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Leaf area index and light interception relationship with seed yield of soybean cultivars under reduced seeding rates

Relações entre índice de área foliar, interceptação de luz e a produtividade de grãos de cultivares de soja sob redução da densidade de semeadura

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Highlights

Seeding rate (SR) reduction aims for the same yield with lower costs.
Leaf area index (LAI and light interception (LI) were investigated in reduced SR.
Yield is only not harmed by SR reduction if LAI and LI in reproductive remain stable.
High branching cultivar had higher LAI and LI which confers potential for reducing SR.
Recommended SRs resulted in "luxury growth" mainly in vegetative phase.

Abstract

Owing to the recent increase in the cost of germplasm, biotechnology royalties, and seed treatments, studies have been conducted to analyze the capacity of modern cultivars to maintain yield under reduced seeding rates (SR). This study elucidated the effect of reduced SR on the leaf area index (LAI) and light interception by the canopy of soybean cultivars with contrasting branching plasticity and identified the association of these variables with seed yield. Field experiments were conducted in randomized blocks using BRS 1010IPRO (high plasticity) and NS 5959IPRO (medium plasticity) cultivars, with five SRs: 100, 80, 60, 40, and 20% of the recommended SR. The SR reduction did not reduce the seed yield to the point where the LAI and light interception in the reproductive phase were similar to those obtained with the recommended SR. Higher LAI and light interception in cultivars with higher

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branching plasticity confer greater potential for reducing the SR. The minimum optimal SR (MOSR) for cumulative LAI, Normalized Difference Vegetation Index (NDVI), and intercepted photosynthetic active radiation (IPAR) in the reproductive phase was closer to the MOSR for seed yield than in the vegetative phase or the total crop cycle, indicating "luxury growth" in the vegetative phase at the recommended SRs. Cumulative LAI, NDVI, and IPAR in the reproductive phase had a greater correlation with yield than those in the vegetative phase or the total cycle. The cumulative NDVI had a higher correlation with seed yield than cumulative LAI and IPAR.
Key words: *Glycine max* L. (Merril). Minimum optimal plant population. Normalized difference vegetation index. Plant density. Plant population.

Resumo

Devido ao recente aumento no custo do germoplasma, royalties de biotecnologia e tratamentos de sementes, estudos vêm sendo realizados para analisar a capacidade das cultivares modernas de soja, de manter o rendimento de grãos sob densidades de semeadura (DS) reduzidas. Este estudo objetivou elucidar o efeito da redução da DS no índice de área foliar (IAF) e na interceptação de luz pelo dossel de cultivares de soja com potencial de ramificação contrastantes e identificou a associação dessas variáveis com o rendimento de grãos. Os experimentos de campo foram conduzidos em blocos casualizados, utilizando-se as cultivares BRS 1010IPRO (alta plasticidade) e NS 5959IPRO (média plasticidade), com cinco DS: 100, 80, 60, 40 e 20% da DS recomendada. A redução da DS não reduziu o rendimento de grãos até o ponto em que o IAF e a interceptação luminosa na fase reprodutiva foram semelhantes aos obtidos com a DS recomendada. Maior IAF e interceptação luminosa em cultivares com maior plasticidade de ramificação conferem maior potencial de redução da DS. A densidade de semeadura mínima ótima (DSMO) para IAF, Índice de Vegetação por Diferença Normalizada (NDVI) e radiação fotossinteticamente ativa interceptada (RFAI) acumulados, na fase reprodutiva foi mais próximo da DSMO para produção de grãos do que na fase vegetativa ou no ciclo total da cultura, indicando "crescimento de luxo" na fase vegetativa nas DS recomendadas. O IAF, o NDVI e a RFAI acumulados na fase reprodutiva tiveram maior correlação com o rendimento de grãos do que aqueles na fase vegetativa ou no ciclo total. O NDVI acumulado apresentou maior correlação com o rendimento de grãos do que o IAF e a RFAI acumulados.
Palavras-chave: *Glycine max* L. (Merril). População de plantas mínima ótima. Índice de vegetação por diferença normalizada. Densidade de plantas. População de plantas.

Introduction

A reduced seeding rate (SR) has been studied to increase the profitability of soybean production. Owing to a recent increase in seed costs and improvements in seeding operations, in the last few years, some studies have analyzed the capacity of modern soybean cultivars to maintain yield under reduced SR (Carciochi et al., 2019; Corassa et al., 2018; Ferreira et al., 2020; Pereyra et al., 2022; Rigsby & Board, 2003). This practice aims to sow soybeans at the minimum optimal seeding rate (MOSR, the smallest number of seeds necessary to achieve the optimum yield), which may reduce seed costs without changing the seed yield. This is possible because the relationship typically assumed between SR and soybean yield is diminishing marginal physical growth and productivity of each additional plant. Thus, as SR increases, soybean yield is assumed to increase at a decreasing rate. Therefore, in the MOSR, seed yield is expected to plateau, implying that the addition of each plant does not result in a yield increase up to the point of decrease (above the recommended SR) (Thompson et al., 2015).

The plasticity of the soybean crop in relation to reduced SR has been attributed to increased leaf area index (LAI) and branching, which enhances pods per plant (Balbinot et al., 2018) and seeds per pod (Board, 2000; Carpenter & Board, 1997). However, cultivars exhibit substantial differences in their branching plasticity (Agudamu & Shiraiwa, 2016). Indeterminate cultivars with a compact architecture (smaller and more vertical leaflets with less branching ability) have less potential for SR reduction, mainly in environments that limit vegetative growth and seed yield (Ferreira et al., 2020).

Crop yield can be expressed as a result of three main physiological processes: solar radiation interception by the canopy, solar radiation conversion into biomass, and harvest index (Monteith, 1977). Therefore, understanding light interception and leaf area growth during the soybean development cycle under reduced SR will aid in identifying genetic and environmental strategies for reducing the optimal SR without changing the yield. Variables such as LAI, soil cover by plants (Purcell, 2000), and vegetation indices such as the Normalized Difference Vegetation Index (NDVI) (Stepanov et al., 2022) have been used to assess solar interception by the canopy. Of these variables, NDVI can be obtained more quickly, on a large scale, provided the necessary equipment or access to satellite images with the adequate resolution is available (Roznik et al., 2022). Additionally, knowledge of the relationships between the variables linked to radiation interception and seed yield is relevant for estimating crop productivity before harvest (Andrade et al., 2022; Zhou et al., 2022).

Therefore, the hypotheses of this study are as follows:1) The reduction in SR does not result in lower seed yield down to the point where the branching plasticity of soybean provides LAI and radiation interception similar to the recommended SR during the reproductive stages. 2) Cultivars with greater branching plasticity have greater potential for SR reduction because of the increased radiation interception by each plant. 3) The NDVI and soil cover by the canopy, mainly during the reproductive phase, present a greater correlation with seed yield than the LAI because not every increase in LAI leads to a greater light interception.

This study aimed to elucidate the evolution of the leaf area index (LAI) and light interception by the canopy of soybean cultivars with contrasting branching plasticity in response to SR reduction and to identify how these variables are related to seed yield.

Materials and Methods

Site description

The trials were established in the municipality of Londrina (23°11′ S, 51°11′ W; 620 m altitude), state of Paraná, southern Brazil, during the 2016/17 and 2017/18 growing seasons (GSs). The climate is humid subtropical (Cfa), according to the Köppen climate classification, with an annual mean temperature of 21 °C, mean maximum temperature of 28.5 °C in February, and mean minimum temperature of 13.3 °C in July. The mean annual precipitation is 1651 mm, with a mean of 217 mm in January (wettest month) and 60 mm in August (driest month). The precipitation and air temperature data of both GSs were obtained from an agrometeorological station approximately 500 m from the experiment site and are shown with the soybean development stages in Figure 1.

The soil was classified as Oxisol (Eutroferric Red Latosol, in the Brazilian classification, or Rhodic Eutrudox, USA classification) with 710 g clay kg^{-1}, 82 g silt kg^{-1}, and 208 g sand kg^{-1}. The soil of the experimental area had the following characteristics in the 0–0.2 m layer before the implementation of the experiments: 15.3 g kg^{-1} of organic C; pH (CaCl2) 5.9; 20.3 mg kg^{-1} of P (Mehlich-1); 219 mg kg^{-1} of exchangeable K; 1,042 mg kg^{-1} of exchangeable Ca; 316.1 mg kg^{-1} of exchangeable Mg; 5.4 mg kg^{-1} of S and 70% base saturation.

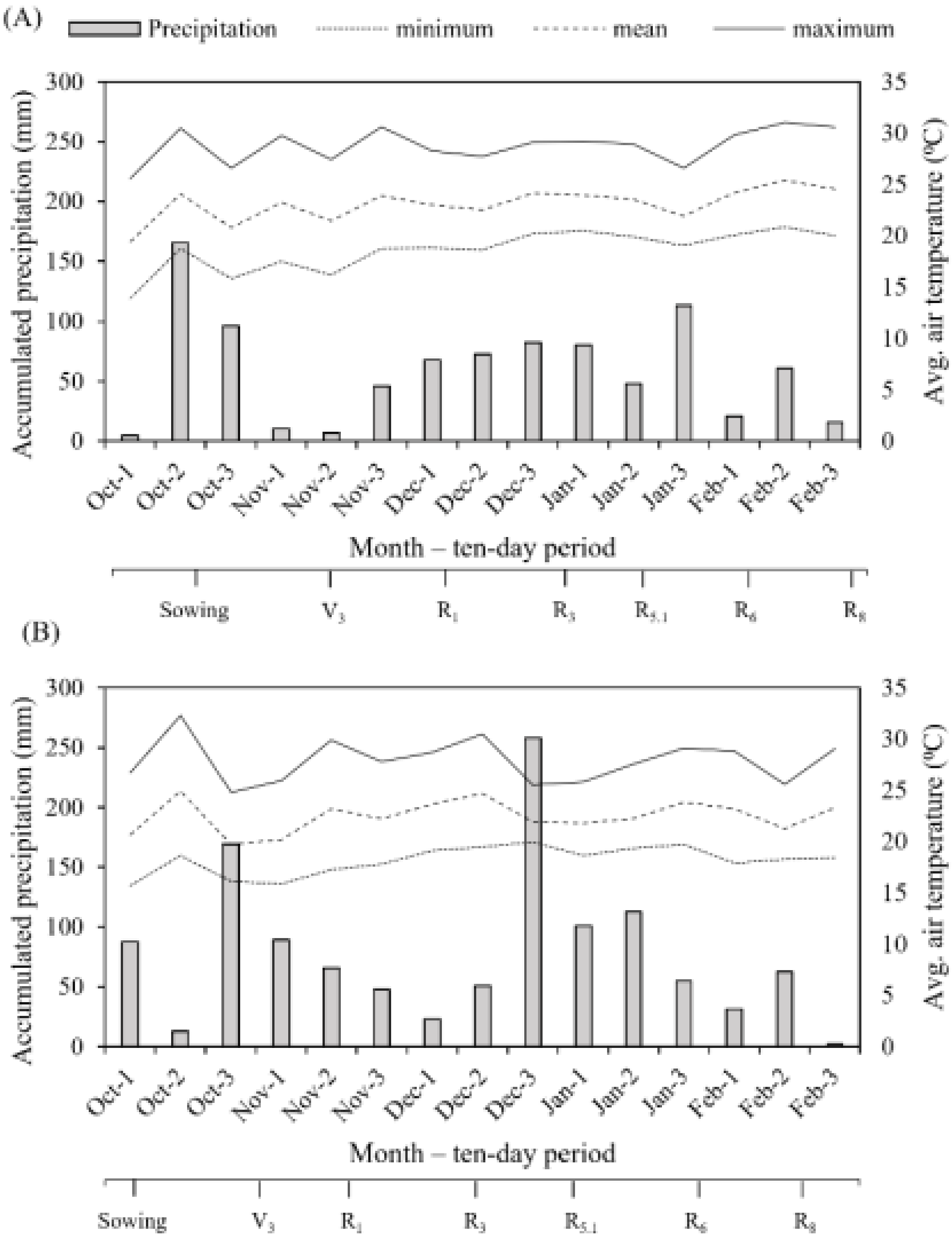

Figure 1. Accumulated precipitation (columns) and air temperature for a ten-day period during different stages of soybean development (Fehr & Caviness, 1977). Londrina, Paraná state, Brazil, 2016/17 (A) and 2017/18 (B) growing seasons.

Experimental design

The present study was obtained from the same experiments reported in Ferreira et al. (2020). For each GS, rainfed field experiments with soybean cultivars BRS 1010IPRO and NS 5959IPRO were conducted in a randomized complete block design with five treatments and five replications. The treatments comprised five SRs (100, 80, 60, 40, and 20% of the SR recommended). These cultivars with an indeterminate growth type were selected to represent genotypes with different branching plasticity. BRS 1010IPRO (6.1 maturity group) is taller and has a higher branching potential than NS 5959IPRO (5.9 maturity group), which is considered a cultivar with compact foliar architecture. The contrast between these cultivars renders a distinctly recommended SR for each cultivar. The recommended SR ranges by the breeders for cultivars BRS 1010IPRO and NS 5959IPRO are 265–310 and 380–420 thousand plants ha^{-1}, respectively. To define the treatments, the maximum range value for each cultivar was considered the recommended value. Thus, the SRs for each cultivar were 310, 248, 186, 124, and 62 thousand viable seeds ha^{-1} for BRS 1010IPRO and 420, 336, 252, 168, and 84 thousand viable seeds ha^{-1} for NS 5959IPRO.

Seeds were sown on October 28, 2016, and October 6, 2017, using a fertilizer-seeder machine (Model Semeato® SHM 11/13). Seeds were treated with Standak Top® (fipronil + thiophanate methyl + pyraclostrobin; 3 mL kg^{-1} of seeds) and the liquid inoculant Gelfix 5® (5 × 10^9 colony-forming units of *Bradyrhizobium elkanii* – 2 mL kg^{-1} of seeds) at the time of sowing. The seeder was set to deliver the same fertilizer rate (80 kg of P_2O_5 and K_2O) for all treatments, and the desired SR for each treatment was corrected for seed viability. Row spacing was 0.45 m. The plots were 10.0 m in length and 5.0 m in width, totaling 50.0 m^2. Pests, diseases and weeds were fully controlled in both years of the experiment and did not have any effect on the leaf area and seed yield.

Evaluations

The leaf area index (LAI) was used to estimate the leaf growth of soybean plants. The light interception by the canopy was estimated using NDVI and fraction of canopy coverage (FCC) evaluations. All evaluations were performed weekly from V_E to R_7 (Fehr & Caviness, 1977), totaling 10 evaluations per GS. In addition, the days after emergence (DAE) for each weekly measurement was recorded.

LAI was determined using a plant canopy analyzer LI-2200C (LI-COR Biosciences Company) with five reading positions inside the canopy, two in the row and three in the intra-row of soybean plants, every time in the same position of the useful area of plots. NDVI is a dimensionless index that varies from 0 to 1 and estimates the amount of green area (leaves) on the terrain. This was measured using a GreenSeeker 505 Handheld Sensor device (Ntech Industries, Inc.). All NDVI measurements were performed from 9 to 11 a.m. under sunny conditions, aiming to meet equipment specifications with the sensor positioned 1.0 m above the canopy top and walking along the full length of each plot at the center of the plot.

The lm() function in the R software was used to perform polynomial regression on the collected LAI and NDVI as a function of DAE, allowing us to estimate the daily values of LAI and NDVI. Cumulative LAI (CumLAI) and NDVI (CumNDVI) were then calculated by summing the daily estimates from V_e (DAE = 1, assuming that 0 DAE means 0 NDVI) to R_2, R_2 to R_7 and V_e to R_7 (total) stages of soybean development according to the Fehr and Caviness (1977) scale. CumLAI and CumNDVI are relative numbers and have no units of measure.

FCC was determined, according to Purcell (2000), using digital images taken every time in the same position of the plot with a camera mounted 1.5 m above the canopy, followed by software processing to estimate the fraction of the area covered by leaves. Digital images were analyzed using Siscob® software (developed by Embrapa). Daily solar radiation (MJ m^{-2} $^{-}$day) was recorded at the experimental site, and daily incident photosynthetic active radiation (PAR) was calculated as 50% of the solar radiation (Edwards et al., 2005). Again, the lm() function in R software was used to perform polynomial regression on the collected DAE and FCC measurements to estimate the FCC for every day of the growing season. Cumulative intercepted photosynthetically active radiation (CIPAR, MJ m^{-2}) was calculated from the daily FCC and PAR (Gaspar & Conley, 2015). CIPAR was calculated for the V_e to R_2, R_2 to R_7, and Ve to R_7 (total) stages of soybean development. Finally, the inner rows of the usable area of the plot (7.5 m^2) were mechanized harvested to determine seed yield (SY) with seed moisture corrected to 13%.

Data analysis

In the first stage of the data analysis, the weekly collected values of LAI, NDVI, and FCC of both cultivars and GS were plotted descriptively using 95% confidence intervals. In the second stage, the CumLAI, CumNDVI, and CIPAR on the V_e to R_2, R_2 to R_7, and total stratum of the crop cycle were submitted to ANOVA considering each GS separately after the verification of normality (Shapiro–Wilk's test) and homoscedasticity of variances (Bartlett's test). Based on the behavior of soybean in response to reduced SRs, significant differences were analyzed by linear and non-linear regression (linear-plateau model), adjusting the model with the highest determination coefficient (R2) (Carciochi et al., 2019; Thompson et al., 2015).

The linear-plateau regression has two segments. The first describes a rising line up to a certain P value of the curve, the response plateau, from which the value assumes a P constant because the increase in SR does not provide a dependent variable (LAI, NDVI, or CIPAR) increase after this point.

MOSR for seed yield, reported in Ferreira et al. (2020) has been used for comparison purposes with the MOSR for CumLAI, CumNDVI, and CIPAR. In the third data analysis stage, the influence of CumLAI, CumNDVI, and CIPAR on soybean seed yield for each cultivar in the average of the two GS was verified through Pearson's linear correlation analysis ($p < 0.05$).

Results

In both GSs, the minimum, medium, and maximum temperatures were close to historical averages. As a result, the cumulative total precipitation was 1009 and 1321 mm for the 2016/17 and 2017/18 GS, respectively, which was sufficient to supply the required amount for the soybean crop (Figure 1). However, in the second GS, there was a drought associated with high temperatures in the second ten-day period of October, immediately after sowing, which resulted in less favorable conditions for the initial growth of the plants (Figure 1B). Regarding soybean development, in the 2016/17 GS, both cultivars reached the R2 growth stage at 48 DAE and the R7 growth stage at 87 DAE. In the 2017/18 GS, soybeans reached the R2 growth stage at 47 DAE and the R7 growth stage at 90 DAE.

Leaf area index evolution

In the BRS 1010IPRO cultivar, 2016/17 GS, the lowest SR (60,000 seeds ha^{-1}) had a lower LAI than the other SR from 30 DAE to the R7 stage. The SRs of 125, 185, 250, and 310 thousand seeds ha^{-1} had statistically similar LAI evolution throughout the cycle, with a maximum LAI point reaching close to 70 DAE and LAI reduction from this point onward, owing to leaf senescence (Figure 2A). In the 2017/18 GS, LAI evolution was similar for all SRs up to approximately 50 DAE, and from that moment on, the lowest SR had a lower LAI than the others. The maximum LAI values in 2017/18 GS were lower than those in the previous season and reached near the end of the crop cycle, indicating that the leaf growth of BRS 1010IPRO was lower in the second season (Figure 2B).

In the NS 5959IPRO cultivar, 2016/17 GS, the reduction in SR of up to 250,000 seeds ha^{-1} did not result in significant differences in LAI evolution. However, reducing the SR to 170 and 85 thousand seeds ha^{-1} reduced the LAI from 30 to 80 DAE (Figure 2C). Particularly, the two lowest SRs had the lowest LAI values during the reproductive stages. In the 2017/18 GS, all tested SRs had slower LAI evolution than in the first GS, with SRs of 250, 335, and 420 thousand seeds ha^{-1} higher only after 60 DAE (Figure 2D). Notably, the leaf growth of NS 5959IPRO was slower and smaller in the second GS than in the first, as well as in the BRS 1010IPRO cultivar.

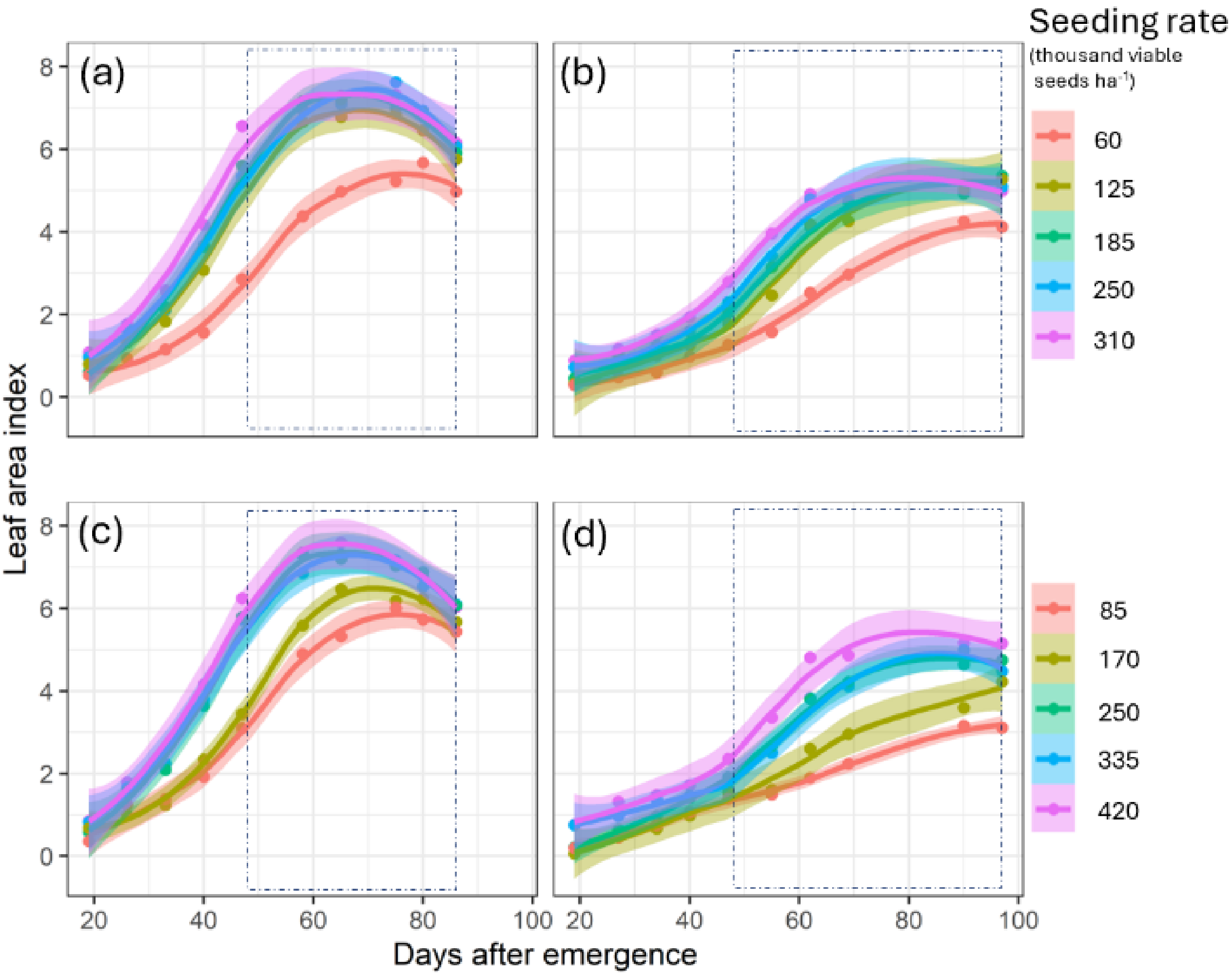

Figure 2. Leaf area index evolution through the growing cycle of soybean cultivars in response to reduced seeding rate (up to 20% of the recommended by the breeder). BRS 1010IPRO (A and B) and NS 5959IPRO (C and D) in the 2016/17 and 2017/18 growing seasons, respectively. Blue dotted rectangle represents the reproductive stages of soybean development (R_2 – R_7).

Normalized difference vegetation index evolution

The evolution of NDVI in the BRS 1010IPRO cultivar in 2016/17 GS was similar for all SRs, except for the lowest SR that differed from the others from approximately 25 to 45 DAE. At 50 DAE, all SRs had already reached an NDVI above 0.9, except for the lowest SR, which only reached this value at the end of the cycle (Figure 3A). In the 2017/18 GS, the lowest SR presented a lower NDVI than the others from the beginning of the cycle to 75 DAE. The SRs of 125 and 185 thousand seeds ha^{-1} had lower NDVI values than the SR of 310 thousand seeds ha^{-1} from 25 to 50 DAE. In this season, the highest SR reached NDVI close to 0.9 at 60 DAE, whereas the lowest SRs reached this value only at the end of the evaluation period (Figure 3B).

In NS 5959IPRO, 2016/17 GS, the SRs of 85 and 170 thousand seeds ha^{-1} provided lower NDVI values than the others up to approximately 50 DAE. Thereafter, all SRs presented an NDVI close to 0.9, except for the lowest SR, which reached this value at 70 DAE (Figure 3C). In the 2017/18 GS, the three highest SRs (420, 335, and 250,000 seeds ha^{-1}) had a similar evolution in NDVI throughout the cycle but only reached a maximum NDVI of approximately 0.85. The SRs of 85 and 170 thousand seeds ha^{-1} had lower NDVI values than the others from the beginning of the cycle up to approximately 75 DAE (Figure 3D).

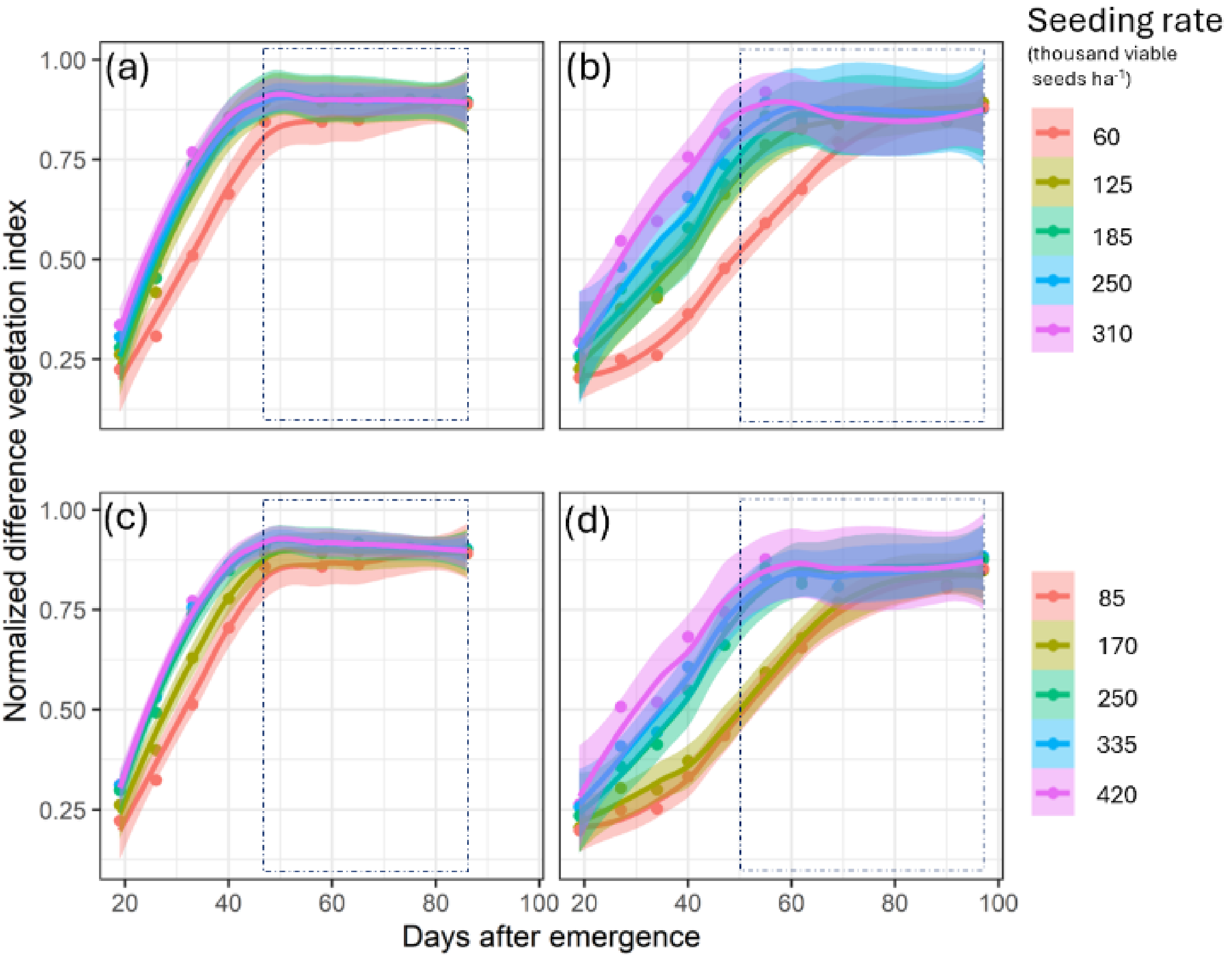

Figure 3. Normalized difference vegetation index evolution through the growing cycle of soybean cultivars in response to reduced seeding rate (up to 20% of the recommended by the breeder). BRS 1010IPRO (A and B) and NS 5959IPRO (C and D) in the 2016/17 and 2017/18 growing seasons, respectively. Blue dotted rectangle represents the reproductive stages of soybean development ($R_2 – R_7$).

Fraction of canopy coverage evolution

The FCC evolution in cultivars and GSs was similar to that reported for NDVI. In BRS 1010IPRO, 2016/17 GS, all SRs had similar FCC throughout the cycle, reaching FCC close to 0.9 at 45 DAE, except for the lowest SR that differed from the others, from the beginning of the cycle to 60 DAE (Figure 4A). In 2017/18 GS, reducing SR to 60,000 seeds ha^{-1} resulted in lower FCC during the entire crop cycle, whereas the SR of 125,000 seeds ha^{-1} resulted in lower FCC only in the early stages of the crop (Figure 4B).

For NS 5959IPRO, 2016/17 GS, the three higher densities had a similar evolution to the FCC and presented canopy coverage close to 0.9 from 40 DAE. However, SRs of 85 and 170 thousand seeds ha^{-1} resulted in a lower FCC up to 60 DAE (Figure 4C). In the 2017/18 GS, the evolution of the FCC was slower, such that the highest SRs reached canopy coverage close to 0.9 only after 70 DAE. In addition, the two lowest SRs had lower FCC values than the others during the entire cycle (Figure 4D).

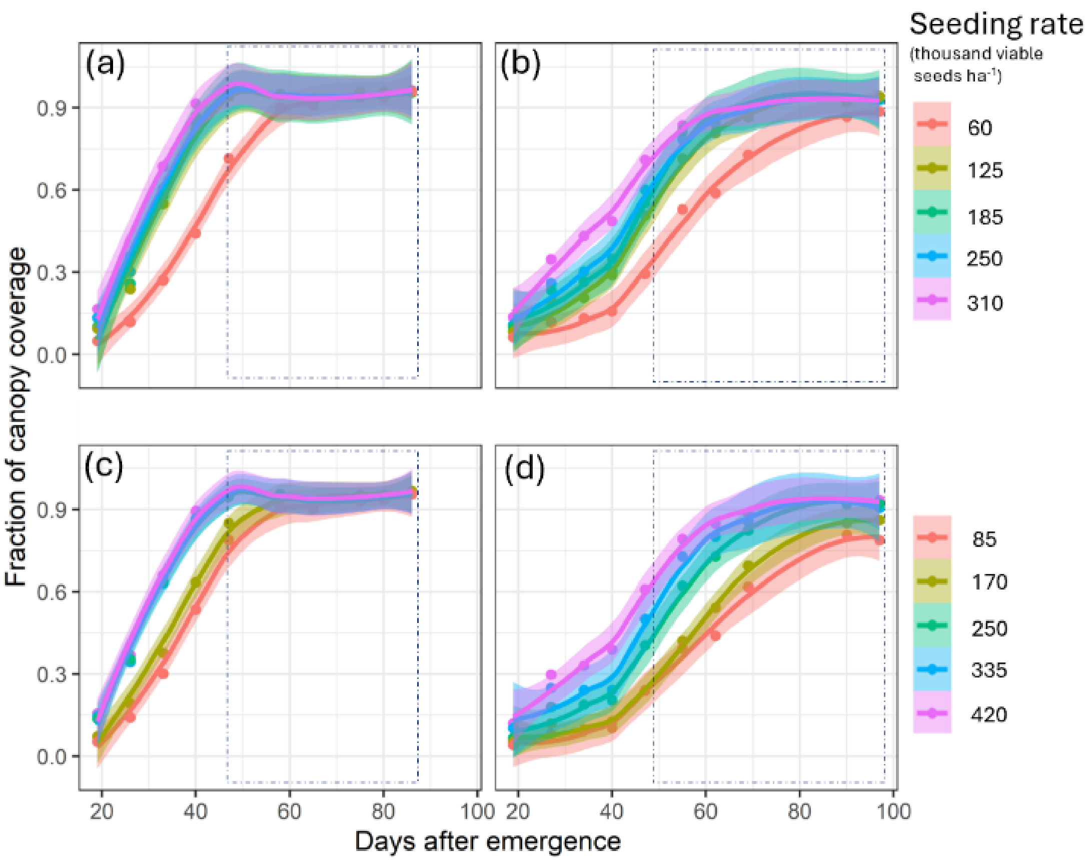

Figure 4. Fraction of canopy coverage evolution through the growing cycle of soybean cultivars in response to reduced seeding rate (up to 20% of the recommended by the breeder). BRS 1010IPRO (A and B) and NS 5959IPRO (C and D) in the 2016/17 and 2017/18 growing seasons, respectively. Blue dotted rectangle represents the reproductive stages of soybean development ($R_2 – R_7$).

Cumulative LAI analysis

The seeding rate significantly influenced the CumLAI from V_e to R_2 and R_2 to R_7 and the Total CumLAI in both cultivars and GS (Figure 5). In both cultivars, there was a higher CumLAI in all stages of development in the first GS than in the second GS. In BRS 1010IPRO, 2016/17 GS, the plateau linear model demonstrates linear growth of CumLAI V_e–R_2 until the SR of 231 thousand seeds ha^{-1}, which consists of MOSR; thereafter, there was no more influence of SR on this variable. In the second GS, soybeans reached lower CumLAI V_e–R_2 values, and there was linear growth throughout the range of SR tested (Figure 5A). During the reproductive stages (R_2–R_7), CumLAI in the 2016/17 GS had a linear-plateau fit with a MOSR of 142,000 seeds ha^{-1}, whereas, in the following season, there was linear growth of CumLAI R_2–R_7 in response to SRs (Figure 5C). Considering the Total CumLAI of BRS 1010IPRO, it was observed that there were 146 and 215 thousand seeds ha^{-1} in the 2016/17 and 2017/18 GSs, respectively (Figure 5E).

In the NS 5959IPRO cultivar, the MOSR for CumLAI V_e–R_2 was 353 thousand seeds ha^{-1} in 2016/17 GS and showed linear growth with the increase in SR in 2017/18 GS (Figure 5B). During the reproductive stages (R_2–R_7), CumLAI had a MOSR of 260 thousand seeds ha^{-1} and a linear fit for the SRs tested in the first and second GS, respectively (Figure 5D). The Total CumLAI also had a linear-plateau fit, with a MOSR of 276 thousand seeds ha^{-1} in the first GS and a linear fit in the second GS (Figure 5F).

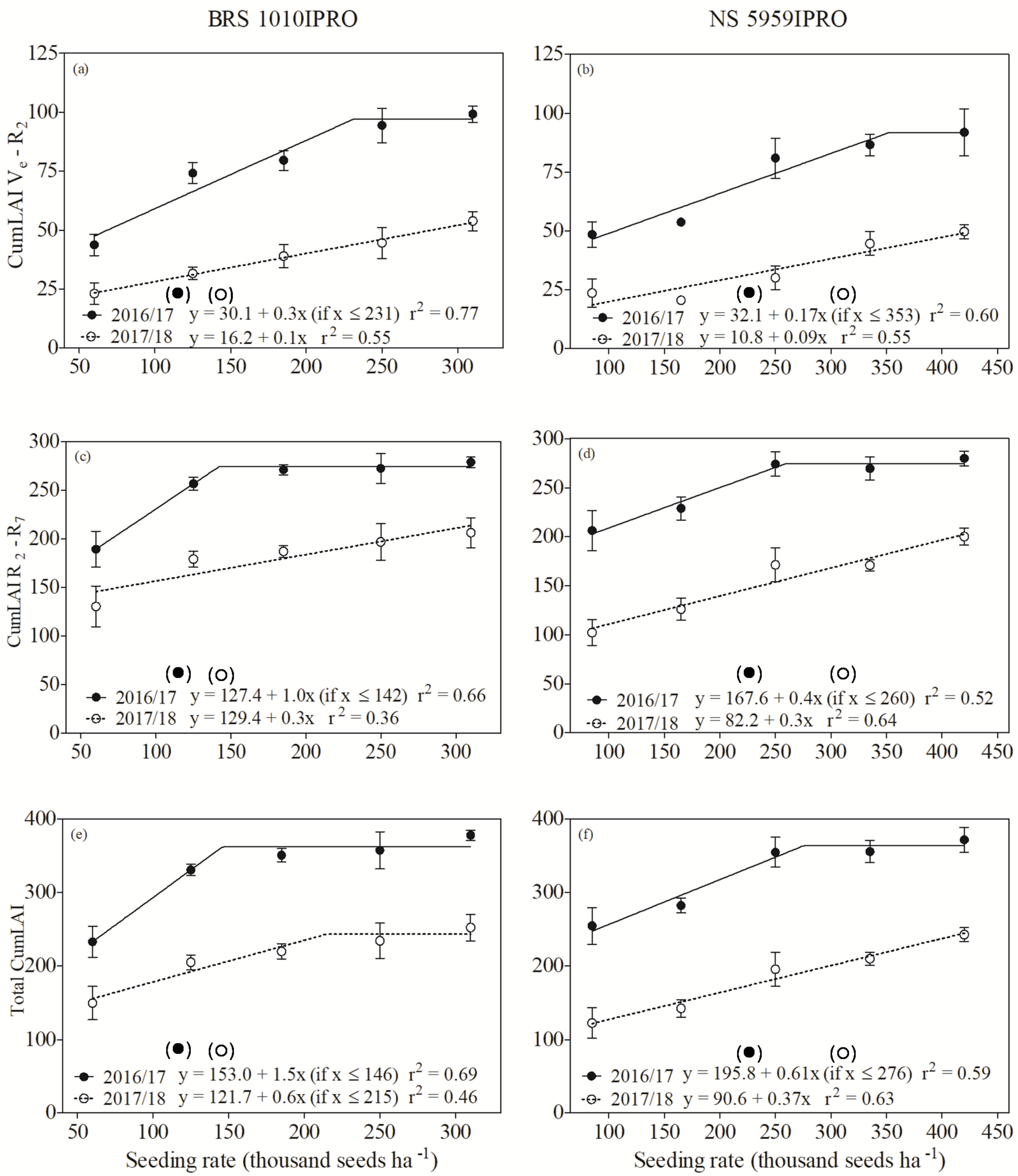

Figure 5. Cumulative leaf area index (CumLAI) during the V_E–R_2, R_2–R_7 stages, and the total cycle of soybean development influenced by the seeding rate reduction (up to 20% of the recommended by the breeder) on cultivars with contrasting branching plasticity, BRS 1010IPRO (higher) and NS 5959IPRO (lower), 2016/17 and 2017/18 growing seasons. (●) and (○): Point of minimum optimal seeding rate for seed yield in 2016/17 and 2017/18 growing seasons, respectively: BRS 1010IPRO: 3,900 and 4,400 kg ha^{-1} and NS 5959IPRO: 4,300 and 4,400 kg ha^{-1} (Ferreira et al., 2020).

Cumulative NDVI analysis

The Cum NDVI V_e–R_2 of BRS 1010IPRO in the 2016/17 GS had a MOSR of 151 thousand seeds ha^{-1}, whereas, in 2017/18, the response was linear in relation to all SRs tested (Figure 6A). The response of CumNDVI R_2–R_7 in 2016/17 GS was linear but with a low angular coefficient, representing a growth rate of only 0.04 CumNDVI for every 10,000 seeds added in the SR. In the 2017/18 GS, there was linear growth up to MOSR, which was 142,000 seeds ha^{-1} (Figure 6C). The Total CumNDVI had a MOSR of 147 and 218 thousand seeds ha^{-1} in the 2016/17 and 2017/18 GSs, respectively (Figure 6E).

In the NS 5959IPRO cultivar, CumNDVI V_e–R_2 showed linear growth up to a MOSR of 272,000 seeds ha^{-1} in the 2016/17 GS and linear growth throughout the tested SR range in the 2017/18 GS (Figure 6B). During the reproductive stages, there was a linear fit in the 2016/17 GS; however, as in the BRS 1010IPRO, the growth rate was very low (0.01 CumNDVI for each 10 thousand seeds ha^{-1} added), demonstrating the little influence of SR on this variable. In contrast, in the 2017/18 GS, CumNDVI R_2–R_7 presented a linear-plateau fit with a MOSR of 287 thousand seeds ha^{-1} (Figure 6D). Regarding the Total CumNDVI, there was a linear increase up to the MOSR, which was 270 and 367 thousand seeds ha^{-1} in the 2016/17 and 2017/18 GSs, respectively (Figure 6F).

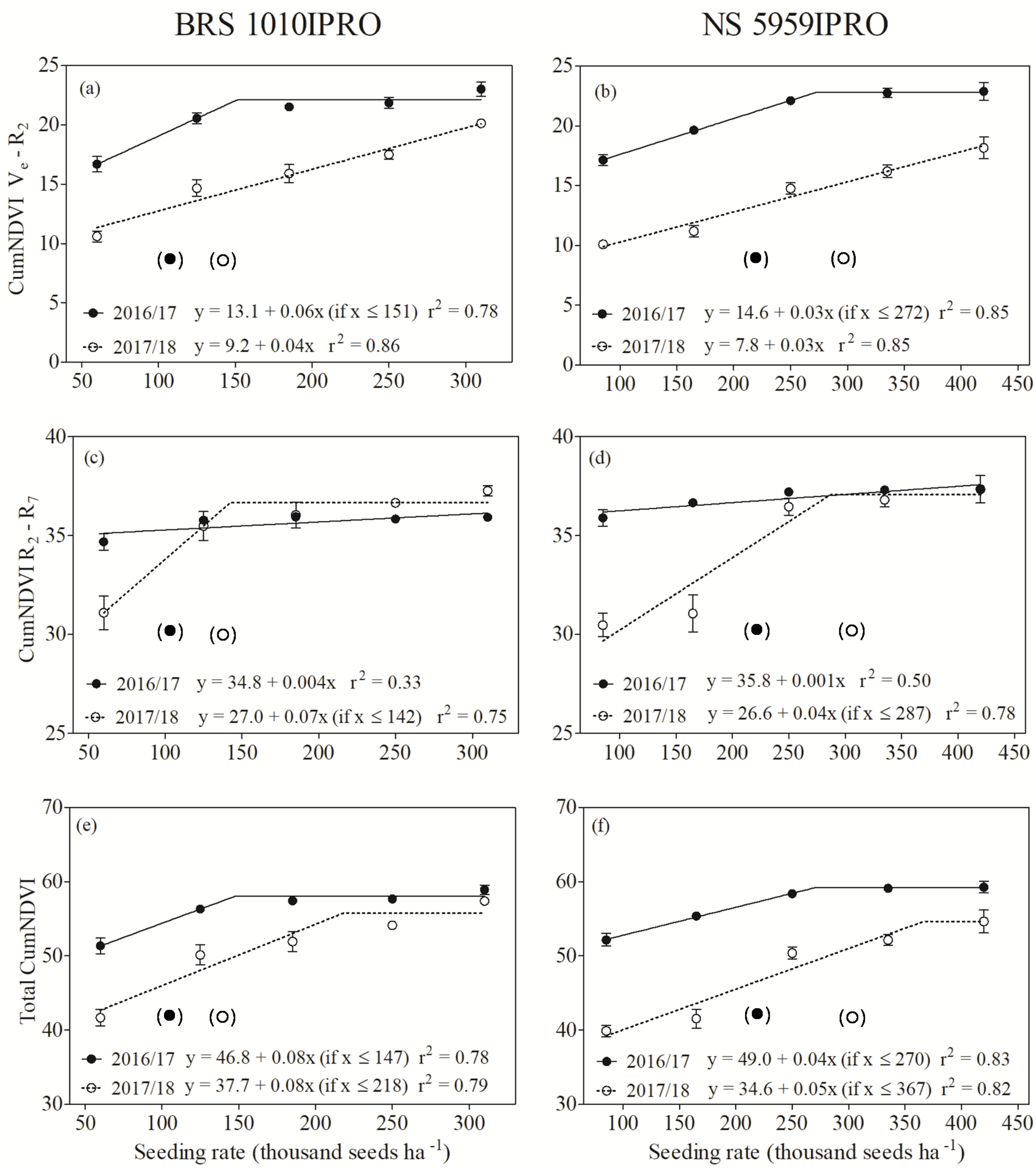

Figure 6. Cumulative normalized difference vegetation index (CumNDVI) during the V_E–R_2, R_2–R_7 stages, and the total cycle of soybean development influenced by the seeding rate reduction (up to 20% of the recommended by the breeder) on cultivars with contrasting branching plasticity, BRS 1010IPRO (higher) and NS 5959IPRO (lower), 2016/17 and 2017/18 growing seasons. (●) and (○): Point of minimum optimal seeding rate for seed yield in 2016/17 and 2017/18 growing seasons, respectively: BRS 1010IPRO: 3,900 and 4,400 kg ha^{-1} and NS 5959IPRO: 4,300 and 4,400 kg ha^{-1} (Ferreira et al., 2020).

Cumulative intercepted photosynthetic active radiation analysis

The behavior of both cultivars in relation to CIPAR was similar to that observed for CumNDVI. In 2016/17 GS, the BRS 1010IPRO cultivar showed linear growth from CIPAR V_e–R_2 to the MOSR of 143 thousand seeds ha^{-1}, whereas in 2017/18 GS, growth was linear throughout the SRs range (Figure 7A). For CIPAR R_2–R_7, there was linear-plateau growth with a MOSR of 127 and 145 thousand seeds ha^{-1} in the 2016/17 and 2017/18 GSs, respectively. It is important to highlight that in 2016/17, although there was a significant linear-plateau fit, the growth rate was low, with only 2.9 MJ m^{-2} for every 10,000 seeds added up to MOSR (Figure 7C). In relation to the Total CIPAR, the MOSR was 140 and 204 for the first and second GSs, respectively (Figure 7E).

In the NS 5959IPRO cultivar, there was a linear increase from CIPAR V_e–R_2 to the MOSR of 272 seeds ha^{-1} in 2016/17 GS. In 2017/18, the increase was linear throughout the tested SRs range (Figure 7B). In the reproductive stages, in 2016/17 GS, SR did not affect CIPAR R_2–R_7; however, in the following GS, there was a linear increase throughout the total range of SRs tested (Figure 7D). Regarding Total CIPAR, there was a linear-plateau fit with a MOSR of 272 and 399 thousand seeds ha^{-1} (Figure 7F).

Correlations of CumLAI, CumNDVI and CIPAR with seed yield

In the BRS 1010IPRO cultivar, there was no correlation between CumLAI in the three developmental periods evaluated and seed yield (Figures 8A, 8D, and 8G). CumNDVI V_e–R_2 was not correlated with seed yield (Figure 8B). Total CumNDVI and CumNDVI R_2–R_7 were significantly correlated with yield; however, the correlation coefficient was higher in the reproductive phase (Figures 8E and 8H). There was a significant correlation between yield and CIPAR throughout the crop cycle and in the V_E–R_2 and R_2–R_7 stages (Figures 8C, 8F, and 8I).

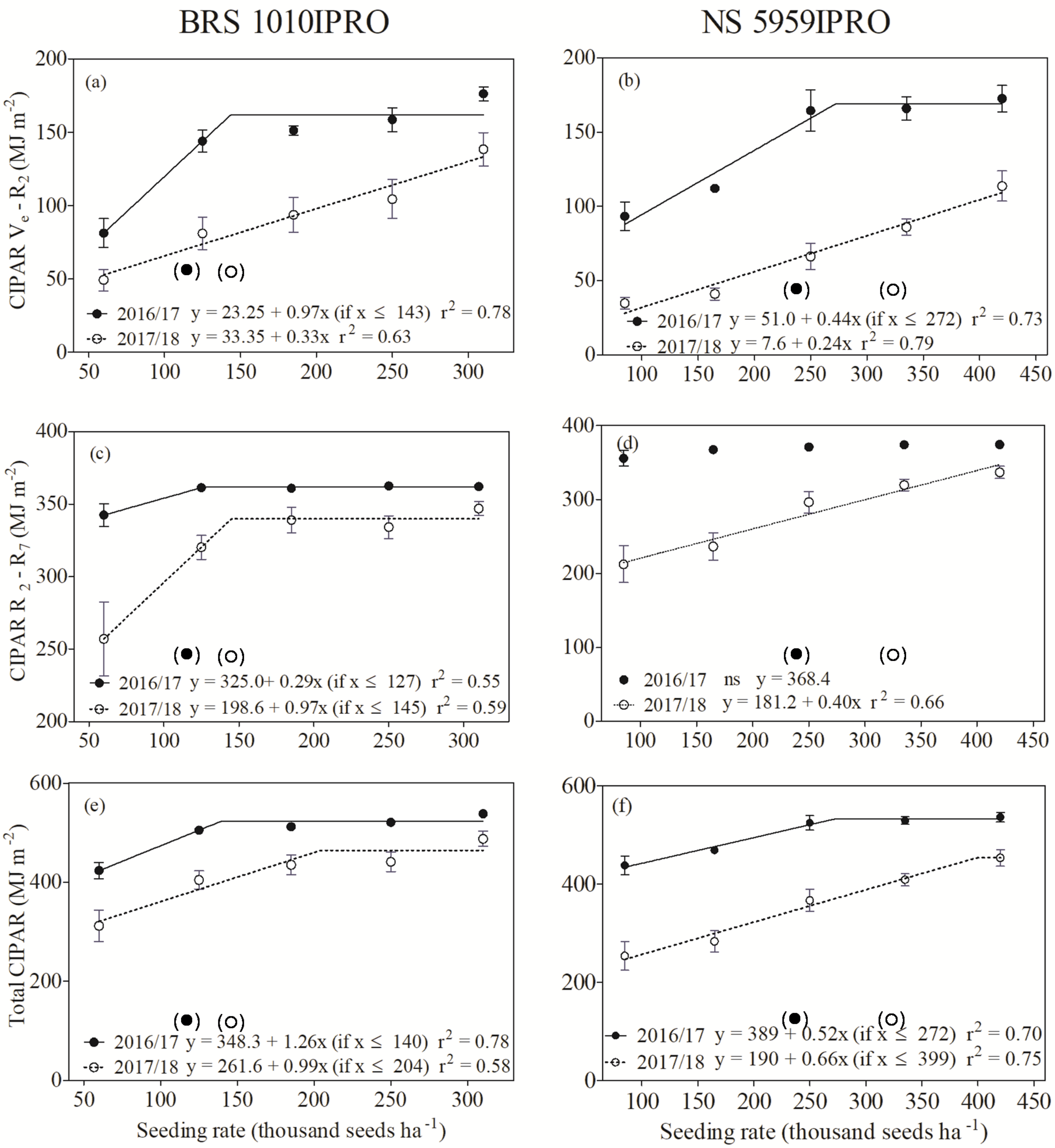

Figure 7. Cumulative intercepted photosynthetic active radiation (CIPAR) during the V_E–R_2, R_2–R_7 stages, and the total cycle of soybean development influenced by the seeding rate reduction (up to 20% of the recommended by the breeder) on cultivars with contrasting branching plasticity, BRS 1010IPRO (higher) and NS 5959IPRO (lower), 2016/17 and 2017/18 growing seasons. (●) and (○): Point of minimum optimal seeding rate for seed yield in 2016/17 and 2017/18 growing seasons, respectively: BRS 1010IPRO: 3,900 and 4,400 kg ha^{-1} and NS 5959IPRO: 4,300 and 4,400 kg ha^{-1} (Ferreira et al., 2020).

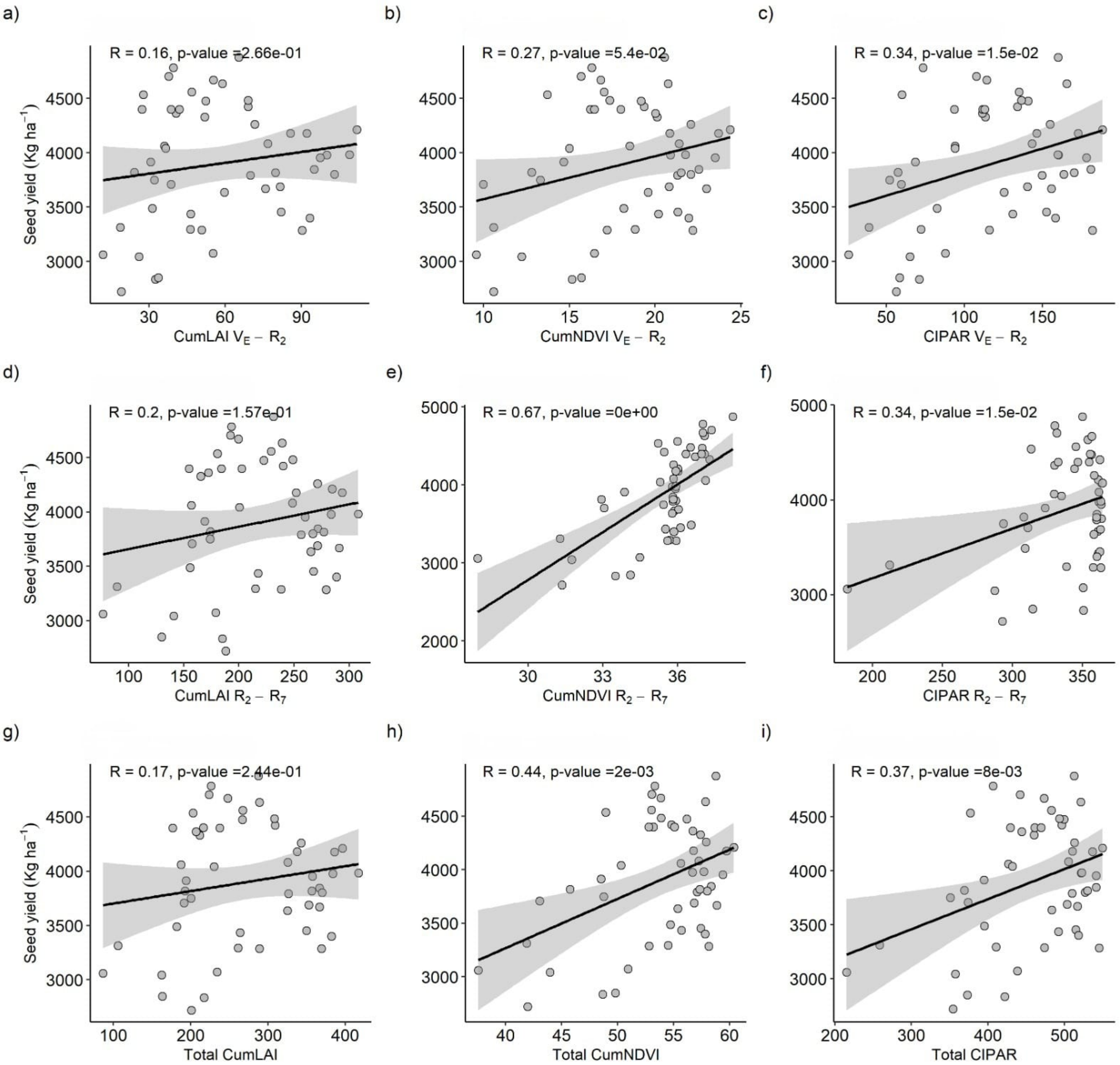

Figure 8. Pearson's correlation between the seed yield and the cumulative leaf area index (CumLAI), cumulative normalized difference vegetation index (CumNDVI), and cumulative intercepted photosynthetic active radiation (CIPAR) during the V_E–R_2, R_2–R_7 stages, and the total cycle of soybean development influenced by the seeding rate reduction (up to 20% of the recommended by the breeder), cultivar BRS 1010IPRO.

In cultivar NS 5959IPRO, there was a correlation between seed yield and CumLAI in all development periods considered (Figures 9A, 9D and 9G), with a higher correlation coefficient for the period R_2–R_7. In contrast, CumNDVI was strongly correlated with yield in all stages, with a higher coefficient observed in the R_2–R_7 period (Figures 9B, 9E and 9H). Regarding CIPAR, there was a significant correlation with yield in all periods, but with a higher coefficient in periods R_2–R_7 and total (Figures 9C, 9F and 9I).

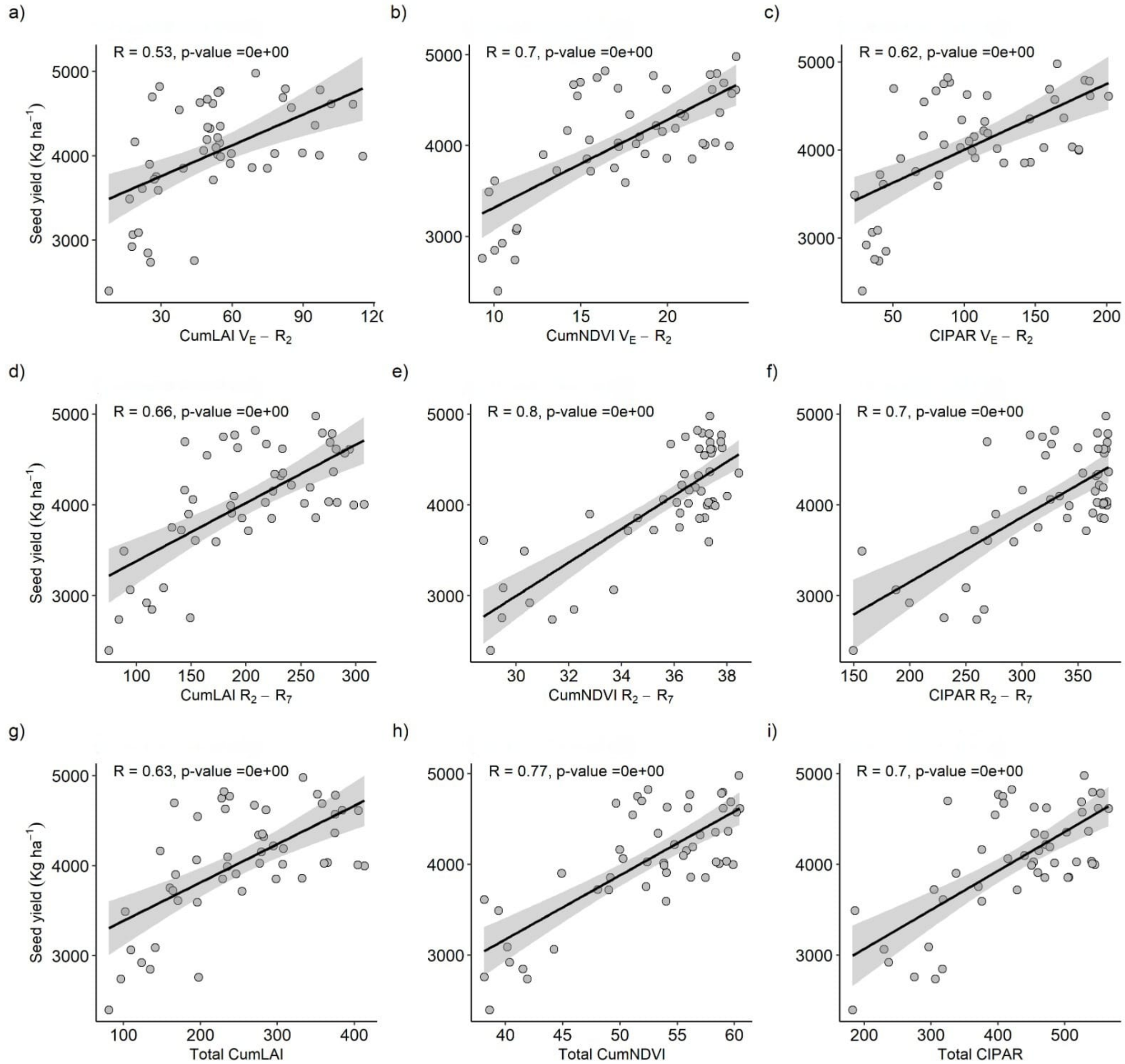

Figure 9. Pearson's correlation between the seed yield and the cumulative leaf area index (CumLAI), cumulative normalized difference vegetation index (CumNDVI), and cumulative intercepted photosynthetic active radiation (CIPAR) during the V_E–R_2, R_2–R_7 stages, and the total cycle of soybean development influenced by the seeding rate reduction (up to 20% of the recommended by the breeder), cultivar NS 5959IPRO.

Discussion

LAI, NDVI, and the FCC evolution

In both soybean cultivars, there was a rapid increase in LAI, NDVI, and FCC, as well as a higher maximum LAI in the 2016/17 GS than in 2017/18. In the second GS, there was a period of low precipitation associated with high temperatures immediately after sowing, which likely impaired the initial growth of the crop. In addition, in 2016/17, there was more precipitation in the first 20 days of December, a period in which there was high plant growth.

The LAI is a key crop biophysical variable influencing many vegetation processes (Nandan et al., 2022). The LAI is a fundamental crop parameter that determines the absorption rate of PAR (Xiao et al., 2015). LAI also affects the exchange of water vapor and near-surface climate by influencing albedo (Li, 2019). The maximum LAI reached by both cultivars was close to 8.0 in 2016/17, demonstrating high plant growth. In the 2017/18 GS, the maximum LAI was close to 6.0. Müller et al. (2017) indicated that, for Brazilian cultivar conditions, a LAI between 4 and 5 was the most appropriate, reaching the R4 stage. Soybeans must attain a LAI of 3.9 to intercept 95% incident solar radiation. However, it should not be generalized because it may vary among cultivars, crop management, phenological stage, and plant leaf features. Under Brazilian subtropical conditions (Tagliapietra et al., 2018), the optimal LAI for high yields of soybean cultivars with an indeterminate growth type is approximately 3.6 at the beginning of flowering, and 6.0, during grain filling, with seed yield reductions at the maximum LAI above 8.0. From this perspective, even with a drastic reduction in SR, the maximum LAI obtained was close to ideal values. However, in the second GS, at the two lowest SRs, LAI was less than ideal, especially in the NS 5959IPRO cultivar. It is important to consider that soybean sowing was carried out at a suitable time for plant growth. In late sowing, carried out in December in southern Brazil, there is a reduction in the LAI; therefore, there is less possibility of reducing the SR (Umburanas et al., 2019).

The BRS 1010IPRO cultivar had greater branching plasticity in relation to NS 5959IPRO because, at SRs above 40% of the recommended 124 thousand seeds ha^{-1}, there was an evolution of LAI, NDVI, and FCC similar to the recommended SR, 310 thousand seeds ha^{-1}, especially in the 2016/17 GS. For the NS 5959IPRO cultivar, at SRs lower than 60% of the indicated (250 thousand seeds ha^{-1}), there was a loss in LAI, NDVI, and FCC. Thus, the practice of reducing soybean sowing SR must be based on the morpho-physiological characteristics of the cultivars to avoid excessive reduction of LAI and radiation interception during the development cycle. Board (2004) also observed an expressive LAI variation among soybean cultivars, which affected defoliation tolerance.

During the vegetative period of the crop, there was a distinction between the SRs evaluated for the LAI, NDVI, and FCC. However, in the reproductive period, only LAI allowed greater distinction between treatments, compared to NDVI and FCC, because LAI continued to increase even after NDVI and FCC reached values close to 1.0, which represents the maximum value, due to the total canopy closure. This may represent a limitation of the NDVI and FCC for measuring soybean growth in canopies that have already had inter-row closure.

CumLAI, CumNDVI, and CIPAR analysis

Owing to the more favorable water and temperature conditions for plant growth observed in the 2016/17 season, the MOSR for variables related to radiation interception was reached at lower SRs compared to the 2017/18 GS. Therefore, under more favorable environmental conditions for soybeans, a greater reduction in SR is possible without harming the interception of radiation by the canopy and seed yield (Corassa et al., 2018).

The cultivar BRS 1010IPRO had LAI, NDVI, and CIPAR stabilization in the vegetative, reproductive, and total cycle periods at lower SRs than NS 5959IPRO. This further indicates the greater plasticity of BRS 1010IPRO and greater possibilities of reducing SR in high branching plasticity cultivars (Ferreira et al., 2020). However, the MOSR for seed yield was lower than the recommended SR in both cultivars. This information is relevant to support the reduction of SR and decision-making on the need for reseeding in conditions of inadequate crop establishment.

In the 2016/17 GS, when there was greater plant growth, the MOSR for CumLAI, CumNDVI, and CIPAR in the reproductive phase had greater similarity with the MOSR points for seed yield in relation to the analysis carried out during the vegetative periods and the total soybean cycle. Consequently, the MOSR for CumLAI, CumNDVI, and CIPAR throughout the soybean cycle was less similar to the MOSR for seed yield in relation to the analysis that considered only the reproductive period. This indicates a “luxury growth” in the reproductive phase at the recommended SR. Hayashida et al. (2021) concluded that in modern soybean cultivars, there is a tolerance to defoliation of 30% during the vegetative phase and 15% during the reproductive phase. Therefore, the “luxury growth” of soybeans is evidently greater in the vegetative phase than in grain filling (Glier et al., 2015). Consequently, attention must focus on the production and maintenance of leaf area during the reproductive phase of the crop (Bueno et al., 2021) to achieve adequate light interception.

Correlations of CumLAI, CumNDVI, and CIPAR with seed yield

NDVI was the variable related to light interception by the soybean canopy, which had the highest correlations with yield, mainly in the reproductive phase. Esquerdo et al. (2011) verified that soybean seed yield could be estimated with adequate accuracy based on NDVI monitoring using satellite images. In contrast, LAI did not correlate with yield in the case of cultivar BRS 1010IPRO (greater plasticity) or had a low correlation for cultivar NS 5959IPRO (lower plasticity). The increase in LAI leads to greater light interception up to a certain point, at which the shading of the lower extract leaves begins to intensify. Therefore, plants might have an energy imbalance because the shaded structures spend energy on respiration without being produced through photosynthesis. Considering that the optimal LAI for soybeans of indeterminate growth type in subtropical conditions of Brazil is between 3.6 to 6 during the flowering and fruiting period, respectively (Tagliapietra et al., 2018), the low influence of LAI on seed yield is because the LAI obtained in all SRs were close to what is considered optimal for soybean under the conditions of the present study, especially in the first GS.

In plant-productive systems, IPAR becomes the most limiting factor for seed yield when other variables are already under control (diseases, pests, and water availability). For example, light enrichment initiated at the early flowering increased the seed yield from 144 to 252%, whereas at the early podding, the increase was between 32 and 115% in seed yield (Mathew et al., 2000). This evidently shows that the light intercepted during and after fruiting can be a factor in determining the seed yield.

The NS 5959IPRO cultivar, which has lower branching plasticity, had higher correlations of LAI, NDVI, and CIPAR with yield than BRS 1010IPRO, which has greater plasticity. In this regard, radiation interception can limit yield more intensely in soybean cultivars with a compact plant architecture, with lower heights, LAI, and branching ability. Therefore, the possibility of reducing SR in cultivars with low plasticity is limited (Ferreira et al., 2020), particularly in low-yielding environments (Corassa et al., 2018). Additionally, in this type of cultivar, there is a need for greater care with insect pests and diseases to minimize plant death and loss of LAI, as loss of interception can limit seed yield. In contrast, in cultivars with high plasticity, such as BRS 1010IPRO, there are greater opportunities to reduce SR and greater tolerance to leaf area losses due to biotic stresses, such as pests and diseases, or abiotic stresses, such as hail.

Generally, among the three periods considered in the analysis of radiation interception, the reproductive phase had the highest correlation with seed yield in both cultivars. This demonstrates that higher LAI, NDVI, and CIPAR in the vegetative phase have a smaller impact on yield than in the reproductive phase. This knowledge is relevant because it indicates that more assertive estimates of seed yield can be obtained by the NDVI of the crop in the reproductive phase and not in the vegetative phase.

Conclusions

The reduction of soybean SR is only advantageous when the smaller number of plants in the area does not result in lower LAI and light interception, mainly in the reproductive stage.

Higher LAI and light interception of the BRS 1010IPRO cultivar, which has higher branching plasticity than NS 5959IPRO, confer greater potential for reducing SR without reducing seed yield.

CumLAI, CumNDVI, and CIPAR in the reproductive phase had a greater correlation with seed yield than in the vegetative phase or the total cycle. In contrast, the higher MOSR for CumLAI, CumNDVI, and CIPAR in the vegetative phase than the MOSR for seed yield indicates “luxury growth” in the vegetative phase at recommended SRs, especially in cultivar BRS 1010IPRO.

CumNDVI had a higher correlation with seed yield than CumLAI or CIPAR.

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