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Wheat-soybean relay cropping allows corn cultivation as the third crop of the year in Southern Brazil

Cultivo intercalar trigo-soja permite cultivo de milho como terceira safra do ano no Sul do Brasil

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Highlights

Soybean-wheat relay cropping.
Advancement of corn sowing.
Increased yield in the soybean, corn, and wheat crops.

Abstract

Relay cropping allows soybean to overlap with wheat for a period, reducing the production risks associated with wheat and enabling earlier sowing and harvesting of soybean. This study aimed to evaluate the technical and economic feasibility of a wheat-soybean relay cropping system and the cultivation of corn as a third crop within the same agricultural year. The experiment was conducted using a randomized block design with a 4 x 3 factorial arrangement, featuring three repetitions during the 2019/2020 and 2020/2021 growing seasons. Four wheat inter-row spacings, with configurations of 17 and 22 cm in single and double rows, resulted in soybean row spacings of 51 and 66 cm. Soybean was sown at the wheat's milk and dough grain stages, and a control was sown after wheat harvest with 45 cm inter-row spacing. The best wheat-soybean relay cropping arrangement was 17D, where wheat produced 2,812 and 2,267 kg ha^{-1}, or 69.41 and 64.82% of the total produced by the control treatment in the first and second evaluated years, respectively. In the first year, soybean in the 51-cm arrangement sown during the second sowing season (09/23/19) produced 6,029.42 kg ha^{-1}, which was 32.5% higher than the first season on 09/13/19 and 11.8% lower than the control on 10/03/19. In the second year, the same treatment sown on September 29 yielded 4,235.00 kg ha^{-1}, which was 12.58% more than the first sowing period on September 14 and 7.4% lower than the control sown on October 23, 2020. Although its yield was 1,239 kg ha^{-1} less than the control (17S), relay cropping allowed corn sowing to be

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advanced by 15 days, which resulted in a grain yield increase of 1,956 kg ha^{-1} compared to corn sown after soybean harvest in the conventional system. The trade-off between wheat yield losses and corn yield gains indicates that wheat-soybean relay cropping has a positive balance and can be used as a management strategy to reduce crop risks and achieve higher grain yields per area. Additionally, wheat-soybean relay cropping provides grain yield gains per area and contributes to the productivity of the system, reducing risks for the three crops and yielding higher economic returns in both studied years.
Key words: Production arrangements. Risk reduction. Sowing time. Spacing.

Resumo

O cultivo intercalar permite a sobreposição da soja com o trigo por um período de tempo, reduzindo os riscos produtivos do trigo e permitindo ganhos em termos de semeadura e colheita mais precoce da soja. Este estudo teve como objetivo avaliar a viabilidade técnica e econômica do cultivo intercalar trigo-soja e o crescimento do milho como cultura de terceira safra no mesmo ano agrícola. O experimento foi conduzido em delineamento de blocos casualizados, sendo um bifatorial 4 × 3 (espaçamento x épocas), com 3 repetições nas safras 2019/2020 (1° ano) e 2020/2021 (2° ano). Quatro espaçamentos entre linhas de trigo, com arranjos de 17 e 22 cm em linhas simples e duplas resultaram em espaçamentos entre linhas de soja de 51 e 66 cm. A soja foi semeada na fase de trigo leitoso e grão seco e uma testemunha semeada após a colheita do trigo com entrelinhas de 45 cm. O melhor arranjo de cultivo intercalar trigo-soja foi o 17D, onde o trigo produziu 2.812 e 2.267 kg ha^{-1}, ou 69,41 e 64,82% do total produzido pelo tratamento controle no 1º e 2º ano, respectivamente. No primeiro ano, a soja no arranjo 51 cm e na 2ª época de semeadura (23/09/19), produziu 6.029,42 kg ha^{-1} (32,5% superior à 1ª época de 13/09/19 e 11,8% inferior do que o controle 03/10/19). No 2º ano, o mesmo tratamento semeado em 29 de setembro rendeu 4.235,00 kg ha^{-1} ou 12,58% a mais que a 1ª época de semeadura que foi em 14 de setembro e 7,4% menor que a testemunha semeada em 23 de outubro de 2020. Mesmo sua produtividade sendo de 1.239 kg ha^{-1} menor que o controle (17S). O consórcio antecipou a semeadura do milho em 15 dias, o que resultou em aumento na produtividade de grãos de 1.956 kg ha^{-1} quando comparado ao milho semeado pós-colheita da soja no sistema convencional. O equilíbrio entre perdas de rendimento de trigo e ganhos de rendimento de milho indicou que o cultivo de revezamento de trigo e soja tem um saldo positivo e pode ser usado como estratégia de manejo para reduzir os riscos da cultura e obter maior rendimento de grãos por área. A continuação do cultivo de trigo-soja proporciona ganhos de rendimento de grãos por área e contribui para o sistema produtivo, reduzindo riscos para as três culturas e trazendo maiores ganhos econômicos nos dois anos estudados.
Palavras-chave: Arranjos produtivos. Espaçamento. Épocas de semeadura. Redução de risco.

Introduction

Different strategies exist to increase grain production within current cropping areas. In locations with extended growing seasons, relay cropping presents a clear and feasible method. Wheat-soybean relay cropping, specifically, is an innovative alternative that addresses the challenge of increasing grain production while maintaining environmental considerations and farm sustainability (Oligini et al., 2021).

Relay cropping, where soybean is sown on standing wheat before its maturity, may reduce production risks compared to sequential cropping, where soybean is sown after wheat harvest. This system has already been proven to be a profitable alternative in environments where double-cropped soybean production following wheat harvest is unreliable (Duncan et al., 1990; Monzon et al., 2007).

In Brazil, wheat faces higher production risks due to frost damage or excessive rain during the harvest period. Coupled with favorable corn prices, these conditions have led to a significant shift in land use, predominantly characterized by the introduction of soybean-corn double crops.

The state of Paraná, as the largest wheat producer in Brazil, accounts for approximately 60% of the country's total production. However, corn cultivation in these areas faces environmental conditions such as shorter days with lower temperatures and radiation, resulting in a corn grain yield reduction at a rate of 201 kg ha^{-1} per day of sowing delay after January 16th, highlighting the importance of timely sowing (Oligini et al., 2021).

In the short term, management practices such as the use of short-season wheat cultivars and non-selective herbicides to expedite wheat drying before harvest may allow earlier soybean sowing. However, in the long term, cultivars specifically adapted for double cropping could further increase the yield of the cropping system, as reported by Monzon et al. (2007). In the context of relay cropping, lower frost risk due to later wheat sowing or the possibility of using longer cycle cultivars and the yield gain associated with their higher disease and abiotic stress tolerance need consideration.

Delayed sowing of soybean after wheat harvest shifts the soybean's reproductive growth to less favorable conditions, including high disease and bug pressure, and also increases the risk of corn frost losses due to delayed sowing, which can compromise the system's income. Moreover, planting corn in many regions becomes a risky activity due to climatic adversities, such as water deficiency and early frost during crop development, especially in late-sown crops, prolonging their development and subjecting the plants to potential environmental risks (Oligini et al., 2021).

The objective of this study was to improve the understanding of the potential use of the wheat-soybean relay crop system and to gain insight into the competitive advantages of growing a third corn crop within the same annual cycle.

Material and Methods

Experimental site and edaphoclimatic conditions

The study was conducted at the Agricultural Research Station of the Federal Technological University of Paraná (UTFPR), located in Dois Vizinhos, Paraná, Brazil. The site is situated at a latitude of 25º43'53" S and a longitude of 53º03'55" W, with an altitude of 530 m above sea level. The climate is classified as Cfa (Alvares et al., 2013), with an average annual rainfall of approximately 2000 mm (Monteiro, 2009), distributed throughout the year. Figure 1 presents the data for minimum and maximum temperatures and rainfall recorded during the study.

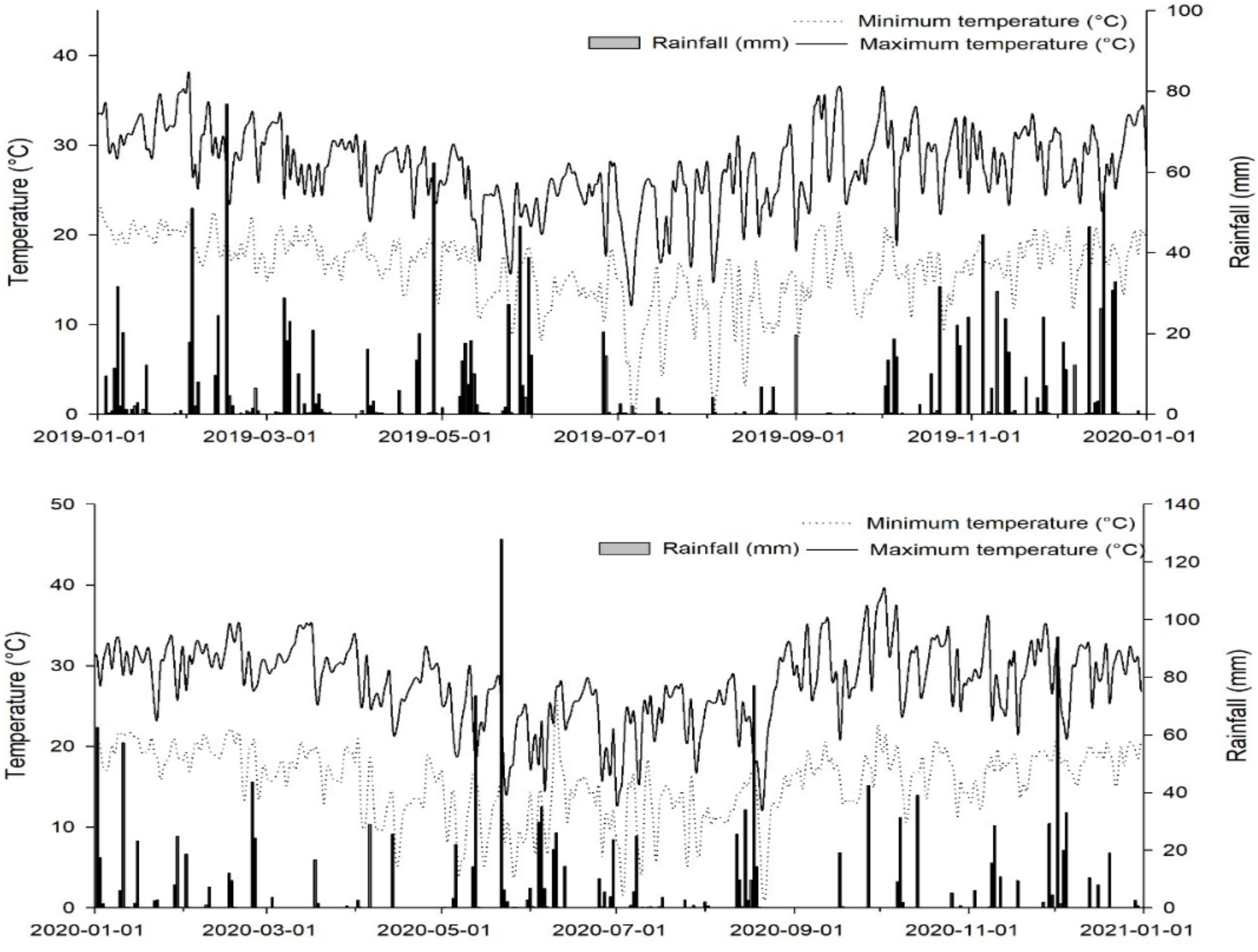

Figure 1. Maximum and minimum air temperatures (ºC) and rainfall in Dois Vizinhos-PR throughout the experimental periods.

The soil at the experimental site is classified as Clayey Oxisol (Bhering et al., 2007). The chemical properties (0.0-0.1 m layer) include organic matter (OM) at 32.90 mg dm^{-3}, phosphorus (P) at 27.65 mg dm^{-3}, potassium (K) at 0.38 cmolc dm^{-3}, magnesium (Mg) at 1.50 cmolc dm^{-3}, calcium (Ca) at 4.40 cmolc dm^{-3}, and a pH of 5.40 $CaCl_2$. Cation exchange capacity is 13.38 cmolc dm dm-3, and base saturation is 73.50%. It is important to note that the area has been under a no-tillage system for over 10 years, with a history of good fertility management. The land is cultivated with soybean, corn, or beans during the summer; and oats (as a cover crop) or wheat during the winter.

Experimental design

The experiment was conducted during the 2019/2020 and 2020/2021 growing seasons using a randomized block design in a 4 × 3 factorial arrangement with three repetitions. This included four wheat row spacings (single and double rows spaced at 17 cm and 22 cm) and two soybean sowing dates in relay cropping at the wheat phenological stages of milky and soft dough grains, with a third period represented by soybean sowing after wheat harvest, as is typical (Figure 2).

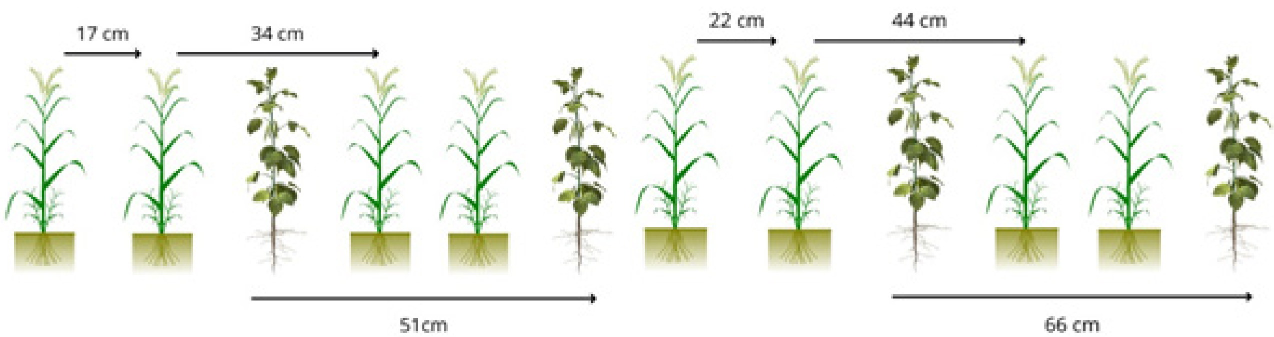

Figure 2. Wheat-soybean relay crop under different row arrangements. UTFPR, Dois Vizinhos - PR, 2024.

In relay double crops, wheat is sown with conventional seeders leaving blank rows where soybean is sown during wheat grain filling. Thus, wheat was sowed a 2:1 skip wheat pattern with rows spaced with 17 and 22 cm, which resulted in soybean row distance of 51 and 66 cm.

In relay double cropping, wheat is sown with conventional seeders that leave blank rows where soybean is sown during the wheat's grain filling stage. Accordingly, wheat was sown in a 2:1 skip row pattern with rows spaced at 17 and 22 cm, resulting in soybean row distances of 51 and 66 cm.

On the same day as the soybean harvest, corn was sown to evaluate the effects of relay cropping (Table 1). Small differences between the sowing dates were due to variations in environmental factors. In the first harvest, drought conditions accelerated the wheat and soybean cycles, which was not the case in the second year, resulting in later harvests. The evaluation of corn grown after soybean was carried out in a randomized block design with three sowing periods and four repetitions. Table 1 summarizes the experimental events of wheat, soybean, and corn sowing and harvesting dates.

Table 1
Timeline of crop sowing and harvest periods during the 2019/2020 and 2020/2021 growing seasons. UTFPR, Dois Vizinhos - PR, 2024

2019/2020 growing season			
Wheat	Soybean sowing	Soybean harvest and corn sowing	Corn harvest
Sowing May 27th	1st period 09/03/2019	1st period 01/20/2020	1st period 06/20/2020
	2nd period 09/23/2019	2nd period 01/31/2020	2nd period 06/30/2020
Harvest October 14th	3rd period 10/14/2019	3rd period 02/14/2020	3rd period 07/30/2020
2020/2021 growing season			
Sowing July 3rd	1st period 09/14/2020	1st period 02/09/2021	1st period 07/12/2021
	2nd period 09/29/2020	2nd period 02/22/2021	2d period 07/22/2021
Harvest October 23rd	3rd period 10/23/2020	3rd period 03/01/2021	3rd period 08/01/2021

Experimental details and evaluations

Recommended sowing dates for wheat were adopted (Table 1). Seeding was performed using a continuous flow seed drill set at 150 kg ha^{-1} for all treatments, targeting a seed density of 400 seeds m^{-2} as recommended for the Sinuelo cultivar (mid-late cycle).

Fertilization for wheat followed technical recommendations and soil analysis results, applying 312 kg ha^{-1} of a 05-20-10 formula as the base and 67 kg of N ha^{-1} in the form of urea side-dressed at wheat tillering. Seeder sowing lines were not removed; only the individual seed outlet compartments were closed, which maintained the same amount of fertilization across treatments.

Soybean BMX 55i57 IPRO®, with a 5.5 maturation group, represented an intermediate-cycle cultivar for the region. Earlier cultivars show lower yield potentials, and longer ones struggle with high insect and disease pressures in February and March. Sowing was done manually with the aid of a manual plot seeder powered by a bicycle wheel. The sowing rate was adjusted based on the row distance to achieve a final stand of 33 plants m-² for all soybean treatments (0.44 m and 0.51–0.66 m row distance for sequential and relay, respectively) (Figure 2). Fertilization involved 400 kg ha^{-1} of 05-25-12 N, P_2O_5, and K_2O, applied side-dressed after soybean sowing.

Corn was sown in an adjacent area to the soybean-wheat plot, maintaining similar fertility and historical management to keep the two years of the soybean-wheat succession under consistent field conditions. The seeder was set to sow 66,000 corn seeds ha^{-1} with rows spaced 0.45 m apart. Base fertilization included 400 kg ha^{-1} of a 10-20-15 chemical fertilizer (40 kg N, 80 kg P_2O_5, and 60 kg K_2O ha^{-1}), and nitrogen was applied as urea (45% N) at a rate of 100 kg ha^{-1} at the V3-V4 corn phenological stages.

Phytosanitary management of all crops (weeds, pests, and diseases) was conducted based on scouting and applying agrochemicals according to the technical recommendations from EMBRAPA (Brazilian Agricultural Research Corporation). Applications were made using a mechanical sprayer attached to a tractor, always considering the weather conditions.

Yield components and grain yield

Assessments of wheat yield components were carried out just prior to harvesting, involving the evaluation of the number of spikelets per spike and the number of grains per spike from ten spikes per plot. The number of spikes per square meter was obtained by counting the spikes in one linear meter. The 1000-grain weight (g) was determined by counting two subsamples of 250 grains per plot and weighing them to obtain the values. Grain yield (kg ha^{-1}) was assessed by harvesting three central rows, each 5 m long, in each plot. These were manually harvested in the sample area and later threshed with the aid of a stationary small-plot corn sheller attached to a tractor. Samples were weighed on a precision scale accurate to 1 g, and moisture content was measured using an electronic meter. The values were extrapolated to per hectare (kg ha^{-1}), considering a moisture content of 13%.

Statistical analysis

The data were tested for normality and homoscedasticity of residuals using the Shapiro-Wilk and Hartley tests, respectively. They were then subjected to an analysis of variance (ANOVA) using SISVAR 5.6 software (Ferreira, 2008). When significance was indicated by the F test ($p < 0.05$), means were compared using Tukey's test at a 5% probability level. Relay cropping treatments were compared to the traditional seeding method using the T test.

Results and Discussion

Wheater conditions

The winter period was drier during the wheat reproductive stages in 2019/20 than in 2020/21, with rainfall values of approximately 90 and 350 mm from June to August, respectively. However, a frost event on August 20th in the second year, despite better rainfall, resulted in lower wheat yields. September was dry in both years, which, along with shorter days and lower temperatures associated with the lack of rain, affected the initial stages of soybean development. Sowing periods were maintained with the goal of achieving the research objectives. It is worth noting that the relay cropping system offers greater flexibility to sow in better soil moisture conditions since soybean sowing can be done before wheat harvest, providing a significant advantage over the conventional system.

Better climatic conditions in spring and summer allowed soybean to reestablish good development, resulting in higher yields. As depicted in Figure 1, temperatures decreased from December to July (from summer to winter). Shorter and cloudier days during fall and winter impair corn grain yield and directly impact overall production.

Wheat yield components and final yield

There was a significant difference in the number of spikes per square meter and yield (kg ha^{-1}) based on the row arrangement in both the first and second years (Table 2). Additionally, an interaction between row arrangement and sowing period for grain yield was observed in the second year (Table 3).

Table 3
Wheat grain yield (kg ha^{-1}) according to sowing period and row arrangements in the 2020/21 growing season

	Sowing period		
Row arrangement	09/14/2020	09/29/2020	10/13/2020
17S	3,025.65 Ac	3,550.34 Ab	3,907.93 Aa
22S	2,648.69 Bb	2,859.09 Bb	3,160.15 Ba
17D	2,144.96 Cb	2,073.69 Cb	2,583.79 Ca
22D	1,517.54 Db	2,018.67 Ca	2,124.42 Da

Mean values followed by different lowercase letters in the row and uppercase letters in the column differ by Tukey's test ($p<0.05$).

Table 2

Wheat yield components and yield according to row arrangement and sowing period of soybean in a relay cropping system in the 2019/20 and 2020/21 growing seasons. UTFPR, Dois Vizinhos – PR, 2024

2019/2020	Spikelets per spike	Grains per spike	Spikes per square meter	1000-grain weight (g)	Yield (kg ha^{-1})
			Row arrangement (RA)		
17 S*	13.14 ns	32.60 ns	518.74 a	32.19 ns	4,051.47 a
22 S	13.72	35.58	426.76 b	31.97	3,089.33 b
17 D	13.41	34.93	358.46 bc	31.76	2,812.64 bc
22 D	13.84	35.51	313.44 c	32.39	2,457.49 c
			Sowing period (SP)		
09/13/2019	13.13 b	33.95 ns	406.01ns	31.99 ns	2,970.81 ns
09/23/2019	13.91 a	33.97	406.09	32.10	3,183.15
10/14/2019	13.55 ab	35.65	400.95	32.13	3,154.25
			P-value		
RA	0.1484	0.0790	0.0000	0.5243	0.0000
SP	0.0339	0.3232	0.9730	0.9282	0.3780
RA * SP	0.0710	0.2242	0.3008	0.7510	0.7942
Mean	13.53	34.52	404.35	32.07	3,102.73
CV (%)	4.99	8.99	15.25	2.93	12.75
2020/21	Spikelets per spike	Grains per spike	Spikes per square meter	1000-grain weight (g)	Yield (kg ha^{-1})
			Row arrangement (RA)		
17 S	15.37 ab	37.59 ab	498.69 a	30.44 ns	3,497.64 a
22 S	15.78 ab	40.93 a	412.48 b	31.19	2,889.31 b
17 D	14.78 b	35.33 b	267.32 c	30.31	2,267.26 bc
22 D	16.07 a	38.63 ab	248.47 c	31.09	1,886.88 c
			Sowing period (SP)		
09/14/2019	15.47ns	41.42 a	354.57 ab	30.72 ns	2,334.04 ns
09/29/2019	15.42	36.44 b	341.82 b	30.97	2,627.70
10/13/2019	15.61	36.50 b	373.84 a	30.59	2,944.07
			P-value		
RA	0.0469	0.0111	0.0000	0.1331	0.0000
SP	0.8768	0.0011	0.0546	0.6078	0.0000
RA * SP	0.6948	0.0945	0.0695	0.4408	0.0121
Mean	15.50	38.12	356.74	30.76	2,635.27
CV (%)	6.15	8.43	8.58	3.01	5.39

*17S and 22S – 17 and 22 cm spacing in a single row, 17D and 22D – 17 and 22 cm spacing in double rows, and CV = coefficient of variation. $p<0.05$ indicates significant differences by Tukey's test. Mean values followed by different letters in the column differ by Tukey's test ($p<0.05$).

The improved plant arrangement in treatments 17S (spacing in a single line) and 22S (spacing in a single line) compared to the 17D (spacing in double lines) and 22D (spacing in double lines) may have resulted in lower intraspecific competition, which facilitated a higher number of spikes in these treatments. The reduction in the number of wheat spikes directly impacts wheat grain yield. Moral et al. (2003) highlighted that the number of spikes per square meter is the most important yield component in determining wheat grain yield under both irrigated and rainfed conditions, with a correlation of 0.942 as previously reported by Donaldson et al. (2001).

In terms of yield, 22S, 17D, and 22D achieved 76%, 69%, and 60% of the yield of the 17S treatment, which was the most productive in both years. Thus, in the second year, despite the interaction between sowing period and row arrangement, the yield from 17S was higher than that of the other treatments.

Monzon et al. (2007) assessed wheat yield penalties in a 2:1 skip sowing pattern in relay cropping and reported lesser effects (averaging 5.4%) compared to sequential cropping. Additionally, relay soybean out-yielded its sequential counterpart (2099 kg ha^{-1} versus 1738 kg ha^{-1}). Likely, a better distribution of plants in the area resulted in greater efficiency of the photosynthetic apparatus and, consequently, greater productive potential (Table 3). The yield difference of 1,239 kg ha^{-1} between 17S and 17D should be analyzed considering the soybean yield potential, since it represents a row spacing of 51 cm, which can optimize productivity compared to 22D, where soybean row spacing is 66 cm.

In any intensification alternative involving two or more crops, the reduced yield of individual crop components can be counterbalanced by an increase in total annual grain yield. In the context of relay cropping, the trade-off between reducing frost risk in later-sown wheat and the yield gain from early-sown soybean needs consideration. At the study site, wheat sowing is timed to reach anthesis around August 10th, when the frost risk is approximately 30% (R. R. Silva et al., 2014).

As previously mentioned, the possibility of delaying wheat sowing under relay cropping allows for greater productive potential. Lower temperatures not only stimulate tillering but also extend the vegetative phase, enabling the crop to develop a higher number of spikelets per spike and thus achieve greater final productivity. This delay also mitigates production risks associated with frost damage and saves time in the production system, as soybean is sown at the optimal time for its development (Oligini et al., 2021).

Soybean relay sowing period within the wheat cycle did not interfere with its yield components or the final wheat yield. In the final stages of wheat development, much of the grain filling occurs due to the remobilization of nutrients from the tissues to the spike. Meanwhile, soybean in the initial stage of development utilizes seed reserves, thus not compromising the wheat yield.

It is possible to infer that longer periods of coexistence could be beneficial, especially when wheat is sown later in the season, even after corn is grown as a second summer crop. Sowing soybean in the first half of September tends to result in lower yield potentials, as noted in Table 4 and reported by Oligini et al. (2021).

Table 4

Soybean yield components and final yield according to row arrangement and sowing period in a wheat-soybean relay cropping system at the 2019/20 and 2020/21 growing seasons. UTFPR, Dois Vizinhos – PR, 2021

2019/20	Plant height (cm)	First pod insertion height (cm)	Number of pods per plant	Number of grains per plant	1000-grain weight (g)	Yield (kg ha^{-1})
Row arrangement (RA)						
17 D - 51 cm	57.67 a	8.47 ns	54.60 ns	125.17 ns	219.50 ns	5,285.77 ns
22 D - 66 cm	50.10 b	7.23	59.37	135.07	221.83	4,660.12
Sowing period (SP)						
09/13/2020	43.10 b	7.57 ns	48.43 b	106.40 b	219.67 ns	4,375.69 ns
09/23/2020	64.67 a	8.13	65.53 a	153.83 a	221.67	5,570.20
P-value						
RA	0.0082	0.1494	0.1266	0.2755	0.4951	0.0010
SP	0.0000	0.4763	0.0007	0.0012	0.5565	0.0000
RA * SP	0.3527	0.4230	0.0996	0.1251	0.6225	0.0320
Mean	53.88	7.85	56.98	130.11	220.67	4,972.94
CV (%)	6.28	16.46	8.17	10.99	2.52	3.67
2020/21	**Plant height (cm)**	**First pod insertion height (cm)**	**Number of pods per plant**	**Number of grains per plant**	**1000-grain weight (g)**	**Yield (kg ha^{-1})**
Row arrangement (RA)						
17 D – 51 cm	76.43 a	11.97	60.12 a	137.26	203.01 a	3,998.53 a
22 D – 66 cm	64.43 b	10.57	44.42 b	106.71	211.48 a	3,315.76 b
Sowing period (SP)						
09/14/2020	69.80 b	10.60	48.99 b	113.13	209.33	3,393.30 b
09/29/2020	83.11 a	12.01	55.64 a	130.86	205.16	3,920.89 a
P-value						
RA	0.0035	0.0602	0.0001	0.0001	0.1668	0.0002
SP	0.0027	0.0902	0.0088	0.0015	0.4682	0.0009
RA * SP	0.8338	0.4126	0.2888	0.0288	0.7142	0.5535
Mean	70.43	11.26	52.26	121.95	207.25	3,657.08
CV (%)	6.34	9.31	5.79	4.58	4.50	4.11

$p<0.05$ indicates significant differences by Tukey's test. Mean values followed by different letters in the column differ by Tukey's test ($p<0.05$).

Soybean yield components and final yield

When evaluating the variable 'plant height,' significant differences were observed in response to row arrangements and sowing periods. Specifically, later sowing resulted in greater final plant heights. In terms of spacing, the shortest final plant heights were recorded at 66 cm spacing. Field observations suggest that plants with wider row spacing develop larger lateral branches to occupy the space, thereby expending more energy and reducing overall height.

According to Oligini et al. (2021), plants sown at the end of September or beginning of October are taller than those sown at the beginning of September. This difference is attributed to the lengthening photoperiod from October/November, which facilitates significant plant growth by allowing an extended vegetative phase and the utilization of photoassimilates produced by the leaves for new leaf production and growth.

Although plant height was greater in the second sowing period and at wider spacings, other yield components showed no significant differences (Table 4). This outcome is believed to be due to the plasticity of the soybean crop, which compensates for the lower height through an enhanced number of grains per plant, 1000-grain weight, and overall yield. Similar compensation effects were observed by A. Garcia (1992) in his study on the components of soybean yields across different sowing periods.

Furthermore, both soybean yield and the number of grains per plant were found to be affected by the interaction between spacing and sowing period. For both variables, the best results were noted with the smallest row spacing and later sowing (Table 5). Peixoto et al. (2000) noted that soybean responds to variations in row spacing, generally yielding better at narrower spacings.

Table 5
Soybean grains per plant and grain yield (kg ha^{-1}) according to sowing period and row arrangements. UTFPR, Dois Vizinhos – PR, 2024

Number of grains per plant in the 2020/21 growing season		
Row arrangement (cm)	09/14/2020	09/29/2020
17 D - 51	123.67 Ab	150.67 Aa
22 D - 66	102.47 Ba	111.00 Ba
Yield (kg ha^{-1}) in the 2019/20 growing season		
Row arrangement (cm)	09/14/2020	09/29/2020
17 D - 51	4.542.11 Ab	6.029.42 Aa
22 D - 66	4.209.27 Ab	5.110.42 Ba

Mean values followed by different lowercase letters in the row and uppercase letters in the column differ by Tukey's test ($p<0.05$).

In addition to evaluating soybean responses across various arrangements, it is essential to compare these data with the conventional production model, where soybean is sown following the wheat harvest. As shown in Table 6, the results of the contrast analysis facilitate a comparison between the different arrangements and sowing periods with the control treatment. Significant differences were observed in plant height for all arrangements compared to the control treatment, which exhibited greater plant height due to the improved solar radiation and temperature conditions that soybean experiences when sown later.

The yield data from the first year of cultivation indicate that the relay cropping strategy of soybean with wheat, besides being feasible, allows for the advancement of soybean sowing by 11 days without yield losses. Additionally, considering the yield of both crops (wheat and soybean), it was observed that in the 17D x 51 cm arrangement, there was no reduction in yield across the two harvest seasons when compared to the control treatment. In contrast, the other treatments resulted in lower yields than the control in both growing years.

It was observed that soybean sown in the first period (09/13/2019) faced several meteorological challenges, with drought being the predominant issue. Despite these challenges, the best yields were achieved from the second period onward. However, its yield surpassed the regional average, indicating that it represents a viable alternative for intercropping. Harvesting could be conducted on January 20th 11 days before the second period and 30 days before the third, thus allowing for an earlier sowing of off-season corn.

Table 6

Analysis of contrast between wheat-soybean relay cropping row arrangement with different sowing periods for soybean yield components and yield (kg ha^{-1}) relative to the control in the 2019/20 and 2020/21 growing seasons. UTFPR, Dois Vizinhos – PR, 2024

Treatment 2019/20	Plant height (cm)	First pod insertion height (cm)	Number of pods per plant	Number of grains per plant	1000-grain weight (g)	Yield
Control –10/03	78.60	6.30	91.53	217.23	188.87	5,867.82
51 cm – 09/13	47.87 *	8.47 ns	48.67 *	108.80 *	219.33 *	4,542.11 *
51 cm – 09/23	67.47 *	8.47 ns	60.53 *	141.53 *	219.67 *	6,029.42 *
66 cm – 09/13	38.33 *	6.67 ns	48.20 *	104.00 *	220.00 *	4,209.27 *
66 cm – 09/23	61.87 *	7.80 ns	70.53 ns	166.13 ns	223.67 *	5,110.98 ns
CV %	5.34	19.01	11.65	12.02	2.63	
Mean	58.83	7.54	63.89	147.54	214.31	5,151.92
Treatment	53.88	7.85	56.98	130.11	220.67	4,972.94
2020/21	Plant height (cm)	First pod insertion height (cm)	Number of pods per plant	Number of grains per plant	1000-grain weight (g)	Yield
Control – 23/10	110.9	12.60	60.80	130.20	197.16	4,573.49
51 cm – 09/14	69.80 *	11.00 ns	55.76 ns	123.66 ns	206.13 ns	3,762.00 *
51 cm – 09/29/	83.06 *	12.93 ns	64.46 ns	150.66 *	199.90 ns	4,235.00 ns
66 cm – 09/14	58.40 *	10.13 ns	42.10 *	102.46 *	212.53 ns	3,024.66 *
66 cm – 09/29	70.46 *	11.00 ns	46.73 *	111.00 *	210.43 ns	3,606.66 *
CV %	5.51	8.80	7.75	4.23	5.23	3.48
Mean	78.53	11.53	53.97	123.60	205.23	3,840.36

T-Test: * and ns = significant not significant at 5% level of error probability in contrast to sequential cropping where soybean is sown after wheat harvest.

According to Oligini (2019), late soybean crops face increased pressures from pests and diseases, which are generally less severe when the crop is sown in the second half of September. This timing not only reduces rust pressure but also enables the cultivation of second-crop corn within the zoning, resulting in satisfactory production levels.

In the context of an intensification process, soybean-corn double cropping is becoming an important component of farming systems in southeastern Brazil. Recent research has focused on the yield constraints for late-sown corn (Oligini et al., 2021). Table 7 displays the corn yield components and final yield in relation to the sowing period as a result of relay wheat-soybean (1st and 2nd SP) or sequential crops (3rd SP) across two growing seasons.

Table 7
Corn yield components and yield in different sowing periods during the 2019/20 and 2020/21 growing seasons. UTFPR, Dois Vizinhos – PR, 2024

Sowing period	Number of grain rows	Number of grains per row	Number of grains per spike	1000-grain weight (g)	Yield (kg ha^{-1})
01/21/2020	13.876 a	35.30 a	489.55 a	308.66 a	8.166.67 a
01/31/2020	13.93 a	30.90 b	430.69 b	281.02 b	7.473.33 b
02/14/2020	14.03 a	29.43 b	412.96 b	256.03 c	5.517.00 c
LSD	0.68	2.05	44.31	22.77	482.07
			P-value (<0.05)		
Block	0.5270	0.0727	0.1990	0.2040	0.4777
Period	0.7016ns	0.0012*	0.0077*	0.0031*	0.0001*
CV (%)	1.67	2.21	3.430	2.78	2.35
Mean	13.94	31.88	444.40	281.89	7.052.33

LSD = least significant difference; CV = coefficient of variation. Mean values followed by different letter differ by Tukey's test (p<0.05).

Corn performance

Results from this study, which evaluated three different corn sowing periods resulting from treatments and soybean harvest timings, revealed no significant differences in the number of grain rows per ear (Table 6). This trait is determined early in the growth cycle and is influenced by factors such as climatic water shortages, management practices (e.g., applications of urea and herbicides), and variations in plant population per area. These factors remained consistent across the sowing times tested in the experiment (Dourado Neto et al., 2003).

For other variables, the first sowing period (01/21) exhibited the highest values. According to Duarte et al. (2018), second-crop corn yields are higher when sowing occurs at the beginning of January, benefiting from favorable climatic conditions such as increased solar radiation and temperatures. Research on various corn genotypes sown off-season by P. R. F. Silva et al. (2010) showed a decline in the productive potential of all hybrids, particularly during the grain filling stage, due to adverse weather conditions associated with delayed sowing.

Literature data indicate that delays in the sowing of second-crop corn can lead to losses exceeding 60 kg ha-1 day-1, which can be mitigated in the absence of water shortages and temperature decreases or exacerbated by climatic events like frost (Garcia et al., 2018).

Studies by Oligini (2019) demonstrate that the later the off-season corn is sown, the lower its productive potential. This is attributed to the high sensitivity of this crop to decreasing solar radiation leading up to the winter solstice on June 21st, resulting in diminished daily dry matter accumulation due to reduced rates of net photosynthesis.

Oligini (2019) also noted that to achieve high yields of off-season corn by sowing in January, it is necessary to plant the soybean at the beginning of the zoning period (September) using early cultivars with maturity groups ranging from 5.0 to 5.5. Nonetheless, these measures heighten the soybean production risk since the climatic conditions in September and the high sensitivity of super early cultivars to adverse weather can lead to low yields, a situation that may not be compensated for by increased productivity in off-season corn.

In this context, the importance of the wheat-soybean relay cropping system should be emphasized. This system allows for the continuation of wheat production on the farm, while also enabling the cultivation of soybean and the sowing of second-crop corn within January.

Conclusions

Wheat cultivation demonstrated higher productivity with a single-row spacing of 17 cm, while soybean achieved higher productivity with a double-row spacing of 17 cm.

The wheat-soybean relay cropping system facilitates the sowing of the second corn crop at the beginning of January, a timing that is conducive to higher productivity.

It is recommended that further studies be carried out to evaluate the performance of different soybean and corn cultivars within the wheat-soybean relay cropping system.

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