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Evaluation of photosynthetic photon flux in lettuce cultivation at different shading levels

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ABSTRACT

Protected cultivation has grown in Brazil. Generally, greenhouses are covered with transparent plastic film and shading screen. The plastic, over time, loses its transparency due to pollution residues, dust and other debris. The loss of transparency reduces lightness, photosynthesis and leads to losses of productivity and product quality. The losses are not always detectable by the farmer. Additionally, internal shading screens are used to reduce heating transmission to the ground. The objective of this study was to evaluate the impact of shading on lettuce crop productivity and to determine the optimum shading to reach the highest productivity. Plots were set up inside and outside the greenhouse, with four shading levels with black screens (0, 35, 50 and 75%). The treatments were converted to real shading from the photosynthetic photon flux measurement. The results of fresh and dry phytomass were treated and analyzed by regression as a function of the real shading. In ambient conditions of photosynthetic photon fluxes around 1000 μmol m^{-2} s^{-1}, reaching up to 2000 μmol m^{-2} s^{-1} at some hours of the day, typical of tropical environment, lettuce may support a shading of up to 50% without risk of productivity reduction; under these conditions, shading between 20 and 35% is beneficial, and can guarantee its maximum productivity in lettuce cultivation. It is recommended that the lettuce producer in protected cultivation monitors the shelf life of the plastic, avoiding that the shading exceeds 50%. In order to compare shading experiments, one should use the incident photon flux (FFI) for the whole crop cycle, indicating the minimum limit value of FFI = 600 mol m^{-2} $cycle^{-1}$ for the crispy lettuce at an average temperature close to 21°C.

Keywords: *Lactuca sativa*, plastic film, crop protection, light.

RESUMO

Avaliação do fluxo de fótons fotossintéticos no cultivo de alface em diferentes níveis de sombreamento

O cultivo protegido tem crescido no Brasil. Geralmente, as estufas utilizam plástico transparente e tela de sombreamento na cobertura. A cobertura de plástico, com o passar do tempo, perde a transparência por adquirir resíduos de poluição, poeira e outros detritos. A perda de transparência reduz a luminosidade, a fotossíntese e acarreta a perda de produtividade e de qualidade dos produtos. O objetivo do trabalho foi estudar o impacto do sombreamento sobre a produtividade da cultura da alface e determinar o sombreamento ótimo para alcançar o máximo de produtividade. Foram montadas parcelas dentro e fora da estufa, com quatro sombreamentos com telas pretas (0, 35, 50 e 75%). Os tratamentos foram convertidos em sombreamento real a partir da medição de fluxo de fótons fotossintéticos transmitidos. Os resultados de fitomassa fresca e seca foram tratados e analisados por regressão em função do sombreamento medido. Em condições ambientais de fluxo de fótons fotossintéticos em torno de 1000 μmol m^{-2} s^{-1}, alcançando até 2000 μmol m^{-2} s^{-1} em algumas horas do dia, típico de ambiente tropical, a cultura da alface pode suportar um sombreamento de até 50% sem risco de redução da produtividade. Sombreamentos entre 20 e 35%, nessas condições, são benéficos, podendo garantir o máximo de sua produtividade. Recomenda-se ao produtor de alface em cultivo protegido monitorar a vida útil do plástico, evitando que o sombreamento ultrapasse 50%. Para fins de comparação entre experimentos com sombreamento, propõe-se que seja utilizado o fluxo de fótons incidentes (FFI) para todo o ciclo da cultura, indicando o valor limite mínimo de FFI = 600 mol m^{-2} $ciclo^{-1}$ para a alface crespa em temperatura média próxima a 21°C.

Palavras-chave: *Lactuca sativa*, filme plástico, cultivo protegido, luminosidade.

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Much of Brazil's vegetable production comes from protected cultivation, which grows rapidly. The crop production is directly related to the photosynthetic activity and, consequently, to the accumulation of photoassimilates. However, when solar radiation is excessively high, there is an increase in the transpiratory rate of the plant, causing stomatal closure and reduction of photosynthesis (Poljakoff-Mayber & Gale, 2012). In addition, photorespiration can increase, thus reducing liquid photosynthesis (Taiz & Zeiger, 2013). Greenhouses are generally covered with transparent plastic film and shading screen. The plastic film loses its transparency over time due to pollution residues, dust and other debris, and deteriorates with sunlight exposure. The loss of transparency reduces lightness, photosynthesis and leads to losses of productivity and product quality, increasing economic losses. These losses are not always detectable by the farmer. In addition to the use of clear plastic for crop protection, shading screens are commonly used to reduce irradiance and temperature within the greenhouses, thus increasing the productivity of the protected crops (Santosh *et al.*, 2017; Lemos Neto *et al.*, 2017). Costa *et al.* (2011) did not observe significant differences in the arugula productivity in treatments with shading up to 40%, but there was an improvement in productivity with shading of 50%. Seabra *et al.* (2009) found similar data for lettuce in tropical environment with high temperatures. In this case, the productivity was higher when shading was close to 50%, and crops were favored with a specific type of reflective screen, which also promoted the reduction of temperature by 10 to 20%. Bezerra Neto *et al.* (2005) showed that the use of a polypropylene screen reduces the direct incidence of solar rays, increasing the photosynthesis and reducing lettuce respiration due to the favorable conditions, which increased accumulated dry matter.

On one hand, the fact that the farmer does not have scientific knowledge on the subject makes him unaware that shading can be at an excessive level; this way, he does not know the occasion to change the greenhouse plastic cover. By the other hand, he does not have simple and cheap mechanisms to make the decision to change the greenhouse cover safely. This decision is usually subjective, due to common sense, and can be both early and late, both leading to economic losses. In order to avoid further losses in productivity, the plastic cover is replaced every two years, but it can also cause financial loss by the early replacing, because the plastic could still have some useful time.

In addition to the effect of light on growth, it is critical to consider the temperature that significantly affects growth (Frantz *et al*., 2004). The thermal accumulation, consolidated in the Degrees-Day concept, is the simplest means of productivity comparability as a function of the difference between the average temperature and the basal temperature of the crop, below which the crop stops growing (Araújo *et al.*, 2010).

In order to assist the producer in protected cultivation, our group developed a mobile application, called "*Estufa Inteligente*" which allows, with relative precision, to determine the percentage of greenhouse shading indicating whether it is still suitable for the crop (Silva & Cometti, 2017). In this case, one should know the ideal shading pattern for the crop as well as the shading limit so that there is no loss of productivity in order to properly feed data into the application.

The objective of this study was to evaluate the impact of shading on lettuce crop productivity and to determine the optimum shade for maximum productivity.

MATERIAL AND METHODS

A research was carried out at Campus Planaltina, Instituto Federal de Brasilia, Distrito Federal, Brazil (15°39'24"S, 47°41'50"W, 969 m altitude). The tropical climate with dry winter and climate classification is Aw according to Köppen, and the average temperature is 21.1°C.

The research was set during the period of April to May 2017 with crisp lettuce cultivar Wanda. Two beds containing the plots were cultivated, one inside and other outside the greenhouse. Both were conducted under the same conditions of irrigation, fertilization and cultural treatment.

The experimental design, in blocks, had two environments, inside and outside the greenhouse, four shading levels (0, 35, 50 and 75%) and three replications. Each plot was composed of 1.0 m^2, with 16 plants spaced 25x25 cm. Only the four central plants of the bed were collected for the phytomass measurement. The others were discarded as border. The shading was done with plastic screens of different meshes, placed on supports at 0.7 m from the ground covering the entire treatment portion, both inside and outside the greenhouse. The greenhouse, three meters high, was covered with transparent plastic with anti-UV additive, 100 µm thick, and three years old. In order to avoid differences in temperatures within treatments, the protective screen was removed on the sides of the greenhouse. The average temperature observed in the treatments was 21°C with a maximum variation of 1°C between treatments accompanied by a set of DS18B20 sensors connected in a datalogger built with Arduino MEGA 2560 board (Arduino, 2017).

After the transplanting of the seedlings, the photosynthetic photon flux (PPF) measurement was made three times a day, close to 9:00 a.m., 12:00 a.m. and 15:00 p.m., always recording PPF, date, and time. We used a portable radiometer QMSW brand Apogee Instruments® for these measurements. The PPF readings were adjusted in quadratic curves. These curves were integrated to total the mol volume of photons incident in the experiment for a period of 60 days for 12 hours a day.

The plants were collected 35 days after transplanting when the plots with larger plants were ready for commercialization. At harvest, the plants were weighed into the fresh phytomass and taken to the dehydrator to measure the dry mass.

The calculation of the thermal sum, in degrees day, was made based in equation 1:

$$DD = \sum_{i=1}^{n} Taveg - Tb \quad (1)$$

where DD= cumulative day degree; *Taveg*= average air temperature (ºC); and *Tb*= base temperature, which for this experiment were considered 10.0ºC, and n= number of days at harvest (Araújo *et al.*, 2010).

Data were analyzed on Microsoft Office Excel and plotted in charts on Sigmaplot® in which the regression curves were elaborated.

RESULTS AND DISCUSSION

The treatments used in the experiment with photosynthetic photon fluxes (PPF) are shown in Figure 1 (A). The error bars have large amplitude, especially in treatments with lower shading (external cultivation, 0 and 35%) because they contain data collected at different times (near 9:00, 12:00 and 15:00). The PPF readings on these moments allowed us to calculate the actual shading as shown in Figure 1B. These actual (measured) shading treatments were used for regression and shading effect analysis. From now on the term shading will be used for the actual (real) shading calculated from the PPF readings.

The PPF readings throughout the day were adjusted in polynomial curves shown in Figure 2, indicating the greater amplitude of the flux of photosynthetic photons throughout the day in the treatments with less or no shading, especially 0 and 35% in the outside of the greenhouse.

The fresh phytomass production as a function of the PPF reduction by the actual (measured) shading is shown in Figure 3A, and the dried phytomass in Figure 3B. In both variables there was a sharp fall up to 60% of shading, indicating in general terms that the lettuce would not support such shading without loss of productivity. The maximum fresh phytomass production calculated from the second degree polynomial was 186.5 g plant^{-1}, with 23.6% shading. Calculating a loss as high as 10% in fresh phytomass production, 167.8 g plant^{-1} would be obtained with 48% actual shading (dashed line cutting the "x" axis). The maximum dry mass calculated from the second degree polynomial fit was 16.8 g plant^{-1}, with 28% shading. Assuming a reduction of up to 10% in dry biomass, 15.1 g plant^{-1}, would be obtained with 58% shading. In both variables, fresh and dry biomass, with shading of 48 and 58%, respectively, aiming to guarantee a maximum of 10% productivity loss, yields are above the lower limit of the 95% confidence interval indicated in Figure 3 by the dotted curves.

The obtained data show that there is a great plasticity in the adaptation of lettuce plants to the photosynthetically active radiation. In this experiment, the 0% treatment (full sunlight), the PPF average was 986±544 µmol m^{-2} s^{-1}, depending on the time during the day. In treatments with shading, results show that productivity was maintained until the treatment with 50% of actual shading, ie, PPF= 436±255 µmol m^{-2} s^{-1} (Figure 1B, treatment 0%). Therefore, productivity can be maintained with an average PPF variation of approximately 450 to 1000 µmol m^{-2} s^{-1}. C3 plants, which include lettuce, have a saturated photon acceptor system usually above 500 µmol m^{-2} s^{-1}, well stated by Taiz & Zeiger (2013); this explains why there is "surplus" light for plants such as lettuce in the tropical environment. The maximum phytomass productivity reached between 20 and 35% shading (for fresh and dry phytomass) shown in Figure 3 corroborates the premise of the reduction of liquid photosynthesis in C3 plants subjected to high radiance and high temperature (Mondal *et al.*, 2016), which occurs in a tropical environment in full sunlight as observed in the 0% shading treatment of this experiment.

Many C3 species are facultative sun plants and adapted to shading, producing morphological and photosynthetic characteristics similar to shaded plants. They reduce their rate of respiration, reduce the photosynthetic rate, and they present saturation of the photosynthesis in low irradiance. These plants develop the ability to grow in the shade, but their growth is slow as can be observed in treatments with shading above 50%. In a study with arugula, Costa *et al.* (2011) did not observe significant differences in productivity within treatments with shading up to 40%, but favored with shading of 50%. Seabra *et al.* (2009) found similar data for lettuce on tropical environment under high temperature favoring shade productivity close to 50% along with a specific type of reflective screen, which promoted the reduction of temperature by 10 to 20%; this demonstrates that there is actually

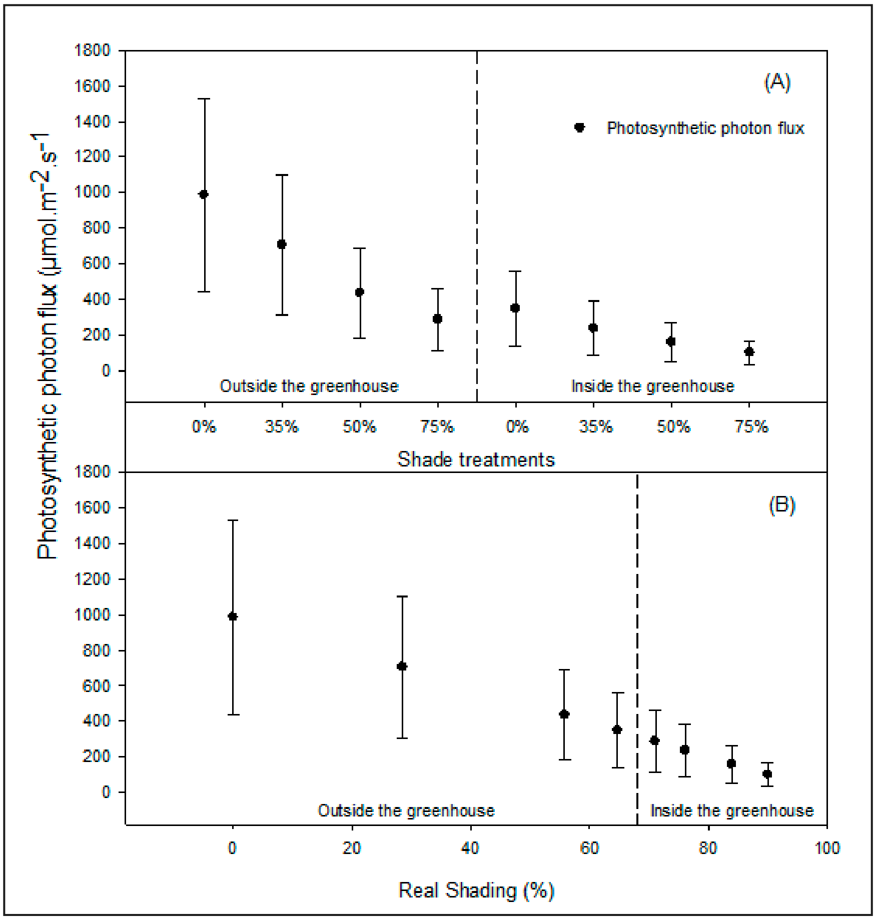

Figure 1. Photosynthetic photon flux (PPF) in different shading levels with black screen. The inside area of the greenhouse had additional shading of the transparent plastic. A= PPF variation as a function of applied treatments; B= PPF variation as a function of measured actual shading. Error bars show PPF measurements throughout the day. Planaltina, IFB, 2017.

surplus light in the tropical environment, and that the use of some shading may even be beneficial. Excessive shading, however, can lead to an abrupt reduction in productivity. In the present study, shading above 60% caused productivity loss of up to 32% every 10% increase in shading. Therefore, one should keep the shading under control so that it does not reach critical levels, in this case, 50% shading. In our experiment, the greenhouse in which the study was based on (which is similar to those found in the surrounding region) already had a shading of 64% leading to a reduction of 35% in phytomass production in relation to the optimum production calculated by the adjustment. This reduction is not easily noticeable on the field because it is measurable only with empirical experiments that can make rigid statistical comparisons, which rural producers are not able to do. Even so, monitoring the transparency conditions of the plastic greenhouse cover is critical, and a simple and inexpensive apparatus is required by the producer such as a mobile app that can express the shading of the greenhouse cover.

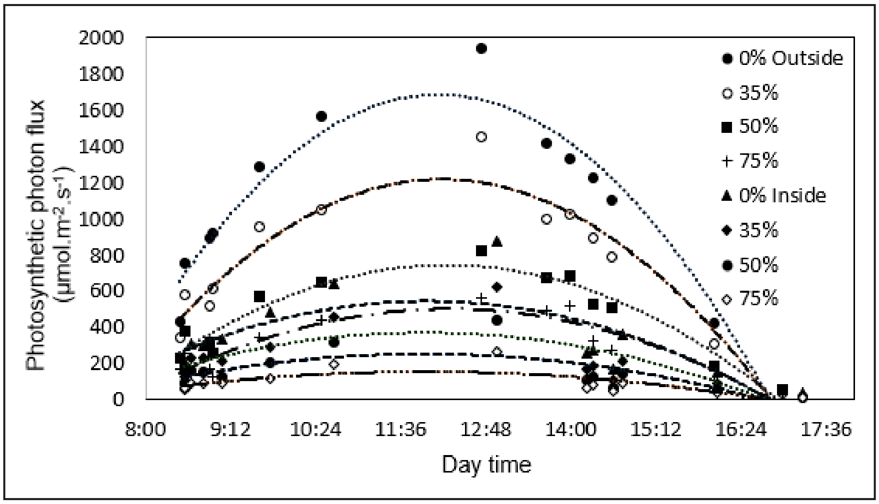

Figure 2. Variation of the photosynthetic photon flux throughout the day in different shading levels with black screen. Planaltina, IFB, 2017.

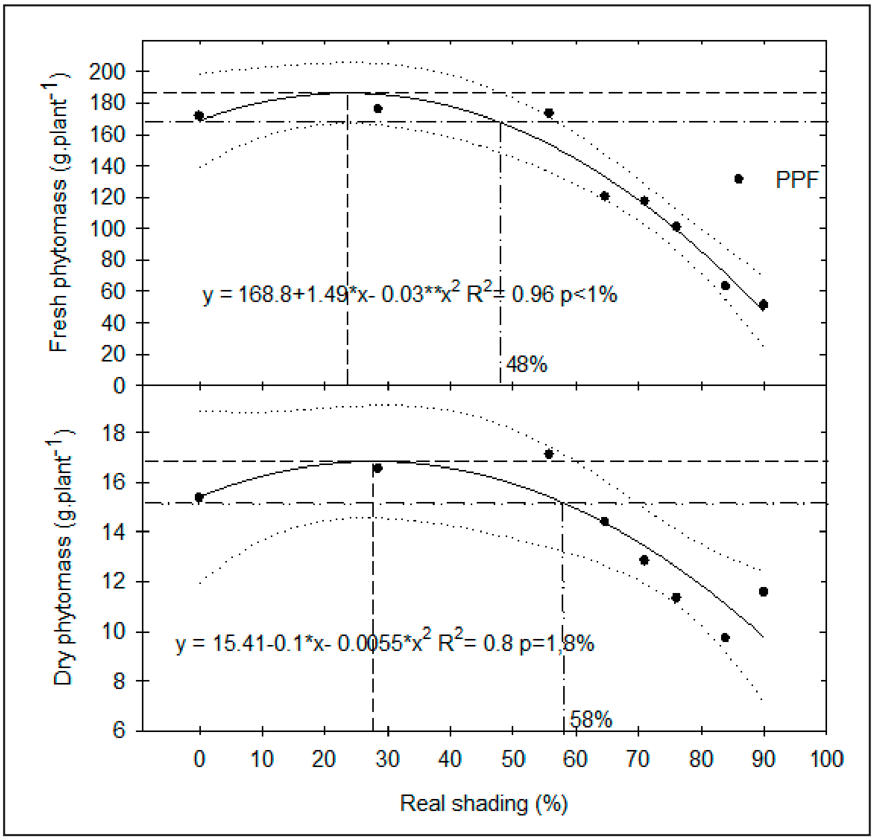

Figure 3. Effect of shading on lettuce phytomass production. Dotted lines indicate 95% confidence interval. Planaltina, IFB, 2017.

The correlation between actual shading and incident photosynthetic photons (IPP) throughout the experiment was fit in the first order equation: "y = 1352-13.7 * x", with R^2 = 0.99 p<1%. It shows how the incident radiation curves of Figure 2 represent the reality of the incidence of photosynthetically active radiation since its integration returns the volume of incident photons perfectly correlated with real shadings. The integration of the incident photon curve is important to establish the shading utilization methodology in experiments since many results presented may be unfeasible considering the use of apparent shading percentages, which were simply originated from values announced for commercial meshes. A commercial shading screen of 50% does not necessarily represent an actual shading of 50%; therefore, results such as of Guerra *et al.* (2017), who found an increase in lettuce productivity in a 50% shading-screen environment as a result of increased photosynthetic activity, became difficult to be introduced on other environments due to lack of a comparative basis since there is no indication of PPF measurements that allow the identification of the actual shading even if the importance of absolute work results remains preserved.

In order to assist the direct measurement of the shading percentage when there is no photosynthetic photon sensor available, we suggest the use of the light sensor of the cell phone, achieving this way a reasonable accuracy at field level as can be observed in the mobile app "*Estufa Inteligente* (Smart Greenhouse)"; this app is available at the Google Play® store, developed by scientists of the Instituto Federal de Brasilia (Silva & Cometti, 2017).

Table 1. Photosynthetic photon flux (PPF), fresh and dry phytomass, incident photosynthetic photons (IPP), and photosynthetic photon efficiency (PPE) of lettuce as a function of shading with black plastic screen. Planaltina, IFB, 2017.

Actual shading (%)	PPF (μmol m^{-2} s^{-1})	Fresh phytomass (g plant^{-1})	Dry phytomass (g plant^{-1})	Curve equation	IPP $\int_6^{18}$ (mol m^{-2} cycle^{-1})	PPE (g_{ms} mol photon^{-1})
0.0	986.0±544.1	171.5±25.9	15.4±1.9	$y = -44531x^2 + 45081x - 9722.9$	1352	0.18
28.5	705.2±396.1	175.9±35.4	16.6±2.3	$y = -32627x^2 + 33159x - 7206.2$	990	0.27
55.8	436.0±255.4	173.3±52.3	17.1±4.6	$y = -19718x^2 + 20159x - 4407.7$	598	0.46
64.7	347.9±209.6	120.3±18.8	12.8±1.9	$y = -14036x^2 + 14387x - 3184.1$	425	0.54
71.0	286.4±175.8	117.2±37.1	14.4±4.9	$y = -13427x^2 + 13412x - 2804.1$	408	0.50
76.1	235.7±150.7	100.9±1.7	11.3±1.5	$y = -9272.7x^2 + 9237.5x - 1928.9$	280	0.65
83.9	158.4±108.3	63.1±9.5	9.7±2.0	$y = -6439.7x^2 + 6415.7x - 1344.6$	196	0.79
90.0	99.0±65.6	51.2±10.2	11.6±4.1	$y = -3893.5x^2 + 3886.6x - 814.33$	118	1.56

The average PPF in the full sun was 986.0 µmol m^{-2} s^{-1}, falling to 99.0 µmol m^{-2} s^{-1} with 90% shading (Table 1). The maximum productivity of fresh phytomass was reached at 753 µmol m^{-2} s^{-1} (with 24% actual shading) and dry mass with 710 µmol m^{-2} s^{-1}, or 28% shading. Thus, we have a reference value, between 24 and 28%, for practical purposes of comparison within experiments with shading. The average reading PPF is not always a determining factor since variations of temperature affect the growth of lettuce. Hammer *et al.* (1978), for example, established the PPF value of 400 µmol m^{-2} s^{-1} as the ideal value for lettuce development in the growth chamber while Galon (2012) cultivated the greenhouse lettuce with an average PPF of 523 µmol m^{-2} s^{-1}. Thus, for comparison purposes, using the variable of incident photosynthetic photons (IPP) is preferable since it integrates the total volume of photons susceptible to assimilation by the plant photosynthetic apparatus.

Frantz *et al.* (2004) cultivated lettuce in a growth chamber with high performance, and high PPF (800 µmol m^{-2} s^{-1}), with a cycle lasting 28 days until harvest with 16 hours of daily light. By integrating PPF, they had 1,290.0 mol of incident photosynthetic photons per square meter. In the present experiment (60-day cycle), we obtained by integrating the curves of Table 1, at full sun, 1,352.0 mol of photons m^{-2} (Table 1) which is a very close value to the one obtained by them. However, the presence of photosynthetic photons incident above the saturation point should be emphasized since the productivity optimum calculated in this experiment was around 950 mol photons. This result demonstrates the importance of determining PPF when treatments are related to shading, allowing this way to make inferences at any location, or latitude. C3 plants usually saturate with PPF in the range between 600 and 800 µmol of quanta m^{-2} s^{-1} (Vieira *et al.*, 2010). In our study, the lettuce grew satisfactorily up to 55.8% of actual shading (Figure 3) without compromising productivity, reaching an average PPF= 436.0 µmol m^{-2} s^{-1} (Table 1), or IPP= 598 mol m^{-2} cycle^{-1} for the crisp lettuce at average temperature close to 21°C.

The quantum efficiency (QE) in C3 ranges from 15.4 (20°C) to 18.9 mol quanta mol CO_2^{-1} (30°C) under natural CO_2 concentration conditions. Considering that the dry mass of the plants contains about 40% of CO_2 assimilated in the photosynthesis (Lambers, 2006), in this experiment the quantum efficiency with 55% shading was 240 mol photosynthetic photons mol CO_2^{-1}. This considerable difference in relation to the one proposed by Lamber *et al.* (2006) probably occurs according to the form of calculation used. In this experiment we opted for the actual calculation of photosynthetic photon efficiency (PPE) (Table 1), which comprises the entire cycle even when most of the photons cannot be assimilated because there is not enough leaf area to cover the entire area. Thus, the PPE with 55% shading was 0.46 g mol^{-1}, very close to the maximum value found by Cometti & Bugbee (2010) for curly lettuce at the growing temperature of 25°C during the day and 20°C during the night, thereby 0.41 g mol^{-1}. According to them, below the aforementioned temperatures, 20/15°C day/night, the PPE drops to 0.2 g mol^{-1}. Frantz *et al.* (2004) found higher values, reaching up to 0.8 g mol^{-1} at temperatures close to 30°C. However, their studies were carried out with high levels of CO_2, which speed up the plant growth. In the present study excessive shading of 90% turns out to be counterproductive although PPE reached 1.56 g mol^{-1}. Thus, shading above 50%, despite the increase of PPE, does not allow sufficient productivity due to absence of photosynthetic photon volume. The PPE stabilizes around 0.5 g mol^{-1} if the shading level is up to 70%; this way it does not make the shading above 50% to be sufficiently advantageous for productivity gain. Therefore, we suggest the use of this methodology of calculation of the PPE since considering the methodology is fundamental when interpreting results in order not to compromise the comparability within different experimental situations.

In this experiment, plants were collected at 35 days after transplantation, that is, 60 days after sowing. The accumulated degree-days (DD) were 666, with a maximum dry mass production of 16.8 g plant^{-1}. Araújo *et al.* (2010) obtained phytomass yields ranging from 8 g plant^{-1} with 514 degree-days to 19 g plant^{-1} with 557 degree-days, that means a large range of productivity as a function of several factors besides temperature. Madariaga & Knott (1951) published a classic one-page article pointing to the inefficiency of the thermal accumulation system for predicting lettuce harvest. Therefore, the accumulation of degree-days cannot be a value analyzed independent of other variables. That's why one should include the incident photosynthetic photons as an important variable.

Concluding, in ambient conditions of photosynthetic photon fluxes around 1000 μmol m^{-2} s^{-1}, reaching up to 2000 μmol m^{-2} s^{-1} at some times of the day, typical of tropical environment, lettuce culture can support a shading of up to 50% without risk of productivity reduction.

Shading between 20 and 35%, under these conditions, is beneficial and can guarantee the maximum productivity to the lettuce crop.

We recommended the lettuce producer of protected crops to monitor the plastic cover lifespan in order to avoid that the shading exceeds 50% opacity; the producer is also recommended to avoid the use of shading screens in greenhouses with plastic that has already been used for some time and may have signs of dusting and transparency loss.

In order to compare shading experiments, we propose to use the incident photon flux (mol m^{-2} $cycle^{-1}$) for the whole crop cycle, indicating the minimum limit value of 600 mol m^{-2} $cycle^{-1}$ for curly lettuce at an average temperature close to 21°C.

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