Australian Journal of
Crop Science
AJCS

AJCS 12(10):1609-1615 (2018)
ISSN:1835-2707
doi: 10.21475/ajcs.18.12.10.p1187

Changes in the spatial distribution of maize plants affect solar radiation use efficiency

Jaqueline Sgarbossa[1*], Diecson Ruy Orsolin da Silva[1], Elvis Felipe Elli[2], Felipe Schwerz[3], Braulio Otomar Caron[1], Denise Schmidt[1] Elder Eloy[4] and Sandro Luiz Petter Medeiros[5]

[1]Federal University of Santa Maria, Frederico Westphalen Campus, Departamento of Agronomic and Environmental Sciences, Frederico Westphalen, RS, Brazil
[2]University of São Paulo, College of Agriculture, Department of Biosystems Enginnering, Piracicaba, SP, Brazil
[3]University of São Paulo, College of Agriculture, Department of Plant Science, Piracicaba, SP, Brazil
[4]Federal University of Santa Maria, Frederico Westphalen Campus, Department of Forest Engineering, Frederico Westphaen, RS, Brazil
[5]Federal University of Santa Maria, Department of Plant Science, Santa Maria, RS, Brazil

***Correponding author: sgarbossajs@yahoo.com**

Abstract

Spatial arrangement of plants is undoubtedly considered to be the key in determining high production levels of the maize crop. This study was conducted to evaluate the benefits of variations in the spatial distribution of maize plants. The spatial distribution has its effect on the leaf area index (LAI) and efficiency in the use of solar radiation. All these factors affect the yield of maize. The experiment was conducted in Frederico Westphalen - RS, in 2015/2016 agricultural year. The experimental design comprised of a randomized but homogenized block in a factorial 4 × 3 × 7, namely, four variations of plants in one sowing line (0, 20, 40 and 60%); three plants with different spacings (pre-determined), and seven plant collections during the crop cycle with four replications. The increase in the variation in the distribution of plants resulted in greater LAI values and more efficient use of solar radiation. However, it did not show any effect on the crop productivity levels. Varation of spatial distribution increased the efficient utilization of solar radiation in different ways between plants in the sowing line. This happened due to increase in LAI values and the capture of solar radiation. Under favorable weather conditions, some possible failures in plant distribution in the sowing line do not interfere with the crop yield. This research recommends the acceptable levels of variation that do not compromise crop yield.

Keywords: leaf area index; plant arrangement; solar radiation; spatial variation; *Zea mays* L.

Abbreviation: a_number of disks made in the samplig; b_the area of the nozzle used to make the disks; Conab_Companhia Nacional de Abastecimento in Brazil; DMD_dry mass of the disks; DML_total dry mass of leaves; iPAR_intercepted photosyntetically active radiation; k_extinction coefficient; LA_leaf area; SA_soil area; LAI_leaf are index; PARa_photosynthetically active radiation absorved; PARi_photosynthetically active radiation; PARinc_incident photosyntetically active radiation; TDM_total dry matter production; Ɛb_efficiency of the use of solar radiation.

Introduction

Maize (*Zea mays* L.) is a very important agricultural plant. In Brazil, the production of 88 million Mg of grain is estimated as the 2017/2018 harvest (Conab, 2018). The introduction of new production technologies as well as improved cultivation management, aiming at the best use of environmental conditions, have resulted in a significant increase in the total cultivated area and production of the maize crop.

Among the several various management practices available, spatial arrangement of plants is considered fundamental in determining its yield (Stacciarini et al., 2010; Farinelli et al., 2012; Demétrio et al., 2008; Lana et al., 2009). Modifications in the spacing between sowing lines, combined with possible failures in the yield can affect water and nutrients utilization of crops (Lana et al., 2009). Furthermore, leaf area index (LAI) and the utilization of solar radiation; thus, affect the efficient use of solar radiation.

Solar radiation affects the plant's ability to accumulate biomass and; therefore, plays an important role in growth and plant development in agricultural systems (Kunz et al., 2007; Caron et al., 2014). In this sense, the plant's production of biomass depends on the quantum of photosynthetically active radiation that is absorbed by the leaves, combined with the efficiency, by which plants can convert this solar radiation into photoassimilates through photosynthesis. Thus, the intercepted photosynthetically active radiation (PARi) plays a role in conversion to biomass. It reveals the solar radiation (Ɛb) efficiency of the species (Monteith, 1977; Van Heerden et al., 2010).

One of the factors that influences Ɛb is the LAI, a characteristic that can be modified by resorting to spatial arrangement of plants. Therefore, studies should be conducted with the aim of determining the ideal arrangement of plants that promotes the maximum absorption of incident solar radiation per unit area and time. The search for methods that enables increase in the production of a particular plant is defined by the maximization of PARi capture by the vegetative canopy (Marchão et al., 2006). This is being associated with plant arrangement factors, which promote changes in leaf LAI and distribution, and consequently, the efficiency of the utilization of solar radiation.

Several studies have been conducted to evaluate the efficiency of biostimulants in conditions involving irregular distribution of plants (Kolling et al., 2016), the yield of grain (Lauer and Rankin, 2004; Liu et al., 2004; Sangoi et al., 2011; Sangoi et al., 2012), and the efficiency of agricultural equipment in seed distribution (Júnior et al., 1999; Silveira et al., 2005; Schimandeiro et al., 2006; Mello et al., 2007; Dias et al., 2009; Stork et al., 2015). However, no study has been conducted for the purpose of identifying the effect of irregular distribution of plants on growth and efficiency involving the utilization of solar radiation by maize. Given the importance of maize for farmers and the lack of information on the theme, we aimed to evaluate the spatial distribution of plants, affecting LAI, efficient utilization of solar radiation and the yield of maize.

Results and Discussion

Meteorological conditions

The air temperature that prevailed during the cycle of the maize crop ranged from 9.4°C to 35.2°C with an overall mean of 22.5°C (Fig. 1). The average ambient temperature was within the ideal range for growing a healthy crop of maize (18–25°C) (Maldaner et al., 2014). The accumulated rainfall during the experimental period was 1,818 mm and; therefore, was not a limiting factor for the development of the crop. The water requirement for the complete cycle of maize is 387 mm (Souza et al., 2015).

Leaf area index and efficient utilization of radiation

Among the tested spatial distributions, it was found that plant #1 with 60% spatial variation presented the highest LAI values (maximum, 12.8) during the vegetative period of the crop (Fig. 2). It is likely because of the relatively small soil area occupied by this plant. Plants #2 and #3 with 60% variation had similar LAIs, as did the plants of the 0, 20 and 40% variation, which presented maximum LAI values of 7.8 (plant #2), 10.0 (plant #2), and 10.2 (plant #1), respectively. The highest values coincided with the end of vegetative development and the beginning of the reproductive stage.

We detected changes in the leaf architecture of those plants with smaller soil exploration areas. Spatial reduction can induce changes in leaf angle as part of morphological adaptations aimed at increasing the absorption of solar radiation (Lacerda et al., 2010). Takasu et al. (2014) and Lana et al. (2009) pointed out that under conditions of cultivation, where there is a high number of plants per unit of soil, such as the irregular distribution of plants in the sowing line, maize responds to rearrange its leaf architecture, presenting a scenario of better nutrients present in the soil. In addition, the existing competition in cultivation results in development of mechanisms that can adapt to the environmental conditions. In this case, the rearrangement of plants occurs to more efficiently intercept and absorb the solar radiation which becomes one of the main factors of competition when there is an irregular distribution of individual plants in the sowing line.

The plants occupying the smallest soil areas had the highest increase in phytomass per unit area as a function of the intercepted PARi (Fig. 3). Plants with smaller soil areas and higher LAIs showed the increased self-shading, as well as being influenced by higher shading rates of neighboring plants, all of which were contributing to a lower availability of radiation incident on the leaves of the lower strata. However, the existing rates of diffuse radiation are potentiated, leading to better penetration in the vegetative canopy (Buriol et al., 1995) and greater efficiency in the utilization of solar radiation (Ɛb).

When comparing the efficiency that solar radiation had on all sample units, the highest values were found for plant #1 with 60% variation (6 g MJ^{-2}), which coincided with the smallest soil area (Figs. 3 and 4). This result can also be explained by the higher LAI obtained by this plant (Fig. 2).

The lower incidence of solar radiation during the months with higher rainfall and more cloudy days (especially in December), was a determining factor of LAI (Fig. 1). For periods of high cloudiness, there was less direct solar radiation but more diffuse, multidirectional radiation (Drechmer and Ricieri, 2006). This highlights the importance that plant arrangement has on the system since it defines the existing interactions between plants and the capture and utilization of solar radiation, which is a fundamental factor for the growth and development of the crop (Caron et al., 2012).

However, it should be noted that higher phytomass values per square meter, and greater efficiency in the use of solar radiation are directly related to the smaller area of soil explored by the plant and not because of the plant itself. Nevertheless, care should be taken when altering the spatial distribution of plants because under conditions of water restriction, thermal stress, and nutritional deficiency, crop yield can be affected. The higher efficiency in the use of radiation does not always lead to higher yield.

Grain yield

In this study, no significant differences were observed for crop yield (Fig. 5), with mean values of 8988, 8577, 9044 and 8859 kg ha^{-1} for variations of 0, 20, 40 and 60%, respectively. Similar results were obtained by Liu et al. (2004) and Lauer and Rankin (2004), who reported that maize yield was not affected by irregular distribution. However, Sangoi et al. (2012) and Kolling et al. (2016) did detect significant differences in maize yield when comparing different plant distributions. These different findings in the literature can be attributed to meteorological variations between agricultural years, especially in conditions of irregularly distributed rainfall during the crop cycle (Sangoi et al., 2011), or water deficit conditions (Nascimento et al., 2015).

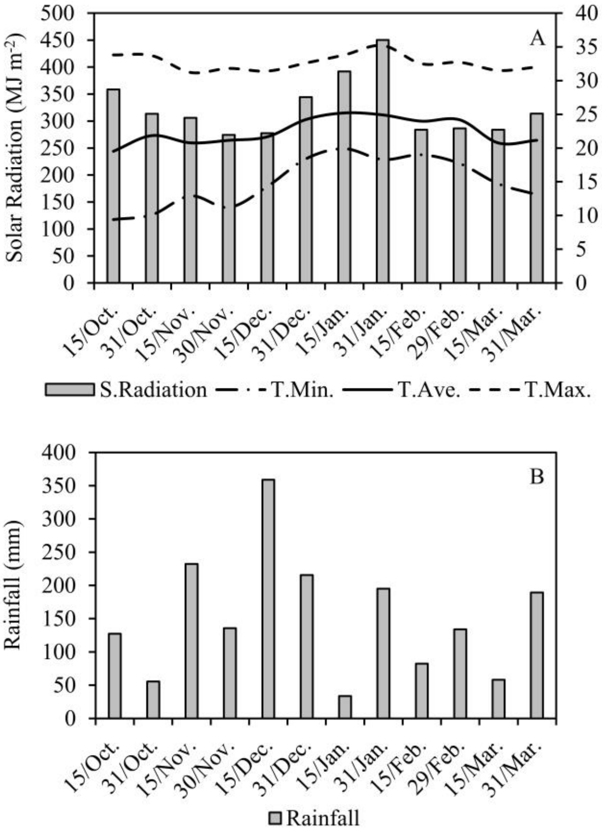

Fig 1. Average biweekly values for minimum, maximum and average temperature (T. Min, T. Ave and T. Max), accumulated incident solar radiation (S. Radiation) – A; accumulated rainfall (B) during the experimental period.

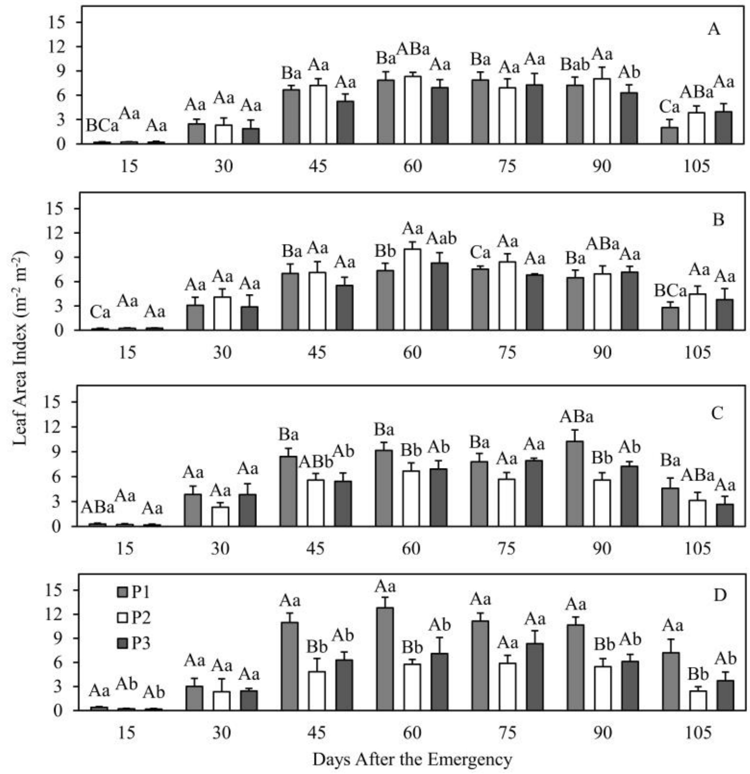

Fig 2. Leaf area index (LAI) of maize subjected to four spatial variation distribution in the sowing line for several days after the emergence of the crop. Variation of 0% (A); 20% (B), 40% (C) and 60% (D), where P1 refers to plant # 1, P2 refers to plant # 2 and P3 refers to plant # 3. * Means followed by the same letter do not differ among themselves. Uppercase letter compare plants between spatial, lowercase variations compare the plants in the sowing line within a same spatial variation.

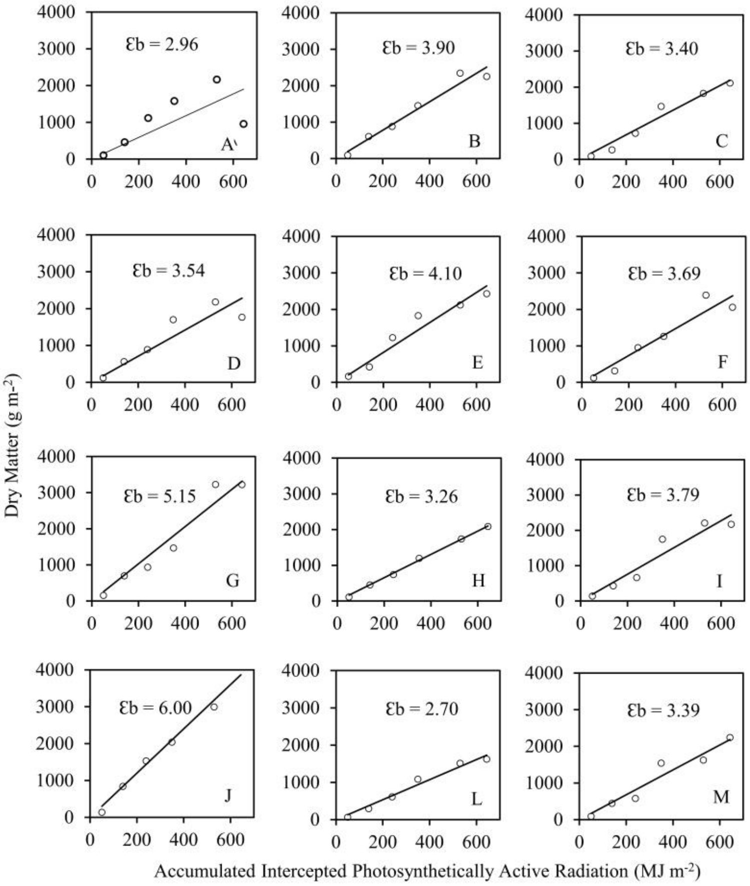

Fig 3. Efficiency of the use of radiation (g MJ^{-1}) of maize plants submitted to four spatial variations in plant distribution: variation 0%, plant # 1 (A), plant # 2 (B) and plant # 3 (C); 20%, plant # 1 (D), plant # 2 (E) and plant # 3 (F); 40%, plant # 1 (G), plant # 2 (H) and plant # 3 (I); 60%, plant # 1 (J), plant # 2 (L) and plant # 3 (M).

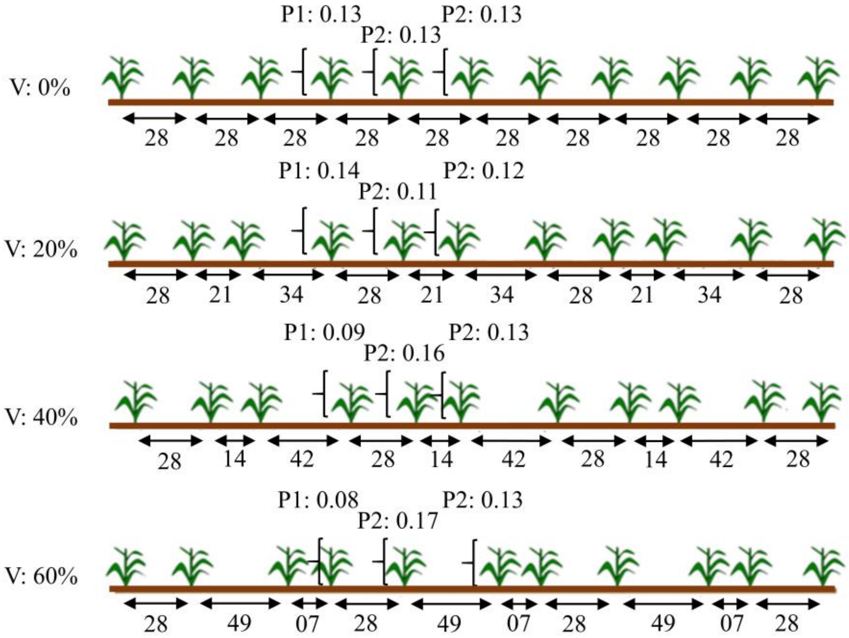

Fig 4. A sketch of spatial distribution of plants in the experimental unit, where P1 refers to plant # 1, P2 refers to plant # 2 and P3 refers to plant # 3. The number that follows the description described above, is referred to the soil area explored by each plant (m^2). The variation between plant distribution is represented by the letter V and their respective values. Each plant is described sequentially to its distribution in the sowing line (cm).

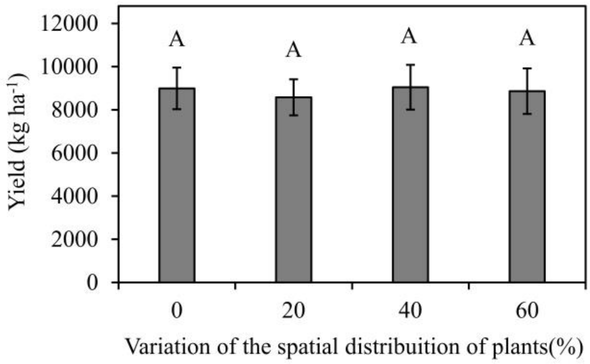

Fig 5. Yield of maize subjected to four different spatial variations in the distribution of plants in the sowing line.

The absence of significant differences in yield of all treatments might be due to existance of one dominant plant, but there was also another one that dominated to meet this pre-established variation associated with the occurrence of favorable air temperature and rainfall during the experimental period. This could have contributed to the values of yield obtained in this study.

Materials and Methods

Study area and experimental design

A field experiment was conducted from October 2015 to March 2016 in the city of Frederico Westphalen, Rio Grande do Sul, Southern Brazil, at coordinates of 27°2'S, 53°25'W, and at an altitude of 461 m. According to Köppen's climate classification (Alvares et al., 2013), the climate is Cfa (i.e., humid subtropical, with a mean annual temperature of 19.1°C, and varying maximum and minimum temperatures of 38°C and 0°C, respectively). The meteorological data were obtained from the automatic meteorological station linked to the National Institute of Meteorology, located at a distance of 400 m from the experimental area.

The experimental layout was composed of randomized complete blocks with four replications. The factorial arrangement was 4 × 3 × 7, including four variations in the spatial distribution of plants in the sowing line (0, 20, 40 and 60%), three plants with different spacings, and seven growth evaluations during the crop cycle. The tested spatial distributions of plants are shown in Fig. 4. At 0% variation, all plants were spaced at 0.28 m in the sowing line. At 20% variation, the spacing sequence of the three plants was 0.28, 0.21 and 0.34 m in the sowing line. At 40% variation, the spacing sequence of the three plants was 0.28, 0.42 and 0.14 m in the sowing line. At 60% variation, the spacing sequence of the three plants was 0.28, 0.49 and 0.07 m in the sowing line. In all variations, plant # 1 was used as the name for the first plant in the sowing line, plant # 2 for the second plant in the sowing line, and plant # 3 for the third plant in the sowing line.

Soil characteristics and cultural management

The soil in the experimental area was typical dystrophic Red Latosol. The physical and chemical characteristics of the soil were as follows: pH in water of 5.1, clay 740 g Kg^{-1}, organic matter 32 g Kg^{-1}, P (Mehlich^{-1}) 9.3 mg dm^{-3}, K^+ 268.0 mg dm^{-3}, Al^{3+} 0.4 cmolc dm^{-3}, potential acidity 5.6 cmolc dm^{-3}, Ca^{2+} 6.0 cmolc dm^{-3}, Mg^{2+} 2.8 cmolc dm^{-3}, cation exchange capacity 11.3 cmolc dm^{-3}, and base saturation 50.6%.

The weed management was carried out by sequential application of glyphosate and 2,4-D (1440 g and ha^{-1}) at 25 days before sowing, and paraquat (400 g e.a. ha^{-1}) at 15 days before sowing. Sowing was manually carried out on 20th October (2015) with line spacing of 0.45 m. The maize hybrid used was DKB 230 VT PRO 3, with a population of 79,012 plants ha^{-1}. After sowing, the equivalent of 40 kg of N ha^{-1}, 112 kg of P_2O_5, and 150 kg of K_2O ha^{-1} were distributed as a base fertilizer. After sowing, 150 kg of N ha^{-1} was applied in two equally divided plots at stages V3 and V6.

Plant growth evaluations

The determination of mass dry matter of the different vegetative and reproductive structures of plant was carried out biweekly, from the beginning of the vegetative growth until the physiological maturation, totaly seven collections. The plants collected in the field were taken to the laboratory and separated into leaves, stem, inflorescence, senescent leaves, ears and leaf discs. These plant parts were then used to determine the active leaf area (LA) of each sample. The leaves were considered senescent when they had more than 50% dead or compromised LAs. After separation of samples, they were packed in paper bags and kept in a forced air circulation oven at a controlled temperature of 60°C until reaching a constant mass. The LA was determined by the disk method, in m^2 and calculated by the equation: $LA = (a*b*(DML+DMD)/DMD)$, where a is the number of disks made in the sampling; b is the area in m^2 of the nozzle used to make the disks; DML is the total dry mass of leaves in grams; and DMD is the dry mass of the disks, also in grams. The LAI was determined from the total LA and the soil area explored by each plant, according to the following equation: LAI=LA/AS, where LA is the leaf area (m^{-2}), and SA is the soil area (m^{-2}) occupied by the plant.

Radiation use efficiency

The efficient utilization of solar radiation was determined by correlating the average production of accumulated dry matter and the intercepted PARi, as described by Monteith (1977): TDM= Ɛb * iPAR, where TDM = total dry matter produced (gm^{-2}); and iPAR = intercepted PARi (MJ m^{-2}). The value for the efficient use of radiation is given by the angular coefficient that represents the amount of accumulated biomass for each unit of intercepted radiation.

The photosynthetically active incident radiation was estimated taking into account 45% of global solar radiation (Assis and Mendez, 1989), with no difference between days of intense light and cloudy days. The estimate of the intercepted PARi was determined using the model described by Varlet-Grancher et al. (1989): $iPAR= 0.95 * (PARinc) * (1-e^{(-k * LAI)})$, where iPAR = intercepted PARi (MJ m^{-2}); PARinc = incident PARi (MJ $m^{-2)}$; k = the extinction coefficient, which, according to Bergamaschi et al. (2010), is 0.42 for maize; and LAI = leaf area index.

Grain yield and statistical analysis

The harvest took place on 2nd March 2016, when the experimental units reached physiological maturity. Three 4-m-long lines were collected, totaling a sample area of 5.40 m^2. Subsequently, the necessary corrections were made to stabilize grain moisture at 13%. Statistical analyses were done using SAS Learning Edition 8.0 (2003). Data were analyzed by Tukey’s test ($P \leq 0.05$) and linear regression analysis.

Conclusion

Varying spatial distribution between plants increased the efficient use of solar radiation in a differentiated way between plants in the sowing line. This is due to the increase in the values of LAI, and the interception of solar radiation. Under favorable weather conditions, incidental failures in the distribution of plants in the sowing line do not interfere with maize yield. It is important that new research is conducted, preferrably on a regular basis, to study the impact that uneven distribution of plants has in the sowing line. This should cover growth and development and the yield of agricultural crops in different meteorological scenarios. This study will gude us into the ideal recommendations of acceptable levels of variation that do not compromise crop yield.

Acknowledgements

The authors wish to acknowledge the National Council for Scientific Technological Development (CNPq-Brazil) and the Coordination for the Improvement of Higher Education Personnel (Capes-Brazil) for their financial support.

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