. Scientia Agricola, 56:827-833.

Conab - Compania Nacional de Abastecimento (2021) Acompanhamento da safra brasileira de grãos. Available at: <https://www.conab.gov.br/component/k2/item/download/39391_157eb9a1b890a11918593c8f-c32ac419>. Accessed on: December 18th, 2021.

Dalmago GA, Pinto DG, Fontana DC, de Gouvea JA, Bergamaschi H, Fochesatto E & Santi A (2018) Use of solar radiation in the improvement of spring canola (*Brassica napus* L., Brassicaceae) yield influenced by nitrogen topdressing fertilization. Agrometeoros, 26:223-237.

De Castro JR, Cuadra SV, Pinto LB, de Souza JMH, dos Santos MP & Heinemann AB (2018) Parametrization of models and use of estimated global solar radiation data in the irrigated rice yield simulation. Revista Brasileira de Meteorologia, 33:238-246.

Elli EF, Caron BO, Medeiros SLP, Eloy E, Monteiro GC & Schmidt D (2015) Effects of growth reducer and nitrogen fertilization on morphological variables, SPAD index, interception of radiation and productivity of wheat. Revista Ceres, 62:577-582.

Embrapa – Empresa Brasileira de Pesquisa Agropecuária (1997) A Cultura do Girassol. Londrina, Centro Nacional de Pesquisa de Soja. 35p. (Circular, 13).

Fagundes JD, Santiago G, de Mello AM, Bellé RA & Streck NA (2007) Crescimento, desenvolvimento e retardamento da senescência foliar em girassol de vaso. Ciência Rural, 7:987-993.

Ferreira DF (2019) SISVAR: A computer analysis system to fixed effects split plot type designs. Revista Brasileira de Biometria, 37:529-535.

França S, Mielniczuk J, Rosa LMG, Bergamaschi H & Bergonci JI (2011) Nitrogênio disponível ao milho: crescimento, absorção e rendimento de grãos. Revista Brasileira de Engenharia Agrícola e Ambiental, 15:1143-1151.

Gazzola A, Ferreira Junior CTG, Cunha DA, Bortolini E, Paiao GD, Primiano IV, Pestana J, D'Andréa MSC & Oliveira MS (2012) A Cultura do Girassol. Piracicaba, Escola Superior de Agricultura Luiz de Queiroz. 69p.

Hernández LF (2010) Leaf angle and light interception in sunflower (Helianthus annuus L.). Role of the petiole's mechanical and anatomical properties. International Journal of Experimental Botany, 79:109-115.

Lobo TF, Filho HG & Brito ICA (2011) Efeito do nitrogênio na nutrição do girassol. Bioscience Journal, 27:380-391.

Loose LH, Heldwein AB, da Silva JR & Bortoluzzi MP (2019) Yield and quality of sunflower oil in Ultisol and Oxisol under water regimes. Revista Brasileira de Engenharia Agrícola e Ambiental, 23:532-537.

Oliveira CR, de Oliveira HL, Barbosa FR, Dario AS, Moura SG & Barros HB (2014) Efeito do nitrogênio em cobertura na produtividade de girassol, no Estado do Tocantins. Científica, 42:233-241.

Pelegrini B (1985) Girassol: uma planta solar que das Américas conquistou o mundo. São Paulo, Ícone. 117p.

Sadras VO & Hall AJ (1988) Quantification of temperature, photoperiod and population effects on plant leaf area in sunflower crops. Field Crops Research, 18:185-196.

Santos HG, Jacomine PKT, dos Anjos LHC, de Oliveira VA , Lumbreras JF, Coelho MR, Almeida JA, de Araújo Filho JC, de Oliveira JB & Cunha TJF (2018) Sistema Brasileiro de Classificação de Solos. 5ª ed. Available at: <https://www.infoteca.cnptia.embrapa.br/infoteca/bitstream/doc/1094003/2/SiBCS2018ISBN9788570358004.pdf>. Accessed on: August 18th, 2020.

Schwerz F, Caron BO, Elli EF, de Oliveira DM, Monteiro GC & de Souza VQ (2016) Avaliação do efeito de doses e fontes de nitrogênio sobre variáveis morfológicas, interceptação de radiação e produtividade do girassol. Revista Ceres, 63:380-386.

Soleymani A (2017) Light response of sunflower and canola as affected by plant density, plant genotype and N fertilization. Journal of Photochemistry & Photobiology, B: Biology, 173:580-588.

Ungaro MRG, Castro C, Farias JRB, Barni N, Ramos NP & Sentelhas PC (2009) Girassol. In: Monteiro JEBA (Ed.) Agrometeorologia dos Cultivos – o fator meteorológico na produção agrícola. Brasília, INMET. p.203-221.

Valeriano TTB, Viana AEC, Neto AP, de Santana MJ & Oliveira AF (2020) Doses de nitrogênio para a cultura do girassol irrigado. Revista Inova Ciência & Tecnologia, 6:05-11.

Zarzicki SA, Mantai RD, Locateli E & Weirich F (2019) Uso da modelagem matemática à produtividade de girassol pelo nitrogênio. UNILUS Ensino e Pesquisa, 16:90-110.