Soybean tolerance to defoliation at the beginning of pod formation as affected by plant density[1]

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ABSTRACT

Soybean tolerance to defoliation may be affected by population density, as the plant population interferes with the crop leaf area index . This study aimed to evaluate the effect of defoliation at the beginning of pod formation on the agronomic performance of soybean at different plant densities. The experiment was conducted under field conditions in Campos Novos, SC, Brazil, during 2016/2017 and 2017/2018 growing season. The experimental design was a randomized block in a split-plot arrangement. The main plot consisted of three densities (100,000, 300,000, and 500,000 plants ha^{-1}), whereas the subplots consisted of the cultivar NA 5909 RG submitted to five defoliation levels (0, 16.6, 33.3, 50, and 66.6%). Grain yield ranged from 4,219 to 5,356 kg ha^{-1} in the 2016/2017 growing season and 3,732 to 5,186 kg ha^{-1} in the 2017/2018 growing season. Plant density did not interfere with the grain yield response to defoliation performed at the beginning of pod formation. The 16.6% defoliation increase grain yield by 7.5 and 5.6% relative to the control in 2016/2017 and 2017/2018 growing seasons, respectively. The soybean tolerate defoliation of up to 33.3% at R3 with no significant decrease in grain yield, regardless of the plant density.

Keywords: *Glycine max*; leaf area; seeding rates; grain yield.

INTRODUCTION

The increase in soybean (*Glycine max*) production evolved in parallel with the conditions that provided high yields. Breeding programs seek to develop cultivars that are more efficient in the use of resources and more productive. They promoted morphological and physiological changes in the characteristics of the cultivars, selecting genotypes with high photosynthetic capacity, low leaf area index (LAI), and indeterminate growth habit (Jin *et al.*, 2010; Liu *et al.*, 2008).

In addition to the breeding alterations, management practices have also changed and evolved. In the last century, the recommended population density in soybean plantations was 400,000 plants ha^{-1} (Rocha *et al.*, 2018). Currently, the recommended population ranges from 250,000 to 300,000 plants ha^{-1} (Indicações Técnicas, 2019). Therefore, there was a decrease in sowing density due to the better physiological seed quality, high seed costs, high precision of seed drills, and the small effect of the population on grain yield due to the high morphological plasticity of the soybean crop (Farias *et al.*, 2007).

The intraspecific competition for water, nutrients, and light is smaller at low densities and the plant emits more branches and leaves (Cruz *et al.*, 2016). On the other hand, the stresses caused by biotic or abiotic factors at sub-optimal densities can cause high damage to grain yield due to the lower LAI of the crop, providing it less capacity to mitigate the negative effect (Tissot & Zotis, 2015).

At high densities, shaded leaves may not contribute to the photosynthesis of the canopy, senescing earlier and being more susceptible to diseases (Luca & Hungria, 2014). In addition, the lack of light penetration into the lower layers of the canopy can reduce photosynthesis. Supra-optimal densities also increase the cost of implementing the crop field and favor plant lodging (Souza *et al.*, 2010).

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Soybean growth habits can also influence the response to population density. Zanon *et al.* (2015a) observed that the LAI contribution from the branches to the total LAI of the plant is low in cultivars with indeterminate growth habits, allowing less tolerance to lower population densities.

Changes in the characteristics of the currently used cultivars, which have a predominant early cycle and an indeterminate growth habit, is one of the factors that most contribute to the low adoption of integrated pest management (Bueno *et al.*, 2012), generating insecurity for farmers and technicians regarding the effectiveness of the currently proposed economic injury levels (EIL). Modern cultivars may be more sensitive to defoliation than older cultivars due to their smaller leaf area, shorter cycle, and higher production potential. These characteristics can be accentuated by the lower density of plants currently used in the field.

This study was carried out based on the hypothesis that plant density interferes with soybean tolerance to defoliation, which is smaller under low plant populations. The experiment aimed to evaluate the effect of defoliation at the beginning of pod formation on the agronomic performance of soybean at different plant densities.

MATERIAL AND METHODS

The experiment was set in Campos Novos, State of Santa Catarina, in the south of Brazil, during the 2016/2017 and 2017/2018 crop seasons. The geographic coordinates of the location are 27°372 S and 51°262 W, with an altitude of 930 m.

The soil of the experimental area is classified as an Oxisol (Latossolo Vermelho, Brazilian Soil Classification System) (Embrapa, 2006). The results of the soil analysis carried out in September 2016 showed the following characteristics at a depth of 0–20 cm: 550 g kg^{-1} of clay, 5.2 of pH in water, 61.4 mg dm^{-3} of P, 329 mg dm^{-3} of K, 56 g kg^{-1} of organic matter, 6.1 cmol$_c$ dm^{-3} of Ca, 1.5 cmol$_c$ dm^{-3} of Mg, 0.4 cmol$_c$ dm^{-3} of Al, and 25.0 cmol$_c$ dm^{-3} of CEC. The experimental area was under rotation with corn (*Zea mays*) and succession with black oat (*Avena sativa*).

The experimental design was a randomized block in a split-plot arrangement, with three replications per treatment. The main plot consisted of three population densities equivalent to 100,000 (sub-optimal density), 300,000 (recommended density), and 500,000 plants ha^{-1} (supra-optimal density). Subplots consisted of five defoliation levels, equivalent to 0, 16.6, 33.3, 50, and 66.6% of the leaf area presented by the crop at defoliation time. The 0% level was the control, 16.6% level represented the EIL currently proposed by Brazilian Soybean Field Production Guide (Indicações Técnicas, 2019) for the reproductive stage, 33.3% represented the EIL proposed by Soybean Guide (Indicações Técnicas, 2019) for the vegetative stage, and 50 and 66, 6% represented values above the EIL at any crop development stage. Defoliation was performed when the crop was at the R3 stage (beginning of pod formation) of the scale proposed by Ritchie *et al.* (1982). Defoliation was performed cutting the leaves longitudinally with scissors, according to the defoliation level (Figure 1). Each subplot was composed of five rows of 6 m long and inter-row spacing of 0.45 cm.

The experiments were set with a seed drill on December 2, 2016, and December 4, 2017, in the first and second growing seasons, respectively. They were carried out under the no-tillage system. The fertilization of the experimental area consisted of the application of 420 kg ha^{-1} of the NPK formulation 4–24–18. The cultivar used was NA 5909 RG, which belongs to the maturation group 5.9 and has an indeterminate growth habit. At the time of implementation of the experiment, it was the most cultivated and of importance in the region. Its seeds were treated with thiamethoxam (Cruiser®) at the dose of 3 mL kg^{-1} of seeds, metalaxyl + thiabendazole + fludioxonil (Maxim Advanced®) at the dose of 1 mL kg^{-1} of seeds, and inoculant (Masterfix L) at the dose of 3 mL kg^{-1} of seeds.

Thinning to adjust populations according to the treatment was carried out when the plants reached the V1 stage. Pest control was performed using 0.5 mL L^{-1} of lambda-cyhalothrin + chlorantraniliprole (Ampligo®), 1.2 ml L^{-1} of profenofos + lufenuron (Curyom®), and 1 mL L^{-1} of thiamethoxam + lambda-cyhalothrin (Engeo Pleno®). Disease control was performed with the application of 1 g L^{-1} of azoxystrobin + benzovindiflupyr (Elatus®) and 2.6 mL L^{-1} of trifloxystrobin + prothioconazole (Fox®). Preventive application of insecticides and fungicides was carried out from the V5 stage, with sequential applications every 14 days, alternating the products to prevent pests and diseases from affecting the crop leaf area.

The leaf area was determined by measuring the length and the largest width of the central leaflet of each trifoliate leaf of the plant and applying the equation proposed by Richter *et al.* (2014): $LA = a \times (L \times W)$, where LA is the leaf area (m^2), L is the leaf length (m), W is the largest leaf width (m), a is the angular coefficient (2.0185). The sum of the leaf area of all leaves of the plant determined the leaf area per individual. The leaf area index (LAI) was obtained by dividing the leaf area by the soil surface occupied by the plant at each density. The first LAI evaluation was carried out at the R3 stage before defoliation and the second evaluation at the R5 stage (beginning of grain filling) of the scale of Ritchie *et al*. (1982). The leaf expansion was determined by the LAI difference between stages R3 and R5.

Harvest was carried out on April 13, 2017, and April 20, 2018, in the first and second crop seasons, respectively. After harvesting, the pods were threshed and the grains were dried in an oven at 60 °C until a constant mass was obtained. Subsequently, grain yield was calculated and expressed at 13% moisture.

The precipitation and temperature values during the soybean development stages in the 2016/2017 and 2017/2018 crop seasons were obtained at the meteorological station of the Agricultural Research and Rural Extension Company of Santa Catarina (Epagri), located 10 km from the experimental area.

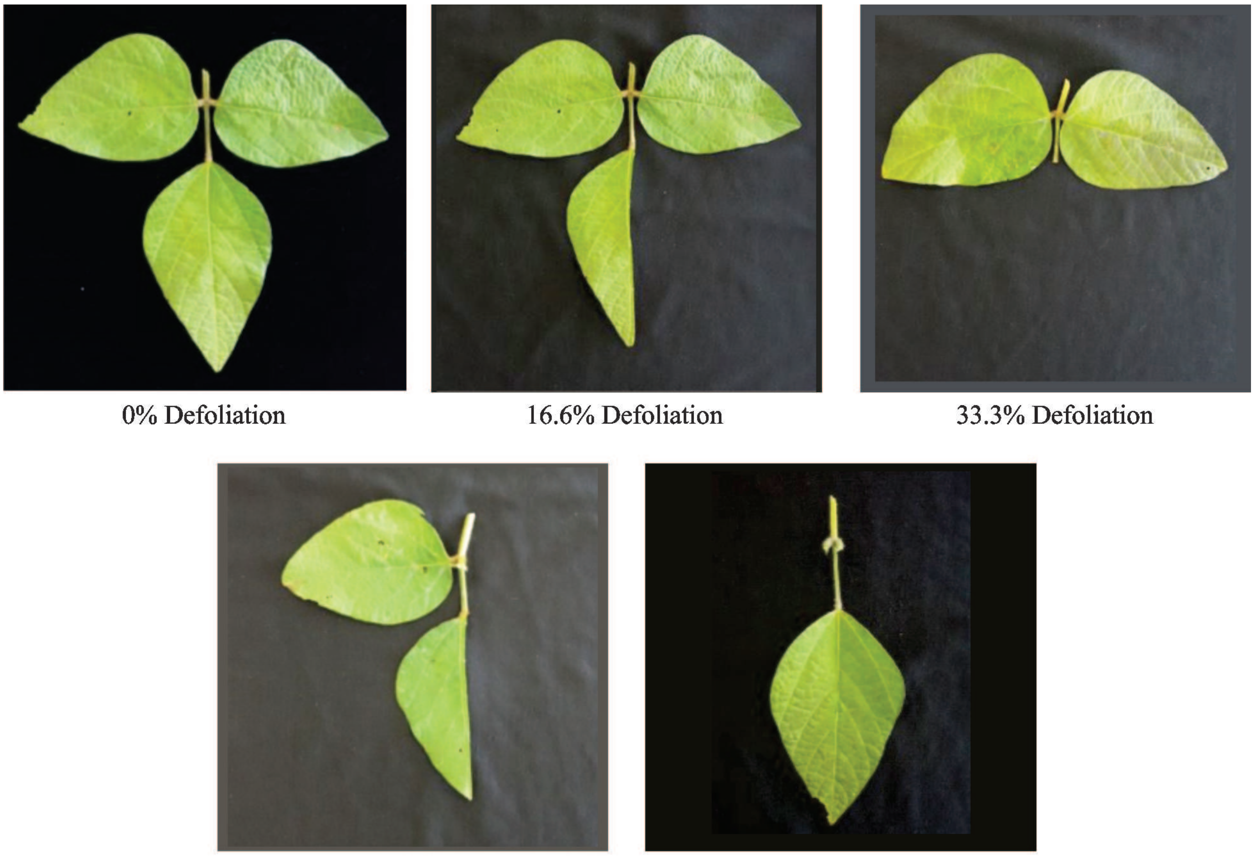
The data were subjected to analysis of variance using the F-test. The F values for the main effects and interactions were considered significant at the 5% significance level ($P < 0.05$). When statistical significance was reached by the F-test, the means of the plant density factor were compared by the t-test and the defoliation levels factor by polynomial regression. Both comparisons were carried out at the 5% significance level.

RESULTS AND DISCUSSION

A significant effect of plant density on the LAI of the crop at R3, before defoliation, was detected at both sowing seasons (Table 1). The highest absolute LAI values were obtained at the supra-optimal density of 500,000 plants ha^{-1} and the lowest values were found at the sub-optimal density of 100,000 plants ha^{-1}. Similar results were found by Balbinot Júnior *et al.* (2016) and Cruz *et al.* (2016), demonstrating that LAI increased as plant density increased.

The crop LAI at R5 was affected by the main effects of plant density and defoliation level. In the first crop season, treatments with the density of 100,000 plants ha^{-1} showed a lower LAI value than treatments with other densities, which showed no significant difference from each other (Table 2). In the second season, the LAI value at the density of 100,000 plants ha^{-1} was lower than at the density of 500,000 plants ha^{-1}, while the density of 300,000 plants ha^{-1} did not differ from the other populations.

The LAI showed a quadratic response to defoliation at the beginning of grain filling (Figure 2). Plants submitted to defoliation higher than 33.3% showed no recovery of their LAI until stage R5 (characterized by the end of leaf emission for cultivars with indeterminate growth habits)



0% Defoliation 16.6% Defoliation 33.3% Defoliation

50% Defoliation 66.6% Defoliation

Figure 1: Defoliation levels imposed on each soybean trifoliate leaf at R3 (begining of pod formation) according to the scale by Ritchie *et al.* (1982).

in the first season (Figure 2a). In the second season, the decrease in LAI occurred from treatments with 16.6% defoliation, on the average of the three plant densities (Figure 2b).

The critical LAI value at the beginning of grain filling is 3.5 (Zanon *et al.*, 2018). This is the LAI required for the interception of 95% of the incident solar radiation. Tagliapietra *et al.* (2018) reported that cultivars with an indeterminate growth habit need a minimum LAI of 3.4 to achieve high yields (above 4 t ha^{-1}). The data in Table 2 show that the LAI value proposed by Tagliapietra *et al.* (2018) to obtain high productivity was achieved at all plant populations, except for the density of 100,000 plants ha^{-1} in the 2016/2017 crop season. The LAI values obtained at the beginning of grain filling were higher than 3.5, with defoliation of up to 33.3%, regardless of the plant density (Figure 2).

The LAI expansion was not affected by the plant population. Although under low densities the soybean crop has higher LAI expansion and branch emission capacity (Buchling *et al.*, 2017), this ability to regenerate the leaf area at the lowest density between stages R3 and R5 was not evidenced in the present study, regardless of the crop season and defoliation level.

On the other hand, the defoliation level showed a significant effect on LAI expansion between R3 and R5. The variable had a quadratic behavior in both crop seasons. Treatments with no defoliation showed less expansion compared to treatments with other defoliation levels (Figure 3). This fact were verified due, in cultivars of indeterminate habit, stop the apical meristem growth for new nodes, internodes and leaves (Zanon *et al.*, 2018). According Durli *et al.* (2020) similar results confirming that soybean defoliation in the vegetative phase make the plants regrowth and expanding LAI, but not significative regrowth are observed on reproductive phases.

The control with no defoliation showed higher senescence than leaf expansion between the beginning of pod formation and grain filling, as the LAI expansion value from R3 to R5 was negative. This behavior was due to the low penetration of light in the canopy, which increases the senescence of leaves located in the lower third of the plant (Zanon *et al.*, 2015b). The LAI expansion values from treatments with defoliation showed little variation, regardless of the percentage of leaf area removed. This demonstrates that the soybean plant showed no capacity to emit higher LAI in treatments with higher defoliation injury to mitigate the highest losses of leaf area. This result differs from the data found by Fontoura *et al.* (2006) and Souza *et al.* (2014), who observed recovery of the leaf area through leaf expansion in treatments subjected to higher injury levels.

Grain yield ranged from 4,219 to 5,356 kg ha^{-1} in the 2016/2017 growing season and from 3,732 to 5,186 kg ha^{-1} in the 2017/2018 growing season, depending on the defoliation level and population density. The average grain yields were 4,760 and 4,486 kg ha^{-1} in the 2016/2017 and 2017/2018 growing seasons, respectively. A 5.8% decrease in grain yield was observed from the first to the second growing season. It possibly occurred due to the amount and distribution of rainfall. The 2016/2017 growing season showed abundant and well-distributed

Table 1: Leaf area index (LAI) of soybean at three plant densities before defoliation in R3. Campos Novos, SC, 2016/2017 and 2017/2018

	Plant density (pl ha^{-1})		
100,000	300,000	500,000	CV %
	LAI in 2016/2017		
3.90 b	5.63 a	6.26 a*	12.35
	IAF em 2017/2018		
4.88 b	5.39 ab	5.82 a	10.53

* Averages followed by the same lower case letter in the row do not differ significantly by the t test at the 5% probability level ($P < 0.05$).

Table 2: Leaf area index (LAI) of soybean in R5 at three plant densities, on the average of five defoliation levels in R3. Campos Novos, SC, 2016/2017 and 2017/2018

	Plant density (pl ha^{-1})		
100,000	300,000	500,000	CV %
	LAI in 2016/2017		
3.19 b	4.39 a	4.84 a*	12.62
	LAI in 2017/2018		
3.88 b	4.13 ab	4.50 a	9.75

* Averages followed by the same lower case letter in the row do not differ significantly by the t test at the 5% probability level ($P < 0.05$).

rainfall, totaling 816 mm over the crop cycle. In the 2017/2018 growing season, rainfall was lower, reaching 597 mm. It also had an uneven distribution, with a dry period between 60 and 80 days after sowing, which coincided with the end of flowering and the beginning of pod formation.

Plant density did not significantly affect grain yield during the 2016/2017 growing season (Table 3). In the 2017/2018 growing season, treatments with a density of 500,000 plants ha^{-1} showed lower grain yield than in the other densities. The higher stability of grain yield in the 2016/2017 growing season was probalby due to the weather conditions. In the first growing season, the rains were well distributed throughout the crop cycle, a fact that was not observed in the 2017/2018 growing season. These results confirm the low soybean response to variations in plant density reported by Balbinot Júnior *et al.* (2015) and Buchling *et al.* (2017) under favorable weather conditions during the crop cycle. It is due to the high phenotypic plasticity of the soybean crop, which allows changing its morphology and yield components, adapting them to the conditions imposed by the plant arrangement and enabling the maintenance of grain yield in a wide range of density. On the other hand, a decrease in the yield of 524 and 476 kg ha^{-1} was observed in the second year of study at

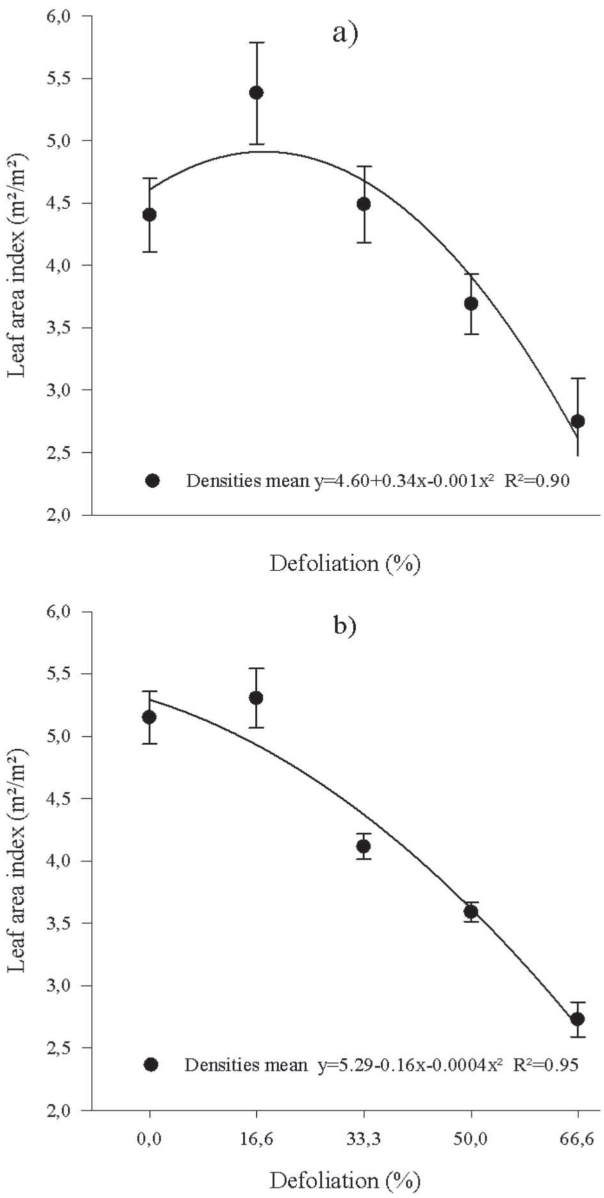


Figure 2: Leaf area index in R5 of soybean under different defoliation levels in R3, on the average of three plant densities. Campos Novos, SC, 2016/2017 (a) and 2017/2018 growing season (b). Bars indicate the treatment average ± the standard error.

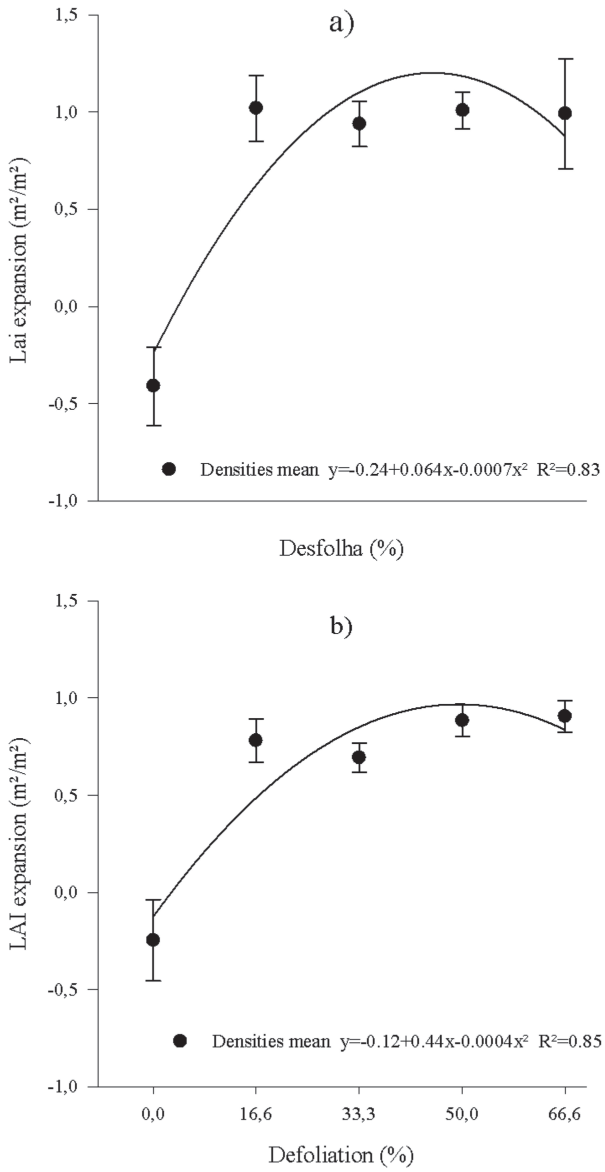


Figure 3: Expansion of soybean leaf area index between R3 and R5 under different defoliation levels in R3, on the average of three plant densities. Campos Novos, SC, 2016/2017 (a) and 2017/2018 growing season (b). Bars indicate the treatment average ± the standard error.

the supra-optimal density of 500,000 plants ha^{-1}, in comparison with the densities of 100,000 and 300,000 plants ha^{-1}, respectively. The increase in plant density enhances the intraspecific competition for environmental resources, such as light, water, and nutrients, decreasing the crop yield potential under conditions of water restriction (Zanon *et al.*, 2018).

In both growing seasons, the main effect of defoliation level affected grain yield, on the average of the three densities. Grain yield showed a quadratic response to the increase in the removed leaf area at R3 (Figure 4). Treatments with 16.6% defoliation showed higher absolute values of grain yield in both growing seasons. The

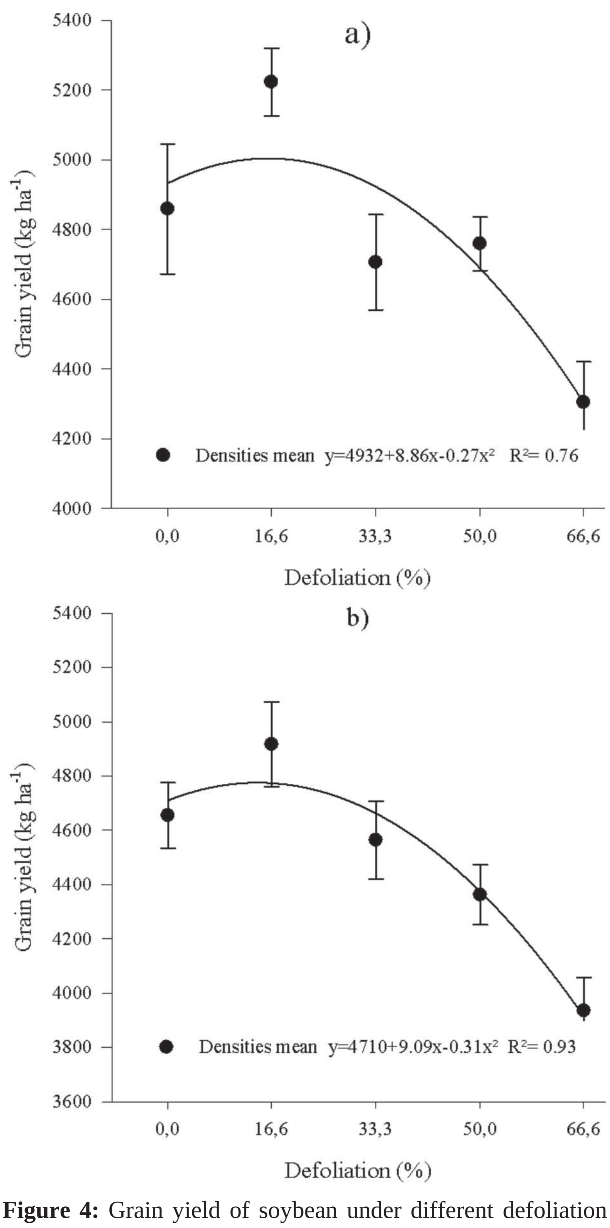


Figure 4: Grain yield of soybean under different defoliation levels in R3, on the average of three plant densities. Campos Novos, SC, 2016/2017 (a) and 2017/2018 growing season (b). Bars indicate the treatment average ± the standard error.

maximum theoretical yield calculated from the quadratic equations adjusted to the data were achieved with percentages of defoliation of 16.4 and 14.7% in the 2016/2017 and 2017/2018 growing seasons, respectively. Grain yield showed no significant decrease with defoliation of up to 33.3%, on the average of the three plant densities. This value is above the EIL of 15% currently proposed by Soybean Guide (Indicações Técnicas, 2019) for the reproductive stage of the soybean crop in southern Brazil on basis to leaf area damaged by insects..

Defoliation below 20% often does not decrease soybean productivity due to an increase in photosynthetic efficiency caused by the higher light penetration into the lower plant layers (Diogo *et al.*, 1997). Light penetration into the canopy may be more important than the total LAI for soybean tolerance to defoliation (Haile *et al.*, 1998). Thus, moderate losses of leaf area can increase grain yield, as found in the present study. The negative leaf expansion recorded in the control between R3 and R5 (Figure 3) corroborates this behavior. Costa *et al.* (2003) and Owen *et al.* (2013) evaluated the response of soybean to defoliation at R3 and observed no decrease in grain yield with moderate defoliation of 15 to 30%.

The indeterminate growth habit of the cultivar NA 5909 RG and the high soil fertility of the experimental area associated with fertilization high level can also be related to the positive effect of the moderate defoliation (16.6%) on light penetration, pod fixation, and grain yield, as they increase soybean plasticity. Cultivars with an indeterminate growth habit have a longer period of transition between the vegetative and reproductive stages, which gives them a higher ability to recover from short periods of stress (Zanon *et al.*, 2015a).

During the two years of study, there was no significant effect of the interaction between plant density and defoliation level on grain yield. The main hypothesis of the study was that grain yield at a sub-optimal density would suffer a higher decrease with defoliation due to a reduction of the crop LAI, compromising its ability to intercept solar radiation. This hypothesis was not confirmed, as the grain yield at a density of 100,000 plants ha^{-1} was not lower than the grain yield achieved in the other treatments, regardless of the defoliation levels (Table 3). Even with an LAI value below the critical in the first growing season (Table 2), the average of treatments with 100,000 plants ha^{-1} showed grain yield with values above 4,500 kg ha^{-1}. Matei *et al.* (2017) reported the high stability and adaptability of the cultivar NA 5909 RG under different plant arrangements. This behavior corroborates the results observed in the present study, showing that this cultivar can reach high yield potentials even when defoliated and subjected to a sub-optimal density of 100,000 plants ha^{-1}.

Table 3: Grain yield of soybean at three plant densities, on the average of five defoliation levels in R3. Campos Novos, SC, 2016/2017 and 2017/2018

Plant density (pl ha^{-1})			
100,000	300,000	500,000	CV %
Grain yield (kg ha^{-1}) in 2016/2017			
4,848 ns	4,760	4,701	6.90
Grain yield (kg ha^{-1}) in 2017/2018			
4,677 a*	4,629 a	4,153 b	7.10

* Averages followed by the same lower case letter in the row do not differ significantly by the t test at the 5% probability level ($P < 0.05$). ns – differences not significant among averages in the row at the 5% probability level.

CONCLUSIONS

Plant density did not interfere with grain yield response of the soybean to defoliation at the beginning of pod formation.

The 16.6% defoliation increase grain yield of the soybean relative to the non-defoliation (control).

The soybean tolerates defoliation of up to 33.3% at R3, with no significant decrease in its grain yield, regardless of the plant density.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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