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Production and profitability of crop rotation systems in southern Brazil

Produção e rentabilidade de sistemas de rotação de culturas no sul do Brasil

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Highlights:
Most diversified crop rotation systems increase yield and profitability.
Diversified crop rotation systems using common bean and maize during the summer increase profitability.
The addition of cover crops enhances crop rotation system potential and improves yield.

Abstract

Crop rotation is one of the pillars of conservation agriculture. This practice has offered a series of advantages in terms of improving soil physical, chemical, and biological conditions. These advantages result in yield increases for all economic crops involved in the rotation systems and may also reduce production costs. In this context, the aim of this study was to compare the profitability of crop rotation systems with different levels of crop diversification. The experimental design was randomized blocks, with five treatments and four replications. The treatments included one less diversified crop rotation system (control) with soybean and wheat and four more diversified crop rotation systems (involving three or more species), including soybean, wheat, black oats, maize, canola, barley, blue lupine, white oats, beans, radish, triticale, rye, hairy vetch, and sorghum, under no-tillage conducted during a three-year cycle. Analyses were conducted considering productivity, operating cost, and economic profit. The highest accumulated gross yields were obtained in the more diversified crop rotation systems. The results show that the more diversified crop rotation systems were more profitable. When the opportunity cost was included, the most diversified crop rotations presented greater economic feasibility. The less diversified crop rotation system presented a negative economic profit. The crop rotation systems including beans presented the highest economic profit.
Key words: Conservation agriculture. No-tillage. Cover crops. Soil conservation. Sustainable agriculture.

Resumo

A rotação de culturas é um dos pilares da agricultura de conservacionista. Esta prática tem uma série de vantagens, melhorando as condições físicas, químicas e biológicas do solo. Isto resulta em aumentos de produtividade de todas as culturas econômicas envolvidas nos sistemas de rotação, podendo também

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reduzir os custos de produção. Neste contexto, o objetivo deste estudo foi comparar a rentabilidade dos sistemas de rotação de culturas com diferentes níveis de diversificação. O desenho experimental foi de blocos ao acaso, com cinco tratamentos e quatro repetições. Os tratamentos foram compostos de um sistema de rotação de culturas pouco diversificado (controle), com trigo no inverno, seguido de soja no verão, e quatro sistemas de rotação de culturas diversificados (envolvendo três ou mais espécies), incluindo soja, trigo, aveia preta, milho, canola, cevada, tremoço azul, aveia branca, feijão, rabanete, triticale, centeio, ervilhaca peluda, sorgo e trigo mourisco, conduzido em plantio direto, por um ciclo de três anos. Para as análises foram considerados a produtividade, a receita, o custo operacional, a margem bruta e o lucro econômico. Os maiores rendimentos brutos foram obtidos em sistemas de rotação de culturas mais diversificados. Os resultados mostram que sistemas mais diversificados de rotação de culturas são mais rentáveis e economicamente mais vantajosos. Quando considerado o custo de oportunidade, apenas as rotações de culturas mais diversificadas apresentaram viabilidade econômica. O sistema de rotação de culturas menos diversificado não apresentou lucro econômico. Os sistemas de rotação de culturas que incluíam o feijão foram os apresentaram o melhor desempenho econômico.
Palavras-chave: Agricultura conservacionista. Plantio direto. Plantas de cobertura.

Introduction

Diversified crop rotation systems positively influence the chemical, physical, and biological attributes of soil, which vary according to the choice of crop species, sequence of crops adopted, period of resistance of vegetal residues and their effects on the soil (Li et al., 2019; Sánchez-Navarro, Zornoza, Faz, & Fernández, 2019). This type of system also changes the dynamics of pests, diseases, weeds, and nematodes in the system and, consequently, affects development of the crops (Weisberger, Nichols, & Liebman, 2019). On the other hand, systems that are repeated over several years can contribute to the development of diseases, pests and weeds as well as soil degradation, resulting in reduced productivity (San Martín, Long, Gourlie, & Barroso, 2019; Jat et al., 2019). In addition, the poor diversification generated by less diversified crop systems accompanied by the seasonality and uncertainties inherent to the agriculture market increases the risk from an economic point of view.

Thus, management systems with greater biodiversity and crop rotation under no-tillage conditions have been recognized as a necessary means for the successful development of sustainable agriculture (Bowman & Zilberman, 2013). Furthermore, several studies have demonstrated the beneficial effects of crop rotation on both soil conditions and the production of subsequent crops (Lin, 2011). Although the agronomic benefits of crop rotation in no-tillage systems are widely reported in the literature (Scopel et al., 2013; Nunes, van Es, Schindelbeck, Ristow, & Ryan, 2018; Hunt, Hill, & Liebman, 2019), studies that address the economic advantages of its adoption are incipient (Gentry, Ruffo, & Below, 2012; Grassini, Torrion, Gassman, Yang, & Specht, 2014; Al-Kaisi, Archontoulis, Kwaw-Mensah, & Miguez, 2015; Al-Kaisi, Archontoulis, & Kwaw-Mensah, 2016), especially in Brazil (Santos, Ambrosi, Ignaczak, & Sandini, 1996; Leal, Lazarini, Tarsitano, Sá, & Gomes, 2005; Volsi, Bordin, Higashi, & Telles, 2020). Thus, it is hypothesized that more diversified crop rotation systems are economically more advantageous than less diversified systems.

The species used for crop rotation must be capable of recovering the soil and, in addition, have commercial value. Therefore, farmers always choose the best cultivation system among the technically viable alternatives, and from an economic point of view, farmers seek to increase the profitability of the property (Abreu et al., 2016). Regarding cost analysis, a farmer is primarily a decision maker and often makes decisions intuitively, seeking to select the best input allocation among the various processes and productive resources (Menegatti & Barros, 2007). In this context, to help this decision making, the aim of this study was to compare the profitability between crop rotation systems under no-tillage with different levels of species diversification.

Material and Methods

This study was carried out at the experimental station of the Agricultural Research Institute of Paraná State, in municipality Ponta Grossa, state of Paraná, Brazil (25°07'32"S, 50°03'37"W), at an altitude of approximately 922 m. The soil is classified as a Latossolo Vermelho Distrófico with sandy clay loam texture (Santos et al., 2018), corresponding to Oxisol according to the United States Department of Agriculture – USDA (1999) derived from reworked sandstone material from the Ponta Grossa formation, a sediment from the Devonian period.

The climate of the region, according to Köppen's classification system, is Cfb, subtropical humid, with an average annual temperature of 18°C and an average annual precipitation of 1550 mm. The monthly precipitation totals (mm) and average temperature (°C) during the period in which the experiment was conducted are presented in Figure 1.

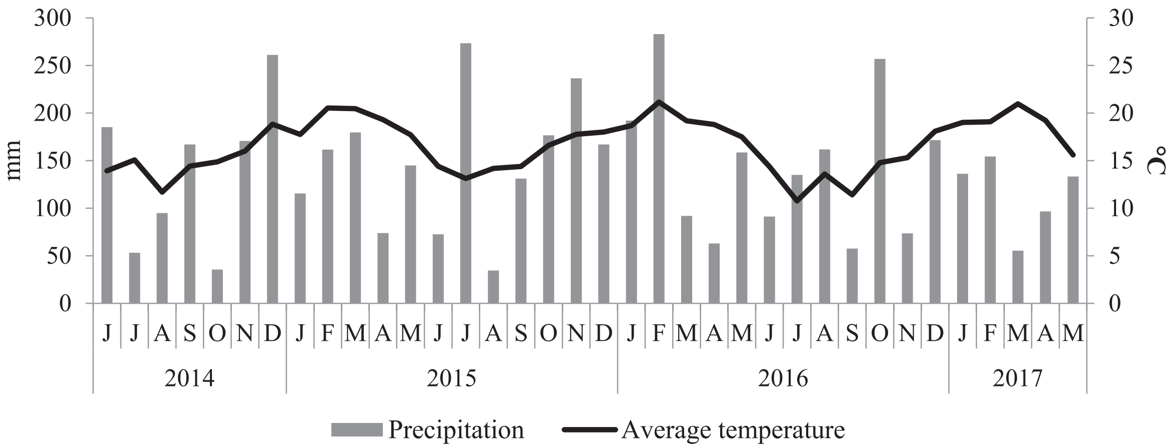

Figure 1. Monthly precipitation (mm) and average temperature (°C) during the period in which the experiment was conducted in Ponta Grossa, PR.

The experimental design was randomized blocks, with five treatments and four replications. The treatments consisted of one less diversified crop rotation system (involving two species) and four more diversified crop rotation systems (involving three or more species), conducted in no-tillage on a three-year cycle, as presented in Table 1.

Before the installation of the experiment, for four years the area was cultivated under no-tillage system, with black oats (*Avena strigosa*) plus ryegrass (*Lolium multiflorum Lam.*) in the winter for animal grazing and, alternately, maize *(Zea mays)* and soybean *(Glycine max L.)* in the summer.

The total area of the experiment was approximately 1.5 ha, with plots that are 10 m wide and 30 m long. Before installation of the crop rotation systems, soil acidity was corrected with 2.0 t ha^{-1} of dolomitic limestone, according to the soil analysis. Between May and June 2014, the winter crops described in Table 1 were sown.

For the economic analysis, all values of services and inputs used in each crop rotation system were considered, as well as the return on capital invested in expenses and land, which are indicators for the analysis of opportunity cost. Therefore, opportunity cost is based on the expression of the basic relationship between scarcity and choice (Jouan, Ridier, & Carof, 2019). According to Kay, Edwards and Duffy (2014), the opportunity cost can be defined in two ways: (i) the income that could have been obtained by selling or renting the input to another person or (ii) the additional income that the producer would have received if the input had been used in its most profitable alternative use, such as leasing the land or capital.

Table 1
Crop rotation systems for the 2014/15 to 2016/17 crop years

Crop rotation system	Crop year	Season	Crop
I	2014/15	Winter	Wheat [*Triticum aestivum*]
		Summer	Soybean [*Glycine max*]
	2015/16	Winter	Wheat
		Summer	Soybean
	2016/17	Winter	Wheat
		Summer	Soybean
II	2014/15	Winter	Wheat
		Summer	Soybean
	2015/16	Winter	Black aot [*Avena strigosa*]
		Summer	Maize [Zea mays]
	2016/17	Winter	Wheat
		Summer	Soybean
III	2014/15	Winter	Wheat
		Summer	Soybean
	2015/16	Winter	Canola [*Brassica napus* L.]
		Summer	Maize
	2016/17	Winter	Barley [*Hordeum vulgare*]
		Summer	Soybean
IV	2014/15	Winter	Black aot + Rye [*Secale cereale*] + Hairy vetch [*Vicia villosa*]
		Summer	Common bean [*Phaseolus vulgaris*] / Sorghum [*Sorghum bicolor*]
	2015/16	Winter	Black aot + Hairy vetch + Radish [*Raphanus sativus* L.]
		Summer	Maize
	2016/17	Winter	Triticale [*Triticosecale* Wittmack] + Black aot + Rye
		Summer	Soybean
V	2014/15	Winter	Blue lupine + Black aot
		Summer	Maize
	2015/16	Winter	White oat [*Avena sativa*]
		Summer	Common bean / Radish
	2016/17	Winter	Triticale
		Summer	Soybean

For the calculation of the opportunity cost, the investment in the savings account was considered, with an interest rate of 7.5% per year. This rate was calculated considering the annual savings rate in each of the three years studied (6.56% in 2014, 8.78% in 2015 and 8.48% in 2016), with an average of approximately 7.5% per year. The choice of savings rate as a parameter of opportunity cost is due to the lower investment risk and greater knowledge and ease of investment for the farmer.

Operating costs incurred in the production process were considered in the analysis (Al-Kaisi et al., 2015; Golpen et al., 2018; Volsi et al., 2020). To calculate the cost of sowing, spraying, and harvesting, as well as labor, we used the technical coefficients of the station where the experiment was conducted. The values of the agricultural operations (manual and mechanical) and the inputs used were extrapolated to hectares. The variables included in the operating cost were inputs, agricultural operations and other costs, which included insurance, financial costs (interest), external transportation, charges, and taxes.

To conduct an economic analysis that was representative of the region where the study was developed and to provide information that allowed the planning and control of future operations, costs for each crop rotation system were carefully recorded to avoid distorting data that may serve as the basis for decision making and for analyzing the efficiency of the activities. Thus, to obtain the costs of both agricultural operations and inputs, the average values paid and received by the producers in July 2014, 2015, and 2016 were obtained based on information from a survey conducted at three cooperatives or companies in the Ponta Grossa region.

The economic net return of each crop rotation system was determined by monitoring all inputs and products used during the three years. The net income and economic profit were used as gain indicators for each crop rotation system. Net income was calculated by subtracting gross revenue by operating cost. Economic profit was calculated by subtracting gross revenue from total cost. Total cost includes factorial compensation indicative of opportunity cost. The indicated yield was analyzed by weighing the harvested grains in the useful areas of the plots, with the values extrapolated to Mg ha^{-1} and corrected to 13% humidity.

Data were stored in electronic spreadsheets in which calculations were performed. All economic and monetary indicators were corrected by the Broad Consumer Price Index (IPCA), which is Brazil's official inflation index, for real values as of June 2018 and transformed into dollars (US$) for the same period.

Results and Discussion

Table 2 presents the productivity results of the five crop rotation systems for the 2014/2015, 2015/2016, and 2016/2017 harvests, indicated as year 1, year 2 and year 3, respectively. It was confirmed that for the soybean crop, the highest productivity presented was in crop rotation system I in agricultural year 1 (4.10 Mg ha^{-1}), which was 30.64% higher than the average yield of Paraná (3.14 Mg ha^{-1}) (Instituto Brasileiro de Geografia e Estatística [IBGE], 2017). For wheat, the highest productivity was observed in system III in the year 1 harvest (3.69 Mg ha^{-1}), which was 45.98% higher than the average yield of Paraná (2.52 Mg ha^{-1}) (IBGE, 2017). For maize, the highest productivity was verified in system V in the year 1 harvest (11.44 Mg ha^{-1}), surpassing the state average yield of 8.41 Mg ha^{-1} (IBGE, 2017) by 36.01%.

When only the summer year 3 harvest was observed, in which all crop rotation systems were sown with soybean crops, among the systems, system II had the highest productivity (3.93 Mg ha^{-1}), which was 25% above the average yield of the state of Paraná. According to Santos et al. (2014), when considering the average yield of soybean in the crop rotation system with maize compared with the verified less diversified crop rotation system with wheat, the accumulated gain in yield corresponded to approximately 17%. Therefore, the higher productivity in systems II, III, and IV may have been linked to the break in the wheat/soybean cycle by planting maize in the summer in the second year.

Table 2
Productivity and gross income of the crops involved in the crop rotation systems for the 2014/15 to 2016/17 crop years

Crop rotation system	Crop year	Season	†Crop	Crop yield	Gross income
				– Mg ha^{-1} –	– US$ ha^{-1} –
I	2014/15	Winter	W	3.55	620.13
		Summer	S	2.22	773.44
	2015/16	Winter	W	2.08	384.49
		Summer	S	4.10	1305.05
	2016/17	Winter	W	2.69	458.21
		Summer	S	3.69	1,043.34
II	2014/15	Winter	W	3.58	626.93
		Summer	S	2.42	841.73
	2015/16	Winter	BO	‡ –	‡ –
		Summer	M	9.97	1,707.97
	2016/17	Winter	W	3.24	550.63
		Summer	S	3.93	1,114.26
III	2014/15	Winter	W	3.69	645.32
		Summer	S	2.46	855.32
	2015/16	Winter	CNL	1.49	498.26
		Summer	M	9.02	1,713.50
	2016/17	Winter	BL	3.67	656.79
		Summer	S	3.77	1,066.80
IV	2014/15	Winter	BO + RY + HV	–	–
		Summer	B / SG	2.66 / 1.71	2,360.39
	2015/16	Winter	BO + HV + RD	–	–
		Summer	M	10.60	1,816.23
	2016/17	Winter	TRT + BO + RY	–	–
		Summer	S	3.81	1,076.68
V	2014/15	Winter	BLP + BO	–	–
		Summer	M	11.44	1,576.27
	2015/16	Winter	WO	–	–
		Summer	B / RD	3.06 / –	2,757.45
	2016/17	Winter	TRT	4.28	455.39
		Summer	S	3.68	1,041.07

† B, common bean; BLP, blue lupine; BL, barley; BO, black oat; CNL, canola; HV, hairy vetch; M, maize; RD, radish; RY, rye; S, soybean; SG, sorghum; TRT, triticale; W, wheat; and WO, white oat. ‡ No grain harvest.

Table 2 also shows the gross income for each agricultural year and the accumulated gross income of the different crop rotation systems for the 3 rotation year harvests. From the analysis of the gross income, the systems with crop rotations obtained higher gross incomes. The less diversified crop system had the lowest accumulated gross incomes at US$ 4,584.67, although it included important commercial crops for the region in both summer and winter. However, when a less diversified crop rotation is implemented continuously over the years, it can cause reductions in productivity, mainly by changes in soil characteristics and increases in the incidence of pests and diseases (Ghorbani, Wilcockson, Koocheki, & Leifert, 2009).

In relation to crop rotation systems II and III, both used the same summer crops and differed only in the winter crops. Of these two systems, crop rotation system III presented the best result, with an accumulated gross income of US$ 5,435.99. It is worth noting that crop rotation system III was also the only system that commercialized all its harvests, i.e., had cash crops in all winters and summers. It represents important commercial crops of the region, but there was no practice of continuous cultivation of the same crops, which led to a break in the cycle of pests and diseases (Ghorbani et al., 2009; Marcelo, Cora, & Fernandes, 2012), in addition to improvements in soil fertility due to use of different crops. On the other hand, the less diversified system also had cash crops in all winters and summers but presented no diversification, leading to the lowest results.

The winter crops used in crop rotation system IV are not commercializable. However, this system had the greatest diversification of crops, whether the crops were intercropped or not, and its accumulated gross income was US$ 5,253.31, which was 14.58% higher than the gross income from the less diversified crop system. Although these non-commercial winter cover crops did not result in commercial gain, they provide an indirect gain by improving soil productive capacity (Blanco-Canqui, Mikha, Presley, & Claassen, 2011). These results show that high diversification of crops result in not only agronomic benefits but also economic benefits. On the other hand, there was an increase in dependence and risk for summer crops.

Crop rotation system V presented the best accumulated result over the three agricultural years, at US$ 5,830.18, or 27.17% higher than that of the less diversified crop system. The high maize productivity in the summer of 2014/15, the high price paid to the producer by the common bean in 2015/16, and the soybean gross income in 2016/17 showed that it is possible to achieve high gross incomes in more diversified systems. Additionally, an increase in gross income was observed when maize was included in the crop rotation systems, without increasing production costs, achieving superior profitability to that of the monoculture, in which successive soybean crops predominated in the summer.

In summary, the best revenues were obtained through the practice of crop rotation, diverging from the wheat/soybean system. However, it should be noted that the success of crop rotation analyzed by means of gross income is linked to a period of high prices, with the seasonal issues as the decisive factor. Another analysis that needs to be conducted is to consider the economic relations in production prices, which was not considered here due to the agronomic character of the article. Thus, only the agronomic characteristics that influence production are discussed. The best option for the producer should be determined later based on an analysis of economic profit.

Table 3 presents the operating cost per hectare for each crop rotation system for the three agricultural years. In general, in comparison to the winter crops, the summer crops presented a higher operating cost. Crop rotation system I presented the highest average variable cost in the winter (US$ 682.39) and the lowest in the summer (US$ 676.35). On average, the costs of producing both winter and summer crops were similar in the less diversified crop system, which can be an issue since winter crops usually have lower yields due to climatic factors (Morrison et al., 2017).

In relation to input costs, fertilizers had the highest percentage cost, generally varying between 28% and 70%, with the exception of canola (*Brassica napus*) that reached 91%, while insecticides and adjuvants presented the lowest costs that did not exceed 2%. In Menegatti and Barros (2007), costs ranged from 49% to 54% for fertilizers and from 5% to 6% for insecticides. According to Zegada-Lizarazu and Monti (2011), when crop rotation is well planned, there is a reduction in the dependence on external inputs due to the cycling of nutrients and the increase in cycle efficiency. Because of the short period of only three years of the crop rotation systems in this study, it was not possible to observe a reduction in the dependence on external inputs.

Table 4 presents the net profit results of the crop rotation systems in annual values. Crop rotation system I, which was less diversified than the other systems, had the lowest accumulated net income of US$ 508.46. A part of this result is explained by the high fertilizer costs in the winter of 2015/16, which led to a negative net profit, therefore indicating harm to the producer.

Table 3
Operating costs of the crop rotation systems for the 2014/15 to 2016/17 crop years

Crop rotation system	Indicator	2014/2015		2015/2016		2016/2017		Average		Accumulated
		Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	
		US$ ha⁻¹								
I		†W	S	W	S	W	S			
	Operating cost	586.89	674.25	882.26	727.86	578.01	626.92	682.39	676.35	4,076.20
	Inputs	316.96	301.65	531.30	306.91	285.94	302.98	378.07	303.85	2,045.75
	Operating expenses	187.21	272.41	222.02	266.36	197.98	198.59	202.40	245.78	1,344.57
	Other costs	82.72	100.19	128.94	154.59	94.10	125.35	101.92	126.71	685.90
II		W	S	BO	M	W	S			
	Operating cost	601.43	697.58	177.28	810.96	593.83	652.56	457.51	720.37	3,533.65
	Inputs	328.39	316.06	56.52	402.21	285.79	302.83	223.57	340.37	1,691.80
	Operating expenses	188.70	276.94	97.61	224.46	207.76	218.27	164.69	239.89	1,213.74
	Other costs	84.34	104.58	23.15	184.29	100.27	131.47	69.25	140.11	628.11
III		W	S	CNL	M	BL	S			
	Operating cost	603.50	699.31	521.57	817.75	636.15	647.51	587.07	721.52	3,925.79
	Inputs	328.39	316.06	291.09	402.21	310.11	302.83	309.86	340.37	1,950.69
	Operating expenses	189.72	277.84	141.51	229.78	215.66	215.73	182.29	241.12	1,270.24
	Other costs	85.39	105.40	88.97	185.76	110.39	128.96	94.92	140.04	704.87
IV		BO+RY+HV	B/SG	BO+HV+RD	M	TRT+BO+RY	S			
	Operating cost	205.39	1,366.57	218.62	823.65	130.00	648.68	184.67	946.30	3,392.92
	Inputs	104.87	739.77	92.69	402.21	39.26	302.83	78.94	481.60	1,681.62
	Operating expenses	81.14	390.48	97.61	230.37	73.51	216.32	84.09	279.06	1,089.44
	Other costs	19.38	236.32	28.32	191.07	17.23	129.54	21.64	185.64	621.86
V		BLP+BO	M	WO	B/RD	TRT	S			
	Operating cost	177.49	860.90	249.45	1,580.12	581.04	644.47	335.99	1,028.50	4,093.47
	Inputs	79.46	459.41	119.65	806.42	260.18	302.83	153.10	522.89	2,027.96
	Operating expenses	81.14	246.33	97.61	445.66	226.51	214.20	135.09	302.06	1,311.45
	Other costs	16.89	155.16	32.18	328.04	94.35	127.45	47.81	203.55	754.07

† B, common bean; BLP, blue lupine; BL, barley; BO, black oat; CNL, canola; HV, hairy vetch; M, maize; RD, radish; RY, rye; S, soybean; SG, sorghum; TRT, triticale; W, wheat; and WO, white oat.

Table 4
Net farm income of the crop rotation systems for the 2014/15 to 2016/17 crop years

Crop rotation system	Crop year	Season	† Crop	Net profit
				–– US$ ha^{-1} ––
I	2014/15	Winter	W	33.24
		Summer	S	99.18
	2015/16	Winter	W	-497.77
		Summer	S	577.19
	2016/17	Winter	W	-119.80
		Summer	S	416.42
			Accumulated	508.46
II	2014/15	Winter	W	25.51
		Summer	S	144.15
	2015/16	Winter	BO	-177.28
		Summer	M	897.00
	2016/17	Winter	W	-43.20
		Summer	S	461.70
			Accumulated	1,307.87
III	2014/15	Winter	W	41.83
		Summer	S	156.01
	2015/16	Winter	CNL	-23.31
		Summer	M	895.75
	2016/17	Winter	BL	20.64
		Summer	S	419.28
			Accumulated	1,510.20
IV	2014/15	Winter	BO + RY + HV	-205.39
		Summer	B / SG	993.82
	2015/16	Winter	BO + HV + RD	-218.62
		Summer	M	992.59
	2016/17	Winter	TRT + BO + RY	-130.00
		Summer	S	428.00
			Accumulated	1,860.39
V	2014/15	Winter	BLP + BO	-177.49
		Summer	M	715.37
	2015/16	Winter	WO	-249.45
		Summer	B / RD	1,177.33
	2016/17	Winter	TRT	-125.66
		Summer	S	396.60
			Accumulated	1,736.71

† B, common bean; BLP, blue lupine; BL, barley; BO, black oat; CNL, canola; HV, hairy vetch; M, maize; RD, radish; RY, rye; S, soybean; SG, sorghum; TRT, triticale; W, wheat; and WO, white oat.

In general, System I did not reach the profit levels of the other systems, although the soybean profit margin of the summer compensated for the wheat profit margin of the winter crops. Crop rotation systems II and III reached net profit levels above US$ 1,300.00 with the same summer crops, two years of soybean and one year of maize. However, the highest accumulated net profit was obtained by System III at US$ 1,510.20, which was different from that in System II, as it obtained two years of positive profits in the winter as a result of the planting of different commercial crops. Crop rotation systems IV and V obtained net profits of US$ 1,860.39 and US$ 1,736.71, respectively, with soybean crops only in the last year. These systems had greater diversification of crops, demonstrating that diversification is an essential factor for the reduction of financial risk (Hauk, Gandorfer, Wittkopf, Müller, & Knoke, 2017).

In summary, the crop rotation systems that obtained positive net profits were those that used crop rotations with greater diversification, diverging from the wheat/soybean crop system. It was also observed that as the inclusion of soybean in the system decreased, the gross margin increased.

Table 5 presents the results of profitability for the crop rotation systems of each system. For the profitability analysis, we considered the opportunity cost, referred to here as the remuneration of factors, including land plus costs. The addition of factor remuneration to the total cost, i.e., the combination of operating cost plus opportunity cost, led to an average 37% increase in costs. The largest fraction came from the land lease, estimated at 1,500 kg per hectare for the municipality of Ponta Grossa. It is uncommon in the literature to calculate the costs of working capital and land remuneration (Ferreira, Freitas, & Moreira, 2015; Ustaoglu, Castillo, Jacobs-Crisioni, & Lavalle, 2016), but this is a necessary component for a cohesive analysis of crop rotation systems.

Regarding the economic profitability of crop rotation systems in the three-year period, System IV presented the highest accumulated economic profit of US$ 570.45 per hectare, followed by crop rotation systems V, III, II and I, with accumulated values per hectare of US$ 404.15, US$ 186.52, US$ 7.85 and US$ -827.92, respectively. It is also worth noting that despite the lack of commercial crops in the winter, the systems were considered viable even with the presence of land cover crops and therefore without economic return, possibly due to increased nutrient cycling (Leal et al., 2005) that favored summer crops.

Crop rotation system I was considered economically unviable, showing that less diversified crop systems are disadvantageous, in not only agronomic terms but also economic terms. The importance of crop rotation as a viable alternative, which allows greater diversification of crops for the region in question, was verified. Mello and Esperancini (2015) also verified that crop rotation is economically positive in comparison with less diversified crop systems, reinforcing the importance of this practice.

Thus, to achieve greater productive capacity in crop rotation systems, planning should preferably consider commercial crops, associating whenever possible with species of cover crops adapted to the region. These crops develop quickly, produce a large amount of dry matter, and can be grown alone or intercropped with other crops, thus contributing to the balance of the system (Bolliger et al., 2006).

Table 5
Economic profits of the crop rotation systems for the 2014/15 to 2016/17 crop years

Crop rotation system	Crop year	†Crops	Gross farm income	Operating cost	Net income	Opportunity cost	Economic profit
			US$ ha^{-1}				
I	2014/15	W-S	1,393.57	1,261.15	132.42	465.61	-333.18
	2015/16	W-S	1,689.54	1,610.12	79.42	485.40	-405.98
	2016/17	W-S	1,501.55	1,204.93	296.62	385.38	-88.76
		Average	1,528.22	1,358.73	169.49	445.46	-275.97
		Accumulated	4,584.67	4,076.20	508.46	1,336.38	-827.92
II	2014/15	W-S	1,468.67	1,299.01	169.66	468.00	-298.35
	2015/16	BO-M	1,707.97	988.24	719.73	444.46	275.26
	2016/17	W-S	1,664.89	1,246.39	418.5	387.57	30.93
		Average	1,613.84	1,177.88	435.96	433.34	2.62
		Accumulated	4,841.52	3,533.65	1,307.87	1,300.02	7.85
III	2014/15	W-S	1,500.64	1,302.81	197.83	468.14	-270.30
	2015/16	CNL-M	2,211.75	1,339.32	872.43	465.74	406.69
	2016/17	BL-S	1,723.59	1,283.66	439.93	389.79	50.13
		Average	1,812.00	1,308.60	503.40	441.23	62.17
		Accumulated	5,435.99	3,925.79	1,510.19	1,323.68	186.52
IV	2014/15	BO+RY+HV-B/SG	2,360.39	1,571.96	788.43	483.46	304.97
	2015/16	BO+HV+RD-M	1,816.23	1,042.27	773.96	447.62	326.34
	2016/17	TRT+BO+RY-S	1,076.68	778.69	297.99	358.86	-60.86
		Average	1,751.10	1,130.97	620.13	429.98	190.15
		Accumulated	5,253.31	3,392.92	1,860.38	1,289.94	570.45
V	2014/15	BLP+BO-M	1,576.27	1,038.39	537.88	449.72	88.16
	2015/16	WO-B/RD	2,757.45	1,829.56	927.89	496.10	431.78
	2016/17	TRT-S	1,496.46	1,225.51	270.95	386.75	-115.80
		Average	1,943.39	1,364.49	578.91	444.19	134.72
		Accumulated	5,830.18	4,093.47	1,736.72	1,332.56	404.15

† B, common bean; BLP, blue lupine; BL, barley; BO, black oat; CNL, canola; HV, hairy vetch; M, maize; RD, radish; RY, rye; S, soybean; SG, sorghum; TRT, triticale; W, wheat; and WO, white oat.

Conclusions

The most diversified crop rotation systems increase yield and profitability. The use of cover crops during the winter and commercial crops during the summer increases the profitability of the crop rotation system, particularly when planting common beans and corn during the summer. Diversification in crop rotation is economically advantageous and improves farm sustainability.

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