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REGULAR ARTICLE

Water supply to lettuce by capillary rise of the water table

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Author contribution
EMA: Conceptualization, Experimental data collection, Data custody, Data analysis, Writing the manuscript; RNTC: Conceptualization, Data analysis, Writing the manuscript, Manuscript review, Supervision; KGN: Data analysis, Writing the manuscript, Manuscript review; AOdaS: Data analysis, Writing the manuscript, Manuscript review, Supervision; CHCdeS: Data analysis, Manuscript review; EMA: Experimental data collection, Manuscript review.

Abstract

Brazil has significant potential for floodplain areas which are suitable for cultivation after the rainy season, with water supply from the water table. Short-cycle crops with shallow root systems are more suitable for these conditions. On this subject, the objective of this study was to determine the responses of the lettuce crop to rising damp rates and water table depth levels. The variables of production, gas exchange, and SEW_{30} values (sum of excess water above 0.30 m depth) were analyzed. A physical model of seven drainage lysimeters was used; in six, the only water supply occurred by capillary rise from the water table (0.10; 0.15; 0.20; 0.25; 0.30 and 0.35 m depth) and, in the remaining lysimeter, irrigation was performed with no water table. The water table level maintained at 0.20 m from the soil surface was able to supply the water demanded by a sandy soil. The factor-product ratio indicates this depth as the most viable option in terms of crop response. Among the analyzed cultivars and under conditions of excess water in the soil, preference should be given to the establishment of the Gloriosa cultivar, for higher yields.

Keywords

Lactuca sativa L.; Crop requirement; Capillary fringe; Soil drainage; Water stress.

Introduction

Irrigated agriculture is fundamental to the local economy development in many arid and semi-arid areas. However, with the intensification of water resources scarcity, increasing irrigation efficiency is an essential factor for the continuity of production in these regions. On a regional scale, the efficiency of water use in irrigation is conditioned by the water cycle, including water present in the soil and groundwater movement processes (Liu et al., 2016).

Detailed knowledge of water dynamics in the soil–plant–atmosphere relationship during the development of a plant species provides essential elements for the establishment or improvement of agricultural management practices, which aim to optimize productivity through efficient management approaches. Water is a fundamental factor in the development of a crop, mainly affecting the development of the plant root system and nutrient absorption and translocation. Its dynamics have been studied through water balances, based mainly on information obtained in the atmosphere, leaving soil information in the background (Haghverdi et al., 2017; Reichardt et al., 1993).

The responses of agricultural crops to stress due to excess water are associated with the internal water content in the soil. Although the effects of this factor are known, there are few practical results. Mingoti et al. (2006), studying lettuce cultivation, verified the influence of the water table lowering rate on the development of the crop.

The movement of water in the soil is considered one of the most important processes in the development of agricultural crops, and this importance is justified by the complexity attributed to understanding and describing the components of this process. Often, in agricultural areas where the water table is relatively shallow, the input provided for crop development is neglected, to the point of causing problems related to excess water in the soil. Liu et al. (2014) report the importance of considering soil variability in this context.

Kahlown et al. (2005) state that the contribution of groundwater as a supply to the water needs of a crop is variable, depending, in general, on the depth of the water table. The soil occupies a prominent role in this process, as in addition to being the place that hosts the development of water transfer processes in the soil–plant–atmosphere system, it also has very defined physical-water characteristics and attributes. Therefore, the flow of water from the water table needs to be quantified, both for its contribution to crop supply and for its importance in the soil salinization process (Huo et al., 2012; Yang et al., 2007).

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Given the complexity of controlling, monitoring, and evaluating the behavior of the water table during the lettuce crop cycle – which is the leafy vegetable most used in salads in Brazil, having great economic, nutritional, and social importance (Sala & Costa, 2012; Schirmer et al., 2019) – there is a need for studies that indicate production limitations and the effects of the presence or absence of groundwater during the crop's production cycle.

In this context, this study addresses the water contribution capacity of the water table for the development of lettuce cultivation, in order to verify whether this contribution fully meets the crop's water demand. The objective was to obtain – through two types of iceberg lettuce cultivars (Lucy Brown and Gloriosa) – information to identify the crop's response relationships to capillary rise rates and groundwater depth levels.

Materials and methods

The experiment was conducted in a physical model consisting of seven drainage lysimeters, in the Hydraulics and Irrigation Laboratory of the Agricultural Engineering Department of the Federal University of Ceará, Fortaleza, Brazil, at 3°45' South latitude, 38°33 ' west longitude, and altitude of 19.53 m. The climatic data used in the experiment irrigation management were obtained at a conventional agrometeorological station close to the site. The region's climate, according to the Köppen classification, is rainy tropical, with an average annual precipitation of 1350 mm concentrated in the months of January to April, an average annual temperature of 26.5°C, and an average annual relative humidity of 80%.

The physical model of the drainage lysimeters was composed of seven masonry structures measuring 1.5 m high, 2.0 m wide, and 1.5 m long, covered with mortar and internally waterproofed. Inside each lysimeter, there was a corrugated and flexible PVC tubular drain (DN 65) at a depth of 1.10 m in relation to the upper part of the lysimeter. Two water inlets were placed at the bottom of the front wall, both connected to a valve, which allowed individual filling of the lysimeters. The physical model made it possible to saturate the soil by upward flow, through a reservoir. A valve and float system regulated the maximum height of water in the reservoir, up to a maximum level of 0.15 m from the upper edge. In addition to the supply and drainage system, the lysimeters had – for the purpose of monitoring the depth of the water table – a piezometer made up of a transparent plastic hose on the front wall of the external part of each lysimeter.

The experiment was conducted in a completely randomized design, in a factorial arrangement (7x2), with three replications. The treatments were obtained by combining six levels of maintenance of the depth of the water table (WT10 = 0.10 m; WT15 = 0.15 m; WT20 = 0.20 m; WT25 = 0.25 m; WT30 = 0.30 m, and WT35 = 0.35 m), plus a treatment with no water table (control), whose daily irrigation met the crop's water needs, in addition to two lettuce cultivars. The rows of plants neighboring the edges of the lysimeters and the lines between the replicates were considered borders, totaling 18 useful plants in each treatment, for each cultivar, in the three replications.

The crop selected for the experiment was iceberg lettuce, in two cultivars, Lucy Brown (C1) and Gloriosa (C2), with a spacing of 0.20 m between rows and 0.20 m between plants, following Lemos Neto et al. (2017). The soil used in the experiment was predominantly sandy: sand – 95%; silt – 4%; clay – 1%. The values of physical attributes of the material used in the composition of the substrate placed in the drainage lysimeters, used to estimate, based on the van Beers equation, the drainable or effective porosity of 32.9%, according to Duarte et al. (2015), were: hydraulic conductivity of saturated soil – 450 mm h^{-1}; total porosity – 45%; soil density – 1480 kg m^{-3}; clay dispersed in water – 0.7%.

To form the substrate, commercial organic compost was incorporated 30 days before transplanting the seedlings, distributed evenly throughout the lysimeters, at a rate of 13 kg m^{-2}.

For sowing, pelleted seeds were used in four trays of two hundred cells (two trays for each cultivar), using an organic compost based on earthworm humus and plant remains as substrate. The seeds germinated two days after sowing (DAS). At seven DAS, the seedlings were effectively established. The cultivars were transplanted at 26 DAS, following the experimental design. In the first ten days after transplanting (DAT), the crop's water demand was met by applying an irrigation level equivalent to the crop's water needs. The experimental period was from August to October, during the dry season, seeking to avoiding the influence of rainfall.

Reference evapotranspiration (ETo) was estimated using the Penman-Monteith method (FAO), using the CropWat for Windows software. The cultivation coefficient (Kc) of lettuce, in its maximum development state, varies between 0.9 and 1.0, depending on the species and cultivar used, so the average value of 0.95 was adopted to calculate the crop evapotranspiration (ETc).

The water table depth data made it possible to quantify, for each treatment, the SEW (sum of excess water) stress index, which represents the sum of the excess water value in the soil, to evaluate the effect of the occurrence of the water table in the root zone of the crop on productivity. Considering the depth of the root system of the studied crop, the SEW_{30} (sum of excess water above 0.30 m depth) stress index was adopted (Duarte et al., 2015). In the calculation, Equation 1 was used:

$$SEW_{30} = \sum_{i=1}^{n} (30 - x_i) \qquad (1)$$

where: x_i is the depth of the water table below the soil surface on day i (cm); n is the number of days in the growing season (d).

SEW_{30} values were determined for treatments corresponding to groundwater levels between 0.10 m and 0.30 m, in a period of 30 days. In this way, the SEW_{30} values corresponding to treatments with water table levels between 0.10 and 0.30 m are 600 cm d, 450 cm d, 300 cm d, 150 cm d, and 0 cm d. A histogram of productivity data was established with SEW_{30} values, with the purpose of analyzing regions with excess and deficit water.

It is worth noting that, for daily monitoring of matric potentials and, consequently, the water content in the soil, tensiometers were installed in each treatment, at depths of 0.10 m, 0.20 m, and 0.30 m.

To measure photosynthesis rates, transpiration, stomatal conductance, and instantaneous water use efficiency, a gas exchange meter IRGA (LICOR 6400XT, Licor, USA) was used. Measurements were carried out between 9 and 11 am, using an artificial light source with 1400 μmol m^{-2} s^{-1} of radiation. In determining crop productivity, each collected sample had the root system removed, and the leafy mass was obtained using a precision scale (fresh mass).

To carry out the statistical analysis, the SISVAR software was used (Ferreira, 2011). The data were subjected to the normality test (Shapiro-Wilk) and subsequently, with the guarantee of their normality, they were subjected to analysis of variance (F test) at 5% ($p<0.05$) probability. When significant, they were subjected to the Tukey test ($p<0.05$). For the relationships between the evaluated variables and the SEW_{30}, regression models were tested, considering the significance of the parameters (T Test) and coefficient of determination.

Results and discussion

Based on the series of data obtained, daily monitoring of the crop water demands (during the monitored period) was carried out, as shown in Figure 1.

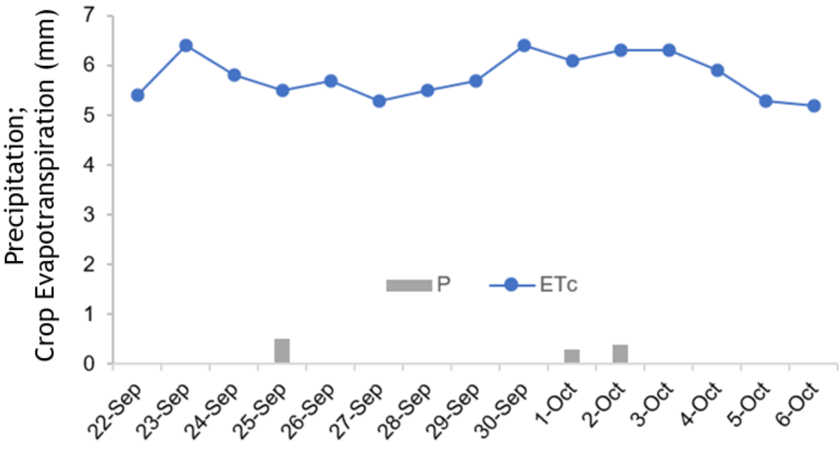

Figure 1. Precipitation (P) and Crop Evapotranspiration (ETc) data.

It is possible to observe that, for the period under analysis, the daily water demand of the crop varied from 5.2 to 6.4 mm and that the occurrence of rainfall was not significant. Therefore, it can be stated that the results and calculations of capillary rise flows were not significantly influenced by possible rain events.

In Figure 2, the distinction between the different groundwater levels is visualized from the point of view of potentials (matric and pressure) at a depth of 0.20 m, which demonstrates that the physical model of the drainage lysimeters was capable of maintaining groundwater levels at different depths.

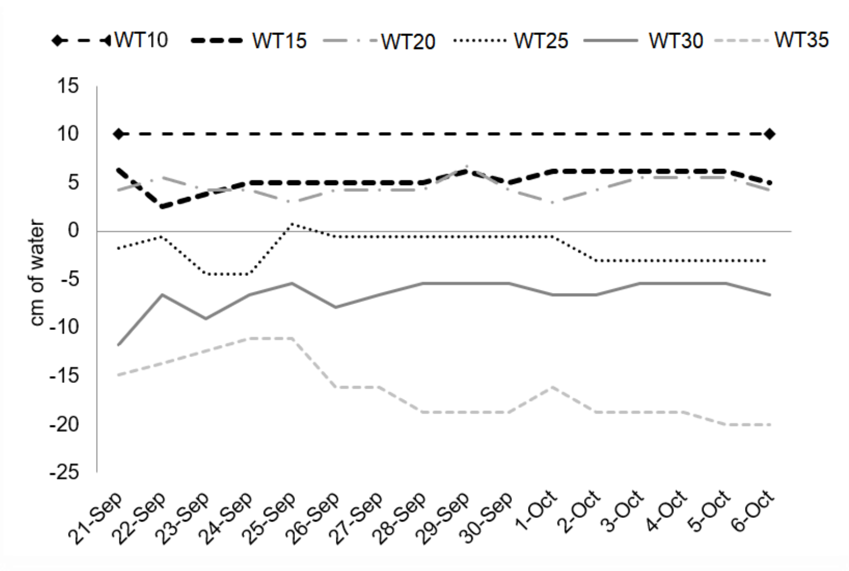

Figure 2. Matric and pressure potentials of groundwater levels for the monitored period. Tensiometer installation depth: 0.20 m.

It is possible to observe that WT10 did not undergo any changes throughout the analysis period and that, at depths WT15 and WT20, due to the tensiometer installation depth (0.20 m), high sensitivity was verified, which highlights the importance of the tensiometer close to the water table level.

Table 1 contains the results of the analysis of variance of the response variables productivity, stomatal conductance, instantaneous water use efficiency, photosynthesis, and crop transpiration for the two cultivars.

Table 1. Analysis of variance of the response variables productivity (Y), stomatal conductance (*gs*), instantaneous water use efficiency (A/E), photosynthesis (A), and transpiration (E)

VS	DF	Y	*gs*	A/E	A	E
WTL	6	342.66**	3.31	3.18*	3.72**	14.96**
C	1	17.66**	0.14	0.08	13.03**	0.01
WTL x C	6	7.534**	1.58	1.31	1.17	0.38
CV (%)		13.06	25.17	23.26	22.68	15.63

VS: variation source; CV: coefficient of variation; DF: degree of freedom; WTL: water table level; C: cultivar; **; *: significant by F test at 1 and 5%, respectively.

Regarding the productivity of lettuce cultivars as a function of groundwater levels (Figure 3a), the behavior is similar, either due to the water table level (0.20 m) associated with maximum productivity, or due to the downward trend in productivity for levels above or below 0.20 m. These results suggest that the depth of the water table at 0.20 m allowed a more favorable condition for water supply to the crop, compared to the other treatments. In the study, the effect of water deficit stress was more limiting on crop yield, whose productivity data for groundwater levels deeper than 0.20 m were lower than for levels smaller than 0.20 m. The behavior observed in Figure 3b highlights water deficit as the most limiting factor when compared to the stress factor due to the elevation of the water table.

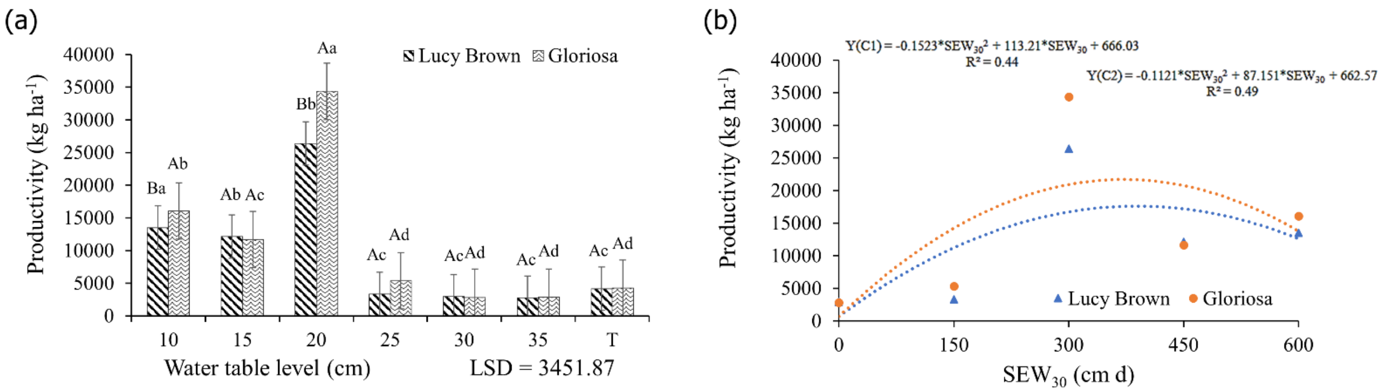

Figure 3. (a) Productivity of lettuce cultivars as a function of water table levels; (b) Relationship between productivity (Y) and the SEW_{30} index of lettuce cultivars (Lucy Brown (C1) and Gloriosa (C2)). *Equal capital letters do not differ according to the Tukey test ($p<0.05$) between cultivars; equal lowercase letters do not differ from each other for groundwater levels, according to the Tukey test ($p<0.05$).

The results of the analysis of variance showed that the cultivar was a significant factor and, in addition, based on the productivity results, it was verified that the Gloriosa cultivar showed a tendency towards higher productivity associated with the groundwater level factor. This difference between cultivar results is common to other studies, such as those by Suinaga et al. (2013) and Blat et al. (2011), who analyzed the responses of several lettuce cultivars to the application of irrigation sheets.

In the condition of groundwater absence (control), where the treatment was supplied with irrigation to meet the crop's potential evapotranspiration, the productivity levels obtained for the two cultivars were similar. However, such productivities were lower than those obtained with the water table varying from 0.10 to 0.20 m, which can be explained by the fact that the total potential or energetic state of water in the soil at these depths provided conditions of absence of stress due to water deficit throughout the crop cycle, which may occur during the irrigation interval.

The maximum average physical productivity was obtained with the water table at a depth of 0.20 m, for the two analyzed cultivars, which corresponds, in general, to the effective depth of the lettuce root system.

Regarding the analysis of productivity as a function of the SEW_{30} stress factor, the water table at a depth of 0.20 m (SEW_{30} = 300 cm d) allowed the achievement of higher productivity levels for both cultivars. Productivity drops in other treatments may be associated with water stress throughout the crop cycle which, according to Pereira et al. (1999), can alter the development of the crop, modifying the physiology and morphology, as well as affecting the biochemical relationships of the plant.

It is worth noting that – although lettuce is considered a water-demanding crop and sensitive to water deficit conditions – Nunes et al. (2017) observed, in lettuce cultivation under localized irrigation conditions, a decrease of less than 6% in the level of average productivity when reducing the applied irrigation depth by 50%. These results demonstrated that this production factor, in addition to being non-limiting, allows the use of the deficit irrigation strategy without major impacts on the production gross value.

For physiological responses, no significant differences were observed between cultivars, except for photosynthesis. The stomatal conductance results can be seen in Figure 4, below.

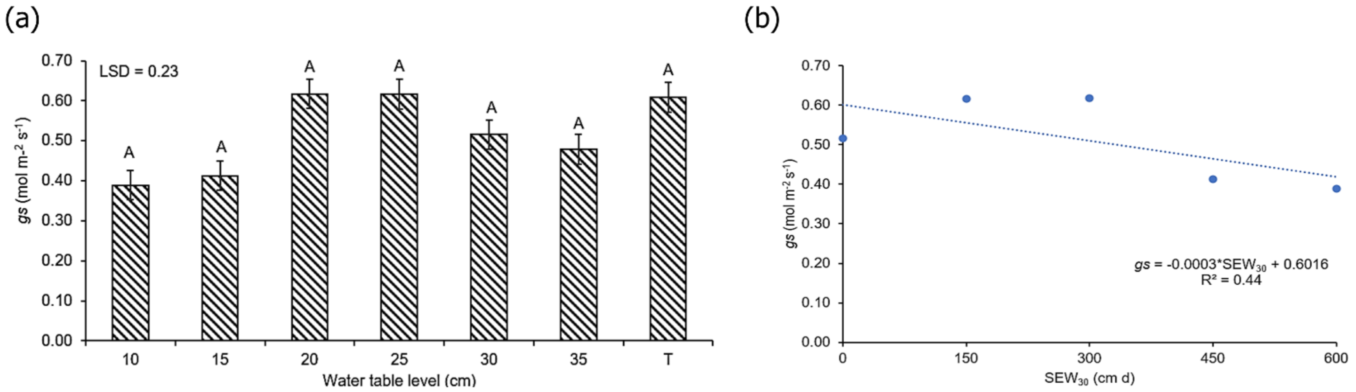

Figure 4. (a) Stomatal conductance (*gs*) depending on groundwater levels; (b) Relationship between the *gs* and the SEW_{30} index.

According to Paiva et al. (2005), the decrease in water in the soil reduces the water potential in the leaf and stomatal conductance, promoting the closure of stomata, which blocks the flow of CO_2 to the leaves, affecting the accumulation of photoassimilates. On the other hand, the plant responds positively to more favorable water conditions in the soil, maintaining high photosynthetic rates, providing greater production of photoassimilates, resulting in greater production of fresh matter.

As the water content in the plant leaves decreases, the cells contract and the walls lose their turgidity. This decrease in cell volume results in lower turgor pressure and subsequent concentration of solutes in the cell. As turgor reduction is the first relevant effect of water deficit, turgor-dependent activities, such as leaf expansion and root elongation, are more sensitive (Taiz & Zeiger, 2009).

In relation to the instantaneous efficiency of water use (Figure 5), it was observed that this variable behaved inversely to the other physiological variables, with superior results with the water table close to the root zone.

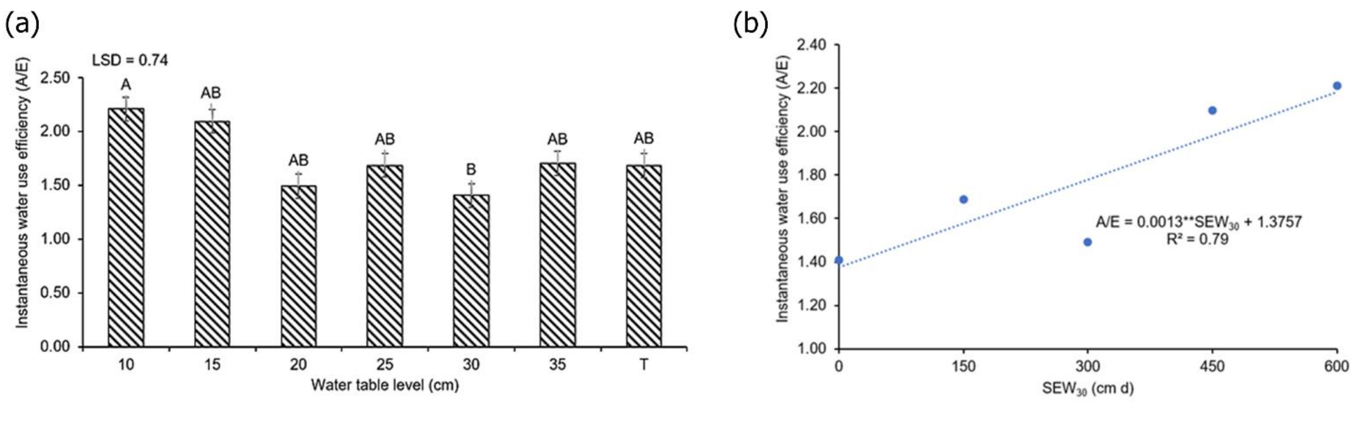

Figure 5. (a) Instantaneous water use efficiency (A/E) as a function of groundwater levels; (b) Relationship between instantaneous water use efficiency and the SEW_{30} index.

This fact corroborates the data obtained by Bandeira et al. (2011), with a decreasing linear response according to increasing irrigation levels. Therefore, it is understood that the crop responds better to the application of small irrigation depths, but with high frequency, a condition similar to that of this study, given the maintenance of groundwater levels. By increasing water availability, the crop can express its productive potential up to a certain point, after which productivity begins to decrease due to excess water in the soil, low aeration in the root zone, and nutrient leaching (Mantovani et al. al., 2013). SEW_{30} Stress Index Responses (Figure 5b) also demonstrated such behavior.

Figures 6 and 7 contain, respectively, data relating to photosynthesis and transpiration in lettuce cultivars as a function of water table levels (a) and as a function of the SEW_{30} index (B). Similar to the relationship between crop productivity and groundwater levels, photosynthesis (Figure 6a) and transpiration (Figure 7a) responded, in general, with higher values at the water table level corresponding to 0.20 m. It is worth noting that a marked reduction in the transpiration rate was observed under conditions of higher levels of stress due to excess water. Regarding photosynthesis, there was also a significant difference between lettuce cultivars, with the superiority of the Lucy Brown cultivar.

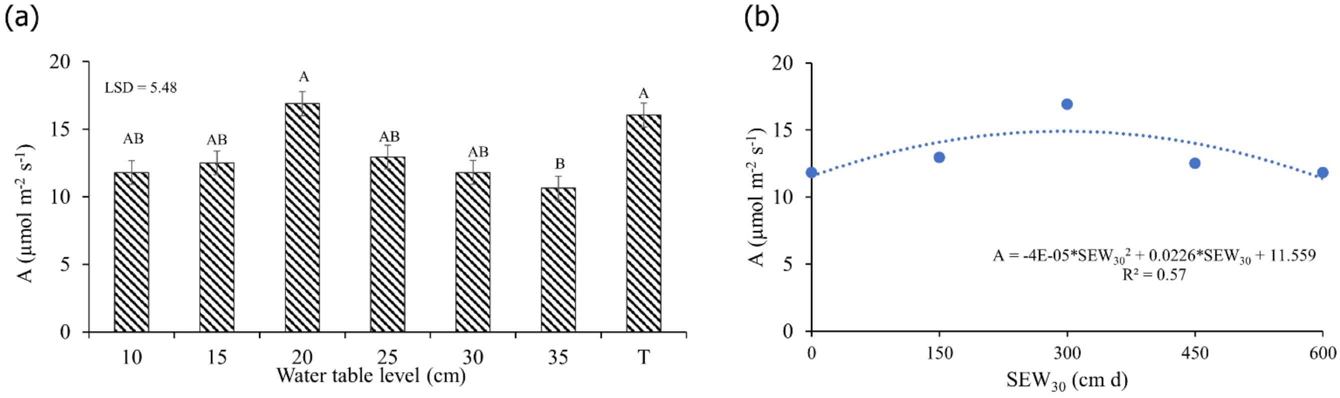

Figure 6. (a) Photosynthesis (A) as a function of water table levels; (b) Photosynthesis (A) as a function of the SEW_{30} index.

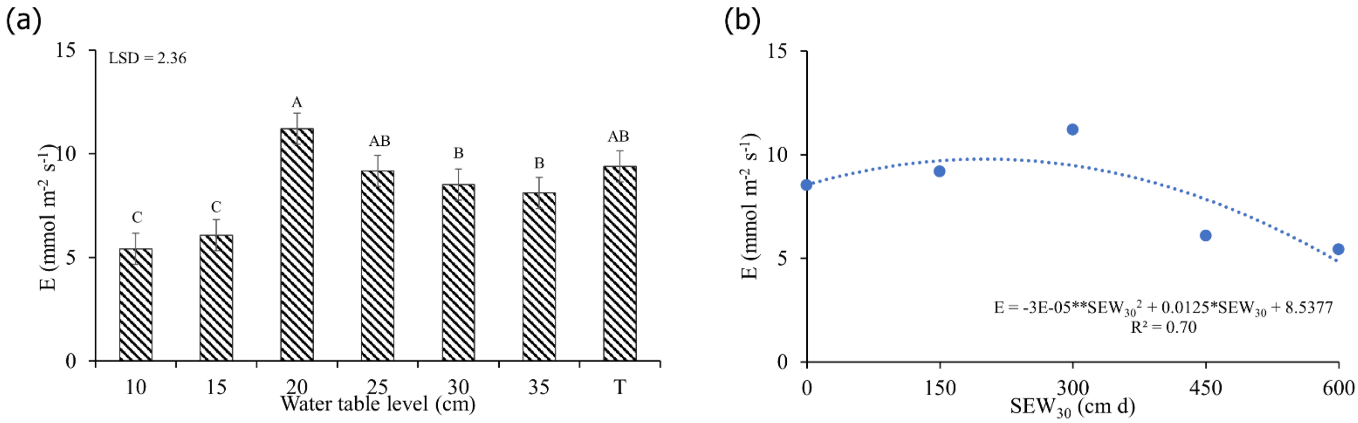

Figure 7. (a) Transpiration (E) as a function of groundwater levels; (b) Transpiration (E) as a function of the SEW_{30} index.

Demuner et al. (2017), studying the emergence of tomato seedlings under different water retention tensions in the soil, observed that the seedlings responded positively to the most favorable water conditions in the soil, maintaining high photosynthetic rates and providing greater production of photoassimilates, which implies greater production of fresh matter.

In the study, photosynthesis reacted to both water excess and deficit, obtaining a better response for the two cultivars analyzed with SEW_{30} at the level of 300 cm d. Kron et al. (2008) corroborate this result when they state that plants, when exposed to situations of water stress, often exhibit physiological responses that result in the conservation of water in the soil.

Jiang and Wang (2006) state that excess water stress causes a reduction in the synthesis of carbohydrates and chlorophylls, compromising plant development and causing loss of its original color and reduced root growth. Nascimento Filho et al. (2020) found, in an experiment with Bermuda grass, that the photosynthetic rate in the treatment with the highest level of stress decreased by approximately 2/3, when compared to the condition in which there was no water table, which resulted in inappropriate coloring for the grass, demonstrating the consequences of inadequate aeration level on the crop's root system. Likewise, lettuce is also a crop sensitive to waterlogging (Mingoti et al., 2006).

It is worth noting that similar performances between stomatal conductance and transpiration are expected and, according to Gonçalves et al. (2010), there is a direct relationship between transpiration rates and stomatal conductance, since stomatal closure induces a decrease in the flow of water vapor into the atmosphere, and, consequently, the amount of transpired water. In this study, it was observed that stress indexes that describe water deficit had more impact on the results of transpiration rates (Figure 7) than stress due to excess water.

Conclusions

Maintaining the water table at 0.20 m is the most viable option in terms of lettuce crop response, based on the physical factor–product relationship.

When cultivating iceberg lettuce in conditions of excess water in the soil, preference should be given to establishing the Gloriosa cultivar, aiming for greater productivity.

Acknowledgments

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