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Profitability of soybean production models with diversified crops in the autumn–winter

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Abstract

In Brazil, soybean (*Glycine max* L.) have been grown in production systems with a low plant species diversification. However, these systems are becoming less efficient and sustainable. This study therefore evaluated the profitability of soybean production systems as a function of the degree of diversification of crops grown in the winter period. We conducted an experiment in Paraná state, Brazil, over 6 yr, under no-tillage. The crop rotation systems included soybean, wheat (*Triticum aestivum* L.), and combinations of tropical forage crops, either planted independently or intercropped with maize (*Zea mays* L.) in the winter. We evaluated the crop yields, gross revenue, total operating cost, gross margin, and profit of each production model. Diversified crop rotation systems increase crop yields and profit compared with the maize–soybean system. The most interesting crop rotations with respect to yield and profit proved to be those that substituted second crop maize for brachiaria ruziziensis (*Urochloa ruziziensis*) grass as a cover crop every 3 yr or intercropped second crop maize with brachiaria ruziziensis.

1 | INTRODUCTION

Soybean (*Glycine max* L.) is one of the most important commodity in the world agriculture and Brazil is one of the largest producers and exporters globally (Sentelhas et al., 2015). A majority of soybean cropped in the country is found within production systems with low plant species diversification, using soybean in the summer (or first crop) and maize (*Zea mays* L.) or wheat (*Triticum aestivum* L.) in the winter (or second crop). The main crop rotation systems in Brazil are maize–soybean and wheat–soybean. On one hand, the simplification of production systems facilitates operational routines on rural properties. However, on the other hand, such production systems accentuate the degradation of the physical, chemical, and biological attributes of the soil (Karami, Homaee, Afzalinia, Ruhipour, & Basirat, 2012), and increase infestations of pests and diseases that are difficult to control (Bajwa et al., 2014). Additionally, agricultural systems with low diversification face numerous obstacles with respect to agricultural sustainability and are becoming increasingly inefficient due to yield stagnation and a reduction in profitability (Al-Kaisi, Archontoulis, & Kwaw-Mensah, 2016; Al-Kaisi, Archontoulis, Kwaw-Mensah, & Miguez, 2015).

Data from the Department of Rural Economy of the Secretary of Agriculture and Supply of Paraná (Secretaria da Agricultura e do Abastecimento, 2019) revealed that 84% of the 576,958 ha cultivated with soybean in the regions of Londrina and Maringá (Paraná state) in the 2016–2017 cropping season were preceded by second crop maize, confirming the low level of diversification of agricultural production systems in the region. One alternative system to the common maize–soybean rotation is wheat–soybean, which is becoming less frequently used due to problems marketing the wheat (Corte, Dill, Oliveira, & Pivotto, 2015).

In the last few decades, most studies recommended the substitution of commercial crops for cover crops that do not generate a profit in the short term (Delgado, Dillon, Sparks, & Essah, 2007). Cover crops additionally present a higher operational complexity. As a function of global soybean market, its high demand, and established factors of production, substituting soybean for other crop on a large scale is extremely difficult (Goldsmith & Montesdeoca, 2018).

As a result, the principal strategy for increasing the diversity of plant species involves the use of tropical forage during the winter period, planted either independently or intercropped with second crop maize. Among the many tropical forage grasses, brachiaria ruziziensis (*Urochloa ruziziensis*) is one of the better options to be grown as a cover crop in soybean production systems due to its agronomic characteristics that improve soil health (Balbinot, Santos, Debiasi, & Yokoyama, 2017; Rosolem & Pivetta, 2017). In practice, crop diversification is operationalized through the planning and adoption of a particular production model that comprises the temporal and spatial arrangement of the plant species of the agricultural system (Mirsky et al., 2012). However, little information is available regarding the best options for these species among grain and oilseed production, especially in terms of spatial and temporal composition (i.e., the percentage of total area that should be reserved for brachiaria ruziziensis), in terms of production modes (i.e., planted independently or intercropped with maize), and in terms of combining higher quality soil with economic gains for the production system. Thus, the hypothesis of this research is that the diversified crop rotation systems using brachiaria ruziziensis increase profitability compared with the maize–soybean system.

The aim of this study was to quantify the profitability of soybean production systems in southern Brazil, as a function of the degree of diversification of their second crop.

Core Ideas

- The profitability of soybean production systems was investigated.
- Diversified crop rotation systems increased soybean productivity.
- Diversified crop rotation systems using brachiaria ruziziensis increased profitability.

2 | MATERIAL AND METHODS

2.1 | Location and area of study

The experiment was conducted from 2012–2013 to 2017–2018 cropping season at the Technology Dissemination Unit of Cocamar, in Floresta, Brazil (23°35′S, 52°04′ W; 390 m average altitude), on a Rhodic Eutrudox (Soil Survey Staff, 2014)-Latossolo Vermelho, according to the Brazilian Soil Classification System (Santos et al., 2018). The average values of the chemical attributes of the soil at a depth of 0 to 0.2 m, prior to the implementation of the experiment, were as follows: soil organic matter (SOM) = 36 g kg^{-1}; pH $CaCl_2$ = 5.5; potential acidity (H+Al) = 27.3 mg kg^{-1}; phosphorous (P; Melich I) = 13.6 mg kg^{-1}; calcium (Ca^{2+}) = 1,136.3 mg kg^{-1}; magnesium (Mg^{2+}) = 254.0 mg kg^{-1}; potassium (K^{+}) = 269.8 mg kg^{-1}; sulfur (SO_4) = 6.9 mg kg^{-1}; exchangeable aluminum (Al^{3+}) = 0.0 mg kg^{-1}; cation-exchange capacity (CEC; pH 7.0) = 1,687.3 mg kg^{-1}; and base saturation (V%) = 76%. The average slope of the experimental area is 5 %. According to the Köppen classification, the climate in the region is humid subtropical–Cfa (Alvares, Stape, Sentelhas, Gonçalves, & Sparovek, 2013). The average temperature is 20.2 °C and average annual precipitation is 1,387 mm. The climactic conditions for the crop years under study are presented in the graphs for minimum, average, and maximum daily temperatures and in the 10-d water balance (Figure 1), which uses the methodology proposed by Thornthwaite (1948), and is calculated based on the spreadsheets of Rolim, Sentelhas, and Barbieri (1998). We considered a water storage capacity (WSC) of 75 mm.

2.2 | Experiment design

The experimental design was randomized complete block with eight treatments and three replications (Table 1). The treatments comprised of the crop rotation systems with different degrees of crop diversification in the winter period. The experimental plots measured 12 by 20 m (240 m^2). The study period included two production cycles of 3 yr each, from 2012 to 2018.

The eight production systems evaluated are shown in Table 1. Soybean was maintained as the summer crop for all production systems. The arrangements were distributed as production systems with low (I, II, III, and V) and high (IV, VI, VII, and VIII) level of diversification of plant species in

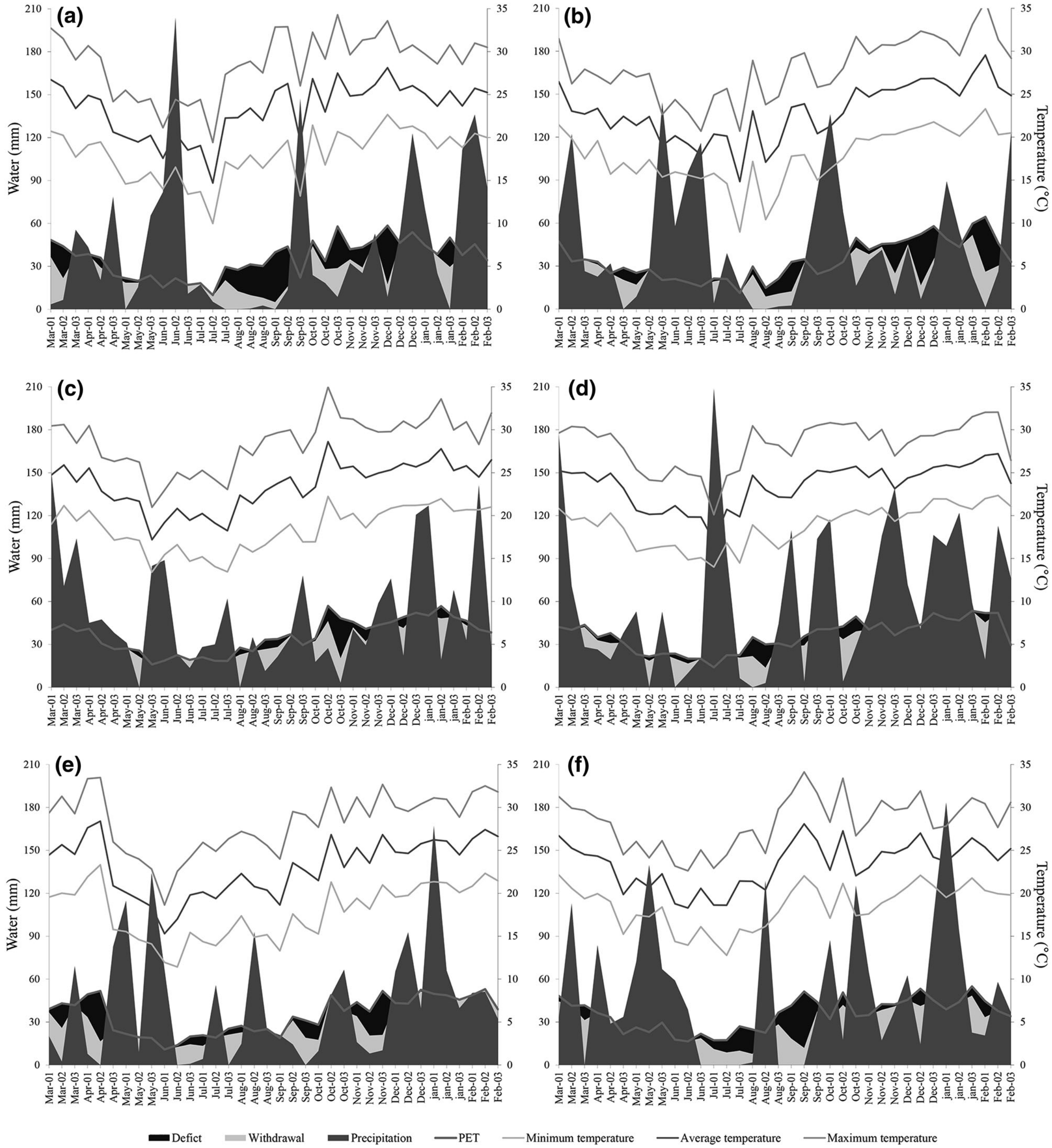

FIGURE 1 Minimum, average, and maximum daily temperatures and 10-d water balance (75 mm) for the (a) 2012–2013, (b) 2013–2014, (c) 2014–2015, (d) 2015–2016, (e) 2016–2017, and (f) 2017–2018 crop years. PET, potential evapotranspiration (mm); withdrawal: actual plant water consumption (mm)

the winter period, according to two production cycles of 3 yr each.

Table 2 presents seeding, desiccation, emergence, and harvest times, in addition to the cultivars and fertilization. Crop management followed the technical recommendations for each crop. The planting of soybean and second crop maize was done using a tractor-pulled planter, equipped with straw cutting disks, and shanks and double-disks as furrow openers for fertilizer and seed deposition, respectively. The row spacing used for both crops was 0.45 m, for a stand count of 300,000 plants ha^{-1} for soybean and 55,000 plants ha^{-1} for maize. The nitrogen fertilizer used on maize involved a surface application of urea on the total area, in a dose of 120 Kg ha^{-1} in 2012, and 67 Kg ha^{-1} in 2013, 2016, and 2017, with no surface fertilizer applied in 2014 and 2015. When intercropped, brachiaria ruziziensis was planted in every maize interrow aiming to obtain 20 plants m^{-2}.

Single wheat and brachiaria ruziziensis were planted with the same planter used in the summer, but with row spacings of 17 cm, with double disks as furrow openers for seed deposition and fluted wheels for seed metering. The seed density was adjusted to obtain 300 plants m^{-2} of wheat and 40 plants m^{-2} for brachiaria ruziziensis. The methodology applied to evaluate the yields of the grains consisted of a manual harvest of the crops and ears of maize. We weighed the samples, corrected for 13% moisture content, and noted yields in kg ha^{-1}.

From the average yields determined for each system and growing season, we estimated the accumulated crop yields (maize, wheat, or soybean). Accordingly, the accumulated yields found in Production Systems I, II, III, and V were directly calculated by the total sum of yields obtained over the 6 yr, separately for each crop (maize, maize + brachiaria ruziziensis, wheat, and soybean). Otherwise, accumulated yields for the production systems with 2 (VII)- or 3 (IV, VI, and VIII)-yr cycles, which included alternating plant species for the winter period, were calculated using Equations 1–6.

$$\mathrm{YS} = \sum_{i=1}^{n} \overline{\mathrm{YS}}_i \quad (1)$$

Where YS is the accumulated soybean yields in each production system (IV, VI, VII, and VIII), over i cropping seasons (in our case, $i = 6$, from 2012–2013 to 2017–2018); $\overline{\mathrm{YS}}$ is the annual average soybean yields in each in each production system (IV, VI, VII, and VIII).

$$\mathrm{YM} = \mathrm{YM}_E + \mathrm{YM}_O \quad (2)$$

Where YM is the accumulated maize yields (2012–2013 to 2017–2018), calculated separately for the production systems involving rotation between maize and single brachiaria ruziziensis (IV) or maize + brachiaria ruziziensis (VI, VII, VIII), during the autumn–winter period.; YM_E is the accumulated maize yields (2012–2013 to 2017–2018), estimated for the cropping seasons whereby single or intercropped maize were not cultivated on the field plots, according to the spatial–temporal arrangement provided by the production system of interest; YM_O is the accumulated maize yields (2012–2013 to 2017–2018) observed on the field plots, measured by harvesting and weighting the crop grains, according to the spatial–temporal arrangement provided by the production system of interest.

TABLE 1 Soybean production systems and levels of crop diversification in the winter period, in Floresta, Brazil, in the 2012–2013 to 2017–2018 crop years

	First cycle						Second cycle					
	2012–2013		2013–2014		2014–2015		2015–2016		2016–2017		2017–2018	
Production System[a]	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer
I	M[b]	S	M	S	M	S	M	S	M	S	M	S
II	W	S	W	S	W	S	W	S	W	S	W	S
III	R	S	R	S	R	S	R	S	R	S	R	S
IV	R	S	M	S	M	S	R	S	M	S	M	S
V	M+R	S	M+R	S	M+R	S	M+R	S	M+R	S	M+R	S
VI	M+R	S	M+R	S	M	S	M+R	S	M+R	S	M	S
VII	M+R	S	M	S	M+R	S	M	S	M+R	S	M	S
VIII	M+R	S	M	S	M	S	M+R	S	M	S	M	S

[a]Production System I, second crop maize–soybean; Production System II, wheat–soybean; Production System III, ruziziensis–soybean; Production System IV, ruziziensis–soybean; second crop maize–soybean; second crop maize–soybean; Production System V, second crop maize intercropped with ruziziensis–soybean; Production System VI, second crop maize intercropped with ruziziensis–soybean; second crop maize intercropped with ruziziensis–soybean; second crop maize–soybean; Production System VII, second crop maize intercropped with ruziziensis–soybean; second crop maize–soybean; second crop maize intercropped with ruziziensis–soybean; second crop maize–soybean; second crop maize intercropped with ruziziensis–soybean; second crop maize–soybean; Production Systems VIII, second crop maize intercropped with ruziziensis–soybean; second crop maize–soybean; second crop maize–soybean; second crop maize intercropped with ruziziensis–soybean; second crop maize–soybean; second crop maize–soybean.

[b]M, second crop maize; S, soybean; W, wheat; R, brachiaria ruziziensis; M+R, second crop maize intercropped with brachiaria ruziziensis.

TABLE 2 Planting, desiccation, and harvest times, cultivars and base fertilizer used, 2012–2013 to 2017–2018 growing seasons

	Date			Base fertilizer	
Crop year	Planting	Harvest	Cultivar	Fertilizer composition	Dose kg ha^{-1}
Soybean					
2012–2013	28 Sept. 2012	12 Feb. 2013	BMX Potência RR	06–30–12	320
2013–2014	8 Oct. 2013	19 Feb. 2014	SS 6336 RR	06–24–12	320
2014–2015	22 Sept. 2014	2 Feb. 2015	BRS 360 RR	06–24–12	320
2015–2016	16 Sept. 2015	23 Jan. 2016	BMX Potência RR	06–24–12	320
2016–2017	21 Sept. 2016	6 Feb. 2017	BRS 1010 IPRO	02–20–18	250
2017–2018	7 Oct. 2017	24 Feb. 2018	BMX Potência RR	06–24–12	320
Wheat					
2012	5 Apr. 2012	6 Aug. 2012	IPR - Catuara TM	10–15–15	300
2013	8 Oct. 2013	19 Feb. 2014	IPR - Catuara TM	10–15–15	250
2014	22 Sept. 2014	2 Feb. 2015	CD 150	10–15–15	310
2015	16 Sept. 2015	23 Jan. 2016	CD 150	10–15–15	300
2016	21 Sept. 2016	6 Feb. 2017	TBIO Mestre	10–15–15	300
2017	7 Oct. 2017	24 Feb. 2018	TBIO Sintonia	10–15–15	300
Maize					
2012	25 Feb. 2012	26 July 2012	AG 9030	06–24–12	300
2013	25 Feb. 2013	30 July 2013	CD 384 HX	10–15–15	300
2014	28 Feb. 2014	3 Aug. 2014	DKB 285 PRO	10–15–15	320
2015	9 Feb. 2015	6 Aug. 2015	2B710 PW	10–15–15	320
2016	3 Feb. 2016	19 July 2016	P 30F53 YH	10–15–15	320
2017	15 Feb. 2017	12 July 2017	P3456 H	10–15–15	320
Brachiaria					
2012	25 Feb. 2012	1 Mar. 2012	Brachiaria ruziziensis	–	–
2013	25 Feb. 2013	3 Mar. 2013	Brachiaria ruziziensis	–	–
2014	28 Feb. 2014	6 Mar. 2014	Brachiaria ruziziensis	–	–
2015	9 Feb. 2015	15 Feb. 2015	Brachiaria ruziziensis	–	–
2016	3 Feb. 2016	9 Feb. 2016	Brachiaria ruziziensis	–	–
2017	15 Feb. 2017	21 Feb. 2017	Brachiaria ruziziensis	–	–

For System IV, YM_E and YM_O were calculated according Equations 3 and 4, respectively:

$$YM_E = \sum \left(\overline{YM}_{Ref}\right)(PAM_{SIV}) \tag{3}$$

Where $\overline{YM}_{Ref}$ is the reference single maize yield, equivalent to the average yield in the System I, obtained in the cropping seasons whereby single (System IV) or intercropped (Systems VI, VII, and VIII) brachiaria ruziziensis were cultivated on the field plots; PAM_{SIV} is the proportion of the area (or years) cultivated with maize in Production System IV, equivalent to 0.67 (two-thirds or 67% of the area or years).

$$YM_O = \sum \left(\overline{YM}_{SIV}\right)(PAM_{SIV}) \tag{4}$$

Where $\overline{YM}_{SIV}$ is the average maize yields over four cropping seasons, whereby maize was cultivated on the field plots of Production System IV (2013–2014, 2014–2015, 2016–2017, and 2017–2018).

For Production Systems VI, VII, and VIII, YM_E and YM_O were calculated according Equations 5 and 6, respectively:

$$YM_E = \left[\sum \left(\overline{YM}_{Ref}\right)(PAM_{IS})\right] + \left[\sum \left(\overline{YMR}_{Ref}\right)(PAMR)\right] \tag{5}$$

$$YM_O = \left[\sum \left(\overline{YM}_{IS}\right)(PAM_{IS})\right] + \left[\sum \left(\overline{YMR}_{IS}\right)(PAMR)\right] \tag{6}$$

Where $\overline{YMR}_{Ref}$ is the reference maize + brachiaria ruziziensis yield, equivalent to the average yield in Production System V, obtained in the cropping seasons whereby single maize (Production Systems VI, VII, and VIII) were cultivated on the field plots; PAM_{IS} is the proportion of the area (or years) cultivated with maize in the production systems involving maize + brachiaria ruziziensis (VI, VII, and VIII); PAMR is the proportion of the area (or years) cultivated with maize + brachiaria ruziziensis.

In summary, the procedure to calculate accumulated soybean yields for Production Systems IV, VI, VII, and VIII were the same used for Production Systems I, II, III, and V. Conversely, we obtained accumulated maize yields weighting average yields by the proportion of the area (one-third, one-half, or two-thirds; 33, 50, and 67%, respectively, depending on the production system) cultivated with each different crop within a given production system and cropping year. This procedure allowed for minimizing the effect of climatic variation on the winter crops for the years under study, which could favor certain production systems at random and lead to errors in the interpretation of the results. This adjustment was necessary since the single crops or intercrops that compose the winter rotation in a given production model are not grown every year.

The adopted procedure can be illustrated by Production System IV. In this treatment, maize was not cultivated in two cropping seasons (2012–2013 and 2015–2016), as shown in Table 1. Following this arrangement, farmers using Production System IV would cultivate 100% of their agricultural area with brachiaria ruziziensis in 2012–2013 and 2015–2016 and, hence, 100% of the area with maize in the other four cropping seasons. However, it is well known that the indicated arrangement is to cultivate both crops (maize and brachiaria ruziziensis) every year, following the area proportion of 33.3% (one-third) for brachiaria ruziziensis, and 66.7% (two-thirds) for maize. Achieving this arrangement at experimental scale would be the ideal condition, but it implies in three additional plots (replications) for each rotation year (i.e., brachiaria ruziziensis and first and second maize cropping seasons), what would not be operationally feasible taking into account the number of treatments and the plot size. In our experiment, we simulated the adequate arrangement for Production Systems IV, VI, VII, and VIII, using the average single maize yield in Production System I as a reference value when this crop was not present on the field plots of a given treatment. Similarly, we adopted the maize + brachiaria ruziziensis grain yield obtained in Production System V as reference value in the cropping season whereby the intercrop was not present on the field plots of a given production system.

2.3 | Economic analysis

The economic analyses were made for the entire production systems instead of analyzing each crop individually and was expressed in U.S. \$ ha^{-1}. In Production Systems I, II, III, and V, we collect the prices paid for inputs and received for grains from all crop years to calculate each economic indicator (gross revenue, total operating cost, and operating profit). We estimated the economic indicators for the models with 3-yr cycles—which included alternating plant species for the winter period (Production Systems IV, VI, VII, and VIII)—by considering the spatial and temporal arrangement of the crops and weighting each indicator according to the percentage of independent or intercropped crops within the model during each crop year.

Due to the small size of the plots, separate herbicide application for each production model was not feasible. Therefore, for the purpose of economic analysis, we assumed a 3% savings in the total operating cost (TOC) for not treating weed infestations (*Conyza spp.* and *Digitaria insularis*). We estimated this 3% value for the particular edaphoclimatic conditions of the experimental area, based on the results obtained by Livingston, Fernandez-Cornejo, and Frisvold (2016), for each year planting wheat and brachiaria ruziziensis, as either independent crops or intercropped with maize.

Our cost analysis is based on the Kay, Edwards, and Duffy (2020). To calculate operating costs, we consider all stages of the production process: land management (lime application, desiccation), seeding (seeds, seed treatment, inoculation, fertilizer application), crop treatment (insecticides, herbicides, fungicides), harvest and transport, technical assistance, fees, and taxes. We exclude any financing costs and charges, as producers in this region commonly adhere to the advance input purchase campaigns or hedging offered by agricultural companies and, moreover, by cooperatives.

We calculated the costs for inputs, mechanized operations, and labor using technical coefficients obtained at the Cocamar Experimental Station in Floresta, Brazil, where the experiment occurred. We surveyed for input prices and operating costs, and specifically, for the average prices paid by the rural producer in three cooperatives or agriculture companies from the region of study, to not distort the values due to regional factors. We used prices for the months when anticipated input sales campaigns or hedging occurred by the principal distribution channels, and for the years of our experiment. In the region of Northern Paraná, such campaigns consistently occurred in the months of May for the summer crop and October for the winter crop.

We calculated revenue, gross margin, and profit according to the concepts presented in Fuentes-Llanillo et al. (2018), and Volsi, Bordin, Higashi, and Telles (2020). To calculate gross revenue, we used the average yearly prices paid for each crop during each respective marketing period, which was obtained from a regional survey

TABLE 3 Economic indicators, equations, and description

Indicator	Equation	Description
Gross revenue (GR)	GR = *Y*Pu	*Y* is the yield per unit of area, and Pu is the unit price of the product
Total operating Cost (TOC)	TOC = $\sum(Pq)$ + AO + IC	$\sum(Pq)$ is the sum of prices (P) by quantity of (q) inputs, AO is the agriculture operations and IC is the indirect costs (insurance, economic costs (interest), external transportation, charges and taxes)
Operating profit (OP)	OP = GR − TOC	GR is the gross revenue, and TOC is the total operating cost
Gross margin (GM)	GM = [(GR − TOC)/TOC]100	GR is the gross revenue, and TOC is the total operating cost

conducted by Secretaria da Agricultura e do Abastecimento (2019). We used the fertilizer composition presented in Table 3.

The remuneration of factors of production, land, and capital (opportunity cost) were not included in the cost of production. We standardized all data used to create the economic indicators to a per-hectare basis and corrected the data to December 2018 real values using the Extended National Consumer Price Index (IPCA). The real values were transformed into U.S. dollars ($) for the December 2018 exchange rate provided by the Central Bank of Brazil.

3 | RESULTS AND DISCUSSION

3.1 | Crop yield

Accumulated soybean yields (Figure 2) were higher in the models with single-cultivated brachiaria ruziziensis in the winter period every year or every 3 yr (Production Systems III and IV), and relative to the soybean yields of the second-crop maize soybean system (M-S, Production System I), they were higher by an average of 1,200 kg ha^{-1} (6%). Meanwhile, in Production Systems V, VI, VII, and VIII, where brachiaria ruziziensis was intercropped with maize, soybean yields were on average 540 kg ha^{-1} (3%) higher than those of the M-S model (Production System I). Similarly, the wheat–soybean system (Production System II) presented yields that were 360 kg ha^{-1} (2%) higher than those of the M-S system. An analysis of the accumulated yield from all crop years (Figure 2) demonstrated the beneficial and consistent effects of a brachiaria ruziziensis cover on soybean. For all production systems, the average yield for the M-S was substantially inferior to that of the other systems.

Water deficits occurred for soybean, particularly in the cropping seasons 2012–2013 and 2013–2014 (Figure 1). We observed that the positive effects of the production systems with brachiaria ruziziensis (in the winter) were most intense in the crop years with a water deficit during soybean growth cycle. This occurred because the brachiaria

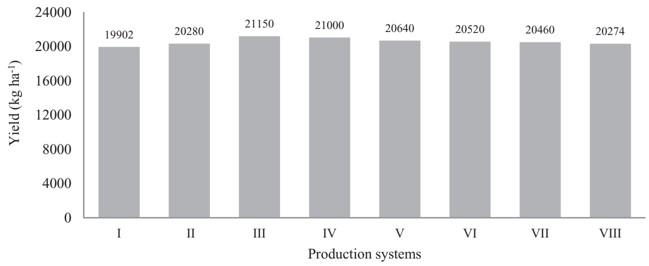

FIGURE 2 Accumulated soybean yields for the eight production systems, for the 2012–2018 crop years. Production System I, second crop maize–soybean; Production System II, wheat–soybean; Production System III, ruziziensis–soybean; Production System IV, ruziziensis–soybean; second crop maize–soybean; second crop maize–soybean; Production System V, second crop maize intercropped with ruziziensis–soybean; Production System VI, second crop maize intercropped with ruziziensis–soybean; second crop maize intercropped with ruziziensis–soybean; second crop maize–soybean; Production System VII, second crop maize intercropped with ruziziensis–soybean; second crop maize–soybean; second crop maize intercropped with ruziziensis–soybean; second crop maize–soybean; second crop maize intercropped with ruziziensis–soybean; second crop maize–soybean; Production Systems VIII, second crop maize intercropped with ruziziensis–soybean; second crop maize–soybean; second crop maize–soybean; second crop maize intercropped with ruziziensis–soybean; second crop maize–soybean; second crop maize–soybean

ruziziensis roots improved the soil structure and the residue left from planting brachiaria ruziziensis reduced the soil surface temperature, and therefore the loss of water from evaporation (Balbinot Junior et al., 2017). Water deficits can often limit the growth and development of the crops, particularly if the deficit occurs during periods of flowering or pod-fill (Fioreze, Pivetta, Fano, Machado, & Guimarães, 2011), which is what occurred during the first two cropping seasons. Several studies have reported the benefits of brachiaria ruziziensis on the yield of soybean (Balbinot et al., 2017; Correia, Leite, & Fuzita, 2013; Rosolem, Neto, Costa, & Grassmann, 2019), specifically improvements in production due to the high residues and

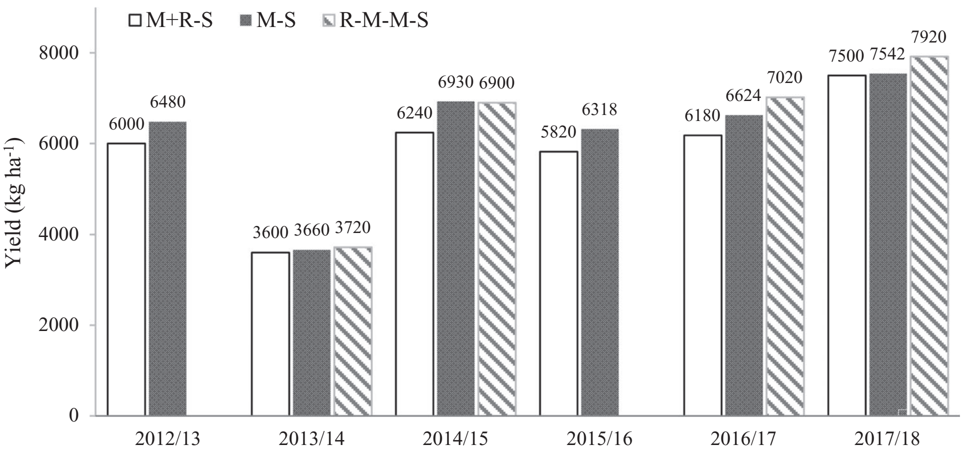

FIGURE 3 Annual maize yields from production systems, during the crop years 2012–2018. Comparison for each crop year, including the rotation of second-crop maize and soybean (M-S), second-crop maize intercropped with brachiaria ruziziensis and soybean (M+R-S), and the alternation of brachiaria ruziziensis for 1 yr followed by maize for 2 yr, all during the second crop season and soybean (R-M-M-S)

roots generated by the plant. The direct benefits of soil cover on crop yields are well known and involve a reduction in thermal amplitude (Altieri et al., 2011); a decrease in soil, water, and nutrient losses from erosion (Dechen, Telles, Guimaraes, & De Maria, 2015; Engel et al., 2009); a decrease in weed infestations, particularly in weeds with herbicide resistance, such as horseweed (*Conyza bonariensis*) and sourgrass (*Digitaria insularis*; Correia et al., 2013); a break in disease cycles; and a reduction in pest infestations (Larkin, 2015). Likewise, the planting of species with abundant and deep root systems, such as brachiaria ruziziensis, increases nutrient cycling (Rosolem et al., 2019).

With respect to soybean, we found that growing brachiaria ruziziensis in the winter period is not necessary every year and can be rotated with second crop maize. This finding is highly relevant, since it indicates that even alternating brachiaria ruziziensis with second crop maize is sufficient to increase the diversification of crop rotation systems.

We found no significant differences in the yields of second crop maize in the 2013–2014 and 2014–2015 cropping seasons, between Production Systems I and IV (Figure 3). However, in the 2016–2017 and 2017–2018 cropping seasons, the highest maize yields were observed for Production System IV, involving single-cultivated brachiaria ruziziensis in the winter every 3 yr. Compared to the M-S (Production System I), Production System IV demonstrated yields that were 420 and 360 kg ha^{-1} higher, respectively, for each crop year (Figure 3).

The low temperature during winter months growing season is a limiting factor for the maize development in the double cropping system. Frost not only interferes with the development of the crop but can also cause plant damage and mortality. During the first 6 yr of the study, we observed only one frost event, in the winter of 2013–2014 (July), with a minimum temperature of 1.3 °C (Figure 1). Frost damage begins with air temperatures below 3 °C. During the winter of 2013–2014, the yield of intercropped maize was near 3% above that found in the M-S system, which may be explained in part by the lower decrease of soil temperature, and consequently, from less surface cooling caused by the brachiaria ruziziensis.

One concern related to the intercropping of second crop maize with brachiaria ruziziensis is the possible yield reduction in maize as a function of the competition between plant species for resources (i.e., water, light, and nutrients; Borghi et al., 2012; Crusciol et al., 2013). The yield of maize planted independently was higher, compared to maize intercropped with brachiaria ruziziensis (Figure 3). Taking the average from six cropping seasons, competition from brachiaria ruziziensis resulted in a 6% decrease in maize yield. We observed the greatest losses in the first production cycle as a function of conditions that favored brachiaria ruziziensis over maize in the competition for resources. This demonstrates that the intercropping of maize with brachiaria ruziziensis is an interesting option to increase diversification and the yields of successive soybean, but should be implemented and conducted following the techniques recommended by the research, so that maize does not suffer any yield decreases (Alves, Padilha, Garcia, & Ceccon, 2013; Queiroz, Chioderoli, Furlani, Holanda, & Zerbato, 2016).

3.2 | Economic analysis

The agronomic and environmental importance of adopting diversified production systems in no-tillage is recognized by the most producers and technicians. However, the

TABLE 4 Estimates for revenue, cost, and operating profit for production systems involving six years of soybean production in the 2012–2013 to 2017–2018 crop years

Production systems[a]		Gross revenue US $ ha^{-1}	Gross revenue %	Operating cost US $ ha^{-1}	Operating cost %	Operating profit US $ ha^{-1}	Operating profit %	Gross margin %
I	M (100%)[b]	4,252.95	41.9	4,392.40	55.1	−139.45	−6.4	27
	S (100%)	5,906.53	58.1	3,576.30	44.9	2,330.23	106.4	
	Total	10,159.48	100.0	7,968.70	100.0	2,190.78	100.0	
II	W (100%)	2,791.00	30.3	3,012.19	45.6	−221.19	−9.8	31
	S (100%)	6,079.12	69.7	3,597.25	54.4	2,481.87	109.8	
	Total	8,870.12	100.0	6,609.44	100.0	2,260.68	100.0	
III	R (100%)	0.00	0.0	669.36	15.6	−669.36	−42.0	46
	S (100%)	6,261.01	100.0	3,623.67	84.4	2,637.34	142.0	
	Total	6,261.01	100.0	4,293.03	100.0	1,967.97	100.0	
IV	R (33%) and M (67%)	2,935.08	31.7	3,151.38	46.7	−216.31	−8.6	37
	S (100%)	6,334.85	68.3	3,593.79	53.3	2,741.07	108.6	
	Total	9,269.93	100.0	6,745.17	100.0	2,524.76	100.0	
V	M + R (100%)	4,018.57	39.4	4,199.26	53.9	−180.69	−7.5	31
	S (100%)	6,193.58	60.6	3,601.46	46.1	2,592.12	107.5	
	Total	10,212.15	100.0	7,800.72	100.0	2,411.43	100.0	
VI	M + R (67%) and (33%)	4,009.32	39.7	4,263.64	54.2	−254.32	−11.4	28
	S (100%)	6,082.87	60.3	3,597.97	45.8	2,484.90	111.4	
	Total	10,092.20	100.0	7,861.61	100.0	2,230.58	100.0	
VII	M + R (50%) and M (50%)	4,105.45	40.3	4,289.92	54.4	−184.47	−8.1	29
	S (100%)	6,071.59	59.7	3,598.41	45.6	2,473.19	108.1	
	Total	10,177.05	100.0	7,888.33	100.0	2,288.72	100.0	
VIII	M + R (33%) and M (67%)	4,183.58	41.0	4,328.02	54.7	−144.44	−6.3	29
	S (100%)	6,023.17	59.0	3,590.29	45.3	2,432.89	106.3	
	Total	10,206.75	100.0	7,918.30	100.0	2,288.45	100.0	

[a]Production System I, second crop maize–soybean; Production System II, wheat–soybean; Production System III, ruziziensis–soybean; Production System IV, ruziziensis–soybean; second crop maize–soybean; second crop maize–soybean; Production System V, second crop maize intercropped with ruziziensis–soybean; Production System VI, second crop maize intercropped with ruziziensis–soybean; second crop maize intercropped with ruziziensis–soybean; second crop maize–soybean; Production System VII, second crop maize intercropped with ruziziensis–soybean; second crop maize–soybean; second crop maize intercropped with ruziziensis–soybean; second crop maize–soybean; second crop maize intercropped with ruziziensis–soybean; second crop maize–soybean; Production Systems VIII, second crop maize intercropped with ruziziensis–soybean; second crop maize–soybean; second crop maize–soybean; second crop maize intercropped with ruziziensis–soybean; second crop maize–soybean; second crop maize–soybean.
[b]M, second crop maize; S, soybean; W, wheat; R, brachiaria ruziziensis; M+R, second crop maize intercropped with brachiaria ruziziensis.

perception that these models are less profitable, particularly when growing cover crops remains widespread. This perception is one of the principal factors driving the predominance of low diversification systems such as second crop maize–soybean. Results of the economic analysis are shown in Table 4.

We found a negative profit for all production systems in the winter period (Table 4). In the grains production in the winter period, the costs are greater than returns. This demonstrates the limited economic return of most usual winter commercial crops (e.g., wheat and maize) in the region, and highlights that crop rotation systems must be managed to prioritize obtaining high yields from soybean, that is the most profitable crop.

The brachiaria ruziziensis–soybean rotation was the system showing the highest operating cost in the summer, due to the higher average yield of soybean. However, the higher profitability of soybean in rotation with brachiaria ruziziensis was insufficient to compensate for the operating cost of second-crop maize, and therefore the brachiaria ruziziensis–soybean system demonstrated the lowest operating profit of all the systems.

The inclusion of brachiaria ruziziensis, either single-cultivated or intercropped with second crop maize, presented a lower operating cost in the winter period, in comparison to the rotation of second-crop maize and soybean. This may be attributed to a reduction in area (Production System IV, where brachiaria ruziziensis was planted independently on 33% of the area) or a reduction in grain yields in models involving intercropping with a cover crop (Figure 3). Considering the accumulated values over a 6-yr period, the decrease in operating profit compared to the second crop maize–soybean system ranged from $ 76.86 ha^{-1} (lower) for the R-S-M-S-M-S production system (IV) to $114.87 ha^{-1} (lower) for the M+R-S-M+R-S-M-S production system (VI). Taking a property with 45 ha, the inclusion of single brachiaria ruziziensis in the second crop can imply an operating profit that is $ 3,458.79–5,169.13 less than that of a M-S rotation, considering an economic analysis exclusively of the winter period. This finding is of great importance, as it is mostly likely the main factor associated with the perception that winter crop diversification in the M-S production system is unprofitable. However, when considering an economic analysis of the production system as a whole, the higher operating profit of soybean from production systems involving the rotation or intercropping of second crop maize with brachiaria ruziziensis in the winter compensated for the worse economic performance obtained in the winter, and consequently resulted in a higher operating profit of these models.

In this context, the two production systems proving to be the most profitable for the producer were R-S-M-S-M-S (System IV) and M+R-S (System V), which demonstrated an operating profit that was $220.65 and $333.98 per ha higher than that of the M-S rotation, respectively (Table 4). If we consider a property with 45 planted ha, production systems involving maize + brachiaria ruziziensis in the winter period every year (M+R-S) or single-cultivated brachiaria ruziziensis in rotation with maize every 3 yr can provide an average increase of $9,929.32 to $15,029.02, respectively, in the accumulated operating profit (6 yr) of the production system.

In general, our economic analysis highlights that second crop maize is an important alternative in composing diversified crop rotation systems in the Northern region of Paraná, since the exclusion of this crop from production systems with a wheat–soybean or brachiaria ruziziensis–soybean demonstrated a lower operating profit. In addition, the production of maize decreases farmers dependence on soybean, decreasing weather and/or market risks. Therefore, crop diversification in the winter period using brachiaria ruziziensis improves the economic performance the production system, as shown in this study.

In the specific case of the R-S-M-S-M-S production system (IV), growing brachiaria ruziziensis on 33% of the area allowed second crop maize to be planted earlier in areas where soybean was harvested earlier (generally in February), allowing for a better productive performance of maize. As a result, brachiaria ruziziensis was cultivated in areas where soybean was harvested later, often in March, as during this period the inherent risk of planting maize was high. Specifically, this production model can help increase yield and provides stability in the production of second crop maize, given that the area dedicated to maize (67%) can be planted at the ideal time (Nóia Jr. & Sentelhas, 2019). However, this important benefit associated with the adoption of production systems with more diversified plant species in the winter period cannot be confirmed within this study, due to the particular experimental design used.

Wheat–soybean (System II) resulted in an accumulated operating profit similar to the Systems I, VI, VII and VIII, greater than System III (brachiaria ruziziensis–soybean) and lower than Systems IV (single-cultivated brachiaria ruziziensis in 33% and maize in 67% of the area) and System V (maize intercropped with brachiaria ruziziensis in the autumn–winter and soybean in the summer every year; Table 3). Despite the profit from soybean in this model being higher than the profit from soybean in the second crop maize–soybean rotation and similar to the profit obtained in the production systems of maize intercropped with brachiaria ruziziensis on 33–50% of the area, the economic return obtained from wheat in the winter period was lower than that from maize. In addition to the historically low prices paid for wheat, the low operating profit of the crop is associated with its low yield (an average of 3,420 kg ha^{-1} for all years), largely explained by the climatic conditions of the region (low altitude and high temperatures during the winter), which are less favorable for wheat. However, we note that the performance of soybean following wheat was generally better than that following second crop maize (Figure 2), which combined with the weed suppression provided by better soil cover, renders wheat a valuable crop to use in production systems to alternate with second-crop wheat and cover crops.

The gross margin indicates both a willingness to cover fixed costs and an entrepreneurial capacity of the land owner, and is an economic indicator that can represent the inherent risk of the agricultural business since it presents the share of return on invested capital (Goplen et al., 2018). In this case, the use of brachiaria ruziziensis as a cover crop and soybean presented the highest gross margin since it implies a lower operating cost due to the absence of second-crop maize in the production system. Among the systems that included the production of second crop maize, the R-S-M-S-M-S production system (IV) presented the highest gross margin and therefore, the lowest risk.

4 | CONCLUSIONS

The diversified crop rotation systems increased profitability. Diversified crop rotation systems increase crop yields and profit compared with the maize–soybean system. Two alternatives for diversifying production systems involving soybean include (a) the substitution of maize in winter for brachiaria ruziziensis every 3 yr; and (b) the intercropping of maize with brachiaria ruziziensis in winter. These production systems presented a higher profit, and furthermore, did not require major changes to equipment or increases in labor.

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