Improving Soybean Production Under Light Supplementation at Field - A Case Study

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Abstract

In modern agriculture, there is a growing need for cropping efficiency e low environmental impacts. Diverse technologies are becoming available in a recent wave of modernization and integration of knowledge. The use of high-efficiency light supplementation to plant development is scarce to high-productive crops at field conditions (outdoor). The objectives of this study were to evaluate soybean plant and yield responses in an open commercial area (field scale) cultivated with artificial light supplementation. A commercial irrigated (pivot) area received an illumination system for light supplementation (LS) in the inner pivot spans. The light applied was a composition of blue, green and red bands. The outer pivot spans did not receive light supplementation (nLS). About 40 hours of LS were applied to the plants during the soybean crop cycle. Internode number, plant height, pods per plant were weekly evaluated to compose the area under the progress curve (AUPC). The grain yield was also evaluated at harvest. Analysis of variance and test of averages were used to evaluate the data. The AUPC of the internode number, plant height and pods per plant were 15.6, 23.3 and 25.3% higher than for the LS treatment. The regular soybean cycle (nLS) was about 17 weeks; however, the harvest of the LS treatment happened three weeks later. The grain productivity of the nLS was about 4,500 kg ha^{-1} (75 bags), and of the LS treatment was about 7,080 kg ha^{-1} (118 bags) - 57.3% superior. Light supplementation at field scale is a challenge; however, affordable and field resistant technologies are now accessible. The present study is the first report of light supplementation used to improve soybean crop production at field scale. The possibility of using light regulation as an additional technique for increasing yields and sustainable production are also discussed.

1. Introduction

Modern agriculture is continuously being pressed to develop and apply sustainable technologies. Such technologies are related to, but not only, breeding genetic tools, efficient-release fertilizers, nanotechnology, soil management strategies, smart use of the water, internet of things, crop and weather monitoring and integrated techniques of farming administration [1-7].

Crop cultivars that express good nutritional aspects for human consumption, high performance across the cropping systems and diverse environmental conditions are also desirable [8]. Other technologies have been implemented like the genetically modified (GM) plants, which brought many benefits for growers, consumers and country economies [9], and the bioactive compounds (e.g., plant growth regulators) [10,11]. Such substances can be applied in small quantities to change plant responses from seed germination to plant senescence. This technology works by enhancing or stimulating either the natural plant development and the source-sink relationship of the photoassimilates [12].

In the past decades, all those technologies mentioned accelerated crop intensification, especially in Latin America and Asia countries, which are reaching the input levels of North America and Europe [13]. Also, a constantly growing human population and the dangerous climate changes (global warming) are challenges for all human activities, especially the crop activity [14-16]. This intensification of the agricultural activities also came with increased agricultural pressure on the environment resources [17]. Therefore, the intensification of crop production is an actual need and must be solved using sustainable approaches and the most advanced technologies available for crop production.

Improve plant efficiency is an approach to significantly raise the potential of the crop production [18-23]. This improvement can be done by different strategies, including the genetic techniques (e.g., genetically modified organisms) [24], or by adding yield factors such as light [25]. The review elaborated by Gomez and Izzo [26] indicates studies that report the positive effects of light supplementation using light-emitting diode (LED) on plant metabolism and the negative effects on the occurrence and severity of pest-insects and diseases. Increasing the canopy light capture efficiency and the controlling of the light output in response to environmental and physiological parameters can optimize the energy efficiency and the plant productivity with LEDs [27,28].

The production of plant protein for stock-farming and subsequently, for human consumption, is of major concern for global food production. Soybean is a strategic crop for plant protein production and Brazil is a leading soybean producer with a grain production of 122.1 million tons [29]. This high crop production is a consequence of combining factors such as genetically improved cultivars and advanced crop management technologies. Sufficient amounts of food for an increasing population in a climate-changing world must be produced; new techniques and advanced farm management strategies must be implemented to raise crop production at lower environmental impacts.

Thus, the objective of this study was to evaluate the soybean plant and the yield responses in a commercial area (field scale) cultivated with artificial light supplementation.

2. Materials And Methods

2.1. Experimental area and soybean cropping

The experiment was implemented a commercial farm (Fienile Group) under rig irrigation (pivot system) in Monte Carmelo, Minas Gerais state, Brazil; located at 18°57" S, 47°25" W, at 980 m above sea level. The most representative biome of the region is the Cerrado (Savannah-like biome). The climate of the region is Cw (humid subtropical with dry winter) [30].

The soil physical analysis (0-0.4 m) indicated 450, 100, 450 g kg^{-1} of sand, silt and clay, respectively. The soil chemical characteristics up to 0.4 m are presented in Table 1.

Despite the large proportion of clay in the soil and its high natural fertility, 300 kg of 6-30-0 (N, P_2O_5, K_2O) and 150 kg of KCl was applied at sown; 40 days after crop emergence, 2 L ha^{-1} of Mn was spray-applied to plant canopy.

The soybean cultivar evaluated was Desafio 8473 RSF (Brasmax® Cambé, Brazil) – indeterminate growth, maturity group 7.4. Fourteen seeds per meter were sown (280,000 plants per hectare) in October

2019 and harvested in February 2020. Daily average air temperature varied between 24 and 34 °C (weatherspark.com) during the experimental period.

Insect pests, diseases and weeds were controlled using soybean-registered products and following label indications. All products used were applied to the entire pivot area (103 hectares).

2.2 Treatments and soybean evaluations

The pivot where the present study was implemented has ten spams and a radius of about 571 meters. In the four internal spams (33.5 ha), a light supplementation system including full-spectrum light-emitting diode (LED) boards were installed. The proportion of the main spectral bands of the LED was about 59% of red, 8% of blue, and 33% of green. A continuous light range was projected bellow the extension of the four internal pivot spams. The light range was about 40 m wide by 230 m long.

Each LED board has a power varying between 50 and 200 watts. The LED boards were positioned about 3 meters above the plant canopy and distributed to equalize the light intensity to the different moving speeds of the various pivot spams. The luminous flux per unit area (lux) at the soybean canopy level was about 30 lx. The light system used to supplement the soybean crop is presented in Figure 1.

The light system was turned on every night (after sunset) and in very cloudy days. During the soybean crop cycle, about 480 hours of light supplementation was applied to the area – since the pivot routine is circular, each plant received about 40 hours of light supplementation. The light supplementation started at the V3-V4 (third-fourth trifoliate leaf fully expanded) and ended at the R5-R6 (beginning-full seed) soybean phenological stage. The six external pivot spams (69.5 ha) received no light supplementation. The pivot completes a full cycle over the cropping area in 12.8 hours.

Between the first and second pivot towers (second spam), a homogeneous area of 50 by 40 m (2,000 m^2) was delimited to be evaluated as the “light-supplemented” (LS) treatment. Between the eighth and ninth pivot tower (ninth spam) a homogeneous area of 50 by 40 m (2,000 m^2) was delimited to be evaluated as the “no-light-supplemented” (nLS) treatment. The experimental sketch is presented in Figure 2.

The evaluations of internode, plant height (from soil level to the highest leaflet node), and pods per plant were done weekly from R3 (beginning pod) to R7 (beginning maturity) soybean phenological stage. During nine weeks, evaluations were done once per week; no more assessments could be done after R7 because the plants of the nLS treatment reached physiological maturity earlier than the plants of the LS treatment. The averages of the variables evaluated were obtained from the assessment of 10 representative plants that were randomly selected in each area (2,000 m^2); each plant evaluated was considered a replication.

The influence of each treatment (LS or nLS) on each variable was evaluated via the area under the progress curve (AUPC) of each variable [32,33]. The AUPC was calculated by the trapezoidal integration: AUPC = $\sum$(Yi + Yi+d)/2×dti, where, *dti* is the time interval between every two observations of *Yi* and *Yi+d*.

Correlations among the AUPC of the variables evaluated were computed to determine if there was a linear relation between them [34].

The areas of each treatment (2,000 m^2) was harvested at 115 and 136 days after sown for the nSL and SL, respectively, and the grain productivity expressed in kg ha^{-1}.

2.3 Statistical analysis

Extreme values (*outliers*) in the AUPC of each variable were sought by boxplot graphs of the residues [35], and when identified, the outlier was replaced by mean values of the data set without the outlier [36,37]. The boxplots were generated using SPSS Statistics® software, which was also used to calculate the Pearson's correlation coefficients between the variables, and the basic assumptions for the analysis of variance (normality of residue distribution by Shapiro-Wilk and homogeneity of variances by Levene, both at $p > 0.01$).

The analysis of variance (ANOVA, F test) was performed after the confirmation of the assumptions and considered a fully randomized design. When significant differences were observed among treatments (LS or nLS), the AUPC of the internode number, plant height, and pods per plant were compared using the Tukey's test of averages ($p < 0.05$). These ANOVA and Tukey's test analyses were performed using SISVAR® statistical program. Graphics were generated by Sigma Plot® v.12 software.

3. Results

The data of the weekly evaluations of all variables (soybean internode number, the plant height and the number of pods per soybean plant) for both treatments (LS and nLS), were free of outliers since none was detected by the boxplots of all variables and treatments. This indicates that the responses are clustered around a mean with low standard error. The evaluations of the soybean variables during nine weeks and respective standard errors are presented in Figure 3.

The number of internodes per soybean plant, the plant height and the number pods per plant of the LS treatment were consistently superior compared to were no-light supplementation was applied. This superiority of the plant responses to the LS treatment can also be observed in Figure 4.

The area under the progress curve (AUPC) of the variables were calculated based on nine evaluations. The weekly evaluations were interrupted when the plants of the nSL treatment reached late R7 (beginning maturity) soybean physiological stage. The results of the AUPC analysis of variance and the presumptions (normality of the residue distribution and homogeneity of the variances) are presented in Table 2.

All the data of the AUPC of the soybean variables (internode number, plant height and pods per plant) attended the ANOVA presumptions (normality of the residue distribution and homogeneity of the variances) ($p > 0.01$). Also, the coefficients of variation, CV (%), were very low (< 2%). Thus, the data was adequate to proceed with the ANOVA, which indicated significant differences ($p < 0.01$) between the treatments (LS and nLS).

The AUPC of the internodes per soybean plant, the plant height and the number pods per plant of the LS treatment presented about 15.6, 23.3 and 25.3% superior AUPC in comparison to were no-light supplementation was applied.

The Pearson's correlation correct computation and interpretation require that the data be normally distributed and with no *outliers* (extreme values) [38]; this requirement was achieved (Table 1). All the correlations observed (Table 3) were significant ($p < 0.01$) and very strong correlations ($r > 0.9$) according to Callegari-Jacques [39].

The soybean cultivar evaluated presents cycle estimated in about 17 weeks. At 115 days after sown, the soybean plants of the no-light-supplemented area (2,000 m^2) were harvested; however, the harvest of the light-supplemented treatment happened three weeks after. The estimated productivity of the no-light-supplemented was about 4,500 kg ha^{-1} (71 bags ha^{-1}; 1 bag = 60 kg), while the light-supplemented treatment was about 7,080 kg ha^{-1} (118 bags ha^{-1}), which is 57.3% superior to where no light supplementation was applied and 113% above the average of the Brazilian soybean productivity (3,324 kg ha^{-1}).

4. Discussion

Soybean development and flowering are majorly influenced by environmental factors such as photoperiod and temperature [40,41]. The increased extension of the soybean crop cycle caused by light supplementation also increased the period of photosynthetic activity. This cycle extension (three weeks in the present study) would increase the biomass accumulation via natural daily photosynthesis when compare to the regular cycle of the soybean cultivar (17 weeks), even if no light was supplemented.

The light supplementation increased the soybean cycle but consequently increased the photosynthesis-active life of the soybean leaves, plus the additional light to the extended-life leaves. This conjunction of factors resulted in taller soybean plants, more internodes, more pods, and, consequently, over 57% further grain productivity.

Increased crop cycle, the number of nodes, pods, and seeds per pod, and the pod distribution within the soybean canopy were reported as variables affected by extended photoperiods [40,42-45]. The photoperiod regulation was also involved in additional changes to the soybean development, such as the number of pods and seeds established per unit land area [44].

However, the number of hours supplemented to the soybean crop (about 40 hours) could not explain the extra yield (57.3%) generated by additional photosynthesis. Other hypotheses should be considered, like photomorphogenesis (light-mediated development) [46,47], upregulation or downregulation of phytohormones and phytochromes [47-49], and changes to the secondary plant metabolism [50,51].

Crop inputs, such as fertilizers, plant inoculants, and phytosanitary products, are applied during crop cycle and are solely intended to maximize crop production and economic returns. Frequently, the negative side effects of such inputs on soil dynamics are often neglected [52]. However, the light supplementation to field crops has the potential to reduce the number of inputs applied, especially fertilizers.

The fertilizer efficiency is likely to be a consequence of the significant increment of the shoot biomass when light supplementation is applied; consequently, this shoot increment will, in turn, causes a proportional increment of the root biomass. This improved root development will increase the efficiency of the root nutrient absorption, thus, increasing the fertilizer efficiency [53].

Crop production has always been intrinsically related to nutritional, microbiological, environmental and economic aspects that correlate with each other in a spatially-sensitive phenomenon [54]. To understand the consequences of such elements and their interactions, the use of response-models is essential. Valuable information about physiological processes, appropriate sowing time, irrigation blade, fertilizer doses, insects and disease management and their impacts on the soil-crop-environment relations can be integrated by models [55].

Also, the use of combined climate information can improve the understanding of the relationship between crop production and the weather oscillations and improve the resilience of the global food system (food security) to unexpected climate-related shocks [16,56-58].

What has been observed in recent years is the vertiginous increase of the digitalization and the integration of the technologies in agriculture. Crop management is achieving a level of integration and application of technologies that, in consonance with the sustainability of the ecosystems, is projecting the modern cropping to a higher level (Agriculture 5.0) [6].

Before the planning of cropping factors such as the genetic to be sown, the phytosanitary management and the level of technology to be used, other primary factors such as nutrient availability, water supply and light (usually from a natural source solely) must be adequately provided. Light supplementation at field scale was a challenge to control; however, now, with affordable and field resistant technologies - plus the results of the present study - the benefits of such light supplementation for crop production are accessible for large commercial crop areas.

The light supplementation technology also has a great potential to diminish the deforestation of new native areas for crop production [59-61], because the crop productivity can be sharply increased with an appropriated implementation of light supplementation throughout the crops cycle.

Currently, the world population is about 7.79 billion people [62]. The crop production intensification can supply the projected food demand now and in the future; however, this does not necessarily mean hunger alleviation. Crop production waste must be reduced and income equity must be sought together with the improvements in the cropping production systems [13,63].

Studies about the results obtained with light supplementation at field scale on many crop species are ongoing, and the results are very promising. The low occurrence of leaf diseases and infestation by pest-insects in light-supplemented areas has also been observed, but directed studies are yet occurring. According to extensive literature research, this is the first report of light-supplementation using full-spectrum LED-lights to improve soybean crop production at field scale in the world.

5. Conclusions

About 40 hours of light supplementation during the soybean crop cycle positively affected the number of internodes, pods, plant height, and crop cycle.

The light supplementation increased soybean grain yield by 57.3% compared to where no artificial light was implemented.

The light supplementation to plants at field scale is now a feasible, sustainable, and promising technique to improve crop production in the same agricultural area.

Declarations

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Federal University of Uberlândia (UFU); Coordination of Superior Level Staff Improvement (CAPES); Fienile Group.

Author Contributions Statement

Ernane M Lemes: Conceptualization; methodology; formal analysis; investigation; data curation; writing. Breno N R Azevedo: Conceptualization. Matheus F I Domiciano: Conceptualization. Samuel L Andrade: Investigation; data curation.

Additional Information

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Tables

Table 1. Soil chemical characterization at 0-0.2 and 0.2-0.4 m soil layer.

pH H_2O	Ca	Mg	Al	H+Al	CEC	V	P	K	S.O.M
1-2.5	——cmol$_c$ dm^{-3}——					%	—mg dm^{-3}—		g kg^{-1}
——0-0.2 m soil depth——									
6.9	6.03	2.87	0	1.26	10.44	88	188	96	2.9
——0.2-0.4 m soil depth——									
6.8	5.70	2.78	0	1.08	9.77	89	158	82	2.3
B	Co	Cu	Fe	Mn	Mo	Si	Zn		
——mg dm^{-3}——									
——0-0.2 m soil depth——									
0.19	1.7	9.0	14.0	1.9	2.9	12.4	12.8		
——0.2-0.4 m soil depth——									
0.14	1.3	7.7	17.0	3.5	2.3	11.4	11.1		

CEC = cation exchange capacity at pH 7; V = saturation of bases; S.O.M. = soil organic matter. Methodologies source: [31].

Table 2. Analysis of variance (F test) and statistics of assumptions of the area under the progress curve of the variables soybean internode number, the plant height and the number of pods per soybean plant.

SV	DF	Internodes	Height	Pods per plant
Light supplementation	1	375**	1,590**	2,649**
Error	18			
CV (%)		1.67	1.17	0.98
KS	20	0.935$^+$	0.985$^+$	0.964$^+$
L	1+18	1.139$^+$	0.106$^+$	0.262$^+$

**: significant differences at 0.01. CV (%): coefficient of variation.

KS: Kolmogorov-Smirnov's statistics for normality of the residue distribution ($p > 0.01$).

L: Levene's statistics for homogeneity of the data variances ($p > 0.01$).

$^+$: normality of residues (KS) or homogeneity of variances (L) fulfill.

Table 3. Pearson's correlation (*r*) between the AUPC of the variables studied.

	Internodes	Plant height	Pods per plant
Internodes	1	0.962**	0.970**
Plant height		1	0.990**
Pods per plant			1

Internodes: soybean internode number; Plant height: soybean plant height; Pods per plant: number of pods per soybean plant. **: significant differences at 0.01.

Figures

Figure 1

Light and water irrigation system (A) used to light-supplement soybean crop (B) at night and very cloud days.

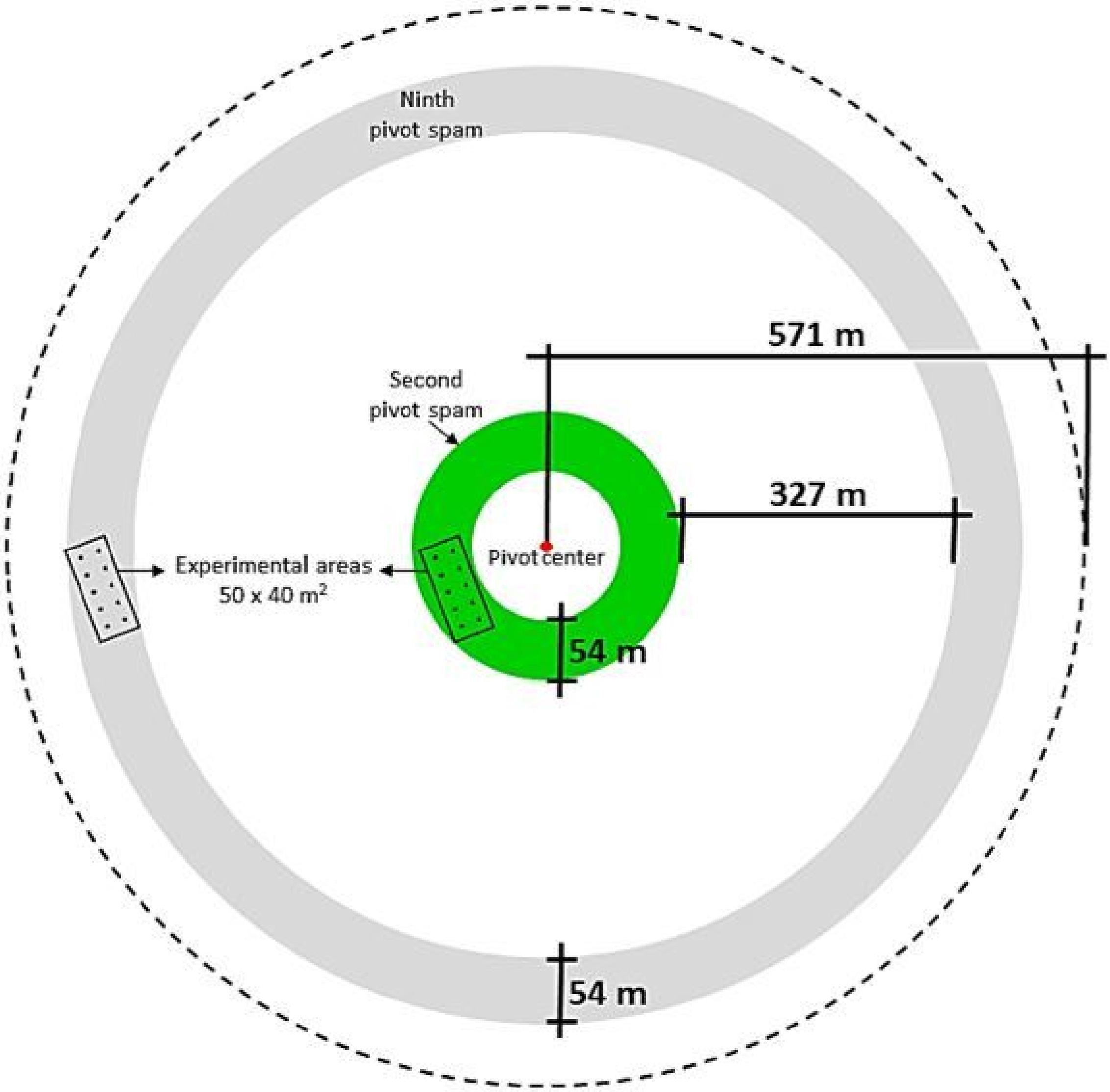

Figure 2

Experimental sketch of the field experiment to evaluate the effects of light supplementation on soybean crop development. Green pivot spam received light supplementation.

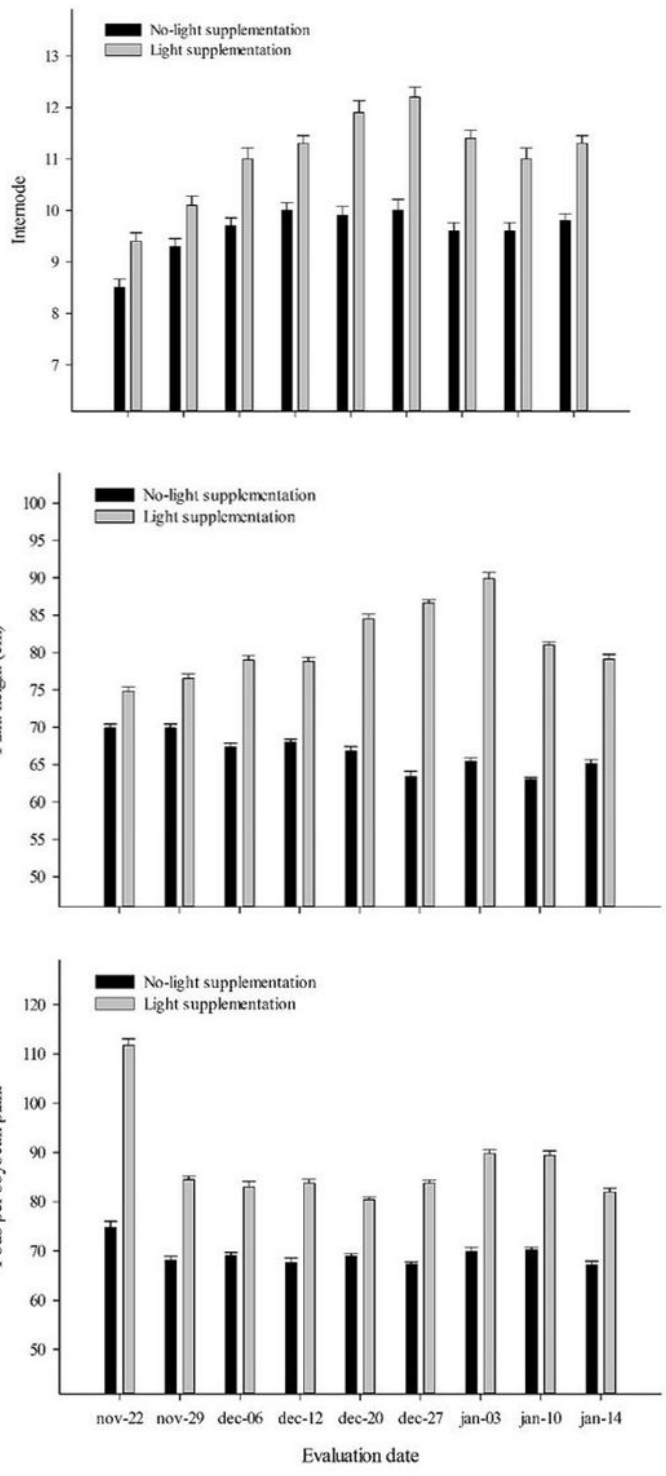

Figure 3

Internodes, height and pods per soybean plant (cultivar Desafio 8473 RSF - Brasmax®) under light supplementation and no-light supplementation. Lines over bars indicate standard error.

Figure 4

Soybean plants at 80 days after sown from the light supplementation (left, R5.3 soybean phenological stage) and no-light supplementation treatments (right, R6-7 soybean phenological stage). Each blue stretch in the metric tape = 0.1 m.