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ORIGINAL PAPER

Residue incorporation in biannual rotations of bean-corn and canola-corn affects soil chemical properties and corn yield*

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Abstract

Residue incorporation is not a common practice in many production systems in areas with a Mediterranean climate. The aim of the research was to study the effect of residue incorporation levels of three cycles of two biannual rotations on corn yield and chemical properties of soil after six years. An experiment was conducted with two biannual rotations (canola-corn and bean-corn) and four residue incorporation levels (0%, 50%, 100%, and 200%) in a Chilean Andisol (Melanoxerand). Corn grain yield and residue production were evaluated during three cycles of crop rotation, and the soil's chemical properties were evaluated at the end of the evaluation round. The experimental design was a split plot, in which the main plot was the previous crop (two crops) and the split plot was the residue level (four levels). The results showed that the highest corn grain yield was obtained in the first evaluation season ($p<0.05$), when the average yield for both rotations was 10.1% higher than the average yield obtained in the third season. On the other hand, the average residue production of the first two seasons was 15.2% higher than that obtained in the third season ($p<0.05$). Chemical properties of the soil were affected by a rotation, with an increase in pH in the bean-corn rotation after bean cultivation, and an increase in both exchangeable Al and available S in the canola-corn and bean-corn rotations after canola. On the other hand, the use of increasing doses of residue enabled a consistent increase in the content of both organic matter and exchangeable K in the soil, and partially the available P in soil. The concentration of exchangeable Ca was increased with an increasing dose of residue only in the rotation with canola. Finally, this work allows us to conclude that continuous incorporation of the residues produced within the biannual rotations evaluated in this volcanic soil contributes to improvement of the soil's chemical properties, without affecting the corn crop yield.

Keywords: biannual crop rotations, crop rotations, grain yield, conservation agriculture, residue incorporation

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INTRODUCTION

Conservation agriculture that practices crop rotation demonstrates conservation and improvement of soil fertility and crop productivity, incorporation of sustainable management practices, improvement of the sanitary condition of the plants and better fertilizer efficiency (Basso et al. 2019, Grahmann et al. 2020, Melander et al. 2020, Taveira et al. 2020, Fang et al. 2021, Passaris et al. 2021, Sainju et al. 2021, Sietz et al. 2021). Paterson et al. (2021) exposes that the organic carbon sequestered in soil within an agroecosystem that uses residue incorporation contributes to the mitigation of effects of climate change by reducing atmospheric CO_2, hence crops that generate large amounts of residues, such as corn, could help to increase carbon sequestration. On the other hand, the residue incorporation increases soil fertility and aggregate stability, and improves gas exchange and nutrient and water cycling in the soil (Khakbazan et al. 2019, Yang et al. 2019, Behnke et al. 2020). Contrary to crop rotation, including corn crop, a monocrop can increase soil acidity (Behnke et al. 2020) and reduce overall crop yield (Huynh et al. 2019, Scott et al. 2021). The use of legumes in crop rotations has been related to higher nitrogen input (Li et al. 2018, Huynh et al. 2019, Taveira et al. 2020, Song et al. 2021), as well as higher crop yield (Hirzel et al. 2020).

As for the soil's chemical properties, the residue incorporation under crops leads to an increase in the soil organic matter content (Pandiaraj et al. 2015, Basir et al. 2017, Chen et al. 2018, Kumar et al. 2018, Stewart et al. 2018, Urra et al. 2018, Passaris et al. 2021), nitrogen concentration (Pandiaraj et al. 2015, Basir et al. 2017, Kumar et al. 2018, Stewart et al. 2018) phosphorus and sulfur concentrations (Sarker et al. 2019), and lower soil acidity (Basir et al. 2017).

The application of residues on the surface of soil, without incorporation, generates an increase in soil organic carbon in the surface layer, but with less effect deeper into the soil (Stewart et al. 2018, Zhang et al. 2018), therefore, to achieve an increase in soil organic carbon at a greater depth, incorporation of residues is suggested (Pandiaraj et al. 2015, Basir et al. 2017). Higher levels of carbon in soil are followed by a higher biological activity, respiration and generation of acid reaction compounds, which in turn affects soil acidity (Neugschwandtner et al. 2020). Agronomic residue management practices that favor an increase in soil acidity could be a valuable indicator of soil life.

Residue incorporation as a conservation practice has benefits (Khakbazan et al. 2019, Yang et al. 2019, Behnke et al. 2020), although most studies only consider a fraction of the residue produced, with no history of using residues at high doses (equivalent to the total residue production or even higher doses than this), given the uncertainty regarding the effect of these high residue doses on the development of the following crop.

Considering that in many situations the benefits of continued conservation agriculture practices in production systems may appear after several years, medium and long-term evaluations are necessary to detect effects of these practices on crop production or soil properties. In this respect, a long-term study on a volcanic soil in Chile with crop rotations including corn and incorporation of residues has shown little effect on soil chemical properties in only two years (Hirzel et al. 2020).

Furthermore, corn production over a significant area of Latin America does not include crop rotation, in addition to which it eliminates residues. Moreover, there are different types of soils cropped with corn, with a significant share of volcanic soils having a high organic matter content, which may be a reason why farmers do not consider it necessary to add organic matter to the soil. Considering this background, our working hypothesis is that crop rotations with residue incorporation in the medium- to long-term can improve chemical properties of volcanic soils and probably contribute to an increase in corn yield. Our research is innovative because it compares the use of residues beyond those produced by a crop, within a rotation, since greater quantities of residues are applied than what the crops produce within a rotation in order to generate differences and compare the outcome versus the total withdrawal of residues.

The present study analyzed the effect of three cycles of two biannual rotations (bean-corn and canola-corn) with four residue incorporation levels for each crop (0%, 50%, 100% and 200%) on corn yield, and the effect on chemical properties after of six years.

MATERIALS AND METHODS

The experiment was conducted over six consecutive seasons from 2016 to 2022 at the Santa Rosa Experimental Station, INIA-Quilamapu, Chillán, Chile (36°31′ S; 71°54′ W). Soil composition is volcanic (Melanoxerand) with moderate effective depth (0.45 to 0.60 m), and the climate is temperate Mediterranean (hot, dry summer and cold, wet winter).

Precipitation, evaporation, and temp. were recorded throughout the 6 annual periods. The mean precipitation was 605, 563, 730, 460, 576 and 920 mm for the 2016-2017, 2017-2018, 2018-2019, 2019-2020, 2020-2021, and 2021-2022 seasons, respectively, with most rainfalls at the end of winter and beginning of spring. The mean temperature was 12.8, 13.2, 13.5, 13.4, 14.3 and 13.2°C and evaporation was 1023, 1041, 990, 980, 1060, and 966 mm for the 2016-2017, 2017-2018, 2018-2019, 2019-2020, 2020-2021, and 2021-2022 seasons, respectively. The seasons when corn was sown were 2017-2018; 2019-2020, and 2021-2022.

Experiment management

The design of this long-term experiment consisted of biannual rotations with two crop combinations: bean-corn and canola-corn (representative of the irrigated valley agriculture on volcanic soils in Chile) in which residues of the previous crop were incorporated at levels of 0%, 50%, 100%, and 200%; the design was maintained throughout the whole period of the study. The present article focuses on grain yield and residue production of corn as the second crop in each biannual rotation (2017-2018, 2019-2020, and 2021-2022 season), and on the soil chemical properties in the last cycle (year 2022, after six years of crop rotation).

On the first biannual rotation experiment, lime was applied at a dose of 3,000 kg ha^{-1} before sowing canola in April 2016 to correct soil acidity (Table 1). There were two previous crops before corn: 1) canola (*Brassica napus* L.) and 2) bean (*Phaseolus vulgaris* L.).

Table 1

Soil chemical properties at the 0-0.2 m soil depth before initiating the crop rotation experiment (year 2016)

Parameters	Value
Clay (%)	16.7
Silt (%)	44.6
Sand (%)	38.7
Bulk density (g cm^{-3})	1.00
pH$_{\text{(soil:water 1:5)}}$	5.52
Organic matter (g kg^{-1})	109.2
Electrical conductivity (dS m^{-1})	0.11
Available N (mg kg^{-1})	54.1
Olsen P (mg kg^{-1})	21.3
Exchangeable K (cmol$_c$ kg^{-1})	0.54
Exchangeable Ca (cmol$_c$ kg^{-1})	4.20
Exchangeable Mg (cmol$_c$ kg^{-1})	0.36
Exchangeable Na (cmol$_c$ kg^{-1})	0.08
Exchangeable Al (cmol$_c$ kg^{-1})	0.12
Available S (mg kg^{-1})	23.5

The experimental unit for each crop rotation (bean-corn and canola-corn) was a 40 m long and 14 m wide (560 m^2) plot with 0.7, 0.7, and 0.7 m inter-row spacing for bean, canola, and corn crops, respectively, and each plot was divided into four split-plots 20 m long and 7 m wide (140 m^2) for the incorporation of each residue level (0, 50, 100 and 200%). Thus, the total experimental area was 4,480 m^2 and included two crop rotations and four replicates.

Canola in the first rotation cycle was sown on 15 May 2016 and harvested on 5 February 2017. Next it was sown on 25 May 2018 and harvested on 15 January 2019 in the second rotation cycle, whereas in the third season, this plant was sown on 31 August 2020 and harvest on 25 January 2021. Canola cultivars used were 'Eminem-von Baer' in the first two seasons and 'Imminent-SIS' in the third season. This change of a canola hybrid was dictated by the genetic materials used by farmers in the search for more precocity of the crop. The seed dose in each season was 30 kg ha^{-1}. Irrigation was applied at the flowering stage. Total weed control was carried out with the herbicide propisochlor (Proponit 720 EC) at 1.44 kg a.i. ha^{-1}, and disease control was unnecessary. N, P, and K fertilization doses were 160, 53, and 67 kg ha^{-1}, respectively. Both P and K were applied 100% at sowing, while N was applied 50% at sowing and the remaining 50% at the 60% crop cover stage. Fertilizer sources were urea, triple superphosphate, and potassium chloride. In addition, Mg, S, Zn, and B were applied at in amounts of 18:33:4:2 kg ha^{-1} before sowing with magnesium sulfate, zinc sulfate, and calcium borate fertilizers based on soil chemical properties (Table 1).

The bean cultivar 'Zorzal-INIA' was sown on 27 October 2016 and harvested on 28 February 2017 in the first rotation cycle. In second and third rotation cycle, another bean culivar called 'Torcaza-INIA' was grown. It was sown on 27 October 2018 and harvested on 28 February 2019 (second season), and on 10 November 2020 and harvested on 11 March 2021 (third season). The change of a variety was again dictated by the choice of the genetic materials by farmers in the search for higher crop yields. The seed dose was 120 kg ha^{-1} in the three seasons. Irrigation was applied at the flowering stage. Total weed control was carried out with the herbicide fomesafen (Flex: 25%) at 0.25 a.i. ha^{-1} at the first trifoliate leaf, and disease control was unnecessary. The N, P, and K fertilization doses were 60, 26, and 50 kg ha^{-1}, respectively. N, P, and K were applied 100% at sowing, and fertilizer sources were urea, triple superphosphate, and potassium chloride. In addition, Mg, S, Zn, and B were applied at doses of 30:33:4:2 kg ha^{-1} before sowing with magnesium sulfate, zinc sulfate, and calcium borate fertilizers based on soil chemical properties (Table 1).

The corn cultivar 'DK-469' (Dekalb) was sown on 25 October 2017 and harvested on 22 April 2018 in the first rotation cycle. In the second rotation, another corn hybrid chosen, namely 'DK-585' (Dekalb). It was sown on 27 October 2019 and harvested on 15 April 2020 in the second rotation cycle, and then sown on 25 October 2021 and harvested on 4 May 2022 in the third season. The seed dose was 40 kg ha^{-1} in the three seasons. The change of a hybrid is dictated by the genetic materials used by farmers in the search for different alternatives for soils in the cropping area. Irrigation was applied weekly from of the beginning of November until 15 March of each year. Total weed control was carried out with dimethenamid-P (Frontier) at 0.94 kg a.i. ha^{-1} and saflufenacil (Heat) at 84 g a.i. ha^{-1} at the pre-sowing stage, and disease control was unnecessary. Nitrogen, P, and K fertilization doses were 350, 53, and 100 kg ha^{-1}, respectively, based on soil chemical properties (Table 1). Under each of the three crops, P and K were applied 100% at sowing, while N was applied 40% at sowing and 60% at the six-leaf stage, respectively. Fertilizer sources were urea, triple superphosphate, and potassium chloride. Based on the soil chemical analysis (Table 1), Mg, S, Zn, and B were applied at doses of 18:33:4:2 kg ha^{-1} under all crops before sowing, applying magnesium sulfate, zinc sulfate, and calcium borate fertilizers.

Once the three crops were harvested, residues were incorporated at levels of 0%, 50%, 100%, and 200% in the same experimental unit during May of each year. The machinery used to grind and incorporate residues was a displaceable mulcher (Tornado 310, Maschio Gaspardo, Campodarsego, Italy) and a compact disk harrow (Rubin 9, Lemken GmbH and Co. KG, Alpen, Germany), respectively.

Corn yield and residue production

The plots were harvested manually at grain maturity in stage R6 of Ritchie and Hanway scale (Ritchie, Hanway 1982), and threshed with a stationary thresher. Plant samples were collected from a 2.1 m^2 plot area and separated as grain and aerial residue. Grain and tissue samples were oven-dried at 70°C for 72 h.

Soil analysis

Samples from the 0-20 cm soil depth were collected manually for each treatment simultaneously with the harvest of corn crop, at the end of the 2021-2022 growing season (May 2022). Samples were collected from each plot. All samples were air-dried and sieved (2 mm mesh). Soil pH was determined in 1:2.5 soil:water extracts. Soil organic matter was established by Walkley-Black wet digestion (Sadzawka et al. 2006). Soil inorganic N (NO_3-N and NH_4-N) was extracted with 2 M KCl and determined by colorimetry with a segmented flux spectrophotometer (autoanalyzer, Skalar Analytical BV, Breda, The Netherlands). Soil extractable P was 0.5 M $NaHCO_3$ (Olsen P) by the molybdate-ascorbic acid method. Exchangeable Ca, Mg, K, and Na were determined by 1 M NH_4OAc extraction followed by flame spectroscopy: absorption (Ca and Mg) and emission (K and Na). Soil exchangeable Al concentration was obtained with 1 M KCl extraction by absorption spectroscopy. Sulfur (SO_4^{2-}) was determined with calcium phosphate 0.01 M and turbidimetry.

Experimental design and statistical analysis

The experimental design was a split plot in which the main plot was the previous crop (two crops) and the split plot was the residue level (four levels) with four replicates. Grain yield and residue production of the corn crop was analyzed as an effect of each two-year rotation (3 cycles), while soil chemical properties were analyzed at the end of the three rotation cycles. Results were analyzed by ANOVA and Tukey's test ($p=0.05$) using the SAS Proc Mixed Model procedure (SAS Institute, Cary, North Carolina, USA). For the significant interactions, contrast analysis was used to compare the treatment effects separately ($p=0.05$).

RESULTS

The analysis of the significance of results revealed that grain yield was only influenced by the evaluation year ($p<0.01$), whereas residue production was impacted by the interaction of evaluation year and crop rotation ($p<0.01$). Additionally, the level of incorporated residue demonstrated a 7% significance in its effect on corn residue production (Table 2).

Table 2

Significance testing (*p*-values) for the corn yield and residue production as affected by two crop rotations with four residue incorporation levels

Source of variation	Grain yield	Residue production
Year (Y)	< 0.01	< 0.01
Crop Rotation (CR)	0.17	< 0.01
Residue Level (RL)	0.29	0.07
Interaction Y × CR	0.85	< 0.01
Interaction Y × RL	0.96	0.62
Interaction CR × RL	0.59	0.11
Interaction Y × CR × RL	0.82	0.79

The highest grain yield was obtained in the first evaluation season ($p<0.05$), whose average for both rotations was 10.1% higher than the yield obtained as the average for the third season (Figure 1). On the other hand, the average residue production of the first two seasons was 15.2% higher than that obtained in the third season ($p<0.05$) – Figure 2. The interaction detected for residue production between crop rotation and the level of residue incorporation was observed in the third evaluation season, when corn residue production was 25.7% higher after canola than after bean ($p<0.05$) – Figure 2.

The chemical properties of the soil analyzed at the end of the three biannual crop rotation cycles indicated that the crop rotation affected soil pH and the concentrations of Na, Al ($p<0.01$) and S ($p<0.05$), while the residue level affected soil organic matter content ($p<0.05$) and the concentrations of P and K ($p<0.01$) – Table 3. The crop rotation and residue level interaction affected

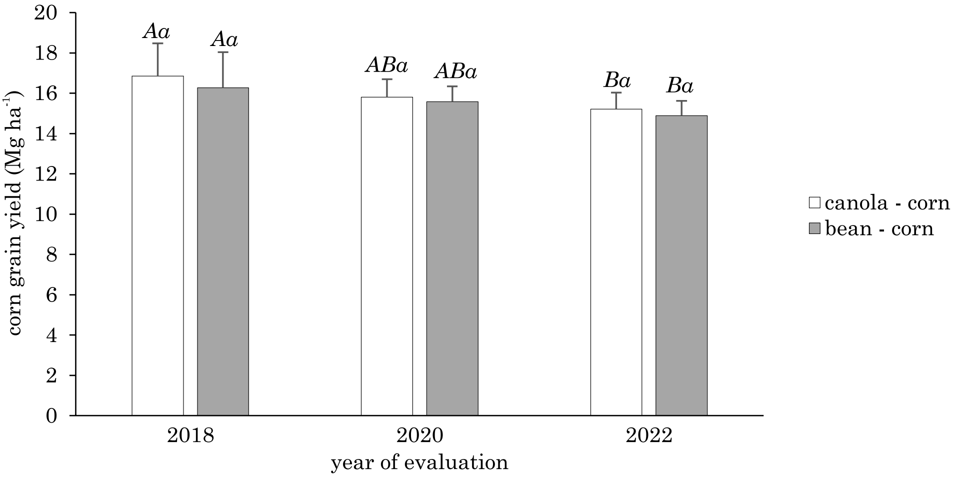

Fig. 1. Corn grain yield during three cycles of two biannual crop rotations (after of canola or bean). Different capital letters above the bars indicate differences between evaluation years, and different lowercase letter above the bars in the same evaluation year indicate difference between crop rotation according to the Tukey's test (p<0.05). Whiskers correspond to the standard error for each bar

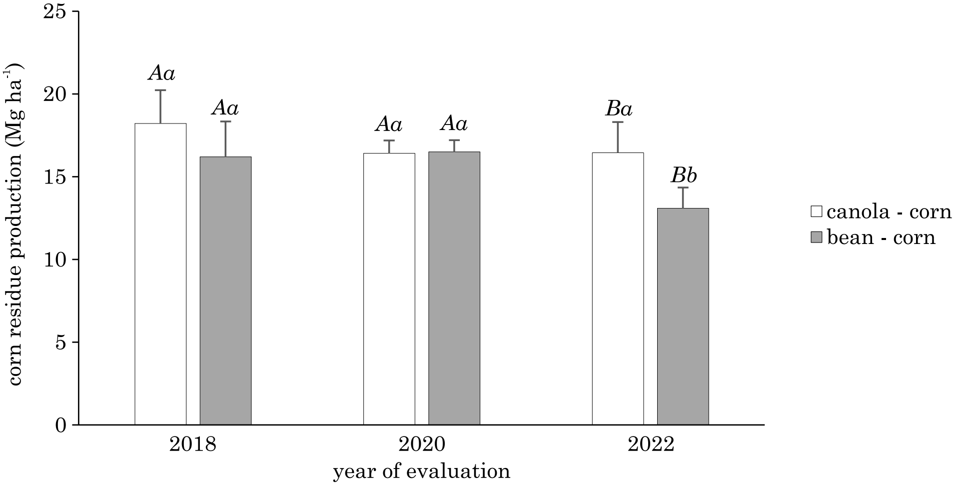

Fig. 2. Corn residue production during three cycles of two biannual crop rotations (after of canola or bean). Different capital letters above the bars indicate differences between evaluation years, and different lowercase letter above the bars in the same evaluation year indicate difference between crop rotation according to the Tukey's test (p<0.05). Whiskers correspond to the standard error for each bar

the Ca concentration (p<0.05). As an effect of the crop rotation, the highest pH was obtained in the bean-corn rotation, as was the Na exchangeable concentration. Meanwhile, the concentrations of both exchangeable Al and available S were higher in the canola-corn rotation (Table 4). The level of residue incorporated generated an increase in the organic matter content

Table 3

Significance testing (p-values) for the soil chemical properties as affected by two crop rotations with four residue incorporation levels after six years of evaluation

Soil properties	Crop rotation (CR)	Residue level (R)	CR × R interaction
pH	< 0.01	0.68	0.95
Organic matter	0.36	0.03	0.06
Available N	0.54	0.27	0.06
Available P	0.06	< 0.01	0.32
Exchangeable Ca	0.80	0.43	0.02
Exchangeable Mg	0.90	0.26	0.76
Exchangeable K	0.15	< 0.01	0.23
Exchangeable Na	< 0.01	0.16	0.17
Exchangeable Al	< 0.01	0.27	0.83
Available S	0.03	0.86	0.74

Table 4

Soil chemical properties affected by two crop rotations, as average values for four residue incorporation levels

Soil properties	Canola – corn	Bean – corn
pH	5.89 *b*	6.05 *a*
Organic matter (g kg^{-1})	87.2 *a*	85.5 *a*
Available N (mg kg^{-1})	11.9 *a*	12.4 *a*
Available P (mg kg^{-1})	20.5 *a*	17.8 *a*
Exchangeable Ca (cmol$_+$ kg^{-1})	4.19 *a*	4.12 *a*
Exchangeable Mg (cmol$_+$ kg^{-1})	0.47 *a*	0.47 *a*
Exchangeable K (cmol$_+$ kg^{-1})	0.54 *a*	0.48 *a*
Exchangeable Na (cmol$_+$ kg^{-1})	0.07 *b*	0.09 *a*
Exchangeable Al (cmol$_+$ kg^{-1})	0.088 *a*	0.047 *b*
Available S (mg kg^{-1})	36.0 *a*	29.5 *b*

Different letters in the same row indicate differences between crop rotations as an average achieved for the four residue incorporation levels according to the Tukey's test ($p<0.05$).

and exchangeable K level, which in general were directly proportional to the dose of residue used, while the concentration of available P with respect to the control was increased by the application of any of the three residual doses, with differences between the doses used ($p>0.05$) – Table 5. Finally, as an effect of the interaction between crop rotation and residue level, the exchangeable Ca concentration only presented differences in the canola-corn rotation, with its concentration increase directly proportional to the applied residue dose (Table 6).

Table 5

Soil chemical properties as affected by four residue levels, as average values for two crop rotations

Soil properties	Residue level (%)			
	0	50	100	200
pH	5.95 *a*	5.94 *a*	5.97 *a*	6.02 *a*
Organic matter (g kg^{-1})	81.5 *b*	88.0 *ab*	86.8 *ab*	89.1 *a*
Available N (mg kg^{-1})	11.5 *a*	12.5 *a*	13.7 *a*	11.1 *a*
Available P (mg kg^{-1})	17.7 *b*	20.4 *a*	19.0 *a*	19.6 *a*
Exchangeable Ca (cmol$_+$ kg^{-1})	4.05 *a*	3.84 *a*	4.21 *a*	4.51 *a*
Exchangeable Mg (cmol$_+$ kg^{-1})	0.41 *a*	0.46 *a*	0.48 *a*	0.52 *a*
Exchangeable K (cmol$_+$ kg^{-1})	0.40 *b*	0.49 *ab*	0.54 *ab*	0.63 *a*
Exchangeable Na (cmol$_+$ kg^{-1})	0.08 *a*	0.08 *a*	0.09 *a*	0.07 *a*
Exchangeable Al (cmol$_+$ kg^{-1})	0.076 *a*	0.081 *a*	0.062 *a*	0.051 *a*
Available S (mg kg^{-1})	34.6 *a*	32.9 *a*	32.1 *a*	31.4 *a*

Different letters in the same row indicate differences between residue incorporation levels as an average achieved for two crop rotations according to the Tukey's test (p<0.05).

Table 6

Soil exchangeable calcium as affected by two crop rotations and four residue level

Crop rotation	Residue level (%)			
	0	50	100	200
	(cmol$^+$ kg^{-1})			
Canola – corn	3.44 *b*	3.69 *b*	4.37 *ab*	5.27 *a*
Bean – corn	3.76 *a*	4.00 *a*	4.05 *a*	4.66 *a*

Different letters in the same row indicate differences between residue incorporation levels for the same crop rotations according to the Tukey's test (p<0.05).

DISCUSSION

Production of grain and residue in the corn crop

The corn grain yield and its residue production were normal for the study area, with 16 Mg ha^{-1} as a mean, and with residue levels of 16 to 17 Mg ha^{-1} (Hirzel et al. 2020); however, there was a difference in grain yield between the first cycle and the following cycles, associated with the use of hybrids with different yield potential and a difference in the adaptation to soil conditions with a medium effective depth, such as the one used in this experiment. A lower effective depth affects the exploration capacity of the roots and the root zone available water-holding capacity, which reduces the yield potential (Hirzel et al. 2020). For grain yield, there was no effect of the previous crop, unlike what was reported by some other authors, such as Sainju et al. (2021), who indicated positive effects of different crop rotations on crop grain yield and biomass production. Residue production also decreased mainly in the third cycle of rotation, associated with the different hybrid used compared to the first cycle, which was previously discussed.

The difference between the residue production between the first and second cycle associated with the hybrids used would also have been expected, although for the first crop cycle there was an increase in the corn harvest index after bean (from 0.48 to 0.50, Figures 1 and 2), which reduced residue production in this rotation and did not allow detection of significant differences versus the average residue production in the second evaluation cycle (2020). In the third crop cycle, there was higher production of residues after canola cultivation, which can be explained by the effects on root exploration ability and nutrient recycling after a crop with high biomass production such as canola (Hirzel et al. 2020, Passaris et al. 2021, Sietz et al. 2021). The beneficial effect of using beans as a preculture on grain production and corn residue was not observed in this experiment, probably due to the high fertilization used in corn cultivation, which decreases the response to the greater natural supply of nutrients provided by legumes in crop rotation (Huynh et al. 2019, Taveira et al. 2020, Song et al. 2021). Another reason that may explain the lack of beneficial effect of including bean as a nutrient input in crop rotation is the volcanic soil used, whose organic matter content ensures a higher delivery of nitrogen. The different levels of incorporated residue did not affect the production of grain or biomass of the corn crop, unlike what was indicated by some other authors (Pandiaraj et al. 2015, Chen et al. 2018, Kumar et al. 2018, Sainju et al. 2021). This can be explained by biological processes associated with the entry of organic C into the soil, which allows the formation of highly organized organic compounds (Chen et al. 2017, Zhang et al. 2018, de Cárcer et al. 2019), which was not evaluated in this experiment. Moreover, the absence of an impact from the level of incorporated residue on corn crop yield could potentially alleviate farmers' concerns regarding any potential negative repercussions of residue utilization on corn yield.

Soil chemical properties

The chemical properties of the soil at the end of the three biannual rotation cycles (6 years after the start of the experiment) showed an increase in soil pH and in the concentration of exchangeable Mg, as well as a decrease in exchangeable Al in response to liming ($CaCO_3$×$MgCO_3$) performed at the beginning of the experiment (Fageria, Nascente 2014). However, there was no increase in exchangeable Ca, which can be explained by the accumulated extraction of this element during the six years of cultivation (Fageria, Nascente 2014). The concentration of available S also increased with respect to the initial value, which was a response to the fertilization used during the six years of cultivation. The use of bean as a preculture enabled an increase of the soil pH and exchangeable Na concentration, which may be associated with a lower extraction of basic reaction nutrients (Fageria, Nascente 2014) given the lower production of biomass by the bean crop than by canola (Hirzel et al. 2020). In general, the organic matter content of the soil after six years of evaluation was lower than at the beginning of the experiment, probably due to the mineralization processes occurring in soil on which agricultural production is carried out with conventional tillage and with N application in doses similar to the extraction by crops that do not perform symbiotic fixation, such as canola and corn (Chen et al. 2017, de Cárcer et al. 2019). The use of canola as a preculture allowed augmentation of the concentrations of exchangeable Al and available S, which can be explained by the greater contribution of these two nutrients following the incorporation of canola residues, which in general is twice as high as the residue incorporated with bean (Hirzel et al. 2020). In turn, canola is characterized by a higher concentration of S in its biomass, which allows the formation of organic compounds with a high concentration of S typical of this species (Fang et al. 2021, Raboanatahiry et al. 2021, Scott et al. 2021). As expected, the effect of the increasing doses of residues made it possible to increase the content of soil organic matter and exchangeable K with an effect directly proportional to the dose used, given the contribution of C (Khakbazan et al. 2019, Yang et al. 2019, Kostrzewska et al. 2022) and K present in the residues (Raboanatahiry et al. 2021). The concentration of available P also increased in response to the application of residues, but there was no difference related to the increasing dose of residues, probably because of the biological processes of formating stable organic compounds in soil (Zhang et al. 2018, de Cárcer et al. 2019, Kostrzewska et al. 2022). Given that N was not applied along with residue incorporation in our experiment, we could have expected a negative effect on N availability associated with the immobilization process (Sarker et al. 2019), which is known as N starvation. However, in soils with a high organic matter content in which shredded crop residues were incorporated 5 to 7 months before planting the following crop and with winter rains, suitable conditions were created for nutrient mineralization in residues, as indicated by Mganga and Kuzyakov (2018) based on the application of C, N, and P in different Andisol soils of the Kilimanjaro region. In addition, residual fertilization of the crop system and soil N mineralization would contribute to supplying the N needs of the soil biomass to achieve residue decomposition (Mganga, Kuzyakov 2018, Piazza et al. 2020). Exudation of carbon compounds would be generated from the roots during a new crop cycle, which activates soil biomass, contributes to the mineralization of soil organic matter (Xiao et al. 2015, Piazza et al. 2020), and can also assist in residue decomposition of the previous crop. Finally, the exchangeable Ca showed an increase directly proportional to the dose of residue incorporated only in the canola-corn rotation, which can be explained by the concentration of Ca in the canola residue and by the greater mass of residue incorporated with this crop compared to bean (Raboanatahiry et al. 2021).

CONCLUSIONS

In conclusion, in this medium-term experiment conducted on volcanic soil, the use of canola or bean as a crop preceding corn in crop rotation did not affect corn grain yield during the three biannual evaluation cycles, with a positive effect of canola on corn residue production only in the third cycle. Both grain and residue production by corn was affected by the hybrid used during the evaluation period. Soil chemical properties after 3 biennial rotation cycles were affected by rotation, with an increase in pH after bean cultivation and an increase in both exchangeable Al and available S after canola. On the other hand, the use of increasing doses of residue led to an increase of the content of both organic matter and exchangeable K in the soil, and partially the available P. The concentration of exchangeable Ca was increased with the increasing dose of residue only in the canola rotation cycle. Finally, this study justifies the conclusion that continuous incorporation of residues produced within biannual rotations evaluated on volcanic soil contributes to an increase in the content of both soil organic matter and exchangeable K, and that the application of high residue amounts does not negatively affect the yield of corn.

Author contributions

Conceptualization – J.H., I.M.; methodology – J.H., I.M. C.V.; validation – J.H., P.U. P.M.; formal analysis – J.H., I.M., P.U.; investigation – J.H., P.U., C.V., I.M., P.M.; resources – J.H., I.M., P.M.; data curation – J.H., P.U., C.V., I.M., P.M.; writing – original draft preparation, J.H., C.V., I.M.; writing – review and editing, P.U.; visualization – J.H., P.U., C.V., I.M., P.M.; supervision – P.U., I.M..; project administration – J.H.; funding acquisition – J.H., I.M., P.M. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interest

The authors declare no conflict of interest.

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