

# Photosynthetic pigments and gas exchange in red and green cabbage under no-tillage and conventional systems<sup>1</sup>

## Pigmentos fotossintéticos e trocas gasosas de repolho roxo e verde sob plantio direto e convencional

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**ABSTRACT** - The aim of the present study was to verify changes in the levels of photosynthetic pigments as well as gas exchange in the Fuyutoyo and Red Cabbage cultivars, grown under no-tillage (NT) and conventional (CT) systems. A randomised block design with four replications was used, in a 2 x 2 factorial scheme, where the Fuyutoyo and Red Cabbage cultivars were evaluated under two tillage systems. The levels of chlorophyll a, chlorophyll b, total chlorophyll and anthocyanins in the leaves were evaluated in triplicate. Localised gas exchange was measured at different times of the day, together with different photosynthetic photon flux density curves (*PPFD*). The Fuyutoyo cultivar showed a higher mean value for chlorophyll a (34.58%), chlorophyll b (35.09%) and total chlorophyll (34.76%), however, no difference was seen between cultivars for the levels of anthocyanin. Greater mean values for chlorophyll a (76.07%), chlorophyll b (77.87%), total chlorophyll (76.74%) and anthocyanin (72.24%) were found under CT compared to the cultivars grown under NT. The relative chlorophyll content of the Red Cabbage plants was influenced by adoption of the no-till system, showing a higher value for the SPAD index. The Fuyutoyo cabbage cultivar showed greater photosynthetic capacity during the day, promoting greater instantaneous carboxylation efficiency. All the cultivars and tillage systems gave a linear reduction in water use efficiency during this period. Under the conventional system, despite presenting higher rates of stomatal conductance, the Red Cabbage cultivar achieved lower values for net photosynthesis when submitted to light-curve analysis.

**Key words:** Photosynthesis. Net CO<sub>2</sub> assimilation rate. Crop management. *Brassica oleracea* var. *capitata*.

**RESUMO** - O objetivo do presente estudo foi verificar alterações nos teores de pigmentos fotossintéticos bem como trocas gasosas de cultivares de repolho Fuyutoyo e repolho Roxo, conduzidas em sistema de plantio direto (SPD) e convencional (SPC). Foi utilizado o delineamento em blocos ao acaso com 4 repetições. Em esquema fatorial 2 x 2 avaliaram-se as cultivares de repolho Fuyutoyo e repolho Roxo, sob sistema de plantio direto e convencional. Em triplicatas foram avaliados teores foliares de clorofila *a*, *b* e *total*, e antocianinas. Realizaram-se medidas pontuais de trocas gasosas em diferentes períodos do dia, e curvas de diferentes densidades de fótons fotossinteticamente ativos (*DFFFA*). A cultivar Fuyutoyo apresentou média superior para clorofila *a* (34,58%), clorofila *b* (35,09%) e *total* (34,76%), porém para o teor de antocianina não foi observado diferença entre cultivares. No SPC foi observado maiores médias de clorofila *a* (76,07%), clorofila *b* (77,87%), *total* (76,74%) e antocianina (72,24%), ao comparar com os teores de cultivares conduzidas em SPD. O teor relativo de clorofila de plantas de Repolho Roxo foi influenciado pela adoção do sistema de plantio direto, apresentando maior índice SPAD. A cultivar Repolho Fuyutoyo apresentou maior capacidade fotossintética durante o período do dia promovendo maior capacidade instantânea de carboxilação. Todas cultivares e sistemas de plantio proporcionaram decréscimo linear na eficiência no uso da água neste período. Sob sistema de plantio convencional apesar de apresentar maiores taxas de condutância estomática, cultivar Repolho Roxo atingiu valores menores de fotossíntese líquida, quando submetida a análise de curva de luz.

**Palavras-chave:** Fotossíntese. Taxa de assimilação líquida de CO<sub>2</sub>. Manejo de culturas. *Brassica oleracea* var. *capitata*.

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## INTRODUCTION

In Brazil, the cabbage (*Brassica oleracea* var. *capitata*) is one of the main commercial leafy vegetables. Production of this vegetable in Brazil was 417,108 tons in 2006, where the main producing states were São Paulo, Paraná and Minas Gerais, with 126,030; 52,612 and 52,443 tons produced that year (IBGE, 2006).

Belonging to family brassicaceae, the cabbage has a high nutrient content, particularly vitamins B, C and K, and is rich in mineral salts, mainly calcium and phosphorus (FILGUEIRA, 2008). The species requires high levels of nutrients such as nitrogen (N), phosphorus (P) and potassium (K); under a boron (B) deficiency, the crop may produce smaller heads, with a reduction in the number of internal leaves (SILVA *et al.*, 2012).

When cultivating vegetables, intensive use and turning of the soil can damage the quantity and quality of the soil organic matter (RAMOS *et al.*, 2015). No-tillage in vegetable cultivation is becoming increasingly more widespread in Brazil, as it affords several benefits to the soil, which favour an increase in both soil microbial biomass and carbon sequestration (PEREIRA *et al.*, 2013). In addition, no-tillage has a direct effect on soil nutrient dynamics, favouring the slow release of nitrogen, for example.

Cabbage plants can show a higher level of photosynthetic pigments in the leaves, depending on the type of fertiliser used on the soil, especially in relation to nitrogen (PEDÓ *et al.*, 2012). As a result, NT may present better soil attributes, including an increase in organic matter, higher levels of N available for absorption, an increase in C stock, particulate organic carbon, and carbon associated with minerals, and the humic and oxidisable fractions (MELO *et al.*, 2016).

The level of photosynthetic pigments can directly interfere with gas exchange in the leaves of cultivated plants, as these pigments originate in the chloroplasts, organelles located in the leaf mesophyll, and which are responsible for fixing CO<sub>2</sub> through the use of specialised enzymes. CO<sub>2</sub> fixation does not depend only on the activity of enzymes, such as rubisco (ribulose-1,5-bisphosphate carboxylase oxygenase); gas exchange by the leaves can be influenced by such morphophysiological attributes as stomatal density, stomatal conductance and leaf position (adaxial or abaxial) (TAIZ; ZEIGER, 2013).

Thus, studies related to the photosynthetic rates of red and green cabbage cultivars grown under different tillage systems (NT and CT) can aid in crop management, affording increased productivity under the different systems. In view of the above, the aim of this study was to evaluate the level of photosynthetic pigments in the

leaves, as well as to measure gas exchange, in cultivars of red and green cabbage grown under no-tillage (NT) and conventional (CT) systems.

## MATERIAL AND METHODS

The experiment was conducted from March to October 2014, at the Prof. Dr. Antônio Carlos dos Santos Pessoa Experimental Station of the State University of Western Paraná, in the district of Marechal Cândido Rondon (24°33' S, 54°31' W and altitude of 420 m). The soil is classified as a Eutrophic Red Latosol with a clayey texture (SANTOS *et al.*, 2018).

The experimental design was of randomised blocks in a 2 x 2 factorial scheme, with four replications. The treatments consisted of two cabbage cultivars (Red and Fuyutoyo) and two tillage systems, direct (NT) and conventional (CT).

The experiment was carried out in two stages, the first starting in March with the sowing and management of millet (*Pennisetum americanum*) and soybean (*Glycine max*) as cover crops; in mid-March 2014, 15 kg ha<sup>-1</sup> millet and 45 kg ha<sup>-1</sup> soybeans were sown manually throughout the experimental area. After spreading the seeds, they were incorporated into the soil to a depth of five centimetres. The plants were desiccated and toppled at the beginning of June 2014.

Soil preparation under the conventional system consisted of ploughing and harrowing, incorporating the straw into the soil to a depth of 0.4 m. Under the no-tillage system, soil turning was minimal, using a mechanical seeder to open the furrows.

The second stage of the experiment started with the production of the cabbage seedlings. The seedlings were produced in expanded polystyrene trays of 128 cells containing commercial substrate. The trays were kept in a greenhouse until transplanting. Twenty-eight days after sowing, when the cabbage seedlings presented two definite leaves, they were transplanted to the field at a spacing of 0.50 m between plants and 0.80 m between rows; sixteen plants were transplanted per plot.

Fertilisation when planting the cabbage was carried out based on the soil analysis and the recommendations of Trani *et al.* (1997). The recommended dose of 600 kg ha<sup>-1</sup> P<sub>2</sub>O<sub>5</sub> (in the form of triple superphosphate), 180 kg ha<sup>-1</sup> of K<sub>2</sub>O (in the form of potassium chloride), 60 kg ha<sup>-1</sup> N (in the form of urea), and 72 kg ha<sup>-1</sup> S (in the form of triple superphosphate) was incorporated into the sowing row to a depth of 0.15 m one day before transplanting the seedlings. Twenty days after transplanting (DAT), leaf fertilisation was carried out using boron, at a dose of 1 g L<sup>-1</sup> boric

acid. Cover fertilisation with nitrogen and potassium was applied at 15, 30 and 45 DAT. Phytosanitary control and other crop treatments were carried out as needed.

The analyses were conducted on fully expanded, outer leaves of the plant, 73, 74 and 75 DAT (sunny with no cloud), at 08:00, 10:00, 12:00, 14:00, 16:00 and 18:00. Initially, the relative chlorophyll content was evaluated using the SPAD 502 plus portable meter (Konica Minolta) to obtain the SPAD index.

A portable infrared photosynthesis gas analyser - IRGA (Li-6400XT, LI-COR) was used in the gas-exchange analysis, when the following were evaluated: the net CO<sub>2</sub> assimilation rate (*A*), leaf transpiration (*E*), stomatal conductance (*g<sub>s</sub>*), internal CO<sub>2</sub> concentration (*C<sub>i</sub>*), water use efficiency (*WUE*), intrinsic water use efficiency (*iWUE*), and instantaneous carboxylation efficiency (*AC<sub>i</sub>*). A standard photon flux of 1200 μmoles m<sup>-2</sup> s<sup>-1</sup>, a standardised air flow of 500 μm per minute, and 400 μmoles CO<sub>2</sub> employing a pressurised carbon dioxide gas cylinder of 12 g were used in the localised analysis, which was carried out at different times of the day. In addition, photosynthetic curves were produced between 09:00 and 12:00, using different photosynthetic photon flux densities (*PPFD*). A range of from 2200 to 0 μmol photons m<sup>-2</sup> s<sup>-1</sup> was used, giving a total of 12 intensities.

The response curves for *A* and *PPFD* were adjusted by the equation:  $A = A_{\max} [1 - e^{-k(Q - Q_c)}]$  (PRADO; MORAES, 1997). Below 240 μmol photons m<sup>-2</sup> s<sup>-1</sup>, the *PPFD* was varied by smaller intervals to allow the curves to be obtained from several points and permit the apparent quantum efficiency ( $\Phi$  [μmol CO<sub>2</sub>/μmol photons]) to be calculated. The data were adjusted by linear equation:  $A = a + \Phi \cdot Q$ , where *a* and  $\Phi$  are adjustment coefficients and *Q* represents the photon density. The light compensation point is found at the intersection of the curve with the X axis.

In addition to the gas exchange analysis, chlorophyll and anthocyanins were determined in the leaves. Leaf samples were collected and kept in liquid nitrogen to ensure the biochemical characteristics were maintained. The levels of chlorophyll a and b, and the anthocyanins

were then established using the methodology described by Arnon (1949), employing extraction with 80% acetone and quantification in a spectrophotometer.

The data were tabulated and submitted to analysis of variance using the Sisvar 5.3 statistical software (FERREIRA, 2014). Where the factors under study were significant, Tukey's mean-value comparison test was carried out. It was decided to use regression analysis for the different evaluation times and *PPFD*.

## RESULT AND DISCUSSION

When evaluating the SPAD index in cabbage cultivars grown under different tillage systems, an interaction was seen between the factors under study (Table 1). The SPAD index in the Fuyutoyo cultivar was not influenced by the tillage system, whereas the Red Cabbage cultivar showed higher values for the SPAD index when grown under NT, being 22.03% superior compared to CT. For the same variable, under NT, the Red Cabbage cultivar showed a higher mean value (20.91%) compared to the Fuyutoyo cultivar. However, under NT, there was no difference in the SPAD index for the two cultivars under study (Fuyutoyo and Red Cabbage). Moreira and Vidigal (2011), evaluating the intensity of the green colouring via the SPAD index, obtained values ranging from 60.8 to 53.5, at 50 to 78 days after sowing.

Despite the Fuyutoyo cultivar having a predominantly green colour and the red cabbage cultivar predominantly purple, 'Fuyutoyo' had a lower relative chlorophyll content (SPAD index). This shows that the use of a portable chlorophyll meter may not be effective in evaluating the chlorophyll content of the leaves in cabbage cultivars.

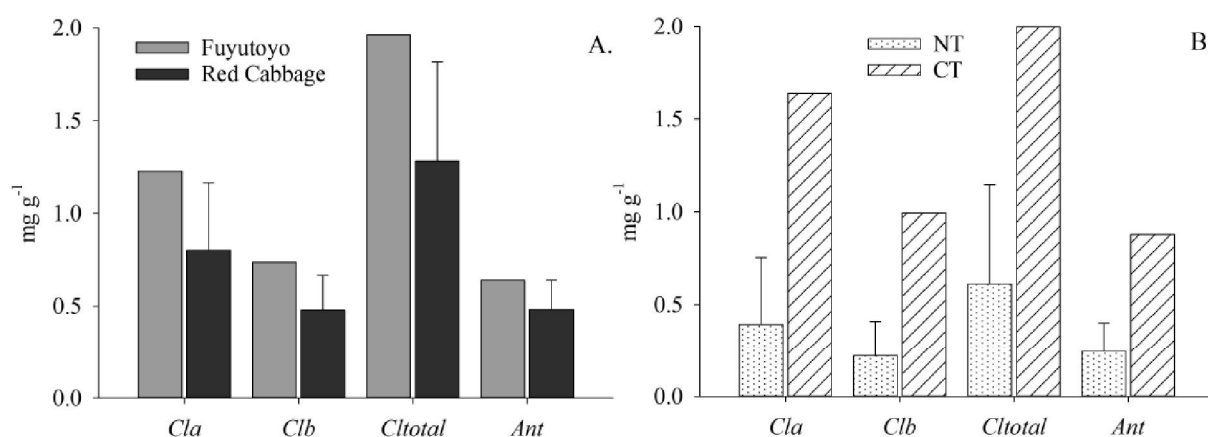
In relation to the levels of chlorophyll a (*Cl<sub>a</sub>*), chlorophyll b (*Cl<sub>b</sub>*), total chlorophyll (*Cl<sub>total</sub>*) and anthocyanins (*Ant*), significance was found for both the cabbage cultivars (Figure 1a) and the tillage systems (Figure 1b).

**Table 1** - SPAD index in the Fuyutoyo and Red Cabbage cultivars grown under no-tillage and conventional tillage systems

Cultivar	Tillage system		Mean
	NT	CT	
Fuyutoyo	31.61 Ab	31.09 Aa	31.35
Red Cabbage	38.22 Aa	29.80 Ba	34.01
CV (%)		11.22	

Mean values followed by the same uppercase letter on a line and lowercase letters in a column do not differ by Tukey's test at 5% probability; NT = no-tillage system; SPC = conventional system

**Figure 1** - Levels of chlorophyll a (Cla), chlorophyll b (Clb), total chlorophyll (Cltotal) and anthocyanin (Ant), in two cabbage cultivars, Fuyutoyo and Red Cabbage (A) grown under no-tillage and conventional tillage (B) systems



Mean values followed by the same lowercase letters do not differ within the same cabbage cultivar; Mean values followed by the same uppercase letters do not differ within the same tillage system; NT = no-tillage system; CT = conventional tillage system; Error bars = LSD

The Fuyutoyo cultivar showed a higher mean value for the Cla (34.58%), Clb (35.09%) and Cltotal (34.76%) content of the leaves, however, no difference was seen between cultivars for the levels of anthocyanin (Figure 1a). These values showed expected results, whereas the cabbage cultivar with predominantly green colouring (Fuyutoyo) tends to present higher levels of leaf chlorophyll compared to the predominantly purple cultivar (Red Cabbage).

Under CT, higher levels of Cla (76.07%), Clb (77.87%), Cltotal (76.74%) and Ant (72.24%) were seen in the leaves, compared with those of cultivars grown under NT (Figure 1b).

The no-tillage system can provide favourable conditions for crop development in general, especially due to the formation of straw and organic matter, soil protection and nutrient cycling. However, for the first crops grown under NT, nutrients that are applied via fertiliser may be immobilised together with the soil organic matter. Results in the literature show that there is generally no increase in production when the no-tillage system is first set up, but only once the system becomes established (ECHER *et al.*, 2016). Under CT, the elements that are important for the plants are readily available, without suffering immobilisation/competition from soil microorganisms.

In the present study, the results found in relation to the photosynthetic pigments Cla, Clb and Ant, did not corroborate results found by Pedó *et al.* (2012). When evaluating seedling quality in 'Sixty-day', 'Red' and 'Bull's Heart' cabbage under nitrogen fertilisation with urea and calcium nitrate, the Red cultivar presented higher mean values for carotenoids, chlorophyll a, chlorophyll b and total chlorophyll.

Cultivation under NT provides the system with a greater amount of organic matter, promoting the mineralisation of elements that are important for plant development. When Vargas *et al.* (2011) studied the effects of using roots and shoots as green manure in the cabbage, they found these could help in supplying the plants with N, but that the root system of the jack bean reduced productivity.

The results of the Pearson Correlation showed that the net CO<sub>2</sub> assimilation rate has no influence on the SPAD index, or on the levels of Cla, Clb, Cltotal and Ant (Table 2). An increase in the levels of Cltotal was seen proportional to the levels of Cla, Clb and Ant, in the same way that the Ant content showed a positive correlation with Cla and Clb. The levels of Cla and Clb in the leaves show a positive correlation of 96%. Although the SPAD index shows no correlation with the total chlorophyll content, the levels of Ant (-38%) and Cla (-36%) show a negative correlation when compared with the SPAD index.

For net photosynthesis (A) evaluated at different times of the day, quadratic growth was seen in the Fuyutoyo cultivar under NT (NTFu), reaching a maximum point of 23.20 μmol CO<sub>2</sub> m<sup>-2</sup> s<sup>-1</sup> at 10:49 (Figure 2a). The same cultivar under CT (CTFu) presented the maximum rate of net CO<sub>2</sub> assimilation at 10:14 (20.95 μmol CO<sub>2</sub> m<sup>-2</sup> s<sup>-1</sup>). The NTFu and CTFu treatments showed no difference (LSD = 2.97) by Tukey's test at 5%.

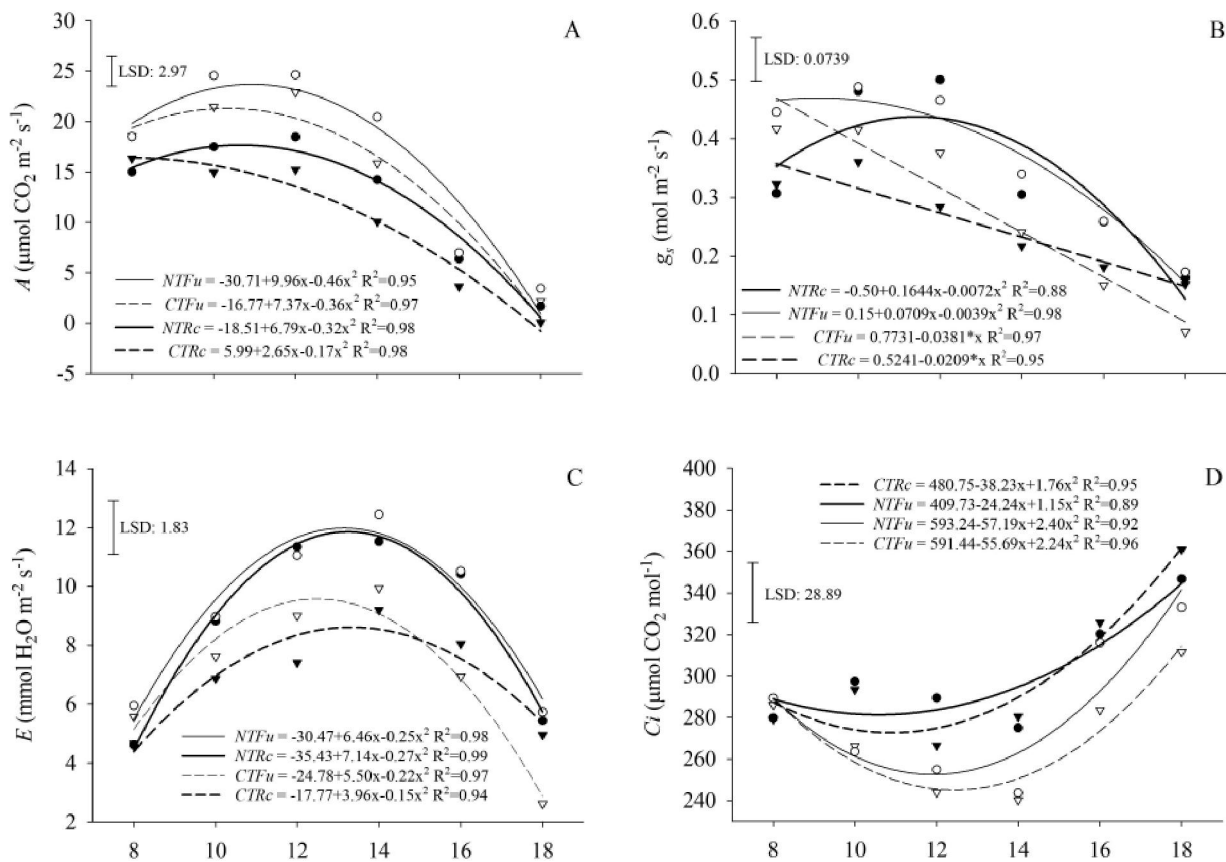
In general, the Red Cabbage cultivar showed lower mean values for A compared to the Fuyutoyo cultivar. The Red Cabbage cultivar under NT (NTRc) showed the highest mean value for A (17.50 μmol CO<sub>2</sub> m<sup>-2</sup> s<sup>-1</sup>) at 10:36, which was similar to the highest value (16.31 μmol CO<sub>2</sub> m<sup>-2</sup> s<sup>-1</sup>) reached by the cultivar under CT (CTRc) at 07:47.

**Table 2** - Pearson correlation coefficients between the chlorophyll a, chlorophyll b, anthocyanin and total chlorophyll content of the leaves, and the net CO<sub>2</sub> assimilation rate (10:00), in two cabbage cultivars, Fuyutoyo and Red Cabbage, grown under no-tillage and conventional tillage systems

	A <sub>(10:00)</sub>	Total chlorophyll	Ant	Clb	Cl a
SPAD Index	-0.1400 <sup>ns</sup>	-0.344 <sup>ns</sup>	-0.377*	-0.300 <sup>ns</sup>	-0.365*
Cl a	-0.0283 <sup>ns</sup>	0.994**	0.873**	0.959**	
Cl b	-0.0316 <sup>ns</sup>	0.984**	0.863**		
Ant	-0.1480 <sup>ns</sup>	0.878**			
Total chlorophyll	-0.0298 <sup>ns</sup>				

\*, \*\* and <sup>ns</sup> = significant at 1% probability, 5% probability and not significant respectively. A = Net CO<sub>2</sub> assimilation rate; Cl a = chlorophyll a; Cl b = chlorophyll b; Ant = anthocyanin

**Figure 2** - Net CO<sub>2</sub> assimilation rate (A), stomatal conductance (B), leaf transpiration (C) and internal CO<sub>2</sub> concentration (D) in different cabbage cultivars grown under no-tillage and conventional tillage systems, at different times of the day



A = net CO<sub>2</sub> assimilation rate; *g<sub>s</sub>* = stomatal conductance; *E* = leaf transpiration; *C<sub>i</sub>* = internal CO<sub>2</sub> concentration. NTFu = Fuyutoyo cultivar under no-tillage; NTRc = Red cultivar under no-tillage; CTFu = Fuyutoyo cultivar under conventional tillage; CTRc = Red cultivar under conventional tillage

Quadratic behaviour was found for the net CO<sub>2</sub> assimilation rate (*A*), with a reduction seen at the end of the day. Higher values for *A* were found under both CT and NT. This may have been due to the higher chlorophyll

content noted in this cultivar (Figure 1a). Monitoring the leaf chlorophyll content using a chlorophyll meter can indicate both satisfactory levels and a deficiency of N in the plants (ARGENTA *et al.*, 2003).

Quadratic behaviour was seen for stomatal conductance in the two cultivars grown under NT (Figure 2b). Red cabbage plants under NT showed the greatest stomatal conductance ( $g_s$ ) ( $0.4384 \text{ mol m}^{-2} \text{ s}^{-1}$ ) at 11:25, followed by a decrease which depended on the time of evaluation, while in plants of the Fuyutoyo cultivar, maximum stomatal opening occurred at 09:05 ( $0.47 \text{ mol m}^{-2} \text{ s}^{-1}$ ). The two cultivars grown under the conventional system showed the highest mean values for  $g_s$  at 08:00, of  $0.4683$  and  $0.3569 \text{ mol m}^{-2} \text{ s}^{-1}$  for 'Fuyutoyo' and 'Red' respectively, followed by a linear decrease until 18:00. The maximum points reached by the Fuyutoyo cultivar were greater than those of the Red Cabbage cultivar under both NT and CT.

The cultivars under evaluation showed a higher rate of leaf transpiration ( $E$ ) (Figure 2c) at the hottest time of the day, between 11:00 and 16:00, as seen from the leaf temperature (Figure 3e). When examining Figure 2c, each cabbage plant shows ascending quadratic behaviour for  $E$ , reaching a maximum point of  $11.97$ ,  $11.85$ ,  $9.57$  and  $8.60 \text{ mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$  under the *NTFu*, *NTRc*, *CTFu* and *CTRc* treatments respectively. The variable  $E$  was significantly influenced by the tillage system, since the plants grown under NT, irrespective of the cultivar, showed a higher rate of water loss compared to those grown under CT.

The internal  $\text{CO}_2$  concentration ( $C_i$ ) of the leaf mesophyll decreases according to the rate of  $\text{CO}_2$  fixation; as such, a reduction in  $C_i$  was seen, which depended on the time of day (Figure 2d). The mean values for  $C_i$  decreased to  $273.15$ ,  $281.99$ ,  $252.54$  and  $245.30 \text{ } \mu\text{mol CO}_2 \text{ mol}^{-1}$  at 10:51, 10h32, 11:52 and 12:26, under the *CTRc*, *NTRc*, *NTFu* and *CTFu* treatments respectively. The Red Cabbage cultivar grown under NT and CT showed similar minimum points for  $C_i$ , as shown by the breakdown of Tukey's test (LSD:  $28.89 \text{ } \mu\text{mol CO}_2 \text{ mol}^{-1}$ ).

Lower minimum points were found for  $C_i$  than those obtained by the Red Cabbage, irrespective of the system, conventional or no-tillage. Therefore,  $C_i$  was influenced by the cultivar, since the Red Cabbage cultivar was able to accumulate higher concentrations of  $\text{CO}_2$  available for fixation, but lower instantaneous carboxylation efficiency (Figure 3c).

The ratio given by the water use efficiency ( $WUE$ ) reveals the amount of water used, in mmols, for fixing  $\mu\text{mol}$ s of  $\text{CO}_2$ . These values showed decreasing linear behaviour depending on the time of evaluation of each treatment (Figure 3a). Plants of the Fuyutoyo cabbage showed the maximum value for  $WUE$  points in the first evaluation (08:00), however, these were not significant by Tukey's test at 5% probability (LSD:  $0.4882$ ). The mean

values for  $WUE$  were reduced depending on the time of the evaluation, whereas for *CTRc* the slope was greater ( $0.3220$ ), a result of the lower mean  $WUE$  ( $-0.01$ ), which differed from the minimum point reached by *CTFu* ( $0.75$ ) and *NTFu* ( $0.48$ ) at 18:00 (LSD:  $0.4882$ ), i.e. based on water use and irrespective of the tillage system, the Red Cabbage cultivar is less efficient in fixing  $\text{CO}_2$  compared to the Fuyutoyo cultivar.

The *CTFu*, *NTFu* and *CTRc* treatments showed ascending quadratic behaviour for intrinsic water use efficiency ( $iWUE$ ), achieving greater mean values of  $63.13$ ,  $54.65$  and  $52.41$  at  $12.41$ ,  $11:42$  and  $10:26$  respectively (Figure 3b). Starting with a higher value for  $iWUE$ , the Red Cabbage cultivar grown under NT presented a linear reduction in mean values, of  $50.43$  at 08:00 to  $21.03$  at 18:00. The highest mean values shown by the regression analysis did not differ by Tukey's test at 5% (LSD:  $16.64$ ).

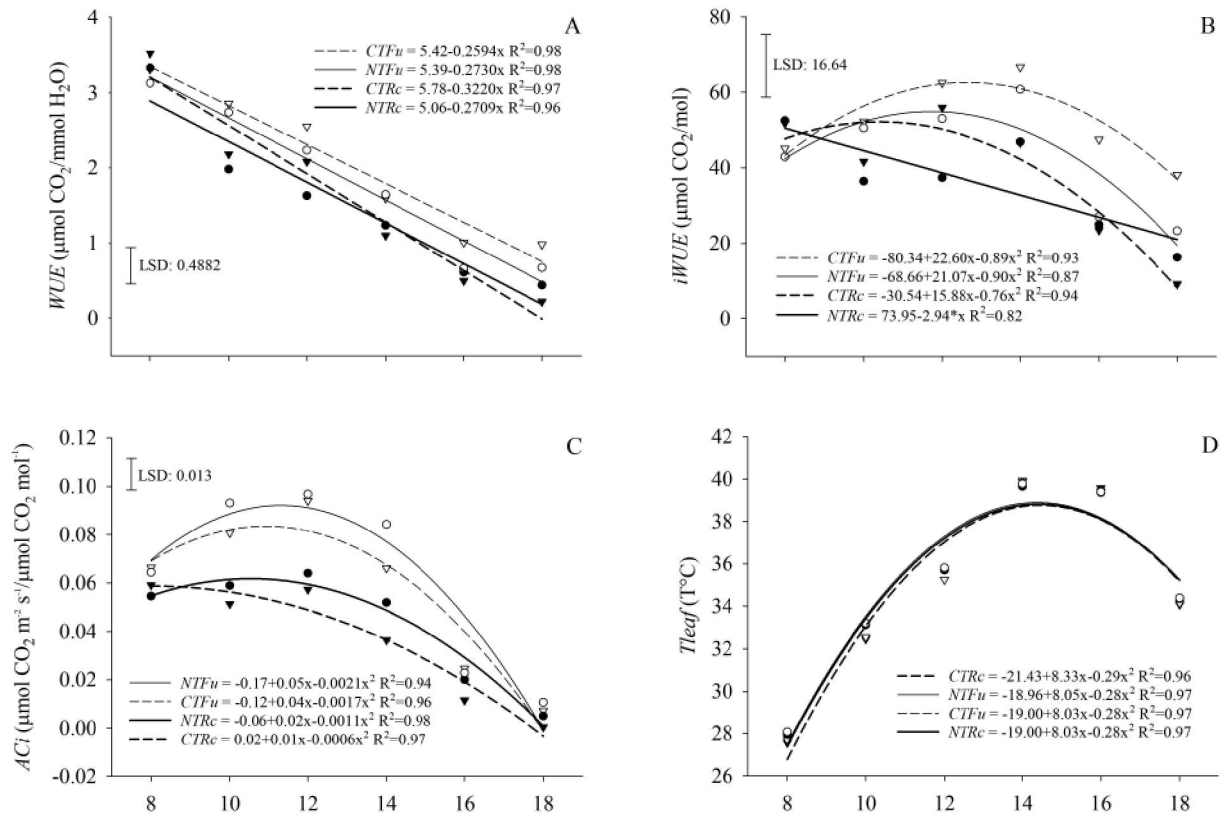
When evaluating instantaneous carboxylation efficiency ( $AC_i$ ), quadratic behaviour was seen for each treatment under evaluation, according to the regression analysis (Figure 3c). The Fuyutoyo cultivar under NT and CT achieved the highest mean values for  $AC_i$  ( $0.089$  and  $0.082$ ) at 11:10 and 10:51 respectively, but did not differ by Tukey's test at 5%. For the Red Cabbage cultivar under NT and CT, maximum points of  $0.061$  and  $0.060$  were found at 10:30 and 08:19 respectively. These values were lower than those obtained by the Fuyutoyo cultivar (LSD:  $0.013$ ), i.e. irrespective of the system adopted, the cultivar with the predominantly green colouring showed a higher rate of net  $\text{CO}_2$  assimilation (Figure 2a), the result of greater carboxylation efficiency (Figure 3c).

Higher values were seen for leaf temperature ( $T_{leaf}$ ), from 14:20 to 14:24 (Figure 3d). From the regression analysis, the quadratic behaviour achieved by the *CTRc*, *NTFu*, *CTFu* and *NTRc* treatments reached leaf temperatures of  $38.38$ ,  $38.89$ ,  $38.57$  and  $38.83$  respectively.

$T_{leaf}$  can be a limiting factor for photosynthesis, as it shows a positive correlation with  $E$  and a negative correlation with  $g_s$ , i.e. as the ambient temperature increases, the leaves heat up, causing greater water loss from the leaf surface, at the same time as stomatal closure (Table 3). As discussed above, the lower the value for  $C_i$  the greater the amount of  $\text{CO}_2$  available for fixation in the leaf mesophyll, so as  $C_i$  and  $AC_i$  are inversely proportional, a correlation coefficient of  $-0.926$  is seen, with a positive correlation for  $A$  and  $AC_i$  of  $0.996$ .

A negative correlation was also seen for  $iWUE$  and  $C_i$ ; this behaviour shows that efficient stomatal opening for  $\text{CO}_2$  fixation is inversely correlated with  $\text{CO}_2$  accumulation in the leaf mesophyll, i.e. variables that afford greater photosynthetic efficiency result in a reduction in  $C_i$ .

**Figure 3** - Water use efficiency (A), intrinsic water use efficiency (B), instantaneous carboxylation efficiency (C) and leaf temperature (D) in different cabbage cultivars grown under no-tillage and conventional tillage systems, at different times of the day



WUE = water use efficiency; *i*WUE = intrinsic water use efficiency; *ACi* = instant carboxylation efficiency; *Tleaf* = leaf temperature. NTFu = Fuyutoyo cultivar under no-tillage; NTRc = Red cultivar under no-tillage; CTFu = Fuyutoyo cultivar under conventional tillage; CTRc = Red cultivar under conventional tillage

**Table 3** - Pearson correlation coefficients between the variables of two cabbage cultivars, Fuyutoyo and Red Cabbage, grown under no-tillage and conventional tillage systems

	<i>Tleaf</i>	<i>ACi</i>	<i>i</i> WUE	WUE	<i>Ci</i>	<i>E</i>	<i>gs</i>
A	-0.3070 <sup>ns</sup>	0.996**	0.904*	0.820*	-0.902*	0.400 <sup>ns</sup>	0.963**
<i>gs</i>	-0.4380 <sup>ns</sup>	0.940**	0.761 <sup>ns</sup>	0.858*	-0.763 <sup>ns</sup>	0.254 <sup>ns</sup>	
<i>E</i>	0.7450	0.446 <sup>ns</sup>	0.579 <sup>ns</sup>	-0.141 <sup>ns</sup>	-0.675 <sup>ns</sup>		
<i>Ci</i>	-0.0477 <sup>ns</sup>	-0.926**	-0.990**	-0.593 <sup>ns</sup>			
WUE	-0.7580 <sup>ns</sup>	0.783 <sup>ns</sup>	0.662 <sup>ns</sup>				
<i>i</i> WUE	-0.0547 <sup>ns</sup>	0.926**					
<i>ACi</i>	-0.2530 <sup>ns</sup>						

\*, \*\* and <sup>ns</sup> = significant at 1% probability, 5% probability and not significant respectively. *A* = net CO<sub>2</sub> assimilation rate; *gs* = stomatal conductance; *E* = leaf transpiration; *Ci* = internal CO<sub>2</sub> concentration; WUE = water use efficiency; *i*WUE = intrinsic water use efficiency; *ACi* = instantaneous carboxylation efficiency; *Tleaf* = leaf temperature

When evaluating the curves for photosynthetic photon flux densities (*PPFD*), the compensation point for the Red Cabbage and Fuyutoyo cultivars under NT

was 44.20 and 46.32 µmol photons m<sup>-2</sup> s<sup>-1</sup> respectively (Figure 4a). Under CT, the Fuyutoyo and Red Cabbage cultivars showed higher compensation points compared to

NT, of 52.53 and 65.69  $\mu\text{mol photons m}^{-2} \text{s}^{-1}$ . The apparent quantum efficiency ( $\Phi$ , slope of the linear region of the light-response curve) was 0.0255, 0.0231, 0.0218 and 0.0223 for the *CTFu*, *NTFu*, *NTRc* and *CTRc* treatments respectively. The Red Cabbage cultivar grown under CT (20.87  $\mu\text{mol CO}_2$ ) and NT (20.30  $\mu\text{mol CO}_2$ ) showed faster *A* saturation than the Fuyutoyo cultivar grown under CT (25.00  $\mu\text{mol CO}_2$ ) and NT (21, 84  $\mu\text{mol CO}_2$ ).

Light increases  $\text{CO}_2$  fixation and affords a drop in transpiration and photorespiration, increasing net photosynthesis (TAIZ; ZEIGER, 2013). When the amount of  $\text{CO}_2$  released into the atmosphere by transpiration and photorespiration is the same as that assimilated by the leaves via photosynthesis, this is known as the light compensation point (LARCHER, 2006).

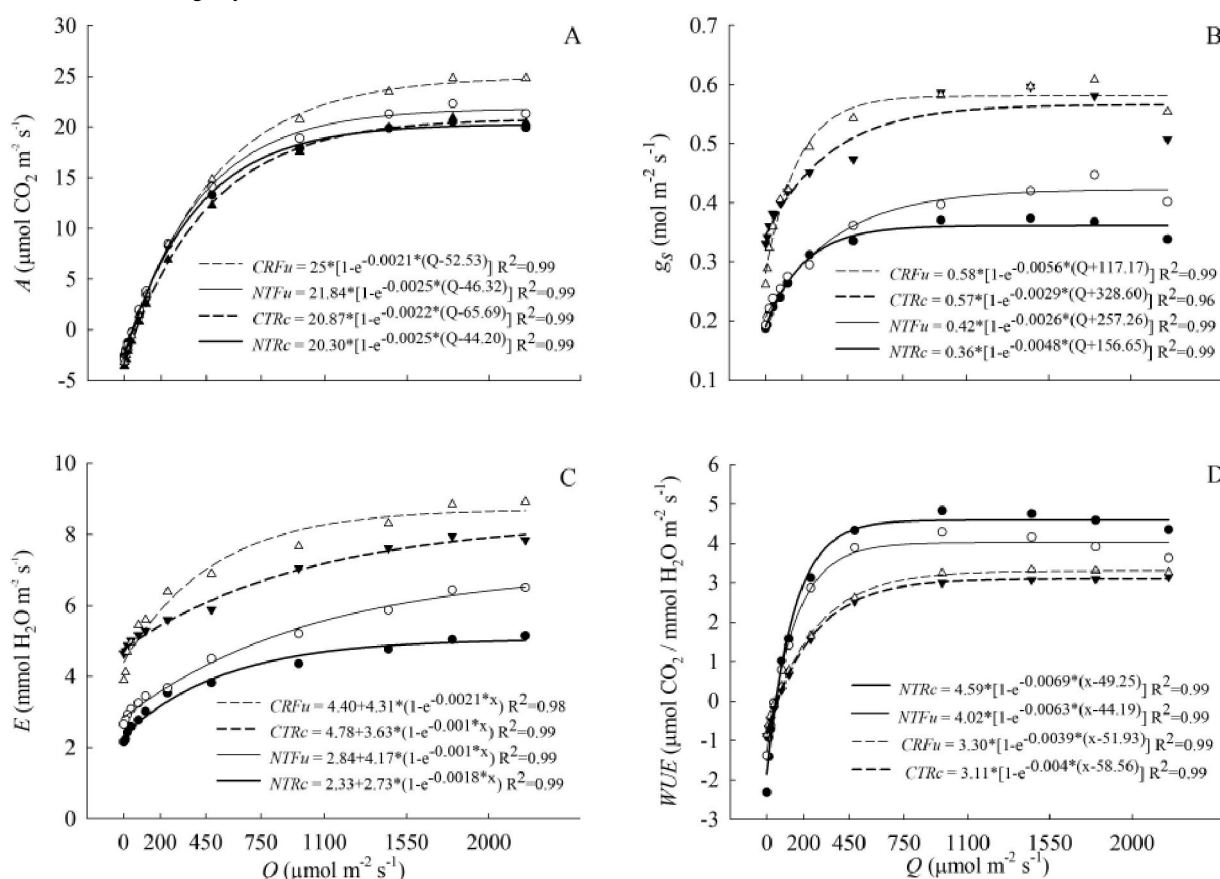
In general, the cultivar with a predominance of green colouring in the leaves showed greater photosynthetic capacity, regardless of the tillage system

adopted. The cabbage cultivar with a predominance of purple colouring showed less apparent quantum efficiency, and as a result, compared to the green-leaved plants, reaches light saturation earlier.

The tillage system directly influenced *gs* values in the cabbage cultivars (Figure 4b). Under CT, the Fuyutoyo and Red Cabbage cultivars had a higher stomatal saturation point compared to NT, of 0.58 and 0.57  $\text{mol m}^{-2} \text{s}^{-1}$  for *CTFu* and *CTRc* respectively, and 0.42 and 0.36  $\text{mol m}^{-2} \text{s}^{-1}$  for *NTFu* and *NTRc* respectively. Turning the soil, together with planting the cabbage cultivars, therefore favoured stomatal opening, probably due to greater soil water percolation, a consequence of the increase in matrix potential increasing water translocation to the leaf mesophyll.

In relation to water loss due to leaf transpiration, the Fuyutoyo cultivar grown under CT showed a greater slope (0.0035) compared to the other treatments (Figure 4c).

**Figure 4** - Photosynthetically active light response curves for net  $\text{CO}_2$  assimilation rate (A), stomatal conductance (B), leaf transpiration (C) and water use efficiency (D), in two cabbage cultivars, Fuyutoyo and Red Cabbage, grown under no-tillage and conventional tillage systems



*A* = net  $\text{CO}_2$  assimilation rate; *gs* = stomatal conductance; *E* = leaf transpiration; *Ci* = internal  $\text{CO}_2$  concentration. *NTFu* = Fuyutoyo cultivar under no-tillage; *NTRc* = Red cultivar under no-tillage; *CTFu* = Fuyutoyo cultivar under conventional tillage; *CTRc* = Red cultivar under conventional tillage



The mean values for  $E$  were lower in the cabbage plants grown under NT, corroborating the results for  $g_s$  (Figure 4b), i.e. the stomatal closure afforded by NT allowed less water to be lost through leaf transpiration, while turning the soil (CT) caused the process to be reversed.

When assessing the ratio of  $A$  to  $E$  to obtain the water use efficiency ( $WUE$ ), maximum points of 4.59 and 4.02 were seen for  $NTRc$  and  $NTFu$  respectively, which were higher than the maximum points achieved by  $CTFu$  and  $CTRc$ , with values of 3.30 and 3.11 (Figure 4d). In view of the above,  $WUE$  values were higher under NT compared to CT, irrespective of the cultivar. This result is related to the smaller water loss seen in Figure 4c; as such, under the conditions of the present study, the tillage system, whether conventional or direct, was crucial for determining greater mean values for  $WUE$ . Although recent, the no-tillage system can promote the reorganisation of primary soil particles, corroborating the soil organic matter (MELO *et al.* 2016).

From the regression analysis, all the plants under evaluation showed linear growth for  $A$  in relation to increases in the ambient  $CO_2$  concentration. When the Red Cabbage cultivar was submitted to different concentrations of ambient  $CO_2$  (0 - 650  $\mu mol mol^{-1}$ ), mean values of 29.53 and 28.10  $\mu mol CO_2 m^{-2} s^{-1}$  were seen under NT and CT respectively, at 650  $\mu mol CO_2 mol^{-1}$  (Figure 5). The  $CTFu$  and  $NTFu$  treatments had maximum points of 33.92 and 31.47  $\mu mol CO_2 m^{-2} s^{-1}$  respectively, at 650  $\mu mol CO_2 mol^{-1}$ , however only  $CTFu$  was greater than either  $NTRc$  or  $NTFu$ . The photosynthetic efficiency seen in the Fuyutoyo cultivar may be related to greater

stomatal opening followed by greater  $CO_2$  diffusion, resulting in an increase in the rate of  $CO_2$  fixation (Figure 2a and b).

The slope of the curve, showed higher values for the Fuyutoyo cultivar (NT:0.0577 and CT: 0.0538) - agreeing with the SPAD index under CT, for the levels of  $Cl_a$ ,  $Cl_b$  and  $Cl_{total}$  in the leaves, and for the localised evaluations at different times of the day. Despite both the Fuyutoyo and Red Cabbage cultivars showing higher values for stomatal opening under CT, allowing for  $CO_2$  diffusion, under NT, the instantaneous carboxylation efficiency presented by the Fuyutoyo cultivar was greater compared to the Red Cabbage cultivar.

The tillage system can influence production in different cabbage cultivars; however, for maize, no differences were found between NT and CT for gas exchange measured at different phenological stages of the crop (LOPES *et al.*, 2009).

Analysis of the photosynthetically active photon curve showed that the green-leafed cabbage cultivar has a higher rate of gas exchange, especially for  $CO_2$  fixation efficiency. Cabbage plants that have higher photosynthetic rates in the outer leaves may show greater head development.

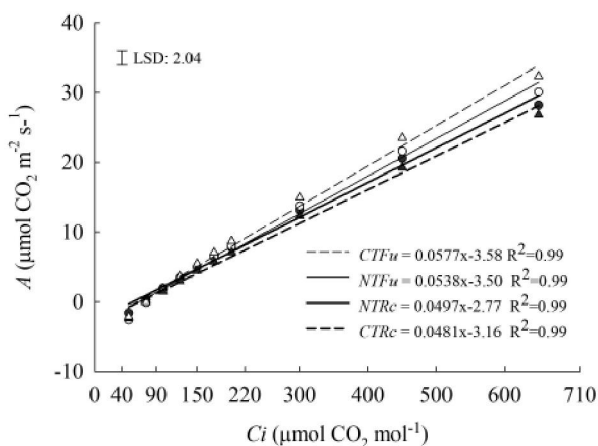
## CONCLUSIONS

1. The relative chlorophyll content of the Red Cabbage was influenced by adoption of the no-tillage system, presenting a higher SPAD index;
2. The Fuyutoyo cultivar showed greater photosynthetic capacity during the day, resulting in greater instantaneous carboxylation efficiency. All the cultivars and tillage systems afforded a linear decrease in water use efficiency during this period;
3. Under the conventional system, despite presenting higher rates of stomatal conductance, the Red Cabbage cultivar achieved lower values for net photosynthesis when submitted to light-curve analysis;
4. In general, plants of the Fuyutoyo cultivar showed high levels of leaf chlorophyll, but higher rates of gas exchange throughout the day under no-tillage, and when measuring the light curves under conventional tillage.

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**Figure 5** - Net  $CO_2$  assimilation rate at different  $CO_2$  concentrations ( $A/C_i$ ) in different cabbage cultivars grown under no-tillage and conventional tillage systems



$A$  = net  $CO_2$  assimilation rate;  $NTFu$  = Fuyutoyo cultivar under no-tillage;  $NTRc$  = Red cultivar under no-tillage;  $CTFu$  = Fuyutoyo cultivar under conventional tillage;  $CTRc$  = Red cultivar under conventional tillage

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