European Journal of Agronomy 137 (2022) 126528

Contents lists available at ScienceDirect

European Journal of Agronomy

journal homepage: www.elsevier.com/locate/eja

Diversified crop rotations increase the yield and economic efficiency of grain production systems

Luiz Gustavo Garbelini [a], Henrique Debiasi [b], Alvadi Antônio Balbinot Junior [b], Julio Cezar Franchini [b], Antonio Eduardo Coelho [c], Tiago Santos Telles [d,*,1]

[a] *Universidade Estadual de Londrina, Londrina, Paraná, Brazil*
[b] *Empresa Brasileira de Pesquisa Agropecuária, Londrina, Paraná, Brazil*
[c] *Universidade do Estado de Santa Catarina, Curitibanos, Santa Catarina, Brazil*
[d] *Instituto de Desenvolvimento Rural do Paraná – IAPAR-EMATER, Londrina, Paraná, Brazil*

ARTICLE INFO

Keywords:
Soybean
Maize
Crop yields
Double cropping
Conservation agriculture
Production cost
Profitability

ABSTRACT

Crop rotations with high plant diversity and biomass input have been recognized worldwide as a crucial practice for increasing the sustainability of grain production systems, particularly in regions under no-tillage (NT) management. Nonetheless, low-diversity grain production systems based on double cropping (two crops in the same agricultural year) repeated over time, including soybean followed by maize (known in Brazil as “second crop maize”) or wheat, remain prevalent in Brazil. The continuous use of these systems can impair soil yield capacity, farmers’ profits, and environmental sustainability. Therefore, this study aimed to verify the grain yield and profitability of different production systems with different levels of plant diversity. This study was based on results obtained during the 2009–2017 cropping seasons through a long-term field trial conducted under NT since 1985 in southern Brazil. The trial covered two 4-year agricultural cycles with two crops per year, resulting in eight crops per cycle and 16 crops over the entire period. The experiment followed a randomized complete block design, with five treatments and four replicates. The treatments involved three diversified crop rotations, comprising different cover crops and two double-crop systems (wheat-soybean and maize-soybean). For a given agricultural year, wheat and cover crops (white oats, black oats, and forage radish) were grown from May to September, and the second crop maize was grown from March to August. Soybean and first crop maize were grown during the summer from October to February. The grain yield, gross revenue, production cost, and cumulative profit were analyzed for each production system. Gross revenue and profit were primarily estimated based on the actual annual average commodity prices received by farmers, and two additional price scenarios (pessimistic and optimistic) were proposed considering the average prices from 2010 to 2017. Regardless of the cropping season, first crop maize and wheat grain yields were higher in diversified crop rotations. The production system only affected the second crop maize yield in 2010/2011, with a higher value obtained in a diversified crop rotation system. The soybean yield in diversified crop rotations was higher than that in double-crop systems. Considering each cash crop separately, soybean produced the highest average profit (US\$ 472.50 ha^{-1}), followed by the first crop maize (US\$ 245.31 ha^{-1}) and wheat (US\$ 77.71 ha^{-1}), whereas the second crop maize led to economic losses (−US\$ 121.73 ha^{-1}). All diversified crop rotations produced a higher 8-year cumulative profit and gross margin than the maize–soybean in double-crop system. The relative economic performance of production systems remained unchanged under alternative price scenarios (pessimistic and optimistic) compared with that under the observed (actual) price scenario. However, the cumulative profit of maize and soybean in double-crop system was the most negatively impacted in the pessimistic scenario (−45.9%), indicating greater economic risk. Overall, lack of direct revenues from cover crops were compensated by increased grain yield in the spring-summer season and profitability of diversified crop rotation systems. Therefore, diversified crop rotation systems are economically competitive with double crop systems, rendering them feasible management options for conserving natural resources and increasing crop resilience to adverse climatic conditions.

---

* Corresponding author.
E-mail address: telles@idr.pr.gov.br (T.S. Telles).
[1] https://orcid.org/0000-0001-5817-3420

https://doi.org/10.1016/j.eja.2022.126528
Received 2 August 2021; Received in revised form 23 April 2022; Accepted 25 April 2022

1. Introduction

Brazil is one of the largest producers and exporters of agricultural products worldwide, accounting for approximately 6.5% of the global grain production (FAO, 2020), particularly soybean (*Glycine max*), maize (*Zea mays* L.), and wheat (*Triticum aestivum* L.). Although plant species diversification is essential for the sustainability of grain production systems, Brazilian farming practices remain specialized (CONAB, 2020). In areas earmarked for grain production, short-term economic returns on soybean production have promoted the adoption of low-diversified systems (Garbelini et al., 2020), predominantly double cropping, involving soybean grown during spring–summer, followed by maize or wheat during autumn–winter (Franchini et al., 2012).

Low plant diversity and biomass input in production systems have long been known to negatively affect soil quality (Calonego et al., 2017; Bertollo et al., 2021), as well as increase pressure from pests, diseases (Li et al., 2019), and herbicide-resistant weeds (Bajwa, 2014). Thus, low-diversity systems have become increasingly inefficient and less sustainable, leading to stagnant yields and high production costs (Canalli et al., 2020).

Crop rotation with high plant diversity and biomass input (plant shoots and roots) under no-tillage (NT) management is one of the pillars of conservation agriculture (Kassam et al., 2019; Telles et al., 2019; Lal, 2015b), positively impacting crop yield (Li et al., 2019; Gentry et al., 2013) and agricultural profitability (Canalli et al., 2020; Fuentes-Llanillo et al., 2018; Volsi et al., 2020, 2021), particularly under tropical and subtropical conditions (Franchini et al., 2012). The presence of soil cover crop species alternating with commercial grain-producing species within the same system allows for exploitation of crop synergy over time, contributing to the overall efficiency of the system (Hallama et al., 2019). Moreover, this system promotes biomass production (Campos et al., 2011), nutrient cycling (Zotarelli et al., 2012), water availability, and organic matter accumulation (Ferreira et al., 2013; Zuber et al., 2017); improves soil structure, biological activity, and diversity (Venter et al., 2016), and prevents soil erosion (Deuschle et al., 2019) and compaction (Bertollo et al., 2021). Furthermore, diversified crop rotation can mitigate adverse abiotic (climatic variations, input costs, and product prices) and biotic (pressure from weeds and diseases) effects on the performance of production systems (Sentelhas et al., 2015).

The benefits of diversified crop rotation in terms of soil quality, as well as pest, disease, and weed control, have been extensively discussed in the literature (Daryanto et al., 2018; Hallama et al., 2019). However, information on the impact of such systems on economic performance is scarce (Al-Kaisi et al., 2015). In this context, an economic analysis could be the key to highlighting the long-term advantages of diversified crop rotation systems (Al-Kaisi et al., 2016; Daryanto et al., 2018), encouraging their large-scale adoption. To this end, we hypothesized that, in addition to promoting crop yields, diversified crop rotation under NT reduces production costs and increases farmers' income. Thus, the present study aimed to verify the grain yield and profitability of agricultural production systems with different levels of plant diversity in southern Brazil.

2. Material and methods

2.1. Experimental characterization

This study was based on results obtained during the 2009–2017 cropping seasons through a long-term field experiment conducted since 1985 in the municipality of Campo Mourão, in the state of Paraná, Brazil (24°05′S, 52°21′W; 630 m elevation). The soil at the study site was classified as Rhodic Eutrudox according to the Keys to Soil Taxonomy (Soil Survey Staff, 2014) and as dystroferric Red Latosol according to the Brazilian classification (Anon, 2018), with a very clayey texture (703 g kg^{-1} clay, 201 g kg^{-1} silt, and 96 g kg^{-1} sand at 0–0.2 m layer). According to the Köppen classification, the regional climate is Cfa (humid subtropical with hot, rainy summers, fairly infrequent frosts, and no clearly defined dry season), with a mean annual temperature of 19.9 °C and mean annual rainfall of 1570 mm (Alvares et al., 2013). The mean slope of the experimental area was 0.05 m^{-1}. Data on the maximum and minimum temperatures, as well as the 10-year water balance during the experimental period, are presented in Fig. 1, following the method proposed by Thornthwaite (1948), based on a soil water storage capacity (WSC) of 75 mm. Rainfall, evapotranspiration, and maximum/minimum temperature data were obtained from a weather station located in the experimental area.

Mean soil chemical attributes at the 0–0.2 m layer during the evaluation period were as follows: organic matter (SOM) of 36 g kg^{-1}; pH ($CaCl_2$) of 5.5; potential acidity (H^+Al) of 27.1 mg kg^{-1}; phosphorus (P, Melich I) of 13.6 mg kg^{-1}; calcium (Ca^{2+}) of 1136.2 mg kg^{-1}; magnesium (Mg^{2+}) of 254.0 mg kg^{-1}; potassium (K^+) of 269.8 mg kg^{-1}; sulfur (SO_4) of 6.9 mg kg^{-1}; exchangeable aluminum (Al^{3+}) of 0.0 mg kg^{-1}; cation exchange capacity (CEC, pH 7.0) of 1687.1 mg kg^{-1}; and base saturation (V%) of 76%.

2.2. Experimental design and treatments

The experiment followed a randomized complete block design, with five treatments and four replicates. The evaluation period involved two 4-year agricultural cycles between the 2009/2010 and 2016/2017 cropping seasons. The treatments were distributed over 180 m^2 plots (30 m × 6 m). The treatments involved five grain production systems under NT management, and the plant layout over time is presented in Table 1.

Production systems I, II, and III were set up as crop rotation alternatives with a higher degree of plant diversity than the double cropping systems involving soybean (spring/summer) followed by wheat or second crop maize in fall–winter (IV and V).

2.3. Crop management

Vegetation in the experimental area before sowing the crops was desiccated with glyphosate herbicide (480 g ha^{-1}), and all plots were directly sown over the remaining plant residues (NT management). Considering that glyphosate use is restricted in some countries, pre-sowing management can be performed using mechanical strategies (e.g., knife rollers) integrated with chemical control using selective herbicides, as necessary.

Soybean and maize were sown using a tractor-pulled planter equipped with perforated horizontal plates for seed metering, a helical fertilizer metering mechanism, residue-cutting disks, and shanks and double disks as furrow openers for fertilizer and seed deposition, respectively. Wheat and cover crops were sown using the same machine but with double disks as furrow openers for both seeds and fertilizer, and fluted wheels for seed metering. Commercial NPK (maize and wheat) or PK (soybean) fertilizers were applied to the furrows (5 cm below the seeds) at rates based on soil analysis and standard recommendations for each crop. Cover crops included forage radish (*Raphanus sativus* L.), white oats (*Avena sativa* L.), and black oats (*Avena strigosa* Schreb.) intercropped with radish. The cover crops were not fertilized. Both the first and second crop maize were top-dressed with 133 kg ha^{-1} of urea (60 kg N ha^{-1}) 35 days after emergence (DAE) using a tractor-pulled broadcast spreader.

Genetically modified (GM) glyphosate-tolerant soybean and insect-tolerant maize varieties were grown during all cropping seasons from 2010 to 2017. Non-GM wheat varieties and cover crops were used in this study. For a given cropping season, the selection was based on the most cultivated varieties and hybrids (either GM or non-GM) by farmers in the region during the preceding cropping season. Hence, the soybean and wheat varieties and maize hybrids used in the experiment varied among growing seasons according to market preferences, aiming to better represent the actual cropping systems. For a given growing season, the same varieties or hybrids were planted in all evaluated production systems, allowing for appropriate statistical comparisons among the treatments.

The cash crop seeds were treated with fungicides and insecticides. Soybean was sown in October after direct inoculation of the seeds with *Bradyrhizobium elkanii* and *B. japonicum*, as described by Hungria et al. (2015). Wheat and cover crops were sown in May during all the cropping seasons. The first crop maize was sown in October, and the second crop maize was sown in the first fortnight of March, except in the 2011/2012 and 2012/2013 cropping seasons, when the seeds were sown in the second fortnight of March.

For soybean, the row spacing was 0.50 m, and the planter was adjusted to obtain a density of 300,000 plants ha^{-1}. For maize, the row spacing was 0.80 m until the 2014/2015 cropping season and 0.60 m thereafter, with a plant density of 60,000 plants ha^{-1} during spring–summer and 55,000 plants ha^{-1} during autumn–winter. For wheat and cover crops, the row spacing was 0.20 m and the density was 300 plants per m^2. The cover crop seeding rates were as follows: 40 kg ha^{-1} for white oats, 20 kg ha^{-1} for forage radish, 32 kg ha^{-1} for black oats, and 8 kg ha^{-1} for forage radish.

Other crop treatments for soybean, maize, wheat, oats, forage radish, and black oats + forage radish intercrop were applied according to the technical parameters and crop monitoring data, following the recommendations for integrated control of pests, diseases, and weeds for each crop under investigation and were the same across all treatments. Spraying was performed using a tractor-pulled sprayer with a 12 m spray boom and a capacity of 600 L. Crops were harvested using a self-propelled grain harvester equipped with a straw chopper and spreader and a 4.0 m harvesting platform.

2.4. *Grain yield*

Grain crops were mechanically harvested along the middle of the plot with a useful harvest area of 120 m^2 (30 m × 4 m). The results were corrected for 13% moisture content and expressed in kg ha^{-1} for all crops. The crop yield in each cropping season was determined based on the averages of each replicate and treatment.

2.5. *Economic analysis*

The economic efficiency of the production systems was determined based on the gross revenue, total cost, cumulative profit, and gross margin throughout the two 4-year agricultural cycles.

Initially, economic analysis was conducted for each cropping season and crop. Gross revenue was estimated as the product of grain yield and mean annual price paid to the farmer in each cropping season. Information on the prices received by farmers was obtained from the Paraná State Office for Agriculture and Supply – SEAB (2022). The total production cost was calculated considering expenditure on inputs and farming operations, as well as indirect costs related to farm administration and management. Specifically, input cost was calculated based

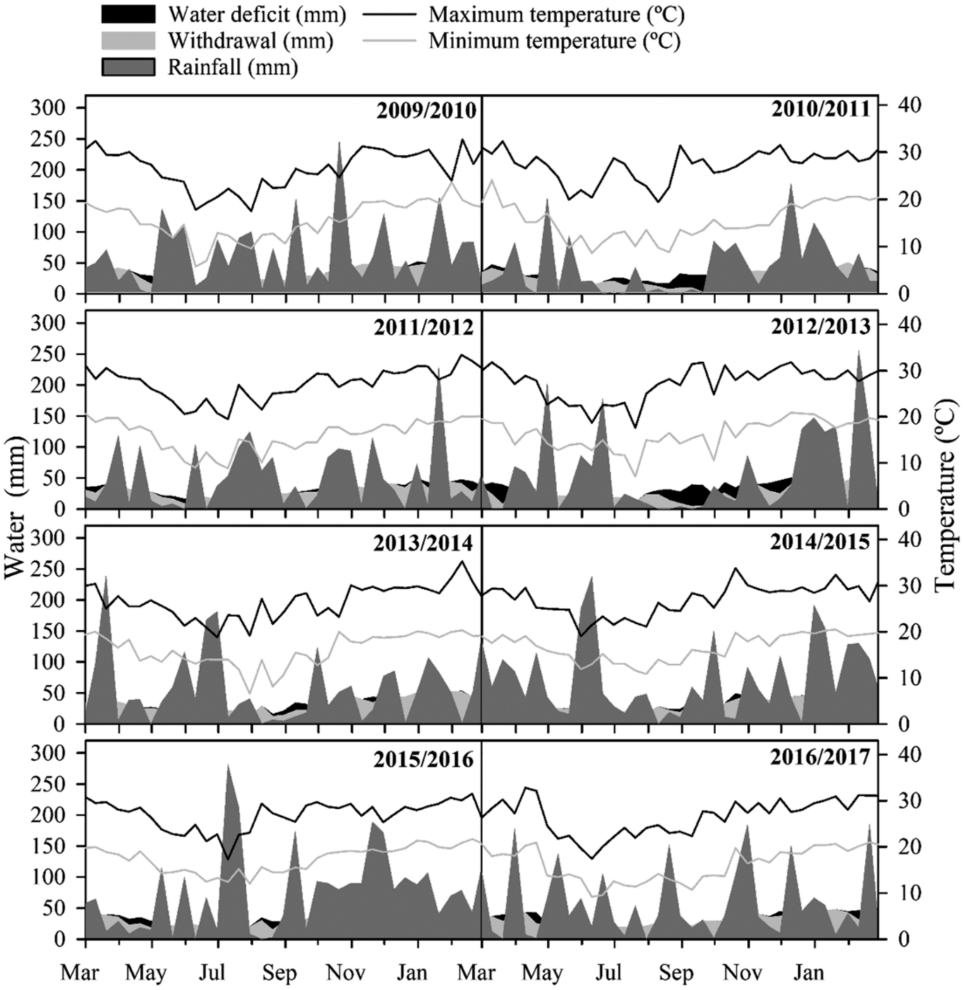


Fig. 1. Rainfall, withdrawal and water deficit, and minimum and maximum daily temperature as well as 10-year water balance (WSC = 75 mm) from the 2009/2010–2016/2017 cropping seasons.

on the quantity of each input and its respective market value. Operational cost was calculated based on all inputs, labor, and mechanized operations used at all stages of crop production: preparation of the area (desiccation), sowing (seeds, seed treatment, inoculation, and fertilizer application), crop management (insecticides, herbicides, fungicides, and additives), and harvesting. Indirect costs (i.e., farm administration and management) involved summing charges, taxes, rural insurance, technical assistance, transportation, and other overheads such as water, electrical energy, telephone, and the Internet. Financing charges and interests were excluded, because producers in this region typically participate in schemes for the early purchase of inputs offered by agricultural companies and cooperatives. Purchase prices for inputs and agricultural operations from at least three agricultural companies or cooperatives in the experimental region were obtained for all cropping seasons considered in this study.

The total cost was deducted from revenue to calculate the profit for each crop. Gross margin was calculated as an indicator of inherent risk in agricultural business based on the percentage return on capital invested; it is one of the most widely used indicators for analyzing farm economic sustainability.

After analyzing each crop and cropping season separately, an economic analysis was performed at the production system level. The cumulative values of gross revenue and total cost in each system were obtained by summing the gross revenue and total costs derived from all crops and cropping seasons. The difference between the cumulative gross revenue and the total cost indicates the profit from a given production system. Notably, the production costs associated with cover crops were considered to estimate the profit from systems I, II, and III.

Furthermore, the cumulative system profit was estimated for two alternative scenarios (pessimistic and optimistic) of soybean, wheat, and maize prices received by the farmers, aiming to add an uncertainty component to the economic analysis. Briefly, we adapted the approach used by Nóia Junior and Sentelhas (2019), whereby alternative scenarios were created by deducting from (pessimistic) or adding to (optimistic) the average price the standard deviation; both parameters were estimated from the temporal series. In the present study, we considered the standard error obtained from Student's t-distribution ($p < 0.05$) rather than the standard deviation to be added to or deducted from the annual average commodity prices. Standard errors and average prices were estimated based on the annual price variations from 2010 to 2017. Statistically, the pessimistic and optimistic scenarios correspond to the lower and upper limits of the confidence intervals ($p < 0.05$) estimated for soybean, maize, and wheat prices, and hence, for cumulative gross revenue and profit.

The economic indicators were updated to real values in June 2020. The inflation adjustment was based on the extended national consumer price index (IPCA), which is the official national inflation index. Real values were converted to dollars (US$) at the exchange rate for June 2020 (US$ 1 = R$ 5.436) published by the Brazilian Central Bank (2020).

2.6. *Statistical analysis*

The production systems were compared in terms of their impacts on grain yields. Comparisons among production systems were performed separately for each grain crop and cropping season, as joint analysis involving all cropping seasons or analysis of cumulative yields over time was not possible, because the number of cultivations for each crop from 2009/2010–2016/2017 varied according to the evaluated production system. Furthermore, soybean and wheat cultivars and maize hybrids varied over time, rendering direct comparisons among cropping seasons difficult. For the same reasons, the production systems compared in terms of second crop maize yield varied among cropping seasons (Table 1 and Fig. 2). Comparisons among production systems in terms of maize and wheat yields were restricted to cropping seasons in which there were at least three treatments applied to the same grain crop (Table 1). For soybean, statistical analysis was performed on cropping seasons in which the crop was sown in all treatments (Table 1).

Regarding the statistical procedures, the data were tested for normality and homogeneity of variance. Variance was analyzed using the F-test ($p < 0.05$), and when significant, the means were compared using Tukey's test at 5% significance. All statistical analyses were performed using R, version 4.1.2.

3. Results

3.1. *Grain yield of first and second crop maize*

The maize yield was affected by the production system. System V negatively affected first crop maize yield compared to systems I and II (Fig. 2A and B). In the 2009/2010 and 2013/2014 cropping seasons, the yield of first crop maize grown in system I was 1020 and 660 kg ha^{-1} higher than that of maize grown in system V, respectively. Similarly, in the same cropping seasons, the yield of first crop maize grown in system II was 1020 and 1200 kg ha^{-1} higher than that of maize grown in system V, respectively. In both cropping seasons, there were no differences in first crop maize yield between systems I and II.

In the 2010/2011 cropping season, the grain yield of second crop maize was higher in production system III than in systems II and V (Fig. 2C). In the same cropping season, the grain yield of second crop maize grown in system III was 1860 and 2760 kg ha^{-1} higher than that of maize grown in systems II and V, respectively. In the 2011/2012 cropping season, frost occurred in June, with temperatures dropping to as low as − 1.6 °C (Fig. 1), which adversely affected all treatments evaluated (Fig. 2E). In the 2014/2015 and 2015/2016 cropping seasons (Fig. 2D and F), second crop maize yield was not affected by the production system.

3.2. *Wheat yield*

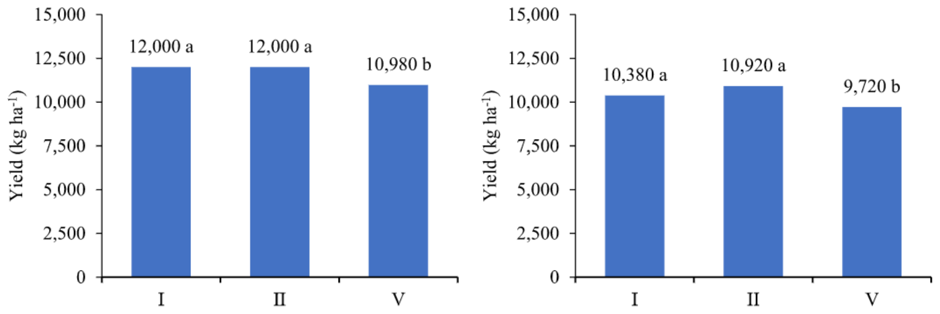
During both cropping seasons 2012/2013 and 2016/2017, wheat yield was higher in systems I and II than in system IV, in which wheat

Table 1

Grain production systems under no-tillage covering two 4-year agricultural cycles evaluated in Campo Mourão, Paraná, from the 2009/2010–2016/2017 cropping seasons.

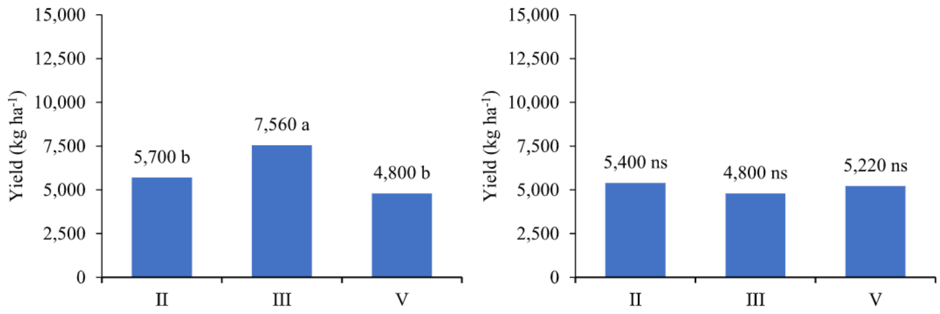
Production system	First cycle								Second cycle							
	2009/2010		2010/2011		2011/2012		2012/2013		2013/2014		2014/2015		2015/2016		2016/2017	
	W	**SU**	**W**	**SU**	**W**	**SU**	**W**	**SU**	**W**	**SU**	**W**	**SU**	**W**	**SU**	**W**	**SU**
I	R	M1	Wh	S	M2	S	Wh	S	R	M1	Wh	S	M2	S	Wh	S
II	Wo	M1	M2	S	M2	S	Wh	S	Wo	M1	M2	S	M2	S	Wh	S
III	Bo+R	S	M2	S	Wh	S	M2	S	Bo+R	S	M2	S	Wh	S	M2	S
IV	Wh	S	Wh	S	Wh	S	Wh	S	Wh	S	Wh	S	Wh	S	Wh	S
V	M2	M1	M2	S	M2	S	M2	S	M2	M1	M2	S	M2	S	M2	S

W: winter; SU: summer; Wo: white oats (*Avena sativa* L.) as ground cover crop; Bo+R: black oats (*Avena strigosa* Schreb.) + forage radish (*Raphanus sativus* L.) intercrop as ground cover crop; M1: first crop maize (summer maize); M2: second crop maize (fall–winter maize); R: radish as ground cover crop; S: soybean; Wh: wheat.



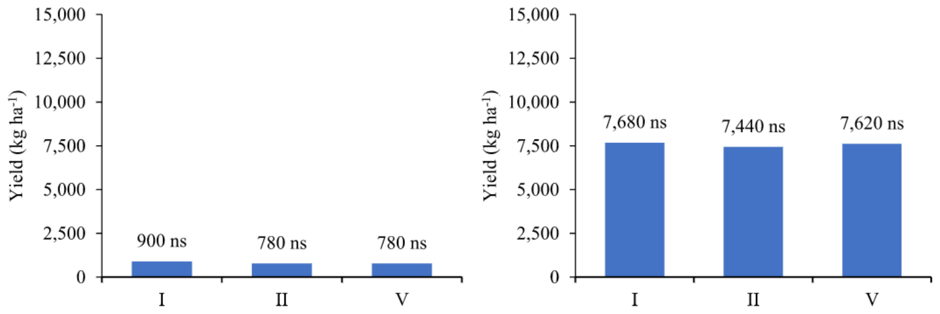
(A) 2009/2010: first crop maize

(B) 2013/2014: first crop maize



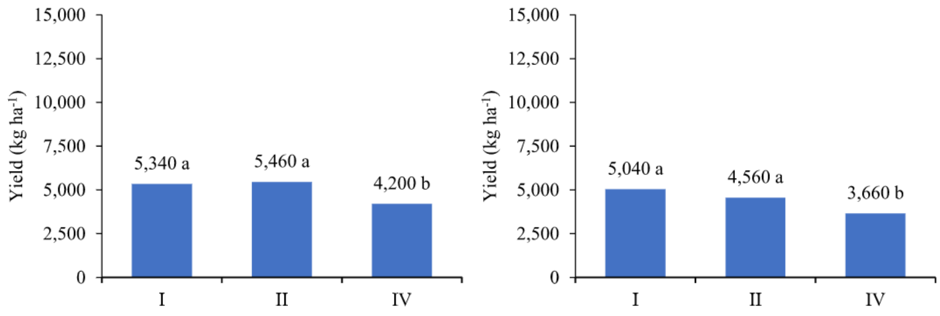
(C) 2010/2011: second crop maize

(D) 2014/2015: second crop maize



(E) 2011/2012: second crop maize

(F) 2015/2016: second crop maize



(G) 2012/2013: wheat

(H) 2016/2017: wheat

Fig. 2. Mean annual grain yield of first crop maize (spring–summer) in 2009/2010 (A) and 2013/2014 (B) cropping seasons; second crop maize (autumn–winter) in 2010/2011 (C), 2014/2015 (D), 2011/2012 (E), and 2015/2016 (F) cropping seasons; and wheat in 2012/2013 (G) and 2016/2017 (H) cropping seasons. Compositions of systems I, II, III (diversified crop rotation), IV, and V (low-diversity double cropping) are described in detail in Table 1. Means followed by different letters are significantly different according to Tukey's test at 5% significance.

was grown continuously every winter (Fig. 2G and H). Wheat yield in system I was 1140 and 1380 kg ha^{-1} higher than that in system IV in the 2012/2013 and 2016/2017 cropping seasons; in the same cropping seasons, wheat yield in system II was 1260 and 900 kg ha^{-1} higher than that in system IV, respectively. There were no significant differences in wheat yields between systems I and II in either cropping season.

3.3. Soybean yield

The soybean grain yield was higher in system I than in systems IV and V (Fig. 3). Specifically, the time-averaged soybean yield in system I was 230 and 270 kg ha^{-1} higher than that in systems IV and V, respectively. However, in systems II and III, soybean yield was moderate, with no significant differences compared to the values in systems I (diversified crop rotation), IV, and V (double cropping).

3.4. Crop economic performance

Based on average across cropping seasons and production systems, soybean generated the highest gross revenue at US$ 935.66 ha^{-1} (Fig. 4). Average gross revenues generated by first crop maize, wheat, and second crop maize were 5.1%, 50%, and 54.9% lower, respectively, than those generated by soybean.

The first and second crop maize incurred the highest mean

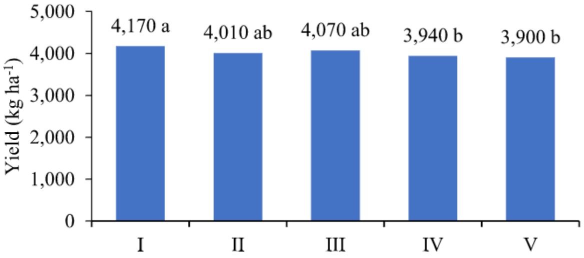


Fig. 3. Soybean grain yield averaged over six cropping seasons (2010/2011, 2011/2012, 2012/2013, 2014/2015, 2015/2016, and 2016/2017). Compositions of systems I, II, III (diversified crop rotation), IV, and V (double cropping) are described in detail in Table 1. Means followed by different letters are significantly different according to Tukey's test at 5% significance.

production costs at US$ 642.52 ha^{-1} and US$ 543.44 ha^{-1}, respectively (Fig. 4). Production costs for first and second crop maize was 38.7% and 17.3% higher, respectively, than that for soybean. In contrast, production cost for wheat was 15.9% lower than that for soybean. The highest cost for inputs was recorded for first crop maize (US$ 382.20 ha^{-1}), followed by second crop maize (US$ 346.99 ha^{-1}). Compared with soybean, first and second crop maize required 67.9% and 54.0% higher costs, respectively, for inputs. In contrast, this cost was 4.0% lower for wheat than for soybeans. The cost of agricultural operations was the highest for first crop maize at US$ 159.81 ha^{-1}, followed by soybean, second crop maize, and wheat. Cost of agricultural operations was 12.5% higher for first crop maize, but 14.7% and 19.5% lower, respectively, for second crop maize and wheat than for soybean. The costs associated with transportation, technical assistance, insurance, charges, and taxes (other costs) were the highest for first crop maize at US$ 99.83 ha^{-1}, followed by second crop maize, soybean, and wheat. Other costs were 17.5% higher for first crop maize, but 5.1% and 6.1% lower, respectively, for second crop maize and wheat than for soybean.

Based on crop averages, soybean was the most profitable crop at US$ 472.50 ha^{-1} (Fig. 4C), whereas second crop maize led to a loss of US$ 121.73 ha^{-1} (Fig. 4B). Compared with those of soybean, the profits on first crop maize and wheat were 48.0% and 84% lower, respectively. The costs related to the cover crops were low. The mean production costs of intercropped black oats and forage radish, forage radish, and white oats were comparable at US$ 111.38, US$ 110.26, and US$ 104.49 ha^{-1}, respectively.

In the economic analysis performed separately for each cash crop, profit was generally higher from diversified crop rotation systems (I, II, and III) than from double-crop systems (IV and V) (data not shown) as a result of higher grain yield (Figs. 2 and 3). The only exceptions to this trend were the spring-summer of 2016/2017 due to climatic factors and the fall-winter of 2009/2010 and 2013/2014, when cover crops were grown in plots under systems I, II, and III (Table 1).

3.5. Economic performance of the production systems

The production systems affected the cumulative economic indices (Fig. 5). System I generated the highest cumulative gross revenue over the eight agricultural years (US$ 10,699.32 ha^{-1}), and there were no differences among the other systems (Fig. 5A). Conversely, system V generated the highest cumulative total production cost (US$ 8383.96 ha^{-1}), followed by systems II, I, III, and IV (Fig. 5B). Similarly, system I generated the highest cumulative profit for this period (US$ 3711.95 ha^{-1}), followed by systems IV, III, and II (Fig. 5C). Low-diversity system V yielded a cumulative profit of US$ 2059.35 ha^{-1}, which was 40.6% lower than the average across the more profitable systems I, II, III, and IV. Winter crops added little to the cumulative profit (systems I and IV) or even resulted in losses (systems II, III, and V). In terms of gross margin, production systems III, I, and IV generated the highest indices (51%, 53%, and 54%, respectively), system II generated an intermediate index (42%), and system V generated the lowest index (25%).

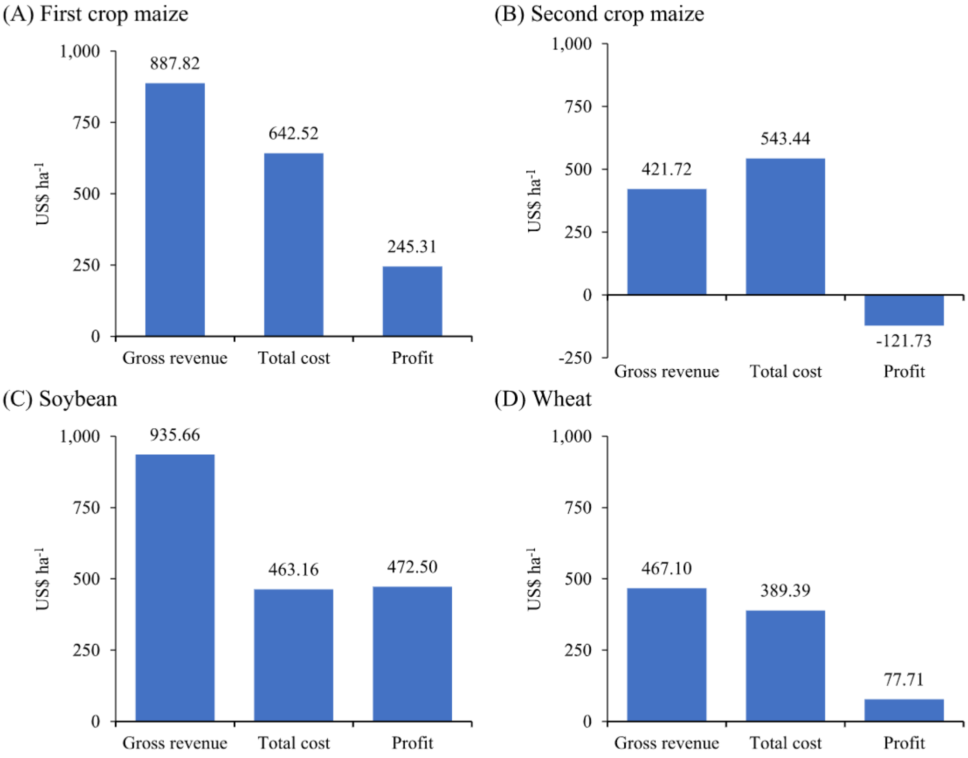


Fig. 4. Average gross revenue, total cost, and profit for the 2009/2010 and 2016/2017 cropping seasons: (A) first crop maize (spring/summer), (B) second crop maize (autumn/winter), (C) soybean, and (D) wheat. Gross revenue was calculated considering the actual annual average prices for maize, wheat, and soybean received by the farmers in each cropping season (observed scenario).

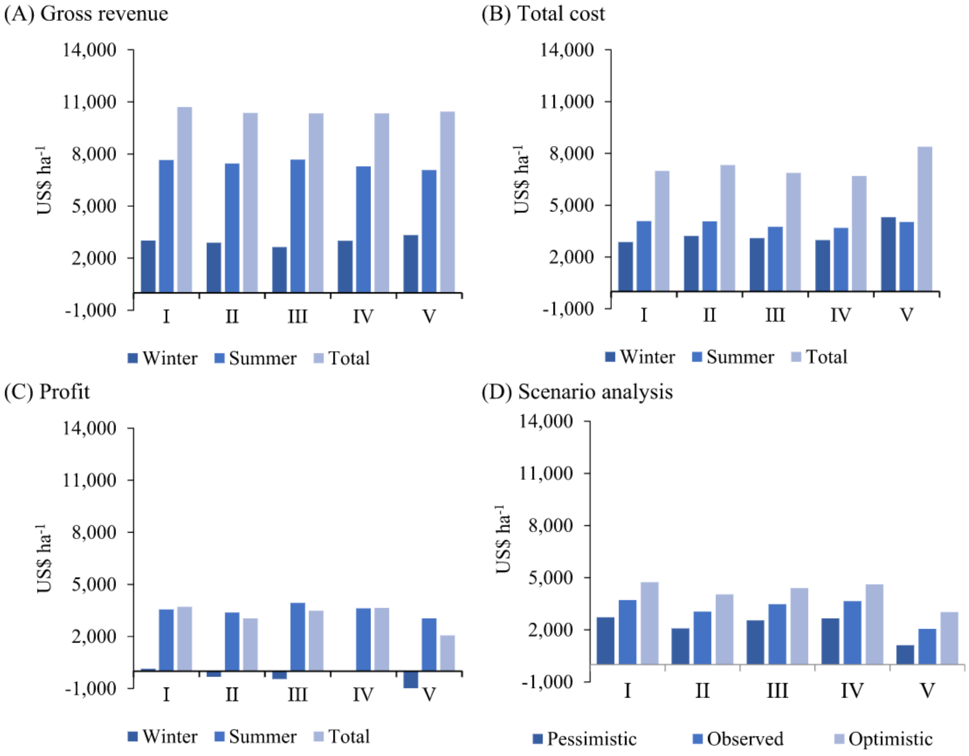


Fig. 5. Cumulative gross revenue (A), total cost (B), profit (C), and scenario analysis of system profit (D) for cropping systems from 2009/2010–2016/2017. Compositions of systems I, II, III (diversified crop rotation), IV, and V (double cropping) are described in detail in Table 1. Cumulative gross revenue (A) and profit (C) were calculated considering the actual annual average prices for maize, wheat, and soybean received by the farmers in each cropping season (observed scenario). The profit interval between the pessimistic and optimistic scenarios reflects the confidence interval (Student's t-distribution, $p < 0.05$) for the average prices for soybean, wheat, and maize from 2010 to 2017.

Fig. 5D shows the changes in system profit in response to pessimistic and optimistic scenarios, reflecting the economic analysis performed for the lower and upper limits of the confidence interval (based on standard error estimated using Student's t-distribution, $p < 0.05$) calculated from the average soybean, wheat, and maize prices (60 kg bags) from 2010 to 2017. The estimated standard errors for soybean, wheat, and maize prices were ± US$ 1.23 bag^{-1}, US$ 0.94 bag^{-1} and US$ 0.23 bag^{-1}, respectively. The profit response of the production systems remained unchanged in the pessimistic and optimistic scenarios. As expected, the system profit decreased and increased in pessimistic and optimistic scenarios, respectively, although all treatments generated net profits even under the pessimistic scenario in terms of soybean, wheat, and maize prices. Absolute cumulative profit between the pessimistic and optimistic scenarios was similar among systems, at US$ 1946.00 ha^{-1}, although relative profit reduction compared with the observed (actual) scenario was higher in system V (45.9%) than in the other systems (28.1% on average).

4. Discussion

4.1. *Grain yield of first and second crop maize*

Maize is a strategic crop for agricultural diversification in Brazil with satisfactory market fundamentals and widely disseminated production techniques. Our findings indicated that the grain yield of first crop maize grown following second crop maize (system V) or vice-versa (systems II) was lower than that of maize grown following soybean (second crop maize) and white oats or radish (first crop maize) (Fig. 2). There may be several reasons for the superior agronomic performance of first crop maize when grown following winter cover crops (systems I and II), as observed in the present study. Firstly, abundant plant residues with a high C/N ratio, such as those produced by the second crop maize in system V, immobilize N during decomposition, reduce N availability, and impair the growth of grasses grown in sequence (Uzoh et al., 2019). Conversely, the C/N ratio and dry mass production of white oats and forage radish are substantially lower than those of maize residues (Schomberg et al., 2006; Silva et al., 2009; Costa et al., 2017), providing better conditions in terms of N availability for maize growth. In a previous study, Acosta et al. (2014) noted no net N immobilization during forage radish straw decomposition and short N immobilization during oat straw decomposition, with net N mineralization occurring 40 days after cover crop desiccation.

In addition to their effects on N availability, forage radish and oat residues are known to improve soil physical properties by preventing soil compaction in the long term, while enabling the uptake of high amounts of nutrients that may otherwise be lost in the system (Adetunji et al., 2020; Okello et al., 2013; Van Eerd, 2018; Tessaro et al., 2019), thereby ultimately improving nutrient cycling. In the present study, in contrast to specialized double cropping in system V, winter cover crops were grown once every four years in systems I and II since 1985 (Table 1), which likely improved the soil structure, increased water availability, and promoted maize root growth in deeper soil layers (Govaerts et al., 2007; Moraes et al., 2018, 2019). In addition, the long-term maize–maize sequence in production system V possibly increased the frequency and severity of pests and diseases, as observed by Govaerts et al. (2007).

Cultivation of second crop maize after a legume that can fix N, leading to a low C/N ratio of residues, such as soybean, in system III increased grain yield by 45% on average compared with the continuous double cropping of maize in system V (Fig. 2C). The superior yield performance of maize grown on soybean plant residues can be ascribed to the low C/N ratio of the residues, which enhances N mineralization (Uzoh et al., 2019). In contrast, the high C/N ratio of biomass added by first crop maize likely led to N immobilization during microbial decomposition (Silva et al., 2009), resulting in lower N availability to second crop maize in system V than in system III. Furthermore, the higher yield of cereals grown after legumes rather than grain cereals can be related either to the addition of N via symbiotic N_2 fixation or to the reduction of inorganic N through removal from soil by the legume crop — called the "N-sparing" or "N-conservation" effect (Chalk et al., 1993). In the present trial, conducted under long-term NT management and using the best practices for inoculation, the amount of biologically fixed

N in soybean was likely equivalent to or marginally lower than that exported through grains (neutral or close to neutral N balance), as reported by Salvagiotti et al. (2008), Mastrodomenico and Purcell (2012), and Landriscini et al. (2019). Accordingly, the superior performance of second crop maize grown after soybean can mainly be explained by the N-sparing effect, together with N immobilization during the microbial decomposition of first crop maize residues. Consequently, greater N availability to maize is expected when it is grown following legume crops (Zotarelli et al., 2012). Similar substantial increases in yield with maize cultivated after soybean compared to those from the maize–maize sequence have frequently been reported in the literature (Govaerts et al., 2007; Sindelar et al., 2015).

Furthermore, by improving the soil physical attributes, water availability, and root growth (Govaerts et al., 2007; Rosolem and Pivetta, 2017), increased crop diversity can offer additional advantages under drought conditions (Bowles et al., 2020). Thus, the absence of second crop maize response to increased crop diversity in the 2014/2015 and 2015/2016 cropping seasons (Fig. 2D and F) may be associated with adequate water availability during the crop cycle (Fig. 1).

4.2. *Wheat yield*

Under the subtropical conditions of southern Brazil, wheat is considered a strategic option for inclusion in diversified crop rotations, mainly as a winter cash crop preceding soybean. Although the biomass production of wheat is lower than that of winter cover crops such as oats and forage radish, the markedly higher C/N ratio of wheat straw (Truong and Marschner, 2019) enables persistent soil mulching (Wenneck et al., 2021). This, in turn, reduces soil erosion, maximum soil temperature, and evaporative soil water loss (Engel et al., 2009; Gava et al., 2013; Daryanto et al., 2018; Cárcer et al., 2019; Rahma et al., 2019), thereby ultimately improving the agronomic performance of subsequent crops (Balbinot Junior et al., 2020). Wheat straw mulching is an important component for integrated weed management in grain production systems (Guareschi et al., 2020).

In the present study, wheat was highly responsive to crop rotation, in terms of increased yield and reduced cost. A higher yield was observed when wheat was grown for one or two cropping seasons within the four 4-year crop rotations. On average, wheat yield was respectively 32.4% and 27.3% higher in systems I and II than in system IV (Fig. 2G and H). Similarly, Franchini et al. (2012) reported consistently higher yields from wheat rotation with black oats and white lupin (*Lupinus albus L.*) (two wheat crops in the same area every 4 years) than from continuous double cropping (wheat/soybean), mainly due to the reduced incidence and severity of root and shoot diseases, such as take-all root rot caused by *Gaeumannomyces graminis*, common root rot and spot blotch caused by *Bipolaris sorokiniana*, yellow leaf spot caused by *Drechslera tritici-repentis*, and fungal glume blotch caused by *Stagonospora nodorum*.

4.3. *Soybean yield*

System I was the only diversified crop rotation system in which soybean yield was higher (by 6% on average) compared with that in the specialized systems IV and V (Fig. 3). Thus, the differences between system I and other diversified crop rotations (systems II and III), in terms of species combinations and temporal planning, warrant attention. Contrary to system I, system III did not involve soybean rotation with first crop maize during spring–summer in 25% cropping seasons or land areas. Various studies have reported substantial increases in soybean yield grown in rotation with maize (e.g., Wilhelm and Wortmann, 2004; Sindelar et al., 2015; Al-Kaisi et al., 2016; Behnke et al., 2018), particularly because of the breaking of the cycle of pests and diseases (Mueller et al., 2002; Reis et al., 2014) as well as the improvement of soil quality (Nouri et al., 2019).

Similar to system I, system II was also characterized by soybean rotation with maize in the summer. However, systems I and II differed in terms of the cover crop species preceding the first maize crop in summer (Table 1). The use of radish rather than white oats may be the major reason for the superior performance of soybean in system I. Radish is known to be efficient in breaking compacted soil layers, facilitating the root growth of subsequent crops in deeper soil layers, and increasing soil water and air availability (Adetunji et al., 2020; Tessaro et al., 2019). Chen et al. (2014) showed that radish reduced soil penetration resistance through its taproot growth, creating biopores that facilitate root penetration, as well as water and air flow. Soil compaction is a major problem in most Brazilian regions at present (Bartzen et al., 2019). Under NT, soil compaction typically occurs at 0.1–0.2 m layers and can impair crop growth and yield, particularly in very clayey soils (Tokura et al., 2017; Bertollo et al., 2021). Furthermore, radish belongs to a different botanical family (Brassicaceae); thus, its inclusion in system I likely increased the soil microbial diversity (Venter et al., 2016), leading to positive effects on various processes mediated by microorganisms and yield (Maron et al., 2018).

Another important difference between systems I and II was associated with the proportion of wheat and second crop maize in autumn and winter (Table 1). System I included a higher proportion of wheat (50% versus 25%), but a lower proportion second crop maize (25% versus 50%) than system II. Other studies in Paraná have reported higher soybean yields after wheat than after second crop maize (Garbelini et al., 2020). Despite their lower straw dry matter yield, wheat residues provide a more persistent, higher soil coverage at the time of soybean planting than second crop maize residues, considering the usual conditions in southern Brazil. Similarly, the second crop maize implies a longer time window (~75–90 days) between its harvest and soybean planting than wheat (~30–40 days), which contributes to the additional reduction in soil coverage percentage at the time of soybean planting. Thus, wheat mulching may be more effective in reducing the maximum soil temperature and increasing water availability because of lower water loss through evaporation and surface runoff, which closely depends on the residual soil coverage percentage (Hillel, 1998).

4.4. *Crop economic performance*

The best economic performance was obtained with summer crops, with soybean generating the highest profit at US$ 472.50 ha^{-1}, followed by first crop maize (48.0% lower than soybean) (Fig. 4). The remarkable result for soybean can mainly be explained by its higher market value during the study period (CONAB, 2020) as well as its more stable and higher yield, which, on average, for the systems evaluated, was 23.3% higher than the regional average for Campo Mourão in the 2009/10–2016/17 cropping seasons (3260 kg ha^{-1}) (SEAB, 2022).

Different results were obtained for the first and second crops of maize, with higher production costs than soybean and wheat. The average revenue for the second crop maize was not sufficient to cover the average production cost, inflicting an average loss of US$ 121.73 ha^{-1} (Fig. 4B). This result may render the second crop maize–soybean double cropping system non-viable. Fertilizers and seeds accounted for approximately 75% of the expenditure on inputs for the first and second maize crops, indicating the highest share of the final production cost.

In addition to its high production costs, the yield of second crop maize was heavily impaired in the 2011/12 cropping season due to climatic adversities (frost), leading to an average loss of 87% compared with the previous cropping season (Fig. 2C and E), which certainly contributed to the poor performance of this crop. However, when sown during autumn–winter, a summer crop with high production costs (Canalli et al., 2020; Volsi et al., 2020, 2021) poses a high risk of economic loss to the producer (Nóia Júnior and Sentelhas, 2019).

The controversy regarding the profitability of wheat production is not centered on the production cost itself, as is the case with other commodities. Crop problems are related to cereal production and commercialization (Flister and Galushko, 2016). In addition, climatic factors often affect the grain quality and price (Cárcer et al., 2019). During the cropping seasons evaluated, the average yield was high at 4710 kg ha^{-1}, but the drop in grain quality and prices paid to the farmers negatively affected crop profitability. Although wheat incurred the lowest commodity production cost (US\$ 389.39 ha^{-1} on average), its profitability was low (Fig. 4D).

Overall, our results related to the economic performance of soybean, second crop maize, and wheat were consistent with previous findings of Garbelini et al. (2020) that soybean returned a profit, thus sustaining the economic viability of the studied production systems. However, both second crop maize and wheat resulted in financial losses in terms of the averages of the crops studied, which were mainly associated with crop yield losses due to climatic adversities (drought and/or frost) and low market prices.

4.5. *Economic performance of the production systems*

The profitability of production system I exceeded that of all other systems by 1.8% (system IV), 6.4% (III), 18% (II), and 44.5% (V) (see Fig. 5 C). In addition, the relative economic performance of the production systems remained unchanged under alternative price scenarios (pessimistic and optimistic) from that under the observed (actual) price scenario (Fig. 5D), which can be attributed to the similar relative price fluctuations of the studied commodities from 2010 to 2017. According to our scenario analysis, if the average annual prices for soybean, wheat, and maize from 2018 onward follow similar trends to those during 2010–2017, the relative performance of production systems is expected to remain unchanged even after the analyzed period (2018 onward) at 5% error probability.

The higher cumulative profit from system I can be ascribed to its higher productivity and economic efficiency. Forage radish, planted every three years in system I, increased the yield of the first crop maize compared with that in system V, in which the previous crop was second crop maize. In addition, forage radish was likely a major reason for the higher soybean yield in system I. Moreover, replacing soybean with first crop maize every three years contributed to the higher soybean yields. Furthermore, replacing second crop maize with wheat for two cropping seasons during the 4-year production cycle boosted the yield of both second crop maize and wheat, and lowered the production costs.

System I is a good example to illustrate the profitability of growing winter cover crops in the grain production systems in southern Brazil. Forage radish did not provide direct revenue, but incurred an additional cumulative production cost of US\$ 110.26 ha^{-1}. Nevertheless, forage radish played a key role in improving soil conditions and increasing wheat, soybean, and maize yields (Fig. 2). Thus, the increased crop yield outweighed the cost and loss of revenues related to forage radish, leading to a higher cumulative profit in system I. Thus, forage radish provided indirect revenues through increased grain crop yield. These results also highlight the importance of performing economic analyses for crop production systems, rather than for specific crops or cropping seasons.

Production system IV generated the second-highest cumulative profit (Fig. 5C). This result can mainly be attributed to the lower total production cost for wheat than for the second crop maize (Fig. 4D), which was grown in all other production systems (Table 1). Despite the problems faced over the past few years in wheat production and commercialization (Flister and Galushko, 2016), improved soil cover provided by wheat helps to control weeds and reduces soil erosion, maximum soil temperature, and soil water evaporation (Gava et al., 2013; Guareschi et al., 2020). This renders wheat as an important option for diversifying production systems in southern Brazil, alternated with second crop maize and/or soil cover crop species (Balbinot Junior et al., 2020; Livingston et al., 2016).

Despite providing the second highest cumulative gross revenue (Fig. 5A), system V generated the lowest cumulative profit (Fig. 5C). The higher production cost of maize planted in double cropping systems (Fig. 5B), along with the generally lower soybean and maize grain yield, explains the low profitability of system V. Low-diversity crop rotations, such as system V, are known to reduce soil productivity (Lal, 2015a; Bertollo et al., 2021), increase the incidence and severity of pests and diseases (Li et al., 2019), and favor the growth of difficult-to-control weeds (Bajwa, 2014). In a previous economic analysis, Nóia Junior and Sentelhas (2019) demonstrated that second crop maize–soybean double-cropping is a high-risk production system, and that its success closely depends on the selection of the ideal sowing date because of the climatic vulnerability posed by the Brazilian autumn–winter season. In Brazil, many farmers use specialized production systems with high production costs and volatile selling prices. The yield losses reported herein for second crop maize due to climatic challenges also explain the drop in profitability, particularly in systems with a higher proportion of this crop produced during the autumn–winter season.

The grain crops grown in autumn–winter (wheat and second crop maize) produced a lower cumulative profit or even economic losses at the system level, with first crop maize and soybean being the crops with the highest profitability (Fig. 5). Additionally, our experiment demonstrated that the economic performance in autumn and winter decreases with higher proportion of second crop maize in a production system. Similarly, the relative proportion of autumn–winter grain crops incorporated into a production system incurs a higher operational cost (~46%) than gross revenue (~29%), indicating the poor economic performance of autumn–winter crops in the studied region, particularly in view of the high production costs and climatic limitations that result in yield losses (Nóia Junior and Sentelhas, 2019; Lollato et al., 2020).

Overall, to improve the economic performance of a production system, farm management should prioritize the achievement of high first crop maize and soybean yields, which are more profitable. In this context, our results indicate that diversified crop rotation, involving winter cover crops in rotation with grain crops, is a management practice that can produce higher first crop maize and soybean yields. Previous studies in southern Brazil have shown that growing autumn–winter cover crops in diversified crop rotations is an ideal practice for increasing system profitability and reducing financial risks, and thereby, to increase crop yield (Balbinot Junior et al., 2017; Tessaro et al., 2019) in a manner that outweighs the total production costs related to cover crops (Garbelini et al., 2020).

Gross margin is an economic indicator that reflects farming risks and represents the percentage of the return on capital invested (Garbelini et al., 2020). The gross margins of systems I, III, and IV were comparable (53%, 51%, and 54%, respectively), but higher than those of systems II (42%) and V (25%). In general, the gross revenue was higher with a higher proportion of maize (particularly second crop maize) in the system. However, the higher gross revenue was outweighed by the respective increases in production costs, leading to a lower gross margin and, hence, a greater financial risk. Similarly, system V resulted in the highest relative profit reduction under the pessimistic scenario (45.9%), indicating that the continuous growth of second crop maize renders the production system more susceptible to commodity price volatility and, hence, riskier. The management of risks involved in farming should be treated as a factor that discourages or incentivizes the adoption of a given practice (Burney et al., 2014; Salazar et al., 2019). In our study, production system I was proven to be the best practice for increasing crop diversification in grain production systems in western central Paraná, since its financial risk was similar to that of system IV, but much lower than that of system V.

To broaden the discussion on crop diversification in production systems, other interesting cover crop options to be cultivated in autumn–winter include tropical perennial forage species, particularly ruzigrass (*Urochloa ruziziensis*), as a monocrop or an intercrop with second crop maize (Garbelini et al., 2020). Ruzigrass is known to yield abundant shoots and roots, leading to increased soil mulching and improved soil quality (Rosolem and Pivetta, 2017; Bertollo et al., 2021), which in turn increases soybean and maize yields (Franchini et al., 2015;

Balbinot Junior et al., 2017).

Our results were corroborated by the findings of studies undertaken in different regions worldwide, demonstrating the profitability of diversified crop rotations. For instance, in a study conducted by Gonzáles et al. (2013) in Chile, higher economic stability was observed when legumes were introduced into production systems, which increased crop diversification. According to the authors, the selection of appropriate crops and correct planning play key roles in improving the economic performance of diversified crop rotation systems. In another study in Iowa (USA), Al-Kaisi et al. (2015) observed a higher soybean yield, profit, and economic stability in diversified systems than in monocultures. Based on a meta-analysis of 347 site-years of yield data from 11 long-term experiments conducted in the USA and Canada, Bowles et al. (2020) reported higher maize yield in diversified crop rotation systems across all growing seasons, particularly during drought years. In a study conducted in Southern Asia, Jat et al. (2014) concluded that diversified production systems were agronomically and economically more advantageous than simplified double-cropping systems. Therefore, the adoption of diversified crop rotation systems is the path to increasing crop yield, ensuring food security, and protecting the environment.

Previous studies in Brazil have associated diversified crop rotations with higher incomes and profitability. For instance, in a long-term study involving soybean, maize, wheat, and tropical forage grasses in southern Brazil, Garbelini et al. (2020) observed higher profits and gross margins for more diversified production systems, including cover crops. In a study in naturally less fertile soils based on 3-year production systems, Volsi et al. (2021) concluded that growing cover crops during winter and cash crops in summer increased system profitability. Similarly, Canalli et al. (2020) undertook an economic analysis of five different production systems in southern Brazil and concluded that crop diversification was economically feasible and enhanced crop sustainability.

Overall, all diversified crop rotations studied herein (systems I, II, and III) offered higher profitability but posed a lower financial risk than specialized, double cropping systems, which are widely adopted by farmers in several Brazilian regions, where the climate conditions allow for growing this cereal during autumn and winter. For instance, in approximately 65% areas under soybean cultivation in the Campo Mourão region, second crop maize was grown in the 2020/21 cropping season, whereas wheat was grown in only ~15% area (SEAB, 2022). In other regions in Paraná with similar climate conditions, second crop maize was cultivated in over 90% soybean-producing areas during spring–summer. Apparently, farmers in this region are motivated to grow maize continuously during autumn–winter because, in certain years, when climate conditions are favorable for obtaining high yields and commodity prices are satisfactory, the profit can be significant. For instance, in the 2015/2016 cropping season, considering the average second crop maize yield (7580 kg·ha^{-1}), along with average production costs (Fig. 3B) and the upper limit of the confidence interval for the average maize price (optimistic scenario, US$ 6.22 per 60 kg bag), the net profit was US$ 242.45 ha^{-1}. Furthermore, some Brazilian farmers frequently make decisions based on gross revenue rather than operational profits, as they rarely conduct an appropriate economic analysis. As previously mentioned, system V yielded the second highest gross revenue, which may lead to an incorrect conclusion of good economic performance.

Wheat/soybean (system IV) double cropping was the second most profitable production system, being only marginally inferior (1.8%) to system I. Likewise, the profitability of system IV was only 4.8% higher than that of system III (Fig. 5 C). Overall, these results demonstrate that diversified production systems I and III are economically competitive with the specialized double-crop system IV, offering the key advantage of contributing to environmental conservation.

Increasing food production to meet the rising global demand without degrading the environment represents a major challenge faced by humanity at present. In this regard, diversified crop rotation systems under NT can reduce soil erosion, thus helping conserve soil and water resources (Deuschle et al., 2019). Furthermore, diversified crop rotation systems, such as those addressed in this study, lead to higher C and N additions (via vegetal biomass) to soil than specialized double cropping systems, thereby increasing the soil organic matter content (SOM) (Diekow et al., 2005). In addition to improved soil physical, chemical, and biological properties, increased SOM content implies atmospheric CO_2 sequestration. Thus, diversified crop rotation has been recognized as a strategy for mitigating greenhouse gas (GHG) emissions and global climate change (Santos et al., 2011; Bayer et al., 2016; Sá et al., 2017). Furthermore, crop diversification increases soil biodiversity, which is crucial for maintaining a multitude of ecological functions of soil (Li et al., 2021). Improved mulching, soil quality, and biodiversity under diversified crop rotation can enhance weed, pest, and disease control (Govaerts et al., 2007; Li et al., 2019; Guareschi et al., 2020) and increase water (Sentelhas et al., 2015; Bowles et al., 2020) and fertilizer use efficiency (Fageria and Baligar, 2021; Soltangheisi et al., 2018), ultimately promoting water conservation, mitigating GHG emissions, and lowering pesticide use (Volanti et al., 2021).

In addition to reducing environmental impacts, diversified crop rotation systems involving cover crops have been increasingly recognized as an important means of mitigating the effects of global climate change on crop yields. Reduced yield losses from heat and drought stress have been frequently ascribed to enhanced mulching and soil quality owing to diversified crop rotation (e.g., Degani et al., 2019; Li et al., 2019; Bowles et al., 2020; Silva et al., 2020). Considering the different climate change scenarios, diversified crop rotation systems (e.g., I, II, and III) are expected to become increasingly important to ensure more stable yield and profitability in southern Brazil.

5. Conclusion

In southern Brazil, expanding the adoption of diversified crop rotation systems rather than low-diversity, specialized double-cropping systems has been a major challenge in enhancing agricultural sustainability. Our results proved that diversified crop rotations increased soybean, maize, and wheat grain yields, while reducing production costs. In terms of crop yield, wheat and first crop (summer) maize exhibited the strongest positive response to crop rotation, contributing to the positive economic performance of the corresponding diversified crop rotation systems. All 4-year diversified crop rotation systems generated a higher cumulative operational profit and gross margin than specialized double cropping systems. Overall, second crop maize was proven to be a high-risk option for autumn-winter cultivation, with high production costs and unstable yields. Wheat/soybean double cropping was the second most profitable system. In general, high production cost and lack of direct revenue from cover crops were compensated by the increased grain crop yield in diversified crop rotation systems. Therefore, diversified crop rotations are economically competitive with specialized double cropping systems, with a proven advantage of environmental conservation (air, water, and soil). Well-planned diversified crop rotation is an important strategy to reduce soil erosion, pesticide consumption, and GHG emissions, as well as to increase water and fertilizer use efficiency.

The relative performance of the production systems was not affected by either the pessimistic or optimistic scenarios. However, maize-soybean in double cropping presented the highest relative profit reduction under the pessimistic scenario (45.9%), indicating that the continuous growth of second crop maize renders the production system more susceptible to commodity price variations and, hence, riskier.

Our findings provide technical insights for the development of more efficient crop rotation systems in southern Brazil. Among the cover crops tested, forage radish can be highlighted as an interesting alternative to compose diversified crop rotation systems, mainly preceding first crop maize. Finally, system management should focus on increasing the summer crop yield and reducing their production costs, since soybean and first crop maize provided the highest sustained profitability of the studied production systems. Accordingly, the use of winter cover crops appears to be a system management strategy for increasing summer crop yields.

CRediT authorship contribution statement

Luiz Gustavo Garbelini: Conceptualization, Data curation, Investigation, Methodology, Formal analysis, Writing – original draft, Visualization. **Henrique Debiasi:** Methodology, Data curation, Investigation, Formal analysis, Validation, Writing – review & editing, Visualization. **Alvadi Antônio Balbinot Junior:** Methodology, Formal analysis, Validation, Writing – review & editing. **Júlio Cezar Franchini:** Conceptualization, Methodology, Validation, Writing – review & editing, Supervision, Project administration. **Antonio Eduardo Coelho:** Methodology, Data curation, Investigation, Formal analysis, Writing – original draft, Visualization. **Tiago Santos Telles:** Conceptualization, Data curation, Investigation, Formal analysis, Validation, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

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

Acknowledgements

This study was supported by the Conselho Nacional de Desenvolvimento Científico e Tecnológico – CNPq (grant number 315529/2020-2) and Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – CAPES (grant number 001).

References

Acosta, J.A.A., Amado, T.J.C., Silva, L.S.S., Santi, A., Weber, M.A., 2014. Decomposição da fitomassa de plantas de cobertura e liberação de nitrogênio em função da quantidade de resíduos aportada ao solo sob sistema plantio direto. Ciência Rural 44, 801–809. https://doi.org/10.1590/S0103-84782014005000002.

Adetunji, A.T., Ncubeb, B., Mulidzi, R., Lewu, F.B., 2020. Management impact and benefit of cover crops on soil quality: A review. Soil Tillage Res. 204, 1–11. https://doi.org/10.1016/j.still.2020.104717.

Al-Kaisi, M.M., Archontoulis, S.V., Kwaw-Mensah, D., Miguez, F., 2015. Tillage and crop rotation effects on corn agronomic response and economic return at seven Iowa locations. Agron. J. 107, 1411–1424. https://doi.org/10.2134/agronj14.0470.

Al-Kaisi, M.M., Archontoulis, S., Kwaw-Mensah, D., 2016. Soybean spatiotemporal yield and economic variability as affected by tillage and crop rotation. Agron. J. 108, 1267–1280. https://doi.org/10.2134/agronj2015.0363.

Alvares, C.A., Stape, J.L., Sentelhas, P.C., Gonçalves, J.L.M., Sparovek, G., 2013. Köppen's climate classification map for Brazil. Meteorol. Z. 22, 711–728. https://doi.org/10.1127/0941-2948/2013/0507.

Santos, H.G.,Jacomine, P.K.T., Anjos, L.H.C., Oliveira, V.A., Lumbreras, J.F., Coelho, M. R.,Almeida, J.A., Araujo Filho, J.C., Oliveira, J.B., Cunha, T.J.F. (Eds.), 2018. Brazilian soil classification system, fifth ed. Embrapa, Brasília, DF.

Bajwa, A.A., 2014. Sustainable weed management in conservation agriculture. Crop Prot. 65, 105–113. https://doi.org/10.1016/j.cropro.2014.07.014.

Balbinot Junior, A.A., Franchini, J.C., Debiasi, H., Yokoyama, A.H., 2017. Contribution of roots and shoots of Brachiaria species to soybean performance in succession. Pesqui. Agropecuária Bras. 52, 592–598. https://doi.org/10.1590/s0100-204×2017000800004.

Balbinot Junior, A.A., Franchini, J.C., Debiasi, H., Coelho, A.E., Sapucay, M.J.L.C., Bratti, F., Locatelli, J.L., 2020. Performance of soybean grown in succession to black oat and wheat. Pesqui. Agropecuária Bras. 55, e01654 https://doi.org/10.1590/S1678-3921.pab2020.v55.01654.

Bartzen, B., Hoelscher, G., Ribeiro, L., Seidel, E., 2019. How the soil resistance to penetration affects the development of agricultural crops? J. Exp. Agric. Int. 30, 1–17. https://doi.org/10.9734/JEAI/2019/46589.

Bayer, C., Gomes, J., Zanatta, J.A., Vieira, F.C.B., Dieckow, J., 2016. Mitigating greenhouse gas emissions from a subtropical Ultisol by using long-term no-tillage in combination with legume cover crops. Soil Tillage Res. 161, 86–94. https://doi.org/10.1016/j.still.2016.03.011.

Behnke, G.D., Zuber, S.M., Pittelkow, C.M., Nafziger, E.D., Villamil, M.B., 2018. Long-term crop rotation and tillage effects on soil greenhouse gas emissions and crop production in hIllinois, USA. Agric. Ecossystems Environ. 261, 72–90. https://doi.org/10.1016/j.agee.2018.03.007.

Bertollo, A.M., Moraes, M.T., Franchini, J.C., Soltangheisi, A., Balbinot Junior, A.A., Levien, R., Debiasi, H., 2021. Precrops alleviate soil physical limitations for soybean root growth in an Oxisol from southern Brazil. Soil Tillage Res. 206, 104820 https://doi.org/10.1016/j.still.2020.104820.

Bowles, T.M., Mooshamer, M., Socolar, Y., Schmer, M.R., Strock, J., Grandy, A.S., 2020. Long-term evidence shows that crop-rotation diversification increases agricultural resilience to adverse growing conditions in North America. One Earth 2, 284–293. https://doi.org/10.1016/j.oneear.2020.02.007.

Burney, J., Cesano, D., Russell, J., La Rovere, E.L., Corral, T., Coelho, N.S., Santos, L., 2014. Climate change adaptation strategies for smallholder farmers in the Brazilian Sertão. Clim. Change 126, 45–59. https://doi.org/10.1007/s10584-014-1186-0.

Calonego, J.C., Raphael, J.P.A., Rigon, J.P.G., Oliveira Neto, L., Rosolem, C.A., 2017. Soil compaction management and soybean yields with cover crops under no-till and occasional chiseling. Eur. J. Agron. 85, 31–37. https://doi.org/10.1016/j.eja.2017.02.001.

Campos, B.-H.C., Amado, T.J.C., Bayer, C., Nicoloso, R.S., Fiorin, J.E., 2011. Carbon stock and its compartments in a subtropical Oxisol under long-term tillage and crop rotation systems. Rev. Bras. Ciência do Solo 35, 805–817. https://doi.org/10.1590/S0100-06832011000300016.

Canalli, L.B.S., Costa, G.V., Volsi, B., Leocadio, A.L.M., Neves, C.S.V.J., Telles, T.S., 2020. Production and profitability of crop rotation systems in southern Brazil. Semin. Ciências Agrar. 41, 2541–2554. https://doi.org/10.5433/1679-0359.2020v41n6p2541.

Cárcer, P.S., Sinaj, S., Santonj, M., Fossati, D., Jeangros, B., 2019. Long-term effects of crop succession, soil tillage and climate on wheat yield and soil properties. Soil Tillage Res. 190, 209–219. https://doi.org/10.1016/j.still.2019.01.012.

Chalk, P.M., Smith, C.J., Hamilton, S.D., Hopmans, P., 1993. Characterization of the N benefit of a grain legume (Lupinus angustifolius L.) to a cereal (Hordeum vulgare L.) by an in situ 15N isotope dilution technique. Biol. Fertil. Soils 15, 39–44. https://doi.org/10.1007/BF00336286.

Chen, G., Weil, R.R., Hill, R.L., 2014. Effects of compaction and cover crops on soil least limiting water range and air permeability. Soil Tillage Res. 136, 61–69. https://doi.org/10.1016/j.still.2013.09.004.

CONAB – Companhia Nacional de Abastecimento, 2020. Acompanhamento da safra brasileira de grãos. ⟨https://www.conab.gov.br⟩ (Accessed 15 August 2020).

Costa, P.F., Oliveira, P.S.R., Piano, J.T., Taffarel, L.E., Arrúa, M.A.M., Sarto, M.V.M., Fróes, C.K., Fernandes, S.S.L., 2017. Dry matter production, chemical composition and nutrient accumulation in winter crops. Afr. J. Agric. Res. 12, 2421–2426. https://doi.org/10.5897/AJAR2016.11942.

Daryanto, S., Fu, B., Wang, L., Jacinthe, P.A., Zhao, W., 2018. Quantitative synthesis on the ecosystem services of cover crops. Earth Sci. Rev. 185, 357–373. https://doi.org/10.1016/j.earscirev.2018.06.013.

Degani, E., Leigh, S.G., Barber, H.M., Jones, H.E., Lukac, M., Sutton, P., Potts, S.G., 2019. Crop rotations in a climate change scenario: short-term effects of crop diversity on resilience and ecosystem service provision under drought. Agric. Ecosyst. Environ. 285, 106625 https://doi.org/10.1016/j.agee.2019.106625.

Deuschle, D., Minella, J.P.G., Hőrbe, T.A.N., Londero, A.L., Schneider, F.J.A., 2019. Erosion and hydrological response in no-tillage subjected to crop rotation intensification in southern Brazil. Geoderma 340, 157–163. https://doi.org/10.1016/j.geoderma.2019.01.010.

Diekow, J., Mielniczuk, J., Knicker, H., Bayer, C., Dick, D.P., Kögel-Knabner, I., 2005. Soil C and N stocks as affected by cropping systems and nitrogen fertilisation in a southern Brazil Acrisol managed under no-tillage for 17 years. Soil Tillage Res. 81, 87–95. https://doi.org/10.1016/j.still.2004.05.003.

Engel, F.L., Bertol, I., Ritter, S.R., Paz-González, A., Pázferreiro, J., Vidal-Vázquez, E., 2009. Soil erosion under simulated rainfall in relation to phenological stages of soybeans and tillage methods in Lages, SC, Brazil. Soil Tillage Res. 103, 216–221. https://doi.org/10.1016/j.still.2008.05.017.

FAO – Food and Agriculture Organization of the United Nations, 2020. FAOSTAT: Food and agriculture data. ⟨http://www.fao.org/faostat/⟩ (Accessed 15 August 2020).

Fageria, N.K., Baligar, V.C., 2021. Improving nutrient use efficiency of annual crops in Brazilian acid soils for sustainable crop production. Commun. Soil Sci. Plant Anal. 32, 1303–1319. https://doi.org/10.1081/CSS-100104114.

Ferreira, A.O., Amado, T.J.C., Nicoloso, R.S., Sá, J.C.M., Fiorin, J.E., Hansel, D.S.S., Menefee, D., 2013. Soil carbon stratification affected by long-term tillage and cropping systems in southern Brazil. Soil Tillage Res. 133, 65–74. https://doi.org/10.1016/j.still.2013.05.011.

Flister, L., Galushko, V., 2016. The impact of wheat market liberalization on the seed industry's innovative capacity: an assessment of Brazil's experience. Agric. Food Econ. 4, 11. https://doi.org/10.1186/s40100-016-0055-8.

Franchini, J.C., Debiasi, H., Balbinot Junior, A.A., Tonon, B.C., Farias, J.R.B., Oliveira, M.C.N., Torres, E., 2012. Evolution of crop yields in different tillage and cropping systems over two decades in southern Brazil. Field Crops Res. 137, 178–185. https://doi.org/10.1016/j.fcr.2012.09.003.

Franchini, J.C., Balbinot Junior, A.A., Debiasi, H., Conte, O., 2015. Desempenho da soja em consequência de manejo de pastagem, época de dessecação e adubação nitrogenada. Pesqui. Agropecuária Bras. 50, 1131–1138. https://doi.org/10.1590/S0100-204×2015001200002.

Fuentes-Llanillo, R., Telles, T.S., Volsi, B., Soares Junior, D., Carneiro, S.L., Guimaraes, M.F., 2018. Profitability of no-till grain production systems. Semin. Ciências Agrar. 39, 77–86. https://doi.org/10.5433/1679-0359.2018v39n1p77.

Garbelini, L.G., Franchini, J.C., Debiasi, H., Balbinot Junior, A.A., Betioli Junior, E., Telles, T.S., 2020. Profitability of soybean production models with diversified crops in the autumn-winter. Agron. J. 112, 4092–4103. https://doi.org/10.1002/agj2.20308.

Gava, R., Freitas, P.S., Faria, R.T., Rezende, R., Frizzone, J.A., 2013. Soil water evaporation under densities of coverage with vegetable residue. Eng. Agríc. 33, 89–98. https://doi.org/10.1590/S0100-69162013000100010.

Gentry, L.F., Ruffo, M.L., Below, F., 2013. Identifying factors controlling the continuous corn yield penalty. Agron. J. 105, 295–303. https://doi.org/10.2134/agronj2012.0246.

Gonzáles, J.U., Undurraga, P., Hirzel, J., Martínez, G.I., 2013. Economic evaluation of a crop rotation portfolio for irrigated farms in central Chile. Chil. J. Agric. Res. 73, 243–249. https://doi.org/10.4067/S0718-58392013000300006.

Govaerts, B., Fuentes, M., Mezzalama, M., Nicol, J.M., Deckers, J., Etchevers, J.D., Figueroa-Sandoval, B., Sayre, K.D., 2007. Infiltration, soil moisture, root rot and nematode populations after 12 years of different tillage, residue and crop rotation managements. Soil Tillage Res. 94, 209–219. https://doi.org/10.1016/j.still.2006.07.013.

Guareschi, A., Cechin, J., Bianchi, M.A., Kruse, N.D., Piccinini, F., Pinheiro, R.T., Machado, S.L.O., 2020. Cover plants as a suppression and increasing tool to hairy fleabane control. Rev. Bras. Ciências Agrar. 15, e7522 https://doi.org/10.5039/agraria.v15i2a7522.

Hallama, M., Pekrun, C., Lamber, H., Kandeler, E., 2019. Hidden miners – the roles of cover crops and soil microorganisms in phosphorus cycling through agroecosystems. Plant Soil 434, 7–45. https://doi.org/10.1007/s11104-018-3810-7.

Hillel, D., 1998. Environmental Soil Physics. Academic Press, San Diego.

Hungria, M., Nogueira, M.A., Araujo, R.S., 2015. Soybean seed with co-inoculation *Bradyrhizobium spp.* Azospirillum brasilense: a new biotechnological tool to improve yield and sustainability. Am. J. Plant Sci. 6, 811–817. https://doi.org/10.4236/ajps.2015.66087.

Jat, R.K., Sapkota, T.B., Singh, R.G., Jat, M.L., Kumar, M., 2014. Seven years of conservation agriculture in a rice-wheat rotation of Eastern Gangetic Plains of South Asia: yield trends and economic profitability. Field Crops Res. 164, 199–210. https://doi.org/10.1016/j.fcr.2014.04.015.

Kassam, A., Friedrich, T., Derpsch, R., 2019. Global spread of conservation agriculture. Int. J. Environ. Stud. 76, 29–51. https://doi.org/10.1080/00207233.2018.1494927.

Lal, R., 2015. Soil carbon sequestration and aggregation by cover cropping. J. Soil Water Conserv. 70, 329–339. https://doi.org/10.2489/jswc.70.6.329.

Lal, R., 2015b. A system approach to conservation agriculture. J. Soil Water Conserv. 70, 82A–88A. https://doi.org/10.2489/jswc.70.4.82A.

Landriscini, M.R., Galantini, J.A., Duval, M.E., Capurro, J.E., 2019. Nitrogen balance in a plant-soil system under different cover crop-soybean cropping in Argentina. Appl. Soil Ecol. 133, 124–131. https://doi.org/10.1016/j.apsoil.2018.10.005.

Li, J., Huang, L., Zhang, J., Coulter, J.A., Lingling, L., Gan, Y., 2019. Diversifying crop rotation improves system robustness. Agron. Sustain. Dev. 39, 2–13. https://doi.org/10.1007/s13593-019-0584-0.

Li, M., Guo, J., Ren, T., Luo, G., Shen, Q., Lu, J., Guo, S., Ling, N., 2021. Crop rotation history constrains soil biodiversity and multifunctionality relationships. Agric. Ecosyst. Environ. 391, 107550 https://doi.org/10.1016/j.agee.2021.107550.

Livingston, M., Fernandez-Cornejo, J., Frisvold, G.B., 2016. Economic returns to herbicide resistance management in the short and long run: the role of neighbor effects. Weed Sci. 64, 595–608. https://doi.org/10.1614/WS-D-15-00047.1.

Lollato, R.P., Bavia, G.P., Perin, V., Knapp, M., Santos, E.A., Patrignani, A., DeWolf, E.D., 2020. Climate-risk assessment for winter wheat using long-term weather data. Agron. J. 112, 2132–2151. https://doi.org/10.1002/agj2.20168.

Maron, P.A., Sarr, A., Kaisermann, A., Lévêque, J., Mathieu, O., Guigue, J., Karimi, B., Bernard, L., Dequiedt, S., Terrat, S., Cchabbi, A.Q., Ranjard, L., 2018. High microbial diversity promotes soil ecosystem functioning. Appl. Environ. Microbiol. 84, e02738–17. https://doi.org/10.1128/AEM.02738-17.

Mastrodomenico, A.T., Purcell, L.C., 2012. Soybean nitrogen fixation and nitrogen remobilization during reproductive development. Crop Sci. 52, 1281–1289. https://doi.org/10.2135/cropsci2011.08.0414.

Moraes, M.T., Levien, R., Trein, C.R., Bonetti, J.A., Debiasi, H., 2018. Corn performance in an Ultisol compacted by tractor traffic. Pesqui. Agropecuária Bras. 53, 464–477. https://doi.org/10.1590/S0100-204×2018000400008.

Moraes, M.T., Debiasi, H., Franchini, J.C., Bonetti, J.A., Levien, R., Schnepf, A., Leitner, D., 2019. Mechanical and hydric stress effects on maize root system development at different soil compaction levels. Front. Plant Sci. 10, 1358. https://doi.org/10.3389/fpls.2019.01358.

Mueller, D.S., Pedersen, W.L., Hartman, G.L., 2002. Effect of crop rotation and tillage system on sclerotinia stem rot on soybean. Can. J. Planta Pathol. 24, 450–456. https://doi.org/10.1080/07060660209507033.

Nóia Júnior, R.S., Sentelhas, P.C., 2019. Soybean-maize succession in Brazil: impacts of sowing dates on climate variability, yields and economic profitability. Eur. J. Agron. 103, 140–151. https://doi.org/10.1016/j.eja.2018.12.008.

Nouri, A., Lee, J., Yin, X., Saxton, A.M., Tyler, D.D., Sykes, V.R., Arell, P., 2019. Crop species in no-tillage summer crop rotations affect soil quality and yield in an Alfisol. Geoderma 345, 51–62. https://doi.org/10.1016/j.geoderma.2019.02.026.

Okello, C., Pindozzi, S., Faugno, S., Boccia, L., 2013. Bioenergy potential of agricultural and forest residues in Uganda. Biomass Bioenergy 56, 515–525. https://doi.org/10.1016/j.biombioe.2013.06.003.

Rahma, A.E., Warrington, D.N., Lei, T., 2019. Efficiency of wheat straw mulching in reducing soil and water losses from three typical soils of the Loess Plateau, China. Int. Soil Water Conserv. Res. 7, 335–345. https://doi.org/10.1016/j.iswcr.2019.08.003.

Reis, E.M., Segalin, M., Moraes, N.L., Ghissi, V.C., 2014. Efeitos da rotação de culturas na incidência de podridões radiciais e na produtividade da soja. Summa Phytopathol. 40, 9–15. https://doi.org/10.1590/S0100-54052014000100001.

Rosolem, C.A., Pivetta, L.A., 2017. Mechanical and biological approaches to alleviate soil compaction in tropical soils: assessed by root growth and activity (Rb uptake) of soybean and maize grown in rotation with cover crops. Soil Use Manag. 33, 141–152. https://doi.org/10.1111/sum.12313.

Sá, J.C.M., Lal, R., Cerri, C.C., Lorenz, K., Hungria, M., Carvalho, P.C., 2017. Low-carbon agriculture in South America to mitigate global climate change and advance food security. Environ. Int. 98, 102–112. https://doi.org/10.1016/j.envint.2016.10.0200160-4120.

Salazar, C., Jaime, M., Pinto, C., Acuña, A., 2019. A. Interaction between crop insurance and technology adoption decisions: The case of wheat farmers in Chile. Aust. J. Agric. Resour. Econ. 63, 593–619. https://doi.org/10.1111/1467-8489.12307.

Salvagiotti, F., Cassman, K.G., Specht, J.E., Walters, D.T., Weiss, A., Dobermann, A., 2008. Nitrogen uptake, fixation and response to fertilizer N in soybeans: a review. Field Crops Res. 108, 1–13. https://doi.org/10.1016/j.fcr.2008.03.001.

Santos, N.Z., Dieckow, J., Bayer, C., Molin, R., Favaretto, N., Pauletti, V., Piva, J.T., 2011. Forages, cover crops and related shoot and root additions in no-till rotations to C sequestration in a subtropical Ferralsol. Soil Tillage Res. 111, 208–218. https://doi.org/10.1016/j.still.2010.10.006.

Schomberg, H.H., Endale, D.M., Calegari, A., Peixoto, R., Miyazawa, M., Cabrera, M.L., 2006. Influence of cover crops on potential nitrogen availability to succeeding crops in a Southern Piedmont soil. Biol. Fertil. Soils 42, 299–307. https://doi.org/10.1007/s00374-005-0027-8.

SEAB – Paraná State Office for Agriculture and Supply (Secretaria da Agricultura e do Abastecimento do Estado do Paraná), 2022. Sistema de Informações do mercado agrícola. ⟨http://celepar7.pr.gov.br/sima⟩ (Accessed 04 February 2022).

Sentelhas, P.C., Battisti, R., Câmara, G.M.S., Farias, J.R.B., Hampf, A.C., Nendel, C., 2015. The soybean yield gap in Brazil - magnitude, causes and possible solutions for sustainable production. J. Agric. Sci. 153, 1394–1411. https://doi.org/10.1017/S0021859615000313.

Silva, C.G., Foloni, J.S.S., Fabris, L.B., Tiritan, C.S., 2009. Fitomassa e relação C/N em consórcios de sorgo e milho com espécies de cobertura. Pesqui. Agropecuária Bras. 44, 1504–1512. https://doi.org/10.1590/S0100-204×2009001100019.

Silva, P.C.G., Tiritan, C.S., Echer, F.R., Cordeiro, C.F.S., Rebonatti, M.D., Santos, C.H., 2020. No-tillage and crop rotation increase crop yields and nitrogen stocks in sandy soils under agroclimatic risk. Field Crops Res. 258, 107947 https://doi.org/10.1016/j.fcr.2020.107947.

Sindelar, A.J., Coulter, J.A., Lamb, J.A., Vetsch, J.A., 2015. Long-term corn and soybean response to crop rotation and tillage. Agron. J. 107, 843–850. https://doi.org/10.2134/agronj15.0085.

Soil Survey Staff, 2014. Keys to soil taxonomy, twelfth ed. USDA-Natural Resources Conservation Service, Washington, DC.

Soltangheisi, A., Rodrigues, M., Coelho, M.J.A., Gasperinim, A.M., Sartor, L.R., Pavinato, P.S., 2018. Changes in soil phosphorus lability promoted by phosphate sources and cover crops. Soil Tillage Res. 179, 20–28.

Telles, T.S., Righetto, A.J., Costa, G.V., Volsi, B., Oliveira, J.F., 2019. Conservation agriculture practices adopted in southern Brazil. Int. J. Agric. Sustain. 17, 1–9. https://doi.org/10.1080/14735903.2019.1655863.

Tessaro, A.A., Pereira, M.A., Calegari, A., Onofre, S.B., Ralisch, R., 2019. Soybean yields and biomass production of winter cover crops in the Southwest of Paraná – Brazil. J. Sustain. Dev. 12, 40–47. https://doi.org/10.5539/jsd.v12n5p40.

Thornthwaite, C.W., 1948. An approach toward a rational classification of climate. Geogr. Rev. 38, 55–94. ⟨https://www.jstor.org/stable/i210711⟩.

Tokura, L.K., Secco, D., Zanão Júnior, L.A., Siqueira, J.A.C., Santos, R.F., Martins, M.F.L., Alovisi, A.M.T., Oliveira, L.C., Hojo, R.H., Pereira, N., Pilatti, M.A., Moreira, M.C.D., Villa, B., Schmatz, M.J., 2017. Structuring potential of some cover crops and crambe in Haplortox under no-tillage system. Afr. J. Agric. Res. 12, 2078–2086. https://doi.org/10.5897/AJAR2016.11725.

Truong, T.H.H., Marschner, P., 2019. Plant growth and nutrient uptake in soil amended with mixes of organic materials differing in C/N ratio and decomposition stage. J. Soil Sci. Plant Nutr. 19, 512–523. https://doi.org/10.1007/s42729-019-00049-4.

Uzoh, I.M., Igwe, C.A., Okebalama, C.B., Babalola, O.O., 2019. Legume-maize rotation effect on maize productivity and soil fertility parameters under selected agronomic practices in a sandy loam soil. Sci. Rep. 9, 8539. https://doi.org/10.1038/s41598-019-43679-5.

Van Eerd, L.L., 2018. Nitrogen dynamics and yields of fresh bean and sweet corn with different cover crops and planting dates. Nutr. Cycl. Agroecosystems 111, 33–46. https://doi.org/10.1007/s10705-018-9914-x.

Venter, Z.S., Jacobs, K., Hawkins, H.J., 2016. The impact of crop rotation on soil microbial diversity: a meta-analysis. Pedobiologia 59, 215–223. https://doi.org/10.1016/j.pedobi.2016.04.001.

Volanti, M., Savarino, F.O., Passarini, F., Vassura, I., Grosso, S.A., 2021. Environmental analysis of crop rotations through the application of the Cereal Unit approach. Ecol. Indic. 121, 107199 https://doi.org/10.1016/j.ecolind.2020.107199.

Volsi, B., Bordin, I., Higashi, G.E., Telles, T.S., 2020. Economic profitability of crop rotation systems in the Caiuá sandstone area. Ciência Rural 50, e20190264. https://doi.org/10.1590/0103-8478cr20190264.

Volsi, B., Higashi, G.E., Bordin, I., Telles, T.S., 2021. Production and profitability of diversified agricultural systems. An. Acad. Bras. Ciências 93, e20191330. https://doi.org/10.1590/0001-3765202120191330.

Wenneck, G.S., Saath, R., Araújo, L.L., Pereira, G.L., Rezende, R., 2021. Decomposition of the remaining straw during soybean growing in the midwestern Paraná, Brazil. Rev. Agric. Neotrop. 8, e6534 https://doi.org/10.32404/rean.v8i4.6534.

Wilhelm, W.W., Wortmann, C.S., 2004. Tillage and rotation interactions for corn and soybean grain yield as affected by precipitation and air temperature. Agron. J. 96, 425–432. https://doi.org/10.2134/agronj2004.4250.

Zotarelli, L., Zatorre, N.P., Boddey, R.M., Urquiaga, S., Jantalia, C.P., Franchini, J.C., Alves, B.J., 2012. Influence of no-tillage and frequency of a green manure legume in crop rotations for balancing N outputs and preserving soil organic C stocks. Field Crops Res. 132, 185–195. https://doi.org/10.1016/j.fcr.2011.12.013.

Zuber, S.M., Behnke, G., Nafziger, E.D., Villamil, M.B., 2017. Multivariate assessment of soil quality indicators for crop rotation and tillage in Illinois. Soil Tillage Res. 174, 147–155. https://doi.org/10.1016/j.still.2017.07.007.