Agronomy Research **18**(1), 241–255, 2020
https://doi.org/10.15159/AR.20.013

Physiological indicators and yield of the Chinese cabbage cultivated at different soil water tensions

D. Paulus*, I. C. Zorzzi, D. Becker, G.A. Nava, A.L. de Paula and F.M. de Paula

Federal University of Technology - Paraná, Campus Dois Vizinhos, Faculty of Agronomia, Department of Agronomy, Street adress Estrada para Boa Esperança, km 04, postal code 157, Dois Vizinhos, Paraná, Brazil
*Correspondence: dalvapaulus@gmail.com

Abstract. The development and yield of Chinese cabbage is influenced by soil moisture. The objective of this study was to evaluate the physiological indicators, development, and yield of Chinese cabbage (*Brassica rapa subsp. pekinensis* (Lour.) Rupr.) grown at different soil water tension ranges. Two experiments were conducted (2016–2017) in the Olericulture Sector of the Federal University of Technology of Paraná. Two cultivars of the Chinese cabbage, Eikoo and Kinjitsu, and four soil water tension ranges 13–17, 23–27, 33–37, and 43–47 kPa were studied. Eikoo presented higher relative chlorophyll index, photosynthesis, and fresh leaf mass than did Kinjitsu. Physiological indicators transpiration (5.8 mmol H_2O m^{-2} s^{-1}), photosynthesis (14.5 µmol CO_2 m^{-2} s^{-1}), stomatal conductance (0.31 mol H_2O m^{-2} s^{-1}), and WUE (39.4 kg m^{-3}) were higher at 13–17 kPa soil water tension. Soil water tension ranges with high water restrictions reduced the fresh leaf mass of both cultivars. Fresh leaf mass decreased by 236.2 and 191.7 g plant^{-1} in the highest soil water tension range in 2016 and 2017, respectively, when compared with the fresh leaf mass at the 13–17 kPa tension range. The lowest water consumption was observed at the 13–17 kPa tension range. The year 2017 resulted in higher internal CO_2 concentration, transpiration rate, fresh leaf mass, number of irrigations and water consumption compared to the year 2016. Thus, the irrigation regime for the most optimal Chinese cabbage cultivation should maintain the soil water tension range at 13–17 kPa.

Key words: *Brassica rapa*, photosynthesis, soil moisture, tensiometer, yield.

INTRODUCTION

Water shortages are increasingly reported in agricultural systems in the wake of climate change–a phenomenon that will negatively affect the livelihoods of rural communities and food security in urban areas. In the same vein, the agricultural sector is growing at a rapid pace and is responsible for mobilizing large volumes of water (Godfray & Garnett, 2014). Addressing water scarcity requires cultivation strategies to save water as efficient use of irrigation water is becoming increasingly important.

Low water-use efficiency, both under irrigation systems and in the field, calls for the introduction of new approaches to enhance efficient exploitation of water resources. The development of systems that maintain or increase yield while minimizing such negative impacts is critical for the achievement of sustainable production (Godfray &

Garnett, 2014). Strategies for reducing water loss and conserving the water resources available for agricultural production, such as deficit irrigation, which aims to increase water-use efficiency while ensuring effective irrigation by reducing the amount of water used (Zorica & Stikic, 2018), alternative wetting and drying (AWD), which has been demonstrated to decrease water use by 23–33% under rice cultivation (Carrijo et al., 2018), in addition to water reuse and adoption of localized irrigation methods (drip and micro sprinkler), with efficiencies greater than 90%, are some alternative approaches that could enhance water-use efficiency (Zorica & Stikic, 2018).

Proper irrigation requires careful consideration of the amount of water and the timing of its application to the soil based on the stage of plant growth. Improper irrigation, either in the form of excessive or inadequate irrigation, results in crop water stress and reduced yield. Excessive irrigation could also cause the pollution of water sources due to the loss of plant nutrients by leaching, runoff, and soil erosion (Yazgan et al., 2008).

The amount of water to be applied by the irrigation system is dependent on soil moisture (Mantovani et al., 2009). One of the most used methods for indirect determination of soil moisture employs tensiometers, because they are easy to install and maintain allow you to determine soil moisture and calculate the net irrigation depth (Shock & Wang, 2011). However, it is necessary to know beyond the matrix potential of soil water, the soil's capacity to store water in the root zone and the maximum tension for irrigation return at levels that do not cause damage to crop development (Shock & Wang, 2011). Tensiometers have been used widely in the management of vegetable crops to determine irrigation frequency for the recommended soil water tension of 10–20 kPa (Marouelli, 2008).

Brassica rapa is an important fresh and processed vegetable, especially in Asian countries. With the migration of the Asian population to other parts of the world, it has become increasingly popular in countries around the world. Due to its flavour and high nutritional value, such as vitamins, minerals, and fiber, the demand for this vegetable is constantly growing (Acikgoz, 2016). According to Artemyeva & Solovyeva (2006), *Brassica* vegetables also have high amounts of plant secondary metabolites, which have anti-carcinogenic, antioxidant, antibacterial, and antiviral properties, in addition to boosting the immune system, reducing inflammation, and preventing the development of cardiovascular diseases.

However, it is a highly water-demanding leafy vegetable grown mainly in a protected environment and using drip irrigation (Maršalkienė et al., 2014), so soil moisture should be kept close to field capacity throughout the growth cycle (Filgueira, 2008). Scheduling irrigation is essential for maximizing the productivity of the crop under different agronomic management practices (Maršalkienė et al., 2014). Research results are presented for this crop, such as indications of cultivars for regions with warm climate (Seabra et al., 2014), fertilizer use (Pascual et al., 2013), nitrogen level, irrigation frequency and planting date (Maseko et al., 2017). However, there is little research related to irrigation management, informing the appropriate soil water tension range for crops, which does not harm the development, productivity and quality of Chinese cabbage and also advise farmers on critical crop limit and soil moisture parameter to determine the frequency of irrigation.

Physiological aspects of a plant, such as photosynthesis and plant development, are closely related to plant's water status and directly affect its yield (Silva et al., 2015). Understanding the changes in these plant parameters in relation to soil water properties prevailing during the cultivation of Chinese cabbage will help to develop an effective irrigation schedule that will increase its quality and productivity. Therefore, the objective of this study was to evaluate the physiological indicators, development, and productivity of Chinese cabbage under different soil water tension ranges.

The present study was conducted as an important contribution to irrigation management practices and assist in deciding which water management option to practice when producing Chinese cabbage under different water tensions in the soil. We hypothesized that the effects of water stress on soil and cultivar on growth regulation, physiology, and efficiency in the use of Chinese cabbage water are related to soil-plant-atmosphere interactions, in order to obtain high yields. In particular, this information should facilitate the establishment of scientific irrigation systems for Chinese cabbage, help maintain sustainable land use and provide a theoretical basis for the sustainable development of agriculture.

MATERIALS AND METHODS

Characterization of the experimental area

Two experiments were performed, in the months of February to May and in the years 2016 and 2017, at the Experimental Station of the Federal Technological University of Paraná (25°42′S, 53°06′W and 520 m altitude). The experiments were conducted in a greenhouse covered with a 150-µm thick transparent polyethylene under controlled light and temperature conditions. The climate in the region according to Köppen classification is humid subtropical (Cfa), with no defined dry season and the warmest month average temperature of 22 °C (Alvares et al., 2013).

Soil physical and chemical analysis

Polyethylene pots (18 L) were filled with dry soil that was previously crushed and sieved through a 2 mm mesh sieve. The soil was Dystroferric Red Latosol (Embrapa, 2018), collected from the ravine, from the top 0–20 cm layer, located in the Experimental Area of the University with 78.3% clay, and therefore characterised as very clay-rich (USDA, 2017). The soil physical and chemical characteristics measured during the pre-planting stage are listed in Table 1.

Granulometry (clay, silt and sand) analyses were performed at the Laboratory of Physics and Soil Water of the University of Passo Fundo – Rio Grande do Sul – Brazil according to the methodology described by Gee & Bauder (1986). For the analyzes was used as dispersant aqueous sodium hydroxide solution (4 kg m^{-3}) and Boyoucos densimeter for the readings. The first reading was performed 40 seconds after 6 hours of agitation to determine the total sand and the second reading 2 hours later to determine the clay, and the silt fraction was determined by difference. The separation of the sand fraction was performed by washing and sieving in a 0.053 mm mesh sieve. After the samples were oven dried, the sand fractions were separated by very thick (> 1 mm), thick (0.5–1.0 mm), medium (0.25–0.5 mm), thin (0.105–0.25 mm) and very thin (< 0.105 mm).

The analyzes of soil density, particle size, microporosity, macroporosity and total porosity were carried out at the Soil Laboratory of the Federal Technological University of Paraná – Dois Vizinhos, according to the methodology proposed by Embrapa (1997), using six replications in soil each analysis.

Soil density was determined using the volumetric ring method, where the volume of the ring was calculated, and then the soil and the ring weighed together, stored in a greenhouse at 105 °C until constant mass, and then removed and weighed after cooling. Soil density was calculated using Eq. (1):

$$Density\ (g\ cm^3) = \frac{a}{b} \quad (1)$$

where a – dry sample weight at 105 °C (g); b – ring volume (cm^3).

Table 1. Physical and chemical characteristics of experimental soil in the 0 to 20 cm depth layer

Measurement	Results
Clay (%)	78.3
Silt (%)	16.7
Sand (%)	5.0
Macroporosity (%)	0.31
Microporosity (%)	0.42
Total porosity (%)	0.73
Particle Density (g cm^{-3})	3.52
Soil density (g cm^{-3})	0.95
pH $CaCl_2$	5.80
Organic matter (%)	1.88
P (mg dm^{-3})	11.78
K^+ (cmol$_c$ dm^{-3})	0.45
Ca^{+2} (cmol$_c$ dm^{-3})	6.10
Mg^{+2} (cmol$_c$ dm^{-3})	3.70
Cu (mg dm^{-3})	4.71
Fe (mg dm^{-3})	45.53
Zn (mg dm^{-3})	12.29
Mn (mg dm^{-3})	188.54
Sum of bases (mg dm^{-3})	10.25
$H^+ + Al^{+3}$ (cmol$_c$ dm^{-3})	3.18
Base saturation (%)	76.32

Notes: Methodologies according to Teixeira et al. (2017), where organic matter by moist digestion; P, K, Cu, Fe, Zn and Mn extracted with Mehlich's –I solution; pH in $CaCl_2$ – 1:2.5; Ca, Mg and Al exchangeable extracted with KCl – 1 mol L^{-1}.

Microporosity (Eq. 2) and macroporosity (Eq. 3) were determined using the stress table method, where in samples saturated with known mass are placed under a stress table and regulated using a 60 cm water column. After 24 h, they are removed and weighed, the percentage saturation determined, and then the samples transferred to an oven and dried at 105 °C until a constant mass is achieved.

$$Microporosity = \frac{(a-b)}{c} \quad (2)$$

where a – mass of sample taken from tension table; b – dry sample weight at 105 °C; c – volume of the ring.

$$Macroporosity = saturation\ percentage - microporosity \quad (3)$$

Total porosity was obtained by Eq. 4.

$$Total\ porsity = microporosity + macroporosity \quad (4)$$

To determine particle density, the density (Eq. 1) and total porosity (Eq. 4) of four samples were determined. Particle density was calculated using Eq. (5):

$$Particle\ density\ (g\ cm^3) = \frac{a}{b} \quad (5)$$

where a – soil density (known mass by volume (g); b – volume occupied by solids (100 – total porosity) (cm^{-3}).

The soil water retention curve was determined from undisturbed samples collected at 0.10 m depth in the field, with six replications (Fig. 1). Volumetric humidity at low tensions points (6 and 10 kPa) was determined using porous plate funnels; the humidity at 1,500 kPa tension was estimated from that at 100 and 300 kPa tensions using Richards chamber and pedotransfer functions (Michelon et al., 2010).

The relationship between stress and volumetric humidity was adjusted using the model proposed by van Genuchten (1980).

The adjustment was conducted in RETC (van Genuchten et al., 1991) with the following parameters at a depth of 0.10 m: residual volumetric humidity (m^3 m^{-3}) = 0.078; volumetric humidity at saturation (m^3 m^{-3}) = 0.43; model tuning parameters: m = 0.359; n = 1.56; α = 0.036, and R^2 = 0.95.

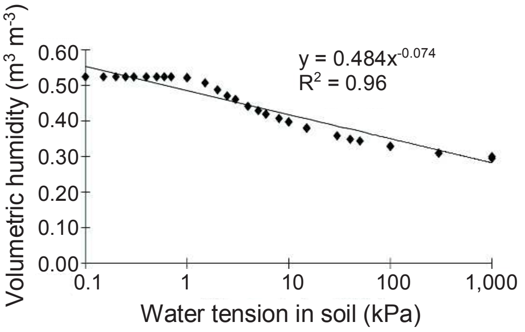

Figure 1. Soil water retention curve 0.10 m depth.

Plant Material and Cultural Practices

Chinese cabbage seedlings from two cultivars, Eikoo and Kinjitsu, were grown in 200-cell polyethylene trays filled with commercial Carolina Soil® substrate. The seeds were bought from the company Horticeres seeds®.

The plants were transplanted 20 days after sowing when they developed between four and six definitive leaves (Segovia et al., 2000) in both experiments.

Mean temperature, relative humidity, and radiation data for the region were obtained from the UTFPR weather station (16 universal time coordinated), located near the experimental unit. Potential evapotranspiration was estimated by the Penman-Monteith method (Allen et al., 1998). The climatic elements used to estimate potential evapotranspiration comprise a set of factors such as maximum and minimum temperature, real vapor pressure, net radiation, and wind speed. The mean temperature and mean evapotranspiration were 17.6 °C and 0.78 mm day^{-1} in the first experiment and 21.8 °C and 1.75 mm day^{-1} in the second experiment, respectively. The temperature conditions were within the optimal range for the culture (Filgueira, 2008).

Pest control such as aphid (*Aphis gossypii* G.), *Diabrotica speciosa* and disease such as erwinia (*Erwinia carotovora*) were performed according to the recommendations by Segovia et al. (2000). Fertilization was calculated based on the soil chemical characteristics and the recommendations by Segovia et al. (2000). Nitrogen fertilization (urea) was conducted in three applications of 40 kg ha^{-1}, at planting, at 15 days, and at 30 days after transplantation. The base fertilization with phosphorus (Monoammonium phosphate) and potassium (Potassium chloride) was applied at 100 kg ha^{-1} P_2O_5 and 40 kg ha^{-1} K_2O, in a single application to the pots.

Irrigation management and water consumption

Soil moisture for each observed tension was determined using the water retention curve according to the depth of the root system (100 mm), the pot area (0.07 m^2), and the average moisture value of the range soil water tension (current θ); the replacement volume was calculated so that it reaches field capacity (FC) of 0.397 m^3 m^{-3}, according to Mantovani et al. (2009).

Irrigation management was performed based on the soil water matrix potential, determined by tensiometers installed at a depth of 10 cm in each experimental unit. Tension readings were taken daily in the late afternoon with a digital tensiometer. When the mean tension reached the treatment tension range, irrigation was performed until reaching FC. For soil water tension ranges 13–17, 23–27, 33–37, and 43–47 kPa at the time of irrigation, the application irrigation depths were 3.14, 9.29, 14.57, and 18.86 mm, respectively. Water was distributed evenly along the irrigation slide using a graduated beaker.

The number of irrigations was monitored during the experiments, and their frequency was expressed as the number of days between two irrigations. Total water consumption of the crop was calculated at the end of the experiments for each treatment based on the number of irrigations and the net irrigation depth, and expressed in millimetres (mm).

Water use efficiency (WUE – kg m^{-3}) was calculated according to Eq. (6), proposed by Doorenbos & Kassan (1994):

$$WUE = \frac{Y}{W} \tag{6}$$

where Y – is the Chinese cabbage yield (kg ha^{-1}); W – amount of water applied (m^3 ha^{-1}).

Treatments and Experimental Design

The experimental design was completely randomized in a 2×4 factorial scheme, with the two cultivars (Eikoo and Kinjitsu) and four soil water tension ranges (13–17, 23–27, 33–37, and 43–47 kPa), with five repetitions. One plant was transplanted per pot and the pots were arranged at 30×60 cm spacing.

Evaluated Parameters

Physiological parameters

The relative chlorophyll index was determined in five plants 70 days after transplantation on two expanded leaves from the middle third of each plant using a portable chlorophyll meter Chlorofilog (Falker®, made in Porto Alegre – Rio Grande do Sul, Brazil).

The net CO_2 assimilation rate (A, μmol CO_2 m^{-2} s^{-1}), stomatal conductance (gS, mol H_2O m^{-2} s^{-1}), intracellular CO_2 concentration (Ci, μmol CO_2 mol^{-1}), transpiration rate (E, mmol H_2O m^{-2} s^{-1}), and water use efficiency (WUE, %) were evaluated between 9:00 and 11:00 on two fully developed, healthy leaves per plant, one in the lower third and one in the middle third of the plant at 70 days after transplantation. The measurements were conducted using a gas exchange measuring system equipped with LI-6400XT infrared gas analyser (IRGA) (LI-COR, Lincoln, NE, USA), with automatic CO_2 injector and artificial light source. The conditions in the measuring chamber were kept constant at 1,300 μmol $m^{-2}s^{-1}$ photosynthetically active radiation (PAR) and 400 μmol CO_2 mol^{-1} during the measurements.

Growth and yield parameters

The harvests in both experiments were performed 88 days after sowing, when the cabbage head was firm to the touch (Segovia et al., 2000). Compactness of the head was evaluated using a grade scale proposed by Souza et al. (2013) with the scores from 0 to 5, where 0, plants with total head absence; 1, plants with a head without a defined core;

2, plants with apparent core head and loose peripheral leaves; 3, plants with heads that have a defined core and peripheral leaves in the beginning stage of compaction; 4, plants with heads that have a defined core and compact peripheral leaves, but the leaves can be visually delimited; and 5, plants with compact head without visually delimited peripheral leaves.

Fresh leaf mass was determined on a precision digital scale (0.0001 g).

Statistical Analysis

The data obtained were subjected to the analysis of variance (F test) and the effect of the treatments was evaluated by the Scott-Knott means test *($P > 0.05$)*. Statistical analyses were performed in SAS Studio (2017).

RESULTS AND DISCUSSION

Physiological parameters

The relative chlorophyll index was higher in Eikoo than in Kinjitsu in 2016 and 2017, and it was the highest under the tension range of 13–17 kPa (Table 2). The year 2016 resulted in higher chlorophyll content. It was 8.9% higher at the tension range of 13–17 kPa than at the 43–47 kPa tension range. As the soil water stress became more negative, the chlorophyll content decreased. The higher soil water stress affected pigment concentration and reduced the photosynthetic capacity. The results are consistent with the findings of other studies. Hanci & Cebeci (2014) observed that water stress decreased the chlorophyll and carotenoid concentrations in onion (*Allium cepa L.*). In addition, the total chlorophyll concentrations in eggplant (*Solanum melongena* L.) at high water stress (40% field capacity) decreased by 55% when compared with the total chlorophyll concentrations in the control (100% field capacity) (Kirnak et al., 2001). Furthermore, decreased or unaltered chlorophyll concentrations have been reported in other species under water stress, depending on the duration and severity of the stress (Pirzad et al., 2011).

Table 2. Chlorophyll relative index of Chinese cabbage cultivars Eikoo and Kinjitsu exposed to different soil water tension ranges in two experiments (2016–2017)

Soil water tension (kPa)	Chlorophyll relative index					
	2016			2017		
	Eikoo	Kinjitsu	Mean	Eikoo	Kinjitsu	Mean
13–17	49.00	44.60	46.80 a*	43.5	36.6	40.05 a
23–27	46.20	43.40	44.80 b	39.5	34.2	37.50 b
33–37	46.40	43.10	44.75 b	40.5	37.4	36.90 b
43–47	45.32	42.00	45.66 b	37.6	37.5	36.50 b
Mean	46.73 A	43.27 B	45.00 A**	40.27 A	36.4 B	38.34 B
C.V. (%)		14.0				12.4

Means followed by the same uppercase letter in the row and lowercase in the column do not differ statistically by the Scott-Knott test ($p > 0.05$*); **Means of years (2016–2017); C.V. Coefficient of variation.

According to Taiz & Zieger (2016), water deficiency is one of the environmental stresses responsible for the reduction of leaf pigments and lowered photosynthesis rate. This effect is associated with a limited capacity for synthesis and greater degradation of total chlorophylls, which stimulated the plants to use alternative energy dissipation routes to avoid photoinhibition and photoxidation under stress conditions.

A differential behaviour in gas exchange was observed between the two cultivars photosynthesis values (net CO_2 assimilation), internal CO_2 concentration (Ci), and transpiration rate (E) were higher in Eikoo in 2016 and 2017 (Table 3). The year 2017 resulted in higher internal CO_2 concentration and transpiration rate. The higher photosynthesis values calculated for Eikoo may be related to the higher relative chlorophyll index, which provided higher photosynthetic efficiency. Chlorophyll directly reflects the overall photosynthesis and assimilates formation that is linked with the overall crop growth and productivity (Ghodke et al., 2018).

The net CO_2 assimilation, internal CO_2 concentration, and transpiration were higher in the soil water tension range of 13–17 kPa than in other ranges, possibly due to the greater water availability at this tension range (Table 3). The greater water availability bestows a higher internal concentration of carbon.

Table 3. Assimilation of liquid CO_2 (A), internal CO_2 concentration (Ci), and transpiration rate (E) of Chinese cabbage cultivars Eikoo and Kinjitsu exposed to different soil water tension ranges in two experiments (2016–2017)

A (µmol CO_2 m^{-2} s^{-1})						
		2016			2017	
Soil water tension (kPa)	Eikoo	Kinjitsu	Mean	Eikoo	Kinjitsu	Mean
13–17	14.5	12.7	13.6 a*	15.8	13.2	14.5 a
23–27	11.9	11.5	11.7 b	12.3	12.0	12.2 b
33–37	11.5	10.0	10.7 b	12.8	10.5	11.6 b
43–47	10.3	9.5	9.9 b	11.2	9.7	10.5 c
Mean	12.3 A	10.9 B	11.6$^{ns\ **}$	13.0 A	11.3 B	12.1
C.V. (%)	20.86				19.30	
Ci (µmol CO_2 mol^{-1})						
13–17	262.9	270.3	266.6 a	291.5	285.0	288.3 a
23–27	257.5	250.6	254.0 b	284.7	259.4	272.1 b
33–37	242.0	257.8	249.9 b	274.0	266.6	270.3 b
43–47	230.3	273.2	251.7 b	262.5	258.3	260.4 c
Mean	248.17B	263.0 A	255.6 B**	278.2 A	267.3 B	272.7 A
C.V. (%)	10.6				11.4	
E (µmol H_2O m^{-2} s^{-1})						
13–17	5.5	4.7	5.1 a	6.2	5.4	5.8 a
23–27	4.9	3.0	3.9 b	5.7	3.7	4.7 b
33–37	4.3	3.7	4.0 b	4.4	4.7	4.5 b
43–47	4.0	3.5	3.7 b	4.1	4.4	4.2 b
Mean	4.7 A	3.7 B	4.2 B**	5.1 A	4.5 B	4.8 A
C.V. (%)	20.3				22.8	

*Means followed by same capital letters in the row and lowercase in the column do not differ statistically by Scott-Knott test ($p > 0.05$); **Means of years (2016–2017); C.V. Coefficient of variation.

The highest rate of net assimilation measured at 13–17 kPa tension is linked to the increased amount of internal CO_2 concentration at the time when the plants exhibited the highest stomatal conductance. Thus, water and CO_2 are among the limiting factors of photosynthesis, and the higher diffusive resistance of stomata reduces photosynthesis, mainly by restricting leaf gas conduction. Therefore, water restriction in the soil water tension range of 23–47 kPa may have inhibited photosynthesis due to stomatal conductance for both water and CO_2 flow decreased by closing the stomata (Nemeskéri & Helyes, 2019), which also explains the lower transpiration rate and productivity under these tension ranges.

The increase in the internal CO_2 concentration values is accompanied by increased stomatal conductance. Thus, stomatal limitation would be the main factor linked to photosynthetic performance; i.e. the larger the stomatal opening, the greater the diffusion of CO_2 into the substomatal chamber (Nascimento et al., 2018).

Stomatal conductance (g_s) was significantly higher in Eikoo than in Kinjitsu (Table 4), and it was higher at 13–17 kPa tension than at other soil water tensions. The amount of water available in the soil at this tension range was sufficient to keep stomata open and provide favourable conditions for the plant to perform physiological processes, without negatively affecting stomatal opening. Under conditions of optimum water availability (field capacity), the transpiration rate was generally high, which explains the increase in transpiration and stomatal conductance of Chinese cabbage plants at the tension range of 13–17 kPa. When soil water becomes scarce, the plant lowers its transpiration rate to reduce water loss and preserve the water available in the soil (Silva et al., 2015).

Table 4. Stomatal conductance (gS) of Chinese cabbage cultivars Eikoo and Kinjitsu exposed to different soil water tension ranges in two experiments (2016–2017)

gS (mol H_2O m^{-2} s^{-1})						
Soil water	2016			2017		
tension (kPa)	Eikoo	Kinjitsu	Mean	Eikoo	Kinjitsu	Mean
13–17	0.33	0.25	0.29 a*	0.35	0.27	0.31 a
23–27	0.25	0.20	0.22 b	0.27	0.22	0.24 b
33–37	0.21	0.19	0.20 b	0.25	0.18	0.21 b
43–47	0.23	0.16	0.19 b	0.24	0.17	0.20 b
Mean	0.26 A	0.20 B	0.23 $^{ns **}$	0.28 A	0.21 B	0.24
C.V. (%)	15.7			19.3		

^{ns} not significant by Scott-Knott test ($p > 0.05$); *Means followed by same capital letters in the row and lowercase in the column do not differ statistically by Scott-Knott test ($p > 0.05$); ** Means of years (2016–2017); C.V. coefficient of variation.

Growth and yield parameters

Eikoo was characterized by more compact heads, and higher biomass accumulation, compared with Kinjitsu in both experiments (Table 5). The year 2017 resulted in higher fresh leaf mass**.** Compactness is valued by consumers and is used as an indicator of proper head formation. The treatment with 13–17 kPa water tension range produced cabbage with a preferred head formation, as indicated by compactness value of 4.1, which is considered to denote a head of better quality and consumers favour plants with very firm, whitish leaves (Seabra et al., 2014). Therefore, cultivation of the Chinese cabbage at a soil water tension of 13–17 kPa is an important feature for producers that will help to reduce volume during transport and provide gains in head weight.

The soil water tension range of 13–17 kPa improved head compactness, and fresh mass compared with the other ranges in 2016 and 2017. Tension ranges with lower available soil water resulted in less compact and malformed heads, thus corroborating a previous study which connected water deficit during head formation with shrunken and malformed heads (Beshir, 2017).

Table 5. Head compactness, fresh leaf mass (FLM), and yield of Chinese cabbage cultivars Eikoo and Kinjitsu grown at different soil water tension ranges in two experiments (2016–2017)

Head compactness						
Soil water tension (kPa)	2016			2017		
	Eikoo	Kinjitsu	Mean	Eikoo	Kinjitsu	Mean
13–17	4.1	3.2	3.7 a*	4.4	3.7	4.1 a
23–27	3.6	3.0	3.3 b	3.8	3.1	3.4 b
33–37	3.3	2.8	3.0 b	3.5	2.9	3.2 b
43–47	2.9	2.5	2.7 b	3.0	2.8	2.9 b
Mean	3.5 A	2.9 B	3.2 $^{ns\,**}$	3.7 A	3.1 B	3.4
CV (%)	21.4			20.6		
FLM (g plant^{-1})						
13–17	880.5 Aa	750.1 Ba	815.3	1180.5 Aa	880.3 Ba	1030.40
23–27	760.7 Ab	655.4 Bb	708.0	1025.3 Ab	820.2 Bb	922.75
33–37	690.4 Ab	640.5 Ab	665.5	995.0 Ab	797.8 Bb	896.40
43–47	582.8 Ac	575.4 Ac	579.1	897.0 Ac	780.3 Bb	838.65
Mean	728.6	655.35	691.97 B**	1024.45	819.65	922.05 A
CV (%)	12.8			16.0		

*Means followed by same capital letters in the row and lowercase in the column do not differ statistically by Scott-Knott test ($p > 0.05$); **Means of years (2016–2017); C.V. coefficient of variation.

Higher soil water stress due to water deficit significantly reduced the leaf fresh mass production (Table 5). This pattern may have resulted from the fact that, at lower tensions (up to 13–17 kPa), the number of irrigations (40.5) was greater and the interval between irrigations was less (1.3 days; Table 6), which contributed to higher formation, growth, and compactness of head.

The fresh leaf mass at a 13–17 kPa tension was higher than that reported by Averbeke & Netshithuthuni (2010) and Maseko et al. (2017). This inconsistency in the fresh leaf mass may be due to cultivar type, higher photosynthetic activity, and environmental factors such as temperature and water availability (Maseko et al., 2017).

Tangune et al. (2016) reported that the irrigation of broccoli (*Brassica oleracea* var. italica) crop when soil water tension reached 15 kPa resulted in higher commercial fresh mass (0.76 kg), and mean inflorescence diameter (20.5 cm).

Chinese cabbage and other leafy vegetables require frequent irrigation, at least twice a week, to maintain soil water content close to field capacity. This will provide the optimum conditions for leaf growth, which is a function of cell expansion, a physiological process highly sensitive to water stress (Costa et al., 2007), probably due to its superficial root system, i.e. more than 90% of the roots extend in the top 35 cm soil layer and 20 cm from the stem (Averbeke & Netshithuthuni 2010).

Irrigation management and water consumption

The response of cultivars to the irrigation management was similar in both experiments (Table 6). Soil water tension ranges governed the number and frequency of irrigations and the amount of irrigated water in 2016 and 2017. Increasing tension ranges reduced the number of irrigations and therefore their frequency. However, water consumption increased by 63% and 52% in 2016 and 2017, respectively, when comparing the water consumption at soil water tension of 13–17 kPa with that at 43–47 kPa. The year 2017 resulted in higher number of irrigations and water consumption.

Table 6. Number of irrigations, interval between irrigations, and water consumption of Chinese cabbage cultivars Eikoo and Kinjitsu exposed to different soil water tension ranges in two experiments (2016–2017)

	Number of irrigations					
Soil water	2016			2017		
tension (kPa)	Eikoo	Kinjitsu	Mean	Eikoo	Kinjitsu	Mean
13–17	25.0	25.0	25.0 a*	41.3	39.8	40.5 a
23–27	15.0	15.0	15.0 b	21.5	21.5	21.5 b
33–37	13.0	11.0	12.0 c	16.3	14.3	15.2 c
43–47	12.0	10.0	11.0 d	16.5	13.5	15.0 c
Mean	16.3	15.3^{ns}	15.8 B**	23.9	22.3^{ns}	23.1 A
C.V. (%)	6.0			15.2		
	Interval between irrigations (dia^{-1})					
13–17	1.9	1.5	1.7 c	1.3	1.3	1.3c
23–27	3.1	3.1	3.1 b	2.6	2.6	2.6b
33–37	3.7	4.3	4.0 a	3.3	3.8	3.6a
43–47	3.5	4.1	3.8 a	3.1	4.0	3.5a
Mean	3.0	3.3^{ns}	**3.2** ^{ns**}	2.89	2.58^{ns}	**2.74**
C.V. (%)	0.75			17.7		
	Water consumption (mm)					
13–17	78.6	78.1	78.3 d	149.6	124.0	136.8 c
23–27	139.3	139.3	139.3 c	199.6	199.9	199.7 b
33–37	204.3	172.6	188.5 b	234.9	205.3	220.1 b
43–47	231.4	192.6	212.0 a	311.1	254.6	282.9 a
Mean	163.4	145.7^{ns}	154.6 B**	223.8	195.7^{ns}	209.8 A
C.V. (%)	6.24			11.4		

^{ns} not significant by Scott-Knott test ($p > 0.05$); Means followed by the same lowercase letter in the column did not differ statistically by the Scott-Knott test ($p > 0.05$); **Means of years (2016–2017); C.V. Coefficient of variation.

With the increase of tension ranges, the number of irrigations was reduced. However, this longer interval between two irrigations caused a water stress to the crop, reducing the rate of photosynthesis and productivity and increasing water consumption.

Kirnak et al. (2017) in studies conducted with chickpea reported that compared to dry treatment without any irrigations, 54.13% decrease was observed in plant water consumption in full irrigation treatment (323 mm). On the other hand, irrigations significantly increased chickpea yields compared to treatment without irrigation.

The average number of irrigations (15.8 and 23.1), the frequency of irrigations (3.2 and 2.7 days), and water consumption (154.6 and 209.8 mm) differed between 2016 and 2017, respectively. These differences may be related to the lower potential evapotranspiration and average temperature observed in 2016 (0.78 mm day^{-1} and 17.6 °C, respectively) when compared with the values in 2017 (1.75 mm day^{-1} and 21.8 °C, respectively).

Similar results were reported by Ünlükara et al. (2017) studied a response of spinach (*Spinacia oleracea* L. Matador) to the salinity of irrigation water in indoor and outdoor greenhouses to reveal different climatic conditions about the salinity tolerance of the plant; they found that the highest water consumption of 36% was observed due to higher indoor temperature, being one of the climatic factors that directly influenced water consumption and salinity tolerance.

For water use efficiency, cultivars responded differently, Eikoo was more efficient in water use compared to Kinjitsu (Table 7). This greater efficiency of 'Eikoo' is the result of higher rates of liquid assimilation, internal CO_2 concentration, and transpiration, which resulted in greater production capacity (biomass accumulation). According to Beshir (2017) the WUE of the crops can be increased by increasing the transpiration rate of the crops to produce greater biomass (CO_2 assimilation) and yield per unit of water used.

Silva et al. (2018a) found that interannual climate variations due to changes in air temperature and relative humidity had significant effects on the growth, productivity and evapotranspiration variables of the coriander (*Coriandrum sativum* L.) cultivated in a tropical environment. The lowest values of yield and WUE in coriander occurred in the summer growing season, due to the higher values inherent to the evapotranspiration of the crop.

The ranges of water tension in the soil significantly influenced the efficiency of water use (Table 7). The WUE was 36.3% higher in the soil water tension range 13–17 kPa, compared to 43–47 kPa. In water tensions in the soil with greater water restriction, water consumption was higher, but productivity was not increasing, resulting in less efficiency in water use. Similar results were reported by Silva et al. (2018b) for lettuce cultivars, found a significant increase in water consumption and a lower WUE in the summer, due to the higher values of the crop evapotranspiration.

Table 7. Water use efficiency of Chinese cabbage cultivars Eikoo and Kinjitsu exposed to different soil water tension ranges in two experiments (2016–2017)

WUE (kg m^{-3})						
Soil water	2016			2017		
tension (kPa)	Eikoo	Kinjitsu	Mean	Eikoo	Kinjitsu	Mean
13–17	44.2	34.6	39.4 a*	46.4	27.1	36.6 a
23–27	25.3	18.1	21.7 b	33.6	18.4	26.0 b
33–37	17.8	16.5	17.2 b	22.3	17.8	20.1 b
43–47	15.1	12.4	13.8 c	15.1	11.5	13.3 c
Mean	25.6 A	20.4 B	23.0^{ns} **	29.4 A	18.7 B	24.1
C.V. (%)	12.4			19.3		

*Means followed by same capital letters in the row and lowercase in the column do not differ statistically by Scott-Knott test ($p > 0.05$); ** Means of years (2016–2017); C.V. Coefficient of variation.

Xiang et al. (2019) observed that the highest productivity and WUE of Chinese cabbage were obtained with an irrigation level of 120% crop evapotranspiration and an irrigation frequency of four days intervals. The results of that study showed that the amount of irrigation had a greater effect on the yield and WUE of Chinese cabbage than the frequency, due to a positive correlation between crop growth and soil moisture.

Thus, the evapotranspiration of the crops is strongly influenced not only by the water content in the soil, but also by the temperature of the air that the plant is submitted (Silva et al., 2018a). Evapotranspiration can be used as an indicator of the evapotranspiration demand by the crop, and therefore, summer-grown crops will likely have higher water consumption.

The frequency of irrigation is directly determined by soil type and weather conditions (Shock & Wang, 2011). The use of tensiometers or other soil moisture monitoring devices contributes to improved productivity and quality of Chinese cabbage as their use ensures a more efficient irrigation and reduces water costs.

In the face of climate change and its impacts on soil water reservoirs, Várallyay (2010) reports on the possibilities for sustainable soil moisture management and the necessary measures for the rational control of water in crop production, such as increasing water use efficiency; reducing evaporation and runoff; thus increasing the water storage capacity and the available soil moisture range, important measures for the rational control of water.

CONCLUSIONS

The research showed that the soil water tension is an important parameter for programming irrigation.

For greater photosynthetic efficiency, productivity, head compactness, water use efficiency, and better development of Eikoo and Kinjitsu cultivars, these crops should be irrigated when the water tension in the soil is in the 13–17 kPa range. At the highest soil water tension ranges, water restriction influenced photosynthesis, head compactness, and yield of the two cultivars negatively.

The lowest irrigation frequency and water consumption were observed under low potential evapotranspiration and mild temperature conditions. The least water consumption was observed at the 13–17 kPa tension range.

The year 2017 resulted in higher internal CO_2 concentration, transpiration rate, fresh leaf mass, number of irrigations and water consumption compared to the year 2016.

The study results help farmers plan irrigation of Chinese cabbage so that it results in productivity and efficient use of water without wasting water.

ACKNOWLEDGEMENTS. We would like to thank to the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) for granting scholarship to the researcher Dislaine Becker and Editage (www.editage.com) for English language editing.

REFERENCES

Acikgoz, F.E. 2016. Seasonal variations on quality parameters of pak choi (*Brassica rapa* L. subsp. *chinensis* L.). *Adv Crop Sci Tech*. **4**, 233. doi:10.4172/2329-8863.1000233

Allen, R.G., Pereira, L.S., Raes, D. & Smith, M. 1998. Crop evapotranspiration – guidelines for computing crop water requirements. *Irrigation and Drainage Paper* **56**. 300 pp.

Alvares, C.A., Stape, J.L., Sentelhas, P.C., Gonçalves, J.L.M. & Sparovek, G. 2013. Köppen's climate classification map for Brazil. *Meteorolo. Z.* **22**, 711–728. doi:10.1127/0941-2948/2013/0507.

Artemyeva, A.M. & Solovyeva, A.E. 2006. Quality evaluation of some cultivar types of leafy *Brassica rapa*. *Acta Hortic*. **706**, 121–128.

Averbeke, W.V. & Netshithuthuni, C. 2010. Effect of irrigation scheduling on leaf yield of non-heading Chinese cabbage (Brassica rapa L. subsp. chinensis). S Afr J Plant Soil. 27, 322–327.

Beshir, S. 2017. Review on estimation of crop water requirement, irrigation frequency and water use efficiency of Cabbage production. *Journal of Geoscience and Environment Protection* **5**, 59–69.

Carrijo, D.R., Akbar, N., Reis, A.F.B., Li, C., Gaudin, A.C.M., Parikh, S.J., Green, P.G. & Linquist, B.A. 2018. Impacts of variable soil drying in alternate wetting and drying rice systems on yields, grain arsenic concentration and soil moisture dynamics. *Field Crops Res*. **222**, 101–110. https://doi.org/10.1016/j.fcr.2018.02.026

Costa, J.M., Ortuño, M.F. & Chaves, M.M. 2007. Deficit irrigation as a strategy to save water: physiology and potential application to horticulture. J. Integrative Plant Biol. 49, 1421–1434.

Doorenbos, J. & Kassam, A.H. 1994. *Effect of water on crop yield*. Campina Grande: UFPB. (*FAO, Irrigation and drainage studies* **33**), 306 pp.

Embrapa – Brazilian Agricultural Research Corporation. 1997. *National Soil Research Center*. (2nd ed.). Rio de Janeiro, 212 pp.

Embrapa – Brazilian Agricultural Research Corporation. 2018. *Brazilian system of soil classification* (5nd ed.). Rio de Janeiro, 355 pp.

Filgueira, F.A.R. 2008. *New Olericulture Handbook*: *Modern agrotechnology in the production and marketing of vegetables* (2nd ed.). Viçosa: UFV, 412 pp.

Gee, G.W. & Bauder, J.W. 1986. Particle size analysis. In: Klute, A. (Ed.) *Methods of soil analysis: physical, chemical and mineralogical methods.* Madison: American Society of Agronomy, pp. 383–411.

Godfray, H.C.J. & Garnett, T. 2014. Food security and sustainable intensification. *Phil. Trans. R. Soc. B*. **369**, 2012–2073. http://dx.doi.org/10.1098/rstb.2012.0273

Ghodke, P.H., Andhale, P.S., Gijare, U.M., Thangasamy, A., Khade, Y.P., Mahajan, V. & Singh, M. 2018. Physiological and biochemical responses in onion crop to drought stress. *Int.J.Curr.Microbiol.App.Sci.* **7**(1), 2054–2062.

Hanci, F. & Cebeci, E. 2014. Investigation of proline, chlorophyll and carotenoids changes under drought stress in some onion (*Allium cepa* L.) cultivars. *Turkish Journal of Agricultural and Natural Sciences* **2**, 1499–1504.

Kirnak, H., Kaya, C., Tas, I. & Higgs, D. 2001. The influence of water deficit on vegetative growth, physiology, fruit yield and quality in eggplants. *Bulg. J. Plant Physiol.* **27**, 34–46.

Kirnak, H., Varol, I.S., Irik, H.A. & Ozaktan, H. 2017. Effects of irrigation applied at different growth stages on chickpea yield. *Agronomy Research* **15**(5), 1928–1933. https://doi.org/10.15159/AR.17.046

Mantovani, E.C., Bernardo, S. & Palaretti, L.F. 2009. *Irrigation: principles and methods*. 3. ed. Viçosa: UFV, 355 pp.

Marouelli, W.A. 2008.*Tensiometers for irrigation control in vegetables*. Brasília: Embrapa. 15pp.

Maršalkienė, N., Sliesaravičius, A., Ramaškevičienė, A., Žilėnaitė, L. & Švirmickas, G.J. 2014. Agrobiological potential of some soil crucifers of Lithuania's spontaneous flora. *Zemdirbyste* **101**, 153–160.

Maseko, I., Beletse, Y.G., Nogemane, N., Plooy, C.P., Musimwa, T.R. & Mabhaudhi, T. 2017. Productivity of non–heading Chinese cabbage (*Brassica rapa* subsp. chinensis) under different agronomic management factors. *S Afr J Plant Soil*. **34**, 275–282.

Michelon, C.J., Carlesso, R., Oliverira, Z.B., Knies, A.E., Petry, M.T. & Martins, J.D. 2010. Pedotransference functions to estimate water retention in some soils of Rio Grande do Sul. *Cienc Rural* **40**, 848–853.

Nascimento, J.L., Almeida, A.A.F., Barroso, J.P., Mangabeira, P.A.O., Ahnert, D., Sousa, A.G.R., Silva, J.V.S. & Baligar, V.C. 2018. Physiological, ultrastructural, biochemical and molecular responses of young cocoa plants to the toxicity of Cr (III) in soil. *Ecotoxicology and Environmental Safety* **159**, 272–283.

Nemeskéri, E. & Helyes, L. 2019. Physiological responses of selected vegetable crop species to water stress. *Agronomy.* **9**(447), 1– 19. doi:10.3390/agronomy9080447

Pascual, P.R.L., Jarwar, A.D. & Nitural, P.S. 2013. Fertilizer, fermented activators, and EM® utilization in pechay (*Brassica pekinensis*) production. *Pak. J. Agri., Agril. Eng., Vet. Sci.* **29**, 56–69.

Pirzad, A., Shakiba, M.R., Salmasi, S.Z., Mohammadi, S.A., Darvishzadeh, R. & Samadi, S. 2011. Effect of water stress on leaf relative water content, chlorophyll, proline and soluble carbohydrates in *Matricaria chamomilla* L. *J. Med. Plant. Res.* **5**(12), 2483–2488.

Seabra, S.J., Pereira, A.S. & Araujo, K.L. 2014. Performance of Chinese cabbage cultivars in Cáceres – MT. *Hortic Bras*. **32**, 504–507.

Segovia, J.F.O., Melem, N.J., Azevedo, J.S. & Lopes, R.P. 2000. *The cultivation of Chinese cabbage in Amapá*. Macapá: Embrapa Amapá, 20 pp.

Shock, C.C. & Wang, F.X. 2011. Soil water tension, a powerful measurement for productivity and stewardship. *HortScience.* **46**(2), 178–185.

Silva, F.G., Dutra, W.F., Dutra, A.F., Oliveira, I.M., Filgueiras, L.M.B. & Melo, A.S. 2015. Gas exchange and chlorophyll fluorescence in eggplant plants under irrigation depths. *Brazilian Journal of Agricultural and Environmental Engineering* **19**(10), 946–952.

Silva, T.G.F., Silva, B.B., Holanda, R. M., Brito, J.I.B., Braga, C.C., Souza, E.P. & Silva, M.T. 2018a. Evapotranspiration, crop coefficient and water use efficiency of coriander grown in tropical environment. *Hortic Bras.* **36**(4), 446–452. https://dx.doi.org/10.1590/s0102-053620180404

Silva, T.G.F., Tavares, A.L., Sousa, I.F., Silva, T.G.F., Holanda, R.M., Souza, E. P., Silva, B.B., Braga, C.C. & Almeida, R.S.R. 2018b. Evapotranspiration, water use efficiency and crop coefficient of three lettuce varieties grown in a tropical region. *Sci. Agrar.* **41**(3), 798–805.

Soil Science Division Staff. 2017. *Soil survey manual.* Ditzler, C., Scheffe, K. & Monger, H.C. (eds.). USDA Handbook 18. Government Printing Office, Washington, D.C., 639 pp.

Souza, A.L., Junior, S.S., Diamante, M.S., Souza, L.H. & Nunes, M.C.M. 2013. Behavior of lettuce cultivars under tropical climate. *Revista Caatinga* **26**, 123–129.

Statistical Analysis System. SAS Studio. 2017. *http://www.sas.com/en_us/software/university–edition.html//*. Acessed 15.2. 2017.

Taiz, L. & Zeiger, E. 2016. *Plant Physiology*. Porto Alegre: Artmed, 888 pp.

Tangune, F.B., Pereira, G.M., Sousa, R.J. & Gatto, R.F. 2016. Production of drip irrigated broccoli under different soil water stresses. *Semin Cienc Agrar*. **37**, 7–16.

Teixeira, P.C., Donagemma, G.K., Fontana, A. & Teixeira, W.G. 2017. *Manual of soil analysis methods*. 2.ed. Rio de Janeiro: CNPS, 573 pp.

Ünlükara, A., Yurtyeri, T. & Cemek, B. 2017. Effects of Irrigation water salinity on evapotranspiration and spinach (*Spinacia oleracea* L. Matador) plant parameters in greenhouse indoor and outdoor conditions. *Agronomy Research* **15**(5), 2183–2194. https://doi.org/10.15159/AR.17.041

Van Guenuchen, M.T. 1980. A closed form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Sci Soc Am* J. **44**, 892–898.

Van Genutchten, M.T., Leij F.J. & Yates S.S. 1991. *The RETC code for quantifying the hydraulic function of unsaturated soils: version 6.02 V.S.* Riverside: USDA, Salinity Laboratory. Avaiable at: http://www.pc–progress.com/en/Default.aspx?retc–downloads, 20 April 2016.

Várallyay, G. 2010. The impact of climate change on soils and on their water management. *Agronomy Research* **8**, 385–396.

Xiang, Y., Zou, H., Zhang, F., Qiang, S., Wu, Y., Yan, S., Wang, H., Wu, L., Fan, J. & Wang, X. 2019. Effect of irrigation level and irrigation frequency on the growth of mini Chinese cabbage and residual soil nitrate nitrogen. *Sustainability* **11**, 111.

Yazgan, S., Ayas, S., Demirtas, C., Buyukcangaz, H. & Candogan, B.N. 2008. Deficit irrigation effects on lettuce (*Lactuca sativa* var. Olenka) yield in unheated greenhouse condition. *Journal of Food Agronomy and Environment* **6**, 357–361.

Zorica, J. & Stikic, R. 2018. Partial root-zone drying technique: from water saving to the improvement of a fruit quality. Front Sustain Food Syst 1, 1–3. doi: 10.3389/fsufs.2017.00003