



Soybean Yield in Different Sowing Dates and Seeding Rates in a Subtropical Environment

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Abstract

The adjustment of sowing date and seeding rate of soybean can optimize plant development and yield. It is well known that the delay of the sowing date anticipates flowering and can reduce yields. In addition, the recommended seeding rate is usually fixed for all sowing dates and the interaction of these management practices is scarce in high yield subtropical environment. So, this study evaluated how soybean yield and its attributes are affected by the management of sowing dates and seeding rates in two growing seasons. Late sowing reduced yield due to reduced shoot biomass per area, leaf area index, final plant height, bottom pod height, pods per area, seeds per area, and seed mass. Increasing seeding rate increased yield, especially in late sowing, due to increased shoot biomass per area, leaf area index, final plant height, bottom pod height, pods per area, and seeds per area. However, higher seeding rates decreased the shoot biomass per plant, leaf area per plant, pods per plant, and seeds per plant. In early sowing, the lowest seeding rate, below the standard, yielded equivalent to the higher seeding rate. In late sowing, the increase in seeding rate increased yield. For growers who aim to increase soybean yields, it is important to consider using specific seeding rates for each sowing date.

Keywords Glycine max · Leaf area index · Plant arrangement · Plant density · Productivity

Introduction

The largest soybean producers are Brazil, USA and Argentina, being the first one responsible for more than 30% of the total world production (Faostat 2018). Yield results from the interaction among genetic potential of the variety, environment, management practices, and pest and disease control. Management practices depend on grower decision-making and have a great impact on yield, e.g. the choice of sowing date and seeding rate. However, there is scarce information

on the interaction of these management practices under subtropical Brazilian high yield environment.

The agriculture is intensive in the south of Brazil and the subtropical climate allows agricultural activity throughout the year. Adjustments to management practices can increase yield and profitability, as well as the organization of crops succession in the field. In this region the most common crops sown in the spring are soybeans and corn, and in fall are wheat, oats and ryegrass. Some regions have frost in the winter, and with this, some winter crops such as wheat and barley are sown later in the season, and as a consequence, soybeans have their sowing delayed as well. In this context the management of the soybean sowing season is a common practice in the region, but the consequences in the development of the crop as well as its interaction with the sowing rate need to be better understood.

Choosing the sowing date determines the environment, the growth, and development of crop along the cycle. In a subtropical environment, the recommended period for soybean sowing surpass 100 days, from mid-September to mid-December. Unfavourable weather conditions and the succession crops normally delays the soybean sowing

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date. It is well known that delaying the soybean sowing date anticipates flowering (Islam et al. 2018) and reduces yield (Coulter et al. 2011; De Bruin and Pedersen 2008b; Faticchin et al. 2013; Meotti et al. 2012; Spader and Deschamps 2015).

Choosing seeding rates is another management practice that influences yield because it affects plant spatial arrangement. Density management can be accomplished by changes in line spacing, as well as changes in the number of plants in the sowing line, the latter being the most practical way to be performed by the producer. In addition, the recommended seeding rate is usually fixed for all sowing dates. The fine tune in seeding rate can improve the intercepted photosynthetically active radiation (De Bruin and Pedersen 2009a; Kamara et al. 2014; Suhre et al. 2014). Furthermore, seeding rate determines plant height, number of branches per plant, other yield components, and when well-chosen promote yield gain (Chen and Wiatrak 2011; Cox and Cherney 2011).

Seed yield depends on three items: the carbohydrate partitioning efficiency, light interception, and energy conversion efficiency (Monteith et al. 1977). The first depends on total shoot biomass and harvest index, mainly, the second depends on attributes such as plant height and leaf area index, and the third depends on photosynthesis apparatus. The management of sowing date and seeding rate affect the first and second mainly. However, the magnitude of these effects in high yield environment needs to be better characterized. This information is useful for crop modelers, breeders, and extensionists, especially.

The objective of this study was to evaluate soybean yield, and its growth attributes, under different sowing dates and seeding rates, in a subtropical environment.

Materials and Methods

Field experiments were conducted during the growing seasons of 2012/2013 and 2013/2014 in a subtropical environment located in ‘Guarapuava’, Paraná State, Brazil (25°23'S, 51°29'W, altitude 1029 m). The soil was classified as a very Clayey Typic Hapludox (USDA taxonomy), *Latossolo Bruno distrófico*, based on the Brazilian system of soil classification (Embrapa 2006). The experimental site had been cultivated with maize in the previous summer and black oat in the winter, in a no-till cultivation system. Soil tests indicated a pH (CaCl₂) of 4.8 and base saturation of 52.3%. Limestone was applied at a rate of 850 kg ha⁻¹ on the soil surface according to local recommendation.

The experimental design consisted of completely randomized blocks in a split-plot arrangement, with three replications, with sowing dates (SD₁: early sowing, October; SD₂: mid-sowing, November; and SD₃: late sowing, December) as main-plots, and four seeding rates (SR₁: 150 000; SR₂: 250 000; SR₃: 350 000; and SR₄: 450 000 plants

ha⁻¹) as subplots, in two growing seasons (2012/2013 and 2013/2014). Plots of 15 by 6.4 m and subplots of 15 by 1.6 m were used. The soybean (*Glycine max* (L.) Merrill) variety was ‘Brasmax Energia RR’, a Maturity Group 5.3, indeterminate growth habit, medium canopy width, high-branched index and resistant to lodging variety. Seeds were inoculated on the sowing days with *Bradyrhizobium japonicum*, in a turf inoculant with around 1.2 million viable cells per seed. Seeds were sown on October 18 (SD₁), November 19 (SD₂) and December 19 (SD₃) in the 2012/2013 season, and on October 23 (SD₁), November 22 (SD₂) and December 20 (SD₃) in the 2013/2014 season, using a 1.6 m wide seed drill, in rows spaced 0.40 m. Basic fertilizer application consisted of 34.9 kg ha⁻¹ of P (superphosphate fertilizer) and 58.1 kg ha⁻¹ of K (potassium chloride fertilizer). Plant density was set by over seeding (600,000 seeds ha⁻¹) and hand-thinning the plots at stage VC-V1 (Fehr and Caviness 1977). Glyphosate [N-(phosphonomethyl) glycine] was applied at the rate of 1.3 kg [a.i.] ha⁻¹ for weed control at V4 phenological stage.

R_{5.1} Evaluations

An area of 0.32 m² per plot was hand-clipped at the beginning of R₅ growth stage to determine leaf area per plant, shoot biomass per plant, leaf area index (LAI), and shoot biomass per area. The dry weight of the plant material was determined after drying in a forced air drier at 60 °C for 48 h. Leaf area was estimated through digital photos using the software ImageJ (version 1.49, National Institutes of Health, <https://imagej.nih.gov/ij/>).

R₈ Evaluations

An area of 4.0 m² per plot was hand-clipped at R₈ growth stage to determine final plant density, plant height, bottom pod height, stem diameter, pod number per plant (> 10 mm), pods per area (> 10 mm), seeds per pod, seeds per plant, seeds per area, mass per unit of seed, and seed yield. Stem diameter was measured 10 cm above soil surface. The bottom pod height was measured from the first pod insertion point to soil surface. Seed moisture content was adjusted to 130 g kg⁻¹. The harvest index (HI) was determined by the ratio between the seed mass and the total shoot biomass in R_{5.1} with R₈ grain mass. Final plant densities were determined from the average of plant numbers per area at harvest. Lodging was visually evaluated in each subplot at harvest, however minimal lodging was observed and therefore not reported.

Daily meteorological data including solar radiation (Fig. 1a, b), temperature (Fig. 1c, d), and precipitation (Fig. 1e, f) were collected 100 m far from the field site by the Meteorological System of Paraná (SIMEPAR) station.

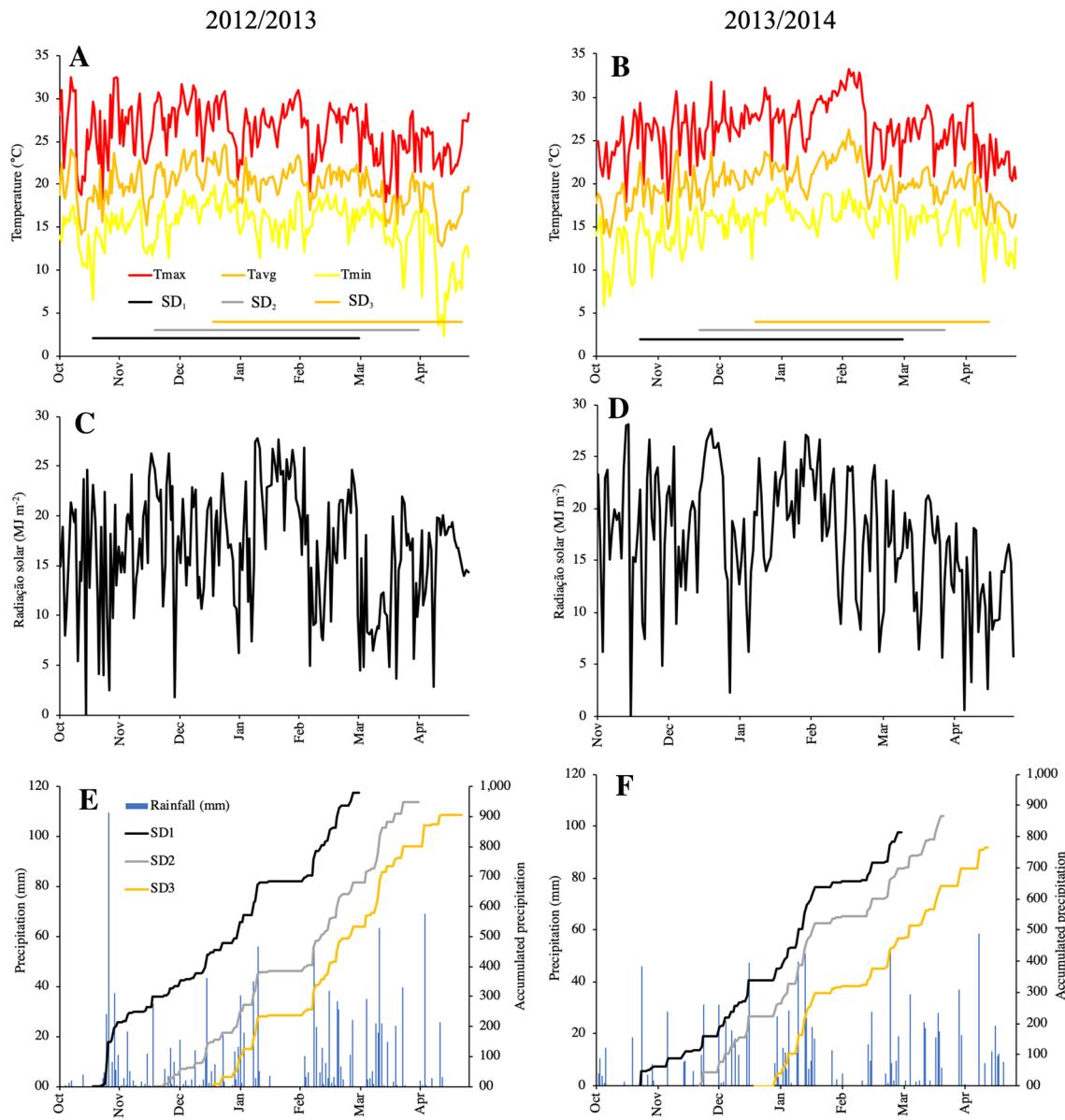


Fig. 1 Meteorological data for the 2012/2013 and 2013/2014 experimental growing seasons. **a, b** Show the daily total solar radiation; **c, d** show the daily maximum (red), average (orange), and minimum (yellow)

temperatures; **e, f** rainfall (blue bars) along with the accumulated precipitation across the growing season for each sowing date. Early, mid, and late sowing are SD₁, SD₂, and SD₃, respectively

Statistical Analysis

The Shapiro–Wilk statistic test indicated normality for all data. Sowing date (SD), seeding rate (SR), and growing season were considered fixed factors and growing seasons and replicates were considered the random effect in ANOVA, using a split-plot design. Qualitative data (sowing dates) were evaluated by the Tukey test and quantitative data (seeding rate) were assessed by the method of polynomial regression, selecting the highest coefficient of determination. Significance was determined at $P < 0.05$. Season did not show three-way interactions, so results were averaged

over seasons and whenever season two-way interactions were observed, they were stated in the text. These analyzes were performed using Assistat software (Silva and Azevedo 2016). A multivariate analysis was performed through Principal Component Analysis.

Results

Solar radiation for the two growing seasons was similar (Fig. 1a, b). Soybean plants grown in late sowing (SD₃) have the cycle shortened in relation to the plants sown at the

beginning (SD_1) and middle (SD_2) of the agricultural zoning, due to the anticipated flowering caused by the shorter photoperiod. Average air temperatures differed little between growing seasons (Fig. 1c, d). Total rainfall was, on average, 9% higher in 2012/2013 growing season than 2013/2014 growing season (Fig. 1e, f).

Analysis of Variance of Sowing Date and Seeding Rate on the Attributes Evaluated in R_5

In this experiment, ANOVA (Table 1) showed that growing season have significant effects in soybean shoot biomass per plant, and shoot biomass per area. There was SD versus SR interaction for leaf area per plant and shoot biomass per plant. Sowing dates (SD) had significant effects on leaf area per plant, LAI, shoot biomass per plant, and shoot biomass per area. Seeding rates (SR) had significant effects on leaf area per plant, LAI, shoot biomass per plant, and shoot biomass per area.

Analysis of Variance of Sowing Date and Seeding Rate on the Attributes Evaluated in R_8

In this experiment, ANOVA (Tables 2, 3 and 4) showed that growing season have significant effects in soybean bottom pod height, pods per plant, seed mass, harvest index and seed yield. There was SD versus SR interaction for pods per plant, seeds per plant, and seed yield. SD had significant effects on plant height, bottom pod height, ratio of plant height by stem diameter, pods per plant, pods per area, seeds per plant, seeds per area, seed mass, and seed yield. SR had significant effects on plant height, bottom pod height, ratio of plant height by stem diameter, pods per plant, pods per area, seeds per plant, seeds per area, harvest index and seed yield.

Effects of Sowing Date and Seeding Rate on the Attributes Evaluated in R_5

Leaf area per plant had an SD versus SR interaction: from SD_1 to SD_3 , the leaf area per plant was reduced by 34%, 35%, 31%, and 29% in SR_1 , SR_2 , SR_3 , and SR_4 , respectively (Table 1). From SR_1 to SR_4 , the leaf area per plant was reduced by 60%, 56%, and 57% in SD_1 , SD_2 , and SD_3 , respectively.

LAI did not differ between SD_1 and SD_2 , and reduced 34% in SD_3 in relation to the average of SD_1 and SD_2 . From SR_1 to SR_4 LAI increased 20% (Table 1). Despite the reduction of leaf area per plant in higher SR's, the higher number of plants per area compensated and increased the LAI.

Shoot biomass per plant had also a SD versus SR interaction: from SD_1 and SD_2 , the shoot biomass per plant was reduced by 14% in SR_1 and did not differ among another

Table 1 Leaf area per plant, leaf area index (LAI), shoot biomass per plant, and shoot biomass per area at seed initiation (R_5) stage of soybean plants in three sowing dates (SD), four seeding rates (SR), and two growing seasons in Guarapuava, PR, Brazil

SR (plants m ⁻²)	SD			
	SD ₁ : Early	SD ₂ : Mid	SD ₃ : Late	Avg.
Leaf area (m ² plant ⁻¹)				
SR ₁ : 15	0.35a [†]	0.34a	0.23b	0.3
SR ₂ : 25	0.23a	0.23a	0.15b	0.2
SR ₃ : 35	0.16a	0.17a	0.11b	0.15
SR ₄ : 45	0.14a	0.15a	0.10b	0.13
Avg.	0.22	0.22	0.15	
LAI (m ² m ⁻²)				
SR ₁ : 15	5.41	5.25	3.33	4.66
SR ₂ : 25	5.88	5.76	3.78	5.14
SR ₃ : 35	5.8	6.08	4.24	5.37
SR ₄ : 45	6.03	6.57	4.17	5.59
Avg.	5.78a	5.91a	3.88b	
Shoot biomass (SBP) (g plant ⁻¹)				
SR ₁ : 15	42.6a	36.7b	29.3c	36.2
SR ₂ : 25	26.0a	25.1a	18.8b	23.3
SR ₃ : 35	19.3a	20.4a	15.0b	18.3
SR ₄ : 45	16.5a	16.8a	12.6a	15.3
Avg.	26.1	24.8	18.9	
Shoot biomass per area (SBA) (g m ⁻²)				
SR ₁ : 15	688	618	466	590
SR ₂ : 25	680	658	515	618
SR ₃ : 35	742	768	608	706
SR ₄ : 45	766	816	586	722
Avg.	719a	715a	544b	
Significance (P values)	Leaf area	LAI	SBP	SBA
Year (Y)	0.15	0.2	0.01	0.02
Sowing date (SD)	< 0.01	< 0.01	< 0.01	< 0.01
Seeding rate (SR)	< 0.01	< 0.01	< 0.01	< 0.01
Linear	< 0.01	< 0.01	< 0.01	< 0.01
Quadratic	< 0.01	0.39	< 0.01	0.71
SD × SR	< 0.01	0.73	< 0.01	0.2

[†]Means followed by the same letter on the lines are not significantly different at the 0.05 level

SR's (Table 1). From SD_1 to SD_3 , shoot biomass per plant reduced 31%, 28%, 22%, and 24% in SR_1 , SR_2 , SR_3 , and SR_4 , respectively. From SR_1 to SR_4 , the shoot biomass per plant was reduced by 61%, 54%, and 57% in SD_1 , SD_2 , and SD_3 , respectively. In the 2012/2013 season shoot biomass per plant was greater than in the 2013/2014 season, because in this last season there were periods of drought during the vegetative growth period of all SDs.

The shoot biomass per area did not differ between SD_1 and SD_2 , and in SD_3 was reduced by 24% in relation to the average of SD_2 and SD_1 (Table 1). From SR_1 to SR_4 , the shoot biomass per area increased 22%. The higher shoot

Table 2 Final plant density, plant height, bottom pod height, and ratio of plant height by stem diameter at maturity (R_8) stage of soybean plants in three sowing dates (SD), four seeding rates (SR), and two growing seasons in Guarapuava, PR, Brazil

SR (plants m^{-2})	SD			
	SD ₁ : Early	SD ₂ : Mid	SD ₃ : Late	Avg.
Final plant density (FPD), plants m^{-2}				
SR ₁ : 15	15.5	14.9	16	15.5
SR ₂ : 25	23.8	23.9	25.1	24.2
SR ₃ : 35	34.5	32.5	33.6	33.5
SR ₄ : 45	39.5	40	39.1	39.5
Avg.	28.3	27.8	28.5	
Plant height (PH), cm				
SR ₁ : 15	81	72	55	69
SR ₂ : 25	83	77	57	72
SR ₃ : 35	86	75	59	73
SR ₄ : 45	85	74	61	74
Avg.	84a [†]	75b	58c	
Bottom pod height (BPH), cm				
SR ₁ : 15	10	11	8	9
SR ₂ : 25	12	13	9	12
SR ₃ : 35	16	15	12	14
SR ₄ : 45	17	17	12	15
Avg.	14a	14a	10b	
Ratio of plant height by stem diameter (H/S)				
SR ₁ : 15	9.3	8.2	7.1	8.2
SR ₂ : 25	11.3	9.9	8.9	10
SR ₃ : 35	13.8	11.2	10.4	11.8
SR ₄ : 45	14.2	13	11.7	13
Avg.	12.1a	10.6b	9.5c	
Significance (P values)	FPD	PH	BPH	H/S
Year (Y)	0.57	0.12	< 0.01	0.02
Sowing date (SD)	0.17	< 0.01	< 0.01	< 0.01
Seeding rate (SR)	< 0.01	< 0.01	< 0.01	< 0.01
Linear	< 0.01	< 0.01	< 0.01	< 0.01
Quadratic	< 0.01	0.07	0.04	0.12
SD × SR	0.22	0.08	0.11	0.39

[†]Means followed by the same letter on the lines are not significantly different at the 0.05 level

biomass per plant of the lower SRs could not compensate the shoot biomass per area of higher SRs.

Effects of Sowing Date and Seeding Rate on R_8 Evaluation

Final plant density did not differ among SD, and SR was according expected, with no SD versus SR interaction (Table 2). The final plant density evidence the plant mortality rate, and in this study, it ranged from 0 to 11%.

Plant height was reduced by 11% from SD₁ to SD₂ and was reduced by 31% from SD₁ to SD₃ (Table 2). Also, plant height increased 7% from SR₁ to SR₄.

The bottom pod height did not differ between SD₁ and SD₂, and from SD₁ to SD₃ was reduced by 29% (Table 2). From SR₁ to SR₄, bottom pod height increased 67%.

The ratio of plant height by stem diameter was reduced by 12% from SD₁ to SD₂ and was reduced by 21% from SD₁ to SD₃ (Table 2). Also, the ratio of plant height by stem diameter increased 58% from SR₁ to SR₄.

Pods per plant had a SD versus SR interaction: from SD₁ to SD₂ pods per plant was reduced by 9% in SR₁ and did not differ among the other SR's (Table 3). From SD₁ to SD₃ pods per plant was reduced by 16% and 14% in SR₁ and SR₂, respectively, but did not change in SR₃ and SR₄. From SR₁ to SR₄, pods per plant was reduced by 62%, 59%, and 55% in SD₁, SD₂, and SD₃, respectively.

Pods per area was reduced by 7% from SD₁ to SD₂ and reduced by 11% from SD₁ to SD₃ (Table 3). Also, pods per area was increased by 5% from SR₁ to SR₄.

Seeds per pod did not respond to both SD and SR (Table 3). Seeds per plant had a SD versus SR interaction: from SD₁ to SD₂ seeds per plant was reduced by 8% in SR₁ and did not change among other SR's (Table 3).

Seeds per plant was reduced by 17% from SD₁ to SD₃ and 14% in SR₁ and SR₂, respectively, and did not change among other SRs. From SR₁ to SR₄ pods per plant was reduced by 59%, 59%, and 55% in SD₁, SD₂, and SD₃, respectively.

Seeds per area was stable between SD₁ and SD₂ but reduced by 10% in SD₃ (Table 4). From SR₁ to SR₄ seeds per area increased 12%.

Seed mass also did not present difference between SD₁ and SD₂ but was reduced by 9% from SD₁ to SD₃ (Table 4). There was no difference in seed mass among SR's.

The harvest index was 0.39 during the growing season 2012/2013 and increased to 0.41 in 2013/2014 (Table 4). There was no difference in harvest index among SDs. Also, the harvest index decreased from 0.41 to 0.39 from SR₁ to SR₄.

Seed yield had a SD versus SR interaction: from SD₁ to SD₂ seed yield reduced 11% in SR₁ and did not change among other SRs (Table 4). From SD₁ to SD₃ seed yield was reduced by 28%, 23%, 21%, and 17% in SR₁, SR₂, SR₃, and SR₄, respectively. From SR₁ to SR₄ seed yield increased by 5%, 14%, and 21% in SD₁, SD₂, and SD₃, respectively.

Byplot Analisys

The variables that presented more percentage of variance on PC₁ were bottom pod height, plant height by stem diameter (PHxD), shoot biomass per area and yield, and on PC₂ were leaf area per plant and shoot biomass per plant (Table 5).

Table 3 Pods per plant, pods per area, seeds per pod, and seeds per plant at maturity (R_8) of soybean plants in 195 three sowing dates (SD), four seeding rates (SR), and two growing seasons in Guarapuava, PR, Brazil

SR (plants m^{-2})	SD			
	SD ₁ : Early	SD ₂ : Mid	SD ₃ : Late	Avg.
No.				
Pods plant ⁻¹				
SR ₁ : 15	74.0a†	67.0b	61.9c	67.6
SR ₂ : 25	46.7a	45.9a	40.1b	44.2
SR ₃ : 35	34.4a	34.8a	30.8a	33.3
SR ₄ : 45	28.1a	27.7a	27.8a	27.9
Avg.	45.8	43.8	40.2	
Pods per area, m^{-2}				
SR ₁ : 15	1155	1012	998	1055
SR ₂ : 25	1109	1092	992	1064
SR ₃ : 35	1183	1123	1032	1112
SR ₄ : 45	1156	1079	1087	1107
Avg.	1151a	1076b	1027c	
Seeds pod ⁻¹				
SR ₁ : 15	2.36	2.42	2.36	2.38
SR ₂ : 25	2.31	2.43	2.38	2.38
SR ₃ : 35	2.35	2.43	2.45	2.41
SR ₄ : 45	2.40	2.45	2.46	2.44
Avg.	2.36	2.43	2.41	
Seeds plant ⁻¹				
SR ₁ : 15	176a	162b	146c	161
SR ₂ : 25	109a	111a	94b	105
SR ₃ : 35	81a	83a	75a	80
SR ₄ : 45	72a	66a	66a	68
Avg.	109	106	95	
Significance (P values)				
Year (Y)	0.05	0.14	0.47	0.07
Sowing date (SD)	< 0.01	< 0.01	0.12	< 0.01
Seeding rate (SR)	< 0.01	0.04	0.21	< 0.01
Linear	< 0.01	0.01	0.06	< 0.01
Quadratic	< 0.01	0.66	0.48	< 0.01
SD × SR	< 0.01	0.20	0.81	0.01

†Means followed by the same letter on the lines are not significantly different at the 0.05 level

In general, in late sowing (SD₃), regardless of the SR, plants had lower yield, shoot biomass per area, shoot biomass per plant, pods per area, seeds per area, plant height and bottom pod height (Fig. 2). The Byplot analysis shows a good relationship between late sowings with higher SR (SR₃ and SR₄) with the number of seeds per pod, a relationship which was not detected in the ANOVA (Table 3). In early and mid-sowings (SD₁ and SD₂), higher seeding rates (SR₃ and SR₄) have heavier seed mass, higher bottom pod height and plant height, more seeds per area and shoot biomass per area, higher yield and LAI (Fig. 2). Early and mid-sowings (SD₁ and SD₂) with lower SR had more leaf area per plant, shoot biomass per plant, seeds per plant, pods per plant and harvest index (Fig. 2). Among evaluated attributes, seeds per pod has inverse correlation with leaf area per plant and shoot

biomass per plant, seeds per plant, and pods per plant. All results obtained in the principal component analysis were summarized in Fig. 3.

Discussion

Effects of Sowing Date and Seeding Rate on the Attributes Evaluated in R_5

With the delay in SD, especially for the late sowing (SD₃), the period of vegetative growth was reduced in approximately 10 days, which in consequence reduced its leaf area per plant and LAI. The increase of SR₁ to SR₄, although reduced leaf area per plant in 56% and shoot biomass per

Table 4 Number of seeds per area, seed mass, and yield at maturity (R_5) of soybean plants in three sowing dates (SD), four seeding rates (SR), and two growing seasons in Guarapuava, PR, Brazil

SR (plants m^{-2})	SD			
	SD ₁ : Early	SD ₂ : Mid	SD ₃ : Late	Avg.
Seeds m^{-2} (no.)				
SR ₁ : 15	2616	2385	2189	2397
SR ₂ : 25	2572	2656	2328	2518
SR ₃ : 35	2782	2734	2522	2679
SR ₄ : 45	2768	2641	2658	2689
Avg.	2684a [†]	2604a	2424b	
Seed mass (mg seed $^{-1}$)				
SR ₁ : 15	176	173	160	170
SR ₂ : 25	174	174	156	168
SR ₃ : 35	173	174	159	168
SR ₄ : 45	173	180	160	171
Avg.	174a	175a	159b	
Harvest index				
SR ₁ : 15	0.41	0.40	0.42	0.41
SR ₂ : 25	0.41	0.42	0.40	0.41
SR ₃ : 35	0.40	0.39	0.39	0.39
SR ₄ : 45	0.39	0.37	0.41	0.39
Avg.	0.40	0.39	0.41	
Seed yield (Mg ha^{-1})				
SR ₁ : 15	4.66a	4.15 b	3.35 c	4.05
SR ₂ : 25	4.57a	4.72 a	3.49 b	4.26
SR ₃ : 35	4.83a	4.83 a	3.82 b	4.49
SR ₄ : 45	4.89a	4.75 a	4.07 b	4.57
Avg.	4.74	4.61	3.68	
Significance (P values)	Seeds m^{-2}	Seed mass	HI	Seed yield
Year (Y)	0.13	0.01	0.01	0.02
Sowing date (SD)	< 0.01	< 0.01	0.51	< 0.01
Seeding rate (SR)	< 0.01	0.25	0.02	< 0.01
Linear	< 0.01	0.54	0.09	< 0.01
Quadratic	0.99	0.06	0.10	0.31
SD × SR	0.12	0.46	0.16	0.04

[†]Means followed by the same letter on the lines are not significantly different at the 0.05 level

plant in 57%, increased LAI by 20% and shoot biomass per area in 38%.

According to growth models, to produce an average yield of 5 Mg ha^{-1} , soybean LAI at R_5 in high yield environment should be around 6 to 8 (Setiyono et al. 2008). Another study carried out in a subtropical environment, suggests a LAI at R_5 of 6–6.5 to obtain higher yields in this environment (Tagliapietra et al. 2018), which is related to the LAI in higher yields obtained in this study (Tables 1 and 4). In late sowing (SD₃), the lower LAI, from 3.3 to 4.2 limited yield potential in this study. This suggests that in order to obtain higher yields in late sowing, it is important to increase LAI, which

can be done with the use of cultivars which can reach LAI 6 at R_5 in these conditions, so it should be considered on the development of more productive cultivars for late sowing.

Shoot biomass per area of 600 g m^{-2} at the R_5 stage is a critical threshold when aiming for maximum seed yield in temperate environment (Board and Modali 2005). In SD₁ and SD₂, all SR's overcome the proposed critical values, and in SD₃, only the SR₃ and SR₄ reached the proposed critical values. However, the data from this study showed that the increase of shoot biomass per area beyond this level contributed to increasing seed yield (Tables 1 and 4), evidencing that this critical threshold may be higher for the subtropical environment conditions.

The current rate of seed yield increase is insufficient to meet the goal of the United Nations to double food production by 2050 (Ray et al. 2013). Considering that this study was carried out in a high yield environment, the heavier shoot biomass per area in higher SR shows that there is a gap in the efficiency in capturing solar radiation and convert it into shoot biomass, that consequently could increase yield. This can be achieved through more efficient arrangement of plants to capture light, as well as the selection of cultivars with morphological attributes favorable to it.

Effects of Sowing Date and Seeding Rate on R_5 Evaluation

The final plant density evidences the plant mortality rate, and differences in plant height among SR were small (0.69–0.74 m) but increase with the increase of SR (Chen and Wiatrak 2011). Among SD the differences in plant height were more evident, reducing 31% from SD₁ to SD₃, indicating the importance of day length, that in the late sowing (SD₃) anticipated the start of the reproductive growth and reduced the period of vegetative growth. The plant height was highly associated with yield (Tables 2 and 4 and Fig. 2), probably a greater plant height favors a better light interception. The erect stature is a feature that help increase yield in soybean, when the plant is resistant to lodging (Koester et al. 2014).

Increasing SR may contribute to mechanical harvesting due to the increase in the bottom pod height, especially in the late sowing (Table 2). Higher bottom pod height can contribute to minimize yield losses in mechanical harvests, since it was higher than the cutter bar height of harvesters. The harvest height commonly used by Brazilian growers is around 15 cm, and values close to that were obtained by soybean plants from SD₁ and SD₂ in SR₃ or above. At late sowing (SD₃) the plants from all SRs had pod insertion height below 12 cm, susceptible to harvest losses.

Lodging was not observed in this experiment, but the increase in the relationship of plant height by stem diameter due the increase in the SR could make plants more

Table 5 Eigenvalues, percentage of variance, cumulative variance, eigen vectors for different principal components

Principal component (PC)	Eigenvalues	Percentage of variance	Cumulative variance	Eigenvectors		
				Variable	PC ₁	PC ₂
1	8.13	0.54	0.54	Yield	0.321	0.19
2	4.67	0.31	0.85	Seed mass	0.24	0.30
3	1.06	0.07	0.92	Shoot biomass area ⁻¹	0.331	0.10
4	0.68	0.05	0.97	Seeds area ⁻¹	0.30	0.10
5	0.34	0.02	0.99	LAI	0.30	0.19
6	0.06	0.00	1.00	Plant height	0.26	0.28
7	0.04	0.00	1.00	Pods area ⁻¹	0.27	0.17
8	0.01	0.00	1.00	Shoot biomass plant ⁻¹	-0.14	0.411
9	0.00	0.00	1.00	PHxD	0.331	-0.15
10	0.00	0.00	1.00	Bottom pod height	0.341	-0.06
11	0.00	0.00	1.00	Leaf area plant ⁻¹	-0.12	0.421
12	0.00	0.00	1.00	Seeds pod ⁻¹	0.07	-0.23
13	0.00	0.00	1.00	Seeds plant ⁻¹	-0.21	0.36
14	0.00	0.00	1.00	Pods plant ⁻¹	-0.21	0.36
15	0.00	0.00	1.00	Harvest index	-0.23	0.11

1 Values with higher weights within PC

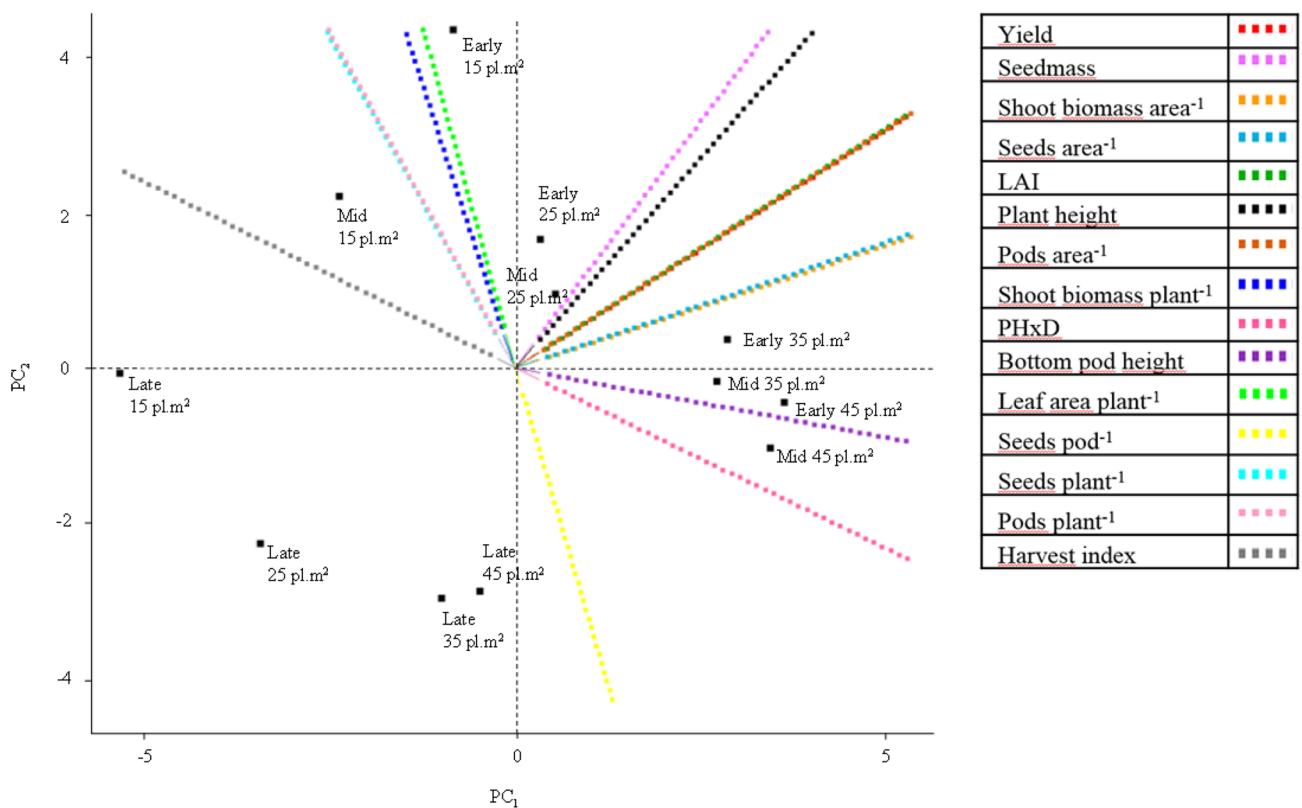


Fig. 2 Biplot obtained from the principal components analysis (PC) of the results of the variables evaluated: Yield; Seedmass; Shoot biomass area⁻¹; Seeds area⁻¹; LAI; Plant height; Pods area⁻¹; Shoot biomass plant⁻¹; PHxD (plant height by stem diameter); Bottom pod

height; Leaf area plant⁻¹; Seeds pod⁻¹; Seeds plant⁻¹; Pods plant⁻¹; Harvest index. Seeding rates: 15, 25, 35, and 45 pl m⁻² are SR₁, SR₂, SR₃, and SR₄, respectively. Sowing dates: Early, mid and late are SD₁, SD₂, and SD₃, respectively

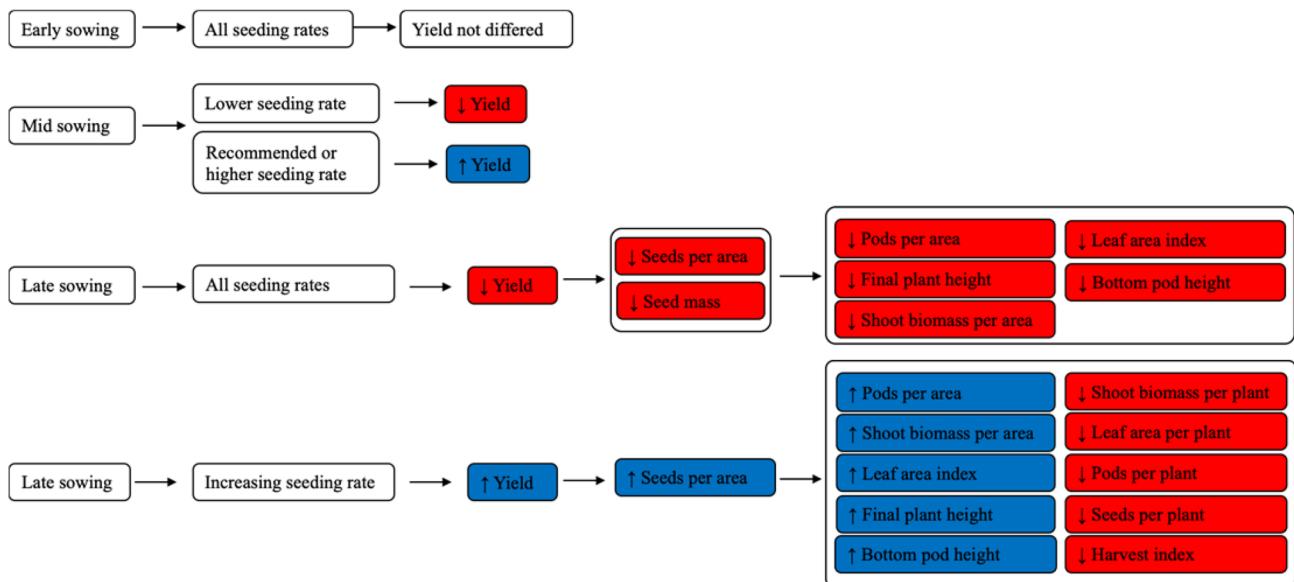


Fig. 3 Summary of the effect of sowing dates and seeding rates in soybean yield in field experiment

susceptible to lodging (Chen and Wiatrak 2011). The lodging resistance in high SR is an interesting attribute to be sought in the selection of cultivars in breeding programs, because it contributes to increased light interception (Koester et al. 2014), and it was related to the cellulose content (Liu et al. 2016).

Pods per plant was reduced, on average, by 59% from SR₁ to SR₄, although the number of pods per area increased 5%. Results with different soybean cultivars reported the same tendency (Cox and Cherney 2011; Suhre et al. 2014). The number of pods per area was slightly higher for higher SRs, despite the lower SRs having shown higher number of pods per plant. Plants from late sowing (SD₃) had lower number of pods per area, which reduced yield (Tables 3 and 4).

Seeds per pod is a yield component that typically does not respond to SR (Cox and Cherney 2011; Souza et al. 2010). The water deficit and/or high air temperature stress can reduce the number of seeds per pod (Pedersen and Lauer 2004). It's already known that water deficit and/or high air temperature stress can reduce the seed filling (Egli 2011) although these stress conditions did not occur in this experiment.

Due the fact that smaller SR's can produce more than double number of seeds per plant than higher SRs (Table 4) it should be considered to use lower plant densities when aiming at a rapid rate of seed multiplication.

Seeds per area was closely linked to yield (Table 4 and Fig. 2) and is more related to yield reduction in late sowing (SD₃) than seed mass (Fatichin et al. 2013). This is explained by the fact that late sowing (SD₃) has less vegetative growth, smaller number of nodes, fewer flowers, fewer number of pods, and consequently the seed number

(Fatichin et al. 2013). Seed number is determined before seed mass and they are dependent on the duration of vegetative growth, which was reduced in late sowing (SD₃).

The seed number per area was the yield component most affected by SR which in turn was affected by the number of pods per plant. Seeds number per area was more important in determining yield than seed mass (De Bruin and Pedersen 2008b; Fatichin et al. 2013). The fact that the SR did not affect the seed mass in two growing seasons, even with the high variations in the relationships between leaf area per plant and pods per plant, evidences that the SR did not affect the seed source to sink relation. The interspecific variation between soybean plants also did not affect the seed mass and seeds per pod in other studies (De Bruin and Pedersen 2009a; Cox et al. 2010).

Seed mass was reduced for late sowing (SD₃) mainly due to lower average temperatures and shorter day length during seed filling, in relation to anticipated sowings. The 2012/2013 season had higher seed mass in SD₁ and SD₂ than the 2013/2014 season, this because in the last season there was less soil water availability during the seed-filling period. Some studies have shown that seed mass is related the seed filling capacity of the soybean variety (Cox and Cherney 2011; Pierozan Junior et al. 2017).

De Bruin and Pedersen (2008b) reported an increase of 0.3 g in seed mass among the SR ranging from 185,000 to 556,000 plants ha⁻¹. This difference in seed mass might not have been perceived in this work because our range of SR's was shorter than the range of SR used by these authors. Seed mass is a component of yield that can be easily affected by environmental conditions, favored by higher incidence of solar radiation associated with soil

water availability in the seed-filling period (Fatichin et al. 2013).

In general, for the two growing seasons, it was found that for late sowing (SD_3) the SR_4 yielded 17% (575 kg ha^{-1}) more than SR_2 , which is the recommended SR by the company owner. These results show that the SR recommendation to growers could be adjusted to the SD. This management practice can increase yield, especially in late sowing (SD_3), but in this case the cultivar must have favorable characteristics for high SR, such as early maturity, lodging resistance and high yield potential.

Seed yield of SR_3 and SR_4 had minor loss of yield in late sowing (SD_3) than SR_1 and SR_2 , probably because they compensated better the reduction of shoot biomass and LAI (Tables 1 and 4). On the other hand, data show that in early sowing (SD_1) the SR_1 , lower than that recommended by the company owner (SR_2), showed similar yield as that of the recommended SR. Under such conditions, if the plant density is below the expected value, reseeding may not be necessary, if the plants are well distributed.

Despite some disadvantages of higher SR such as increased susceptibility for diseases like soybean rust and white mold, higher wheel damage, higher lodging potential, and higher cost of seeds (Cox et al. 2010), there is still a considerable profit margin with this management practice. It should be considered that maximum yield seeding rate is not always the same maximum seeding rate that brings economic return (Chen and Wiatrak 2011). Also, the higher yield potential in higher SR depends on the cultivar used (Spader and Deschamps 2015), especially lodging resistant and modern ones (De Bruin and Pedersen 2009b). In early sowing, the seeding rate 33% lower than the recommended one matched the same yield performance. In late sowing, the seeding rate 40 and 80% higher than the recommended increased yield due to increase in seeds per area, pods per area, bottom pod height, plant height, shoot biomass per area and LAI.

Other studies in different environments also found a positive yield response for higher SR (Cox and Cherney 2011; De Bruin and Pedersen 2008a, b; Matsuo et al. 2018). Possibly larger SRs than used in this study will reach a plateau where yield stabilizes or decays. When the rains are poorly distributed, and/or the soybean plants are subjected to stress conditions, the increasing seeding rate did not increase yield (Chen and Wiatrak 2011; Harder et al. 2007; Kamara et al. 2014).

It can be observed that the increase in SR could bring yield gains, especially for the late sowing (SD_3). When unfavorable weather conditions occur, such as drought and in regions of lower yield potential, increased SR does not bring yield gains (Souza et al. 2010; Soares et al. 2015; Ribeiro et al. 2017).

On average, soybean yield in late sowing (SD_3) was 22% lower than in early sowing plants (SD_1). This can be attributed to the lower amount of solar radiation, mild temperatures, and reduced photoperiod (Meotti et al. 2012). In latitudes higher than 23° S , like southern Brazil, there is a marked reduction in temperature and sunlight in March and April, just in the seed-filling period of plants from the SD_3 (Table 1 and Fig. 1). Soybean yield loss from mid-sowing (SD_2) to late sowing (SD_3) was on average, $23 \text{ kg ha}^{-1} \text{ day}^{-1}$.

Overall, the management of sowing date and seeding rate affect some growth attributes of the soybean crop. Late sowing reduces the yield, LAI, shoot biomass per area, pods per area, seeds per area, and yield, although the increase in seeding rate increased these attributes. This information should be considered with caution, since it must be verified if the cultivar has high yield potential and is capable of sustaining a higher seeding rate without lodging. For early sowing, using a seeding rate above than the recommended ones, did not differ in yield in relation to recommended or higher seeding rates. Lower seeding rates could be an option for the multiplication of seeds, since it has more seeds per plant. Also, for early sowing, when plant density was below the expected one, reseeding could not be necessary. The seed mass was reduced in late sowings at all seeding rates. The increase in seeding rate increased soybean yield by increasing the number of seeds per area. These results can help growers to achieve higher yields and can also help crop modelers to improve soybean growth predictions.

Conclusions

In this higher yield subtropical environment, the higher seeding rates can increase yield in late sowing.

In late sowing, the seeding rate 40 and 80% higher than the recommended increased yield due to increase in seeds per area, pods per area, bottom pod height, plant height, shoot biomass per area and leaf area index.

In early sowing, the seeding rate 33% lower than the recommended one matched the same yield performance.

The results of shoot biomass evidenced that the critical threshold to obtain higher yield may be higher for the subtropical environment conditions in relation to the temperate environment conditions, further investigations must be carried out to confirm this hypothesis.

Also, the heavier shoot biomass per area in higher seeding rates than recommended shows that there is a gap in the efficiency in capturing solar radiation and convert it into shoot biomass, that consequently could increase yield.

This experiment was conducted at just one location in two growing seasons, using a 0.45 cm row spacing and one representative soybean variety. This may limit the application of optimum seeding rate determined in this study but

characterize the effect of management of sowing date and seeding rate on soybean under high yield potential subtropical environment.

Future research should evaluate the response to seeding rate with modern varieties, within different MG, conducted at multiple locations within contrasting soils in subtropical environment.

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Compliance with Ethical Standards

Conflict of Interest The authors declared that they have no conflict of interest.

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