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GROWTH ANALYSIS OF MAIZE UNDER WATERLOGGING CONDITIONS

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ABSTRACT - The objective of this work was to evaluate the influence of flooding on the growth of maize plants through growth analysis through simple logistics. The work was conducted in the 2016/2017 growing season. The climate is temperate, with well distributed rainfall, hot summer andthe soil is classified as solodiceutrophic haplic planosol. The experimental design was completely randomized blocks arranged in a factorial scheme, with two soil water conditions x five plant samples, arranged in four replicates. It was carried out the flooding of the parcels. The variables measured were total dry mass; dry matter production rates; relative growth rate; net assimilation rate; leaf area ratio; leaf mass ratio; maximum values of specific leaf area; leaf area index; efficiency of solar energy on version and mass partition, carried out in five collections. There is a reduction in leaf mass ratio, dry mass production rate, and relative growth rate in plants submitted to flooding, compared to those kept at field capacity. Corn plants submitted to soil flooding presented negative changes in the assimilated partition throughout their development. Soil flooding over the period of 72 h adversely affects the physiological parameters of maize plants, leading to a reduction of their productive efficiency.
Key-words: *Zea mays* L., cultivation conditions, hydraulic excess, plants physioly, seed production.

ANÁLISE DE CRESCIMENTO DE MILHO EM CONDIÇÕES DE ALAGAMENTO

RESUMO - O objetivo deste trabalho foi avaliar a influência do alagamento no crescimento de plantas de milho por meio de análise de crescimento por meio de logística simples. O trabalho foi realizado na safra 2016/2017. O clima é temperado, com chuvas bem distribuídas, verão quente e o solo é classificado como planosolo háplico solodiceutrófico. O delineamento experimental foi de blocos inteiramente casualizados dispostos em esquema fatorial, com duas condições de água do solo x cinco amostras de plantas, dispostas em quatro repetições. Foi realizado o alagamento das parcelas. As variáveis medidas foram massa seca total; taxas de produção de matéria seca; taxa de crescimento relativo; taxa de assimilação líquida; razão de área foliar; razão de massa foliar; valores máximos de área foliar específica; índice de área foliar; eficiência da energia solar na versão e partição de massa, realizada em cinco coletas. Há redução na razão de massa foliar, na taxa de produção de massa seca e na taxa de crescimento relativo nas plantas submetidas ao alagamento, em relação àquelas mantidas em capacidade de campo. Plantas de milho submetidas ao alagamento do solo apresentaram alterações negativas na partição assimilada ao longo de seu desenvolvimento. O alagamento do solo no período de 72 h afeta negativamente os parâmetros fisiológicos das plantas de milho, levando à redução de sua eficiência produtiva.
Palavras-chave: *Zea mays* L., condições cultivo, excesso hidráulico, fisiologia de plantas, produção de sementes.

INTRODUCTION

Maize (*Zea mays* L.), which belongs to the Poaceae family, is one of the main cereals grown worldwide. In Brazil, about 17.4 million hectares are grown with production of 100.0 million tons, reaching average yield of 5719 kg ha^{-1} (CONAB, 2021). There are several factors involved in maize productivity, such as genetics, growing environments, genotypes x environments interaction, fertility, soil physicochemical conditions, rainfall, nitrogen management, physiological quality of seeds, among others decisive for yielding potential (CARVALHO et al., 2017; SZARESKI et al., 2018).

In Brazil, there are approximately 33 million hectares of soils prone to flooding. In Rio Grande do Sul, about 5.4 million hectares are lowland soils, and these areas could be incorporated into the productive process through the utilization of waterlogging tolerant cultivars (FERREIRA et al., 2008). Soil flooding is considered one of the main stresses in many ecosystems. The cultivation of species adapted to temporary flooding is an economical alternative for these areas, creating a demand for studies about species which could benefit from rice cropping infrastructure (GAZOLLA NETO et al., 2012; FERRARI et al., 2016).

Maize is grown in several cropping systems including environments susceptible to temporary soil flooding, a major abiotic stress imposed to roots, with effects on the growth and development of the whole plant, affecting its ability to survive under these conditions. This stress may result different physiology changes and lead to the formation of toxic substances (UITZIL et al., 2016), which may cause reduction of leaf area, loss of cell turgor, and extreme cases where shoots suffer necrosis damaging

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biosynthesis, as well as carbon partition among plant organs (LOPES and LIMA, 2015).

According to Batista et al. (2008), when the soil becomes hypoxic, plants respond with greater or less efficiency under these conditions. Another important factor is the lack of oxygen, according to Kolb and Joly (2009), plants activate anaerobic metabolism and induce changes that produce toxic substances such as ethanol and lactate, in addition to low energy yield. In the absence of oxygen, ATP production is reduced (SILVA et al., 2009), increasing the concentrations of reactive oxygen species (ROS) (PERATA et al., 2011), reducing plant growth and development. When plants develop on soil flooding stress, energy yield is lower because the metabolism is anaerobic. In these conditions, the final synthesized product is acetaldehyde and ethanol, which results in the acidification of cytoplasm due to lactate production and H^+ accumulation because of the precarious functioning of the ATPases-tonoplast carriers (WANG et al., 2012).

The tolerance of a genotype to flooding conditions is related to its ability of developing physiological and biochemical responses when subjected to this stress. The growth analysis is an important tool for evaluating the response of plants to managements or factors imposed by growing environments, due to the fact that this simple and low-cost technique allows to observe contributions of different physiological processes on plant behavior (AUMONDE et al., 2013; LOPES and LIMA, 2015).

Soil flooding severely limits plant growth and is considered one of the main abiotic stresses, causing a reduction of seed germination and impairing the initial establishment of seedlings due to changes in the root system and reduction in photoassimilate translocation, as well as reduction of activity metabolism of plants. Studies on the performance of plants, in the face of flood conditions throughout their cycle, are important to assist in the description of the vegetal performance in front of the mentioned environmental stress. In this context, the objective of this work was to evaluate the influence of soil flooding on the growth of maize plants through growth analysis through simple logistics.

MATERIALS AND METHODS

The work was conducted in the 2016/2017 growing season, in the Department of Plant Science of the Federal University of Pelotas, Rio Grande do Sul, Brazil, located at latitude of 31º52’ S, longitude of 52º21’ W and altitude of 13 m. The climate of this region is temperate, with well distributed rainfall and hot summer, of the *Cfa* type, according to Köppen.

The seeds used are from one maize genotype (*Zea mays* L.), with germination of 95%. Seeding was performed manually in December 2016, and each plot consisted of four lines with four meters in length, with 45 cm of spacing between rows, resulting in a population density of 55 thousand plants per hectare. The useful area of the plot was two central lines, andthe soil is classified as solodiceutrophic haplic planosol (STRECK et al., 2008), fertilization and correction were previously performed according to soil analysis (CQFS, 2004). Crop management was carried out according to the recommendations, and the climatological data was accessed from the Weather Station of Pelotas, RS, located 100 m from the trials conduction area.

At 60 days after sowing, when plants reached the vegetative stage V8, the soil was flooded and kept in this condition for 72 h. Soil flooding was established through the construction of slopes around each plot, characterizing the tray system. The flooding period was imposed by introducingand maintaining a water layer of 20 mm above ground within the plots. After 72 h, the slopes were opened to remove the water layers and drain the soil. The experimental design was completely randomized blocks arranged in a factorial scheme, with two soil conditions (field capacity and soil flooding) x five plant samples (20, 40, 60, 80 and 100 days after emergence), arranged in four replicates. For growth evaluations, successive samplings were carried out after emergency with regular intervals of 20 days until seeds harvest (100 DAE). Different plant structures were separated in each sampling (leaf, root, stem, tassel and ear). In order to quantify dry matter, these structures were conditioned separately in brown paper envelopes, being directed to a forced ventilation oven at temperature of 70 ± 2°C until constant mass.

Leaf area (Af) was determined through a Licor® meter model LI-3100, with results expressed in square meters (m^2). Leaf area index (L) was calculated by the formula L = Af/St. Where St is the soil surface occupied by plants. The total dry mass (Wt) primary data were adjusted by the simple logistic equation, $W_t = W_m/(1+A\ e^{-Bt})$, being "Wm" the asymptotic estimate of maximum growth, "A" and "B" are the constants of adjustment, "e" is the natural basis of neperian logarithm, and "t" is the time in days after emergence (RICHARDS, 1969).

The primary leaf area (Af), dry matter of leaf (Wf), stem (Wc), roots (Wr) and ears (Wesp) were adjusted using orthogonal polynomials (RICHARDS, 1969). The instantaneous values of dry mass production rate (Ct) were obtained through temporal derivates of the adjusted equations of total dry mass (Wt) (RADFORD, 1967). For the determination of instantaneous values of relative growth rate (Rw), it was used the equation: $R_w=1/W_t.dW/dt$, and the instantaneous values of the net assimilation rate (Ea), leaf area ratio (Fa), leaf mass ratio (Fw) and specific leaf area (Sa) were estimated through the equations: $E_a= 1/A_f.d_W/dt$; $F_a = A_f/W_t$; $F_w= W_f/W_t$ and $S_a = A_f/W_f$ (RADFORD, 1967).

The determination of dry matter partition among different structures (leaves, roots, stem, tassel and spikes) throughout plant development stages was performed separately by measurements of the mass allocated in each vegetal structure, being the primary data of dry mass allocation of each organ converted into percentage. Primary data of leaf area, dry mass of leaves, stems, roots and ears were subjected to analysis of variance by the F test at 5% of probability, and growth was evaluated by the simple logistic equation and interpreted based on the slope’s tendencies (LOPES and LIMA, 2015).

RESULTS AND DISCUSSION

The production of total dry mass (Wt) in maize plants at field capacity and under flooding conditions presented logistictrend, with high coefficient of determination ($R^2 \geq 0.94$). Until 40 days after emergence (DAE), there was a slow growth with posterior tendency of incrementtowards the end of development cycle, at 100 DAE (Figure 1d). Plants kept at field capacity condition reached higher Wt allocation at 100 DAE, compared to those under soil flooding stress. In the case of soil flooding stress, there occursa restriction of oxygen for the plants, triggering the anaerobic metabolic pathway for ATP production, which results in less energy produced (TAIZ and ZEIGER, 2013). Structural carbon storage is responsible for plant growth in volume, dry mass, linear dimensions and structural units (AUMONDE et al., 2011). Thus, slow initial growth is considered usual and results from a low absorption of water and nutrients. Also, the beginning of leaf area development is small due to the lower rates of respiration and net assimilation (MONTEITH, 1969).

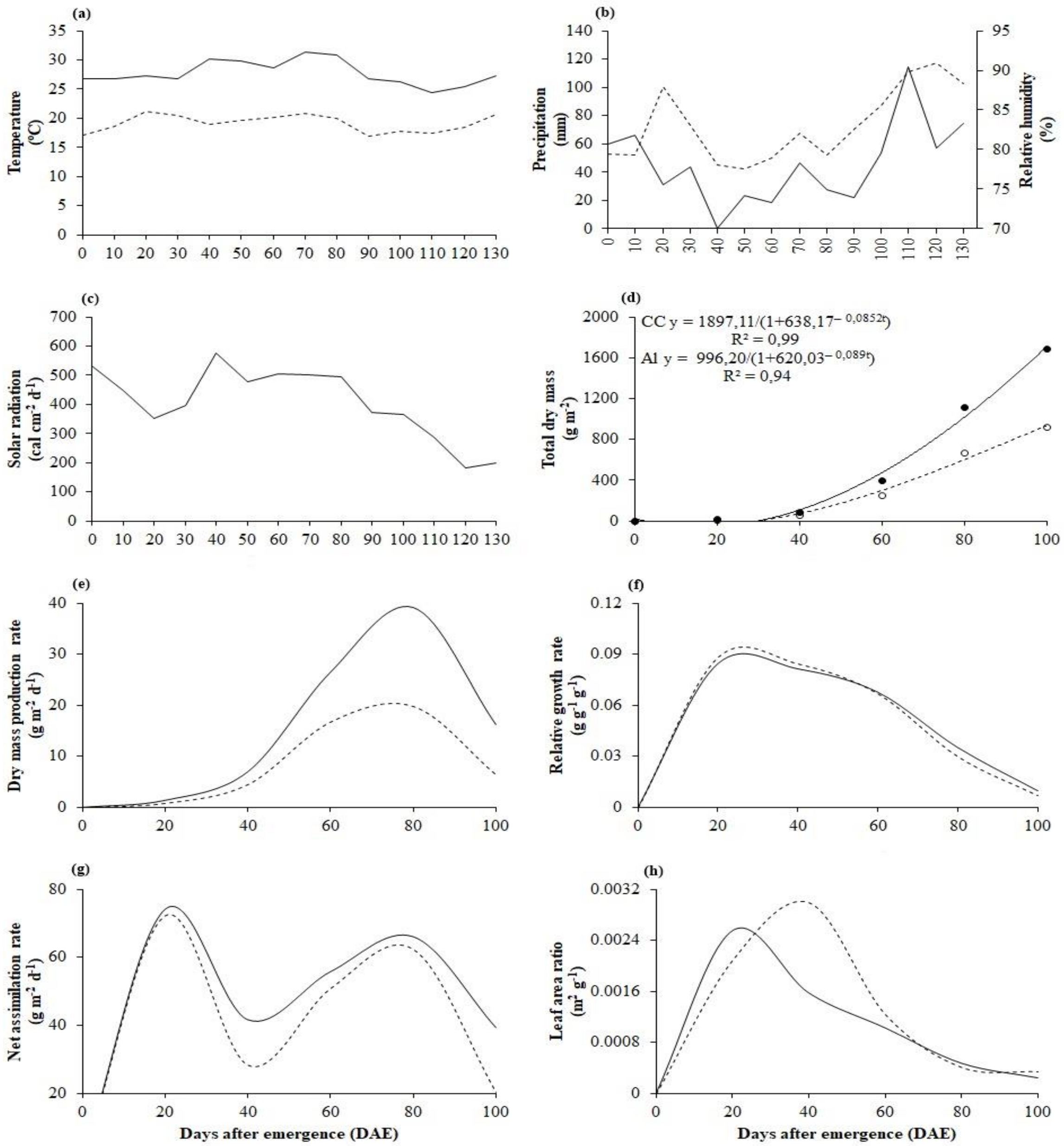

FIGURE 1 - Maximum and minimum temperature (a), precipitation and relative humidity (b), solar radiation (c) total dry mass, dry mass production rate (e), relative growth rate (f), net assimilation rate (g) and leaf area ratio (h) of maize plants throughout plant ontogeny. Being: Field capacity (FC) (——) and soil flooding (SF) (- - - -).

Dry matter production rates (Ct) remained low until approximately 40 DAE for plants submitted to flooding and plants kept at field capacity (Figure 1e), corroborating with the low total mass production, being these minimums until this period (Figure 1d). Maximum dry mass production rates occurred at 80 DAE for plants submitted to flooding, and at 75 DAE for plants kept at field capacity, with subsequent decrease until the end of plant´s development cycle for both conditions. Higher rates of dry mass production were verified in plants kept at field capacity, which reached 40 g m^{-2} d^{-1}. This behavior demonstrates that soil flooding changes the rate of dry mass production in maize plants in quantitative rather than temporal way, being evident that plants under stress are less efficient in increasing dry mass per unit area in relation to time. According to Pedó et al. (2013), the increase in dry mass production rate is related to the increase of leaf area and quantity of assimilates synthesized and assigned to plant growth and development. In contrast, the decrease in Ct might be related to the increase of plant age and non-photosynthetic tissues.

The relative growth rate (Rw) was maximum at 28 DAE, with subsequent systematic tendency to decrease towards the end of plant development cycle (Figure 1f). It is possible to verify that plants kept under field capacity demonstrated superior dry matter accumulation, compared to plantssubmitted to soil flooding at 100 DAE. It was evident that plants affected by soil flooding reduced the efficiency of solar radiation conversion into dry matter, preventing sugar and starch storage and accumulation. The relative growth rate (Rw) presents higher trend in the first stages of plant development because leaf area is composed by young leaves with high photosynthetic capacity and growth rate (PEDÓ et al., 2015a; SZARESKI et al., 2018). The increase of non-photosynthetic tissues trough plant aging may result in Rw reduction, which leads to higher rates of respiration and self-shading (BENINCASA, 2004). This situation may be observed through the leaf area index (Figure 2c). Fontes et al. (2005) reveals that the decline of Rw is related to the decrease of Ea and Fa, as soil flooding promotes lower carbon fixation due to stomatal closure.

The net assimilation rate (Ea) revealed two peaks of maximum assimilates production throughout plant ontogeny (Figure 1g). The first peak occurred at the beginning of plants vegetative growth, about 20 DAE, where plants kept at field capacity presented higher Ea compared to plants submitted to soil flooding. The second peak occurred at 80 DAE, being higher for plants at field capacity, and lower for plants under soil flooding at the beginning of reproductive phase. Ea curves presented two peaks during plant´s development cycle for barley, rice and rye (PEDÓ et al, 2015b).

Leaf area ratio (Fa) revealed higher values at the beginning of maize plants development cycle (Figure 1h), where plants kept under field capacity presented maximum Fa at 20 DAE, and plants submitted to soil flooding reached maximum Fa at 40 DAE. Plants submitted to field capacity and soil flooding reached Fa of 0.0024 and 0.0030 m^2 g^{-1}at 20 and 40 DAE, respectively. However, after these periods, there was a tendency of leaf area ratio reduction, and at 100 DAE, plants submitted to soil flooding were superior to those kept at field capacity. The slightly superior Fa tendency observed in plants submitted to soil flooding is due to the larger useful area for photosynthesis, which is an attempt to survive in response to stress conditions that they were submitted to. The maximum Fa peaks at the beginning of plant development cycle are related to most of the assimilates produced by the differential photosynthesis is directed to leaves (AUMONDE et al., 2011). However, the decrease in Fa throughout plant ontogeny is related to the gradual increase of non-assimilatory tissues and the beginning of reproductive phase, as reproductive structures are considered the preferred metabolic drains (PEDÓ et al., 2013).

The leaf mass ratio (Fw) was highest at the beginning of the plant development cycle until approximately 40 DAE, with subsequent decrease towards the end of the cycle, both for plants kept at field capacity and those submitted to soil flooding (Figure 2a). However, plants that suffered soil flooding presented higher Fw at 40 DAE, compared to plants that were kept at field capacity (AUMONDE et al., 2011; PEDÓ et al., 2013). High values of Fw at the beginning of plant development stageshows higher allocation of assimilates in leaves, which are the preferential metabolic drains. Fw reduction throughout the development cycle is related to modification of preferential drain to stem, and later to reproductive tissues, which occurs in accentuated and definitive ways (LOPES and LIMA, 2015).

The maximum values of specific leaf area (Sa) were obtained at 20 DAE, both for plants keptat field capacity and for plants submitted to soil flooding (Figure 2b). The results express that plants exposed to soil flooding have smaller leaves, however, thicker than those from plants kept at field capacity. Plants at field capacity presented superior Sa when compared to those under soil flooding, being result of a larger leaf area (PEIXOTO and PEIXOTO, 2009).

The leaf area index (L) was obtained with high coefficient of determination (R^2 = 0.94), with reduced growth until 20 DAE, along Wt (Figure 1d), and maximum at 80 DAE for plants kept at field capacity and plants submitted to flooding (Figure 2c). It should be noted that plants submitted to soil flooding reached lower values of L compared to plants kept at field capacity. The leaf area index might be negatively affected by senescence and leaf death process, resulting in lower plant growth and lower performance at 80 DAE.

The efficiency of solar energy conversion (ξ) presented differentiated responses between plants for both treatments, kept at field capacity, and submitted to flooding.The maximum was verified at 80 DAE, with values of 3.7 and 1.9% for maize plants at field capacity and under soil flooding, respectively (Figure 2d). The increase observed for ξ corroborates with the trend observed for Ct (Figure 1e) and solar radiation (Figure 1c). ξ is a measure that relates dry mass production in energy units, reflecting the higher allocation of total dry mass in plants kept at field capacity (TROYJACK et al., 2018; KOCH et al., 2017).

Mass partition among different maize plants structures, both for field capacity and soil flooding conditions, presented subtle changes though the cycle, with similarity of dry mass allocation for the different plant structures (Figure 2e and 2f). Plants submitted to soil flooding allocated lower dry mass in spikes, compared to plants kept at field capacity, and the preferential drains were modified throughout plant ontogeny. At the beginning of the cycle, the preferential metabolic drain are the leaves and roots, and consecutively, with the beginning of reproductive phase, there is a targeting of accumulated assimilates in leaves to seeds, which become the preferential and definitive drains (LOPES et al., 2011).

With the beginning of reproductive stage, roots, stems and leaves continue to import assimilates, however, in small quantity only for structural maintenance. Similarity in the allocation of dry mass of leaves and roots was observed early after soil flooding, compared to plants kept at field capacity (Figure 2e and 2f). Regarding stem dry mass allocation, there was superiority for plants submitted to soil flooding. Considering spikes dry matter allocation, plants keptat field capacity presented higher percentage of dry mass allocation in relation to plants submitted to soil flooding. It was observed that the stress caused by soil flooding quantitatively altered dry mass partition among different structures analyzed, which may be related to physiological changes caused by this stress, resulting in alterations of the different growth variables. Another possible explanation for these alterations may be related to the need of reallocating reserve carbohydrates in vegetative areas and reducing reproductive ones, which is crucial for tolerance to flooding periods (NARDINO et al. 2016).

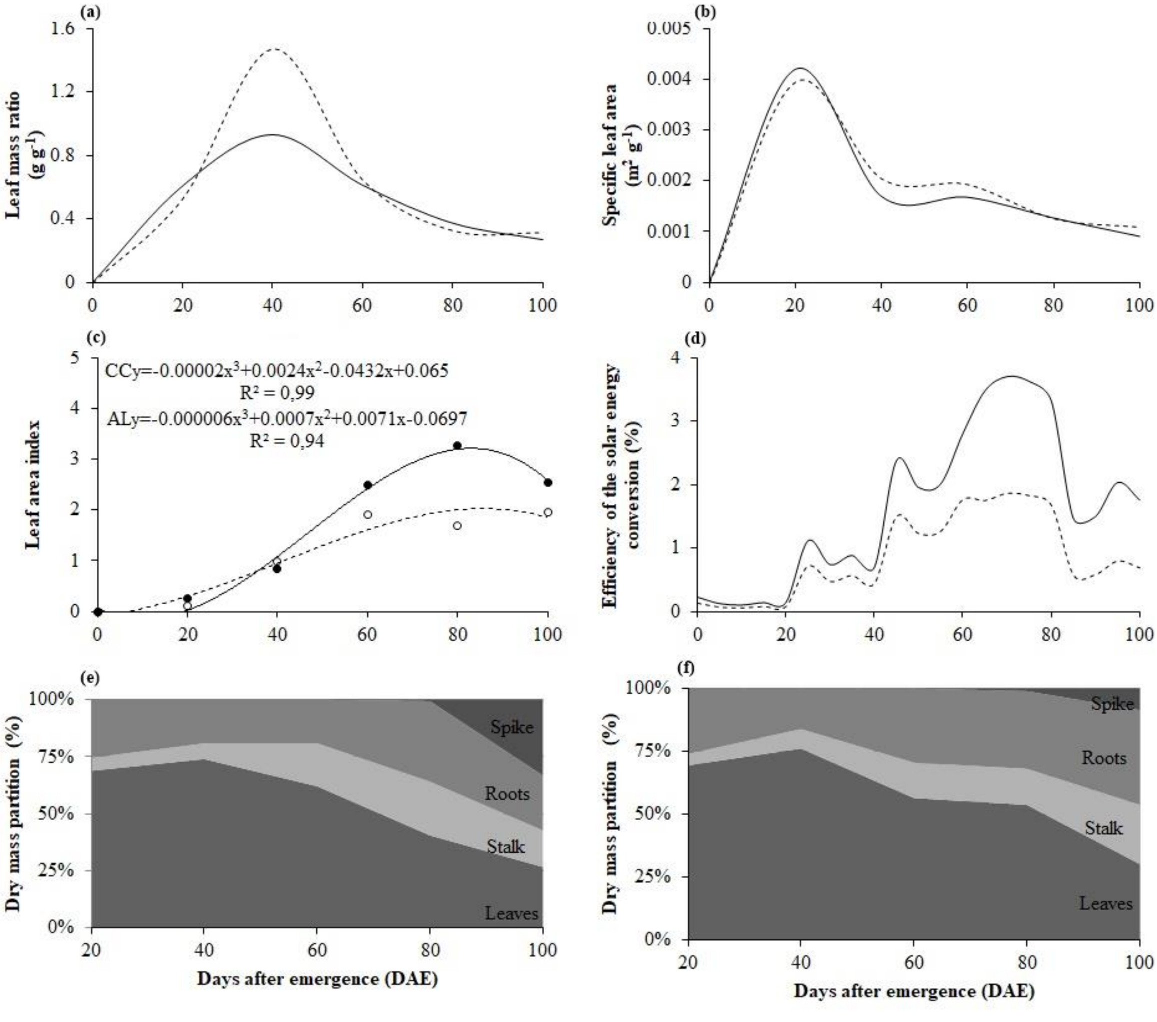

FIGURE 2 - Leaf mass ratio (a), specific leaf area (b), leaf area index (c), efficiency of solar energy conversion (d), dry mass partitioning of plants at field capacity (e) and under flooding conditions (f) of maize plants throughout plant ontogeny. Being: Field capacity (FC) (——) and soil flooding (SF) (- - - -).

The analysis of variance revealed significance for the treatments soil flooding and field capacity for the primary data of leaf area, dry mass of leaves, stem, roots and spike (Table 1). The averages of maximum and minimum air temperatures throughout plant developmentwere 30 and 15°C, respectively (Figure 1a).

The averages of maximum and minimum air relative humidity during maize plants development were 92% and 78%, respectively (Figure 1b). Regarding rainfall, it was possible to observe that, from 110 to 120 days after emergency, themaximum level of precipitation occurred, reaching about 100 mm (Figure 1b). Solar radiation presented decreasing tendency until 20 days after emergency. From 20 to 40 days after emergency, an increase in solar radiation occurred, reaching its peak 40 days after emergency, with 550 cal cm^{-2} day^{-1}. Solar radiation decreased from 40 days after emergency until the end of crop cycle (Figure 1c).

TABLE 1 - Summary of analysis of variance with mean squares for primary data of leaf area (Af), dry mass of leaf (Wf), dry mass of stem (Wc), dry mass of roots (Wr), dry mass of ears (Wesp) of maize plants under soil flooding and field capacity.

Var.	GL	Mean squares				
		Af	Wf	Wc	Wr	Wesp
FC/SF	4	157625.45*	1647.41*	1744.67*	4013.18*	3265.07*
Error	25	10680.23	178.32	131.18	330.88	630.23
Total	29	-	-	-	-	-
Mean	-	2596.12	21.56	14.96	23.57	10.65
CV(%)	-	39.81	31.94	26,54	27,15	25.58

*Significant at 5% of probability, CV = coefficient of variation, Var. = variation.

CONCLUSION

Soil flooding interferes negatively on the growth and physiological performance of maize plants subjected to this environmental stress. There is a reduction in leaf mass ratio, dry mass production rate, relative growth rate in plants submitted to flooding, compared to those kept at field capacity.

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