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RESEARCH ARTICLE

Durum Wheat Production and Soil Chemical Properties in Response to Three Biannual Rotation Cycles with Residue Incorporation

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ABSTRACT

Crop rotations incorporating residues generates benefits in productivity and a better efficiency of resources. However, the incorporation of residues in high quantities is not a common practice, given the lack of comprehension of farmers of the effects on the following crop. This experiment was carried out in an Andisol soil in south-central of Chile. Three biannual rotation cycles (canola-durum wheat and bean-durum wheat) with four levels of residue incorporation (0%, 50%, 100% and 200%) were evaluated on the evolution of grain yield and production of durum wheat residues, and on chemical properties of the soil at the end of the three cycles. The results indicated that pre-cultivation affected the grain yield and residue production of durum wheat, highlighting the positive effect of the bean. In soil, a higher concentration of available N and exchangeable Ca, Mg and K was obtained in the bean-durum wheat rotation, and a higher concentration of available S in the canola-durum wheat rotation. By increasing the dose of waste, an increase in the concentrations of exchangeable Ca, Mg and K was achieved. Finally, the chemical properties of the soil presented positive and negative correlations associated with the management of liming, fertilization and nutrients mostly present in the incorporated waste.

This study helped to validate that the continuous incorporation of the residues produced within the rotations in this volcanic soil contributes to the improvement of some of its chemical properties with no effect of yield of the durum wheat crop.

Introduction

The production of cereals such as bread wheat, rice, corn and durum wheat is of utmost importance for the world's diet [1-3]. For durum wheat, quality requirements in the pasta industry have generated higher production costs [4], therefore those production systems that allow increasing yield could contribute to a better profit [5]. These systems include, for example, crop rotation and residues management as a source of carbon and nutrient recycling for the soil-plant system [3]. In this regard, several authors have shown that conservation practices in crop rotation management have allowed increased yields and production of residues for nutrient recycling [6-8], as well as improving chemical and physical properties of the soil [9-11]. On the other hand, the incorporation of residues contributes to reduce CO_2 emissions and mitigate the effect of greenhouse gases [12]. However, the use of crop residues in agriculture can generate uncertainties that limits its use, such as; effects on the availability of nitrogen (N) or other nutrients for the following crop [13-16]; possible physical limitations for soil preparation and difficulty in establishing the next crop within a rotation [17]. One of the practices that facilitates the decomposition of residues in the soil is crop rotation, since it allows time windows between the incorporation of residues from the recently harvested crop and the planting of the next crop. Furthermore, this practice allows more soil microbial biodiversity and at the same time adding the natural capacity of the soil system to achieve the decomposition of waste [18-19].

Durum wheat area worldwide occupies around 16,000,000 hectares [19], while in Chile this area corresponds to 23,120 hectares [20]. The global average grain yield under irrigated conditions is around 6.2 Mg ha^{-1}, while in Chile this yield is 6.8 Mg ha^{-1} [19-20]. Regarding the effect of crop rotations on durum wheat yield, Lenseen [4] indicated that the durum wheat – canola (*Brassica napus* L.) – durum wheat – pea (*Pisum sativum* L.) rotation under rainfed conditions presented a yield between 2.03 to 2.06 Mg ha^{-1} as an average of 4 years, with differences between years associated with the difference in rainfall, which was similar to the yield obtained by durum wheat in monoculture condition. Woźniak [3] indicated that for a 3-year rotation in rainfed conditions with cropping sequences that included only cereals or pea crops, the yield of durum wheat was improved by the inclusion of the pea crop, and these yields fluctuated between 2.33 to 3.51 Mg ha^{-1} (37% higher on average when peas cultivation was included in the rotation). Hirzel [21] indicated that under irrigation conditions and conventional agriculture in volcanic soils, the grain yield of durum wheat fluctuated between 8.0 and 9.0 Mg ha^{-1}, highlighting the importance of irrigation to improve productivity.

Soil conservation practices adding residues in different crop rotation systems are becoming more used worldwide, but these can generate uncertainty regarding the results on the following crops yield. On the other hand, the consumption of pasta in people's diets is of great importance worldwide, both for its low price and for its nutritional value, highlighting mainly carbohydrates and proteins of plant origin. In addition, durum wheat is a cereal with the highest protein content in the human diet.

We hypothesize that incorporation of residues in different doses within two crop rotations allows a steady yield of the durum wheat crop and at the same time improve the soil chemical properties. The objective of this work was to evaluate the effect on durum wheat production and chemical properties of the soil at the end of the three biannual crop rotation cycle of canola-durum wheat and bean-durum wheat under four levels of annual residues incorporation (0%, 50%, 100% and 200%).

Material and methods

The experiment was conducted from 2016 to 2022 in soil is volcanic (Melanoxerand) [22] with moderate effective depth (0.45 to 0.60 m) of the Santa Rosa Experimental Station, INIA-Quilamapu, Chillán, Chile (36°31' S; 71°54' W). The climate is temperate Mediterranean characterized by a hot, dry summer and cold, wet winter. The mean temperature was 12.8, 13.2, 13.5, 13.4, 14.3 and 13.2 °C for the 2016-2017, 2017-2018, 2018-2019, 2019-2020, 2020-2021, and 2021-2022 seasons, respectively. Precipitation was concentrated in winter and spring and corresponded to 605, 563, 730, 460, 576 and 920 mm, while the 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.

EXPERIMENT MANAGEMENT

The design of this long-term experiment consisted of biannual rotations combining two crops: bean-durum wheat and canola-durum wheat, in which residues of the previous crop have been incorporated at levels of 0%, 50%, 100%, and 200%; the basic design has been maintained over time. The present article focuses on grain yield and residue production of the durum wheat as the second crop in each biannual rotation (2017-2018; 2019-2020, and 2021-2022 season), and on the soil chemical properties ending evaluation period (2022 year). Lime was applied at the rate of 3,000 kg ha^{-1} before start of the biannual rotations in

April 2016 to correct soil acidity (Table 1). There were two previous crops before the durum wheat crop: 1) canola (*Brassica napus* L.) crop and 2) bean (*Phaseolus vulgaris* L.) crop. The experimental unit for each crop rotation (bean-durum wheat and canola-durum wheat) that had 40 m long and 14 m wide (560 m^2) plot with 0.7, 0.7, and 0.2 m inter-row spacing for the bean, canola, and wheat crops, respectively, and the 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%). So, the total experimental area was 4,480 m^2 and included two crop rotations and four replicates.

The sowing and harvesting dates during the 3 cycles of biannual rotation for each crop are presented in Table 2. Canola 'Eminem-von Baer' was used in the first two seasons and 'Imminent-SIS' (a new hybrid with better yield potential for the study area) was used in the thirst season, and the seed rate 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 not necessary. Nitrogen, P (P_2O_5), and K (K_2O) fertilization rates were 160, 120, and 80 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 rates 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 bean crop 'Zorzal-INIA' was used in the first rotation cycle, while the second and third rotation cycle was sown with 'Torcaza-INIA' (a new cultivar with better yield potential for the study area). The seed rate 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 kg a.i.·ha^{-1} at the first trifoliate leaf, and disease control was not necessary. The N, P (P_2O_5), and K (K_2O) fertilization rates were 60, 60, and 60 kg ha^{-1}, respectively. Nitrogen, 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 rates 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 durum wheat crop 'Queule-INIA' was sown during the three cycles of rotation. The seed rate was 220 kg·ha^{-1} in each season. Irrigation was applied at the booting, heading, and milk to dough stages. Total weed control was carried out with Propisochlor (Proponit 720 EC) at 432 g a.i.·ha^{-1}, and flumiozaxin (Pledge 50 WP) at 25 g a.i.·ha^{-1} at the pre-sowing stage, and tritosulphuron at 50 g a.i.·ha^{-1} with dicamba at 100 g a.i.·ha^{-1} (Arrat), metsulphuron-methyl (Aliado) at 4.8 g a.i.·ha^{-1}, at the tillering stage, and disease control was not necessary. Nitrogen, P (P_2O_5), and K (K_2O) fertilization rates were 240, 120, and 120 kg ha^{-1}, respectively, based on soil chemical properties (Table 1). Phosphorous and K were applied 100% at sowing, while N was applied 15%, 45%, and 40% at the sowing, tillering, and flag leaf stages. 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 rates of 30:33:4:2 kg ha^{-1} before sowing in all crops with 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% during May, in each year in the same experimental unit. The treatment with application and incorporation of 200% of the residue was considered as an alternative to recycle residues from areas where the time window or soil moisture conditions do not allow incorporation. In addition, it allows to evaluate the effect of a high dose of carbonated residues on the chemical properties of the soil. 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.

Table 1. Soil chemical properties at the 0-0.2 m soil depth before initiating the crop rotation experiment (year 2016). Methods used are described in the text.

Parameters	Value
Clay (%)	16.7
Silt (%)	44.6
Sand (%)	38.7
Bulk density (g cm^{-3})	1.00
pH (soil:water 1:5)	5.52
Organic matter (g kg^{-1})	109.2
EC (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

EC: electrical conductivity; N: nitrogen; P: phosphorus; K: potassium; Ca: calcium; Mg: magnesium; Na: sodium; Al: aluminum; S: sulfur.

Table 2. Crop sowing and harvest date for each crop rotation.

Cycle of rotation	Rotation bean-durum wheat			Rotation canola-durum wheat		
	Crop	Sowing date	Harvest date	Crop	Sowing date	Harvest date
First	C	May 15th 2016	February 5th 2017	B	October 17th 2016	February 26th 2017
	DW	July 15th 2017	January 20th 2018	DW	July 15th 2017	January 20th 2018
Second	C	May 25th 2018	January 15th 2019	B	October 27th 2018	February 28th 2019
	DW	July 10th 2019	January 22th 2020	DW	July 10th 2019	January 22th 2020
Third	C	August 31th 2020	January 25th 2021	B	November 10th 2020	March 11th 2021
	DW	July 12th 2021	January 15th 2022	DW	July 12th 2021	January 15th 2022

C, canola
B, bean
DW, durum wheat

DURUM WHEAT YIELD AND RESIDUE PRODUCTION

The plots were harvested manually at grain maturity 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

At the beginning of the experiment, composite samples of 0 to 20 cm soil depth were collected manually from throughout the experiment as an initial soil characterization sample. All samples were air-dried and sieved (2 mm mesh). Soil pH was determined in 1:2.5 soil:water extracts. Soil organic C was established by Walkley-Black wet digestion [23]. 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. Ending season 2021-2022 (May of 2022) composite samples were collected manually from the 0-20 cm soil depth for each treatment and replicate and were analyzed by the methodologies described above.

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 durum wheat 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 [24]. For the significant interactions, contrast analysis was used to compare the treatment effects separately ($p = 0.05$). In addition the Pearson correlation was used for determinate the relationships between the soil chemical properties at the finish of the evaluation time.

Results

The analysis for grain yield (Table 3) indicated the significant effect of crop rotation, and the year*crop rotation interaction, therefore we focused on the interaction (Figure 1), which indicated that crop rotation only had an effect in the first two rotation cycles, where the highest grain yield was obtained after bean, with an average rise of 22.3% compared to the canola as a pre-crop. For residue production, the values fluctuated between 5.73 and 7.82 Mg ha^{-1} (Figure 2), with a significant effect of the year, crop rotation and the interaction between both sources of variation (Table 3), therefore the analysis focused on this interaction (Figure 2). The pre-cultivation for the biannual rotations only had a significant effect on the production of residues in the second evaluation cycle, where the highest value was obtained after the bean cultivation (12.1% higher compared to the use of canola as a pre-crop).

For soil properties at the end of three crop rotation cycles, there was an effect of rotation on available N, P and S, and exchangeable Ca, Mg and K ($p<0.01$) (Table 4). The level of residue significantly affected the concentrations of exchangeable Ca, Mg and K ($p<0.01$). The interaction between crop rotation and residue level affected the concentrations of available P ($p<0.01$) and exchangeable K ($p<0.05$), so these nutrients were analyzed as an effect of the interaction.

The use of the canola-durum wheat rotation increased the concentration of available S in the soil ($p<0.05$), while the bean-durum wheat rotation increased the concentrations of available N and exchangeable Ca and Mg ($p<0.05$) (Table 5).

Increasing doses of residue had a directly proportional effect on the concentrations of exchangeable Mg ($R = 0.35$, data not shown) and K ($R = 0.59$, data not shown), while for the concentration of exchangeable Ca there was a directly proportional effect of the residue level only up to the 100% dose ($R = 0.43$, data not shown) (Table 6).

The crop rotation*residue level interaction (Table 7) indicated that for the canola-durum wheat rotation there was a decrease in the contraction of available P with the highest dose of residue ($p<0.05$), while for the exchangeable K there was an increase with the 100% residue dose, surpassing the control without residue application ($p<0.05$). For the bean-durum wheat rotation, the use of increasing doses of residue allowed an increase in both available P ($R = 0.55$, data not shown) and exchangeable K ($R = 0.57$, data not shown) (Table 7). For the available P, the highest value was obtained with the 200% residue dose, surpassing only the control ($p<0.05$), while for the exchangeable K, the highest value was obtained with the 200% residue dose, surpassing the control and the 50% dose ($p<0.05$).

The correlation and significance analysis of the soil chemical properties (Table 8) indicated that pH correlated positively with exchangeable Ca, Mg and K, and negatively with organic matter (OM), available N, P and S, and exchangeable Al. Organic Matter correlated positively with available P and exchangeable Al. Available N presented positive correlation with exchangeable Ca, Mg and K, and negative correlation with available S. Available P presented positive correlation with exchangeable Al and available S. Exchangeable Ca presented positive correlation with exchangeable Mg and K, and negative with both exchangeable Al and available S. Exchangeable Mg presented positive correlation with exchangeable K and negative with both exchangeable Al and available S. Finally exchangeable Al presented positive correlation with available S.

Table 3. Significance testing for the wheat grain yield and residue production as affected by two crop rotations with four residue incorporation levels.

Fuente de variación	Grain Yield	Residue production
Year (Y)	0.25	< 0.01
Crop Rotation (CR)	< 0.01	0.05
Residue Level (RL)	0.09	0.59
Interaction Y * CR	< 0.01	0.02
Interaction Y * RL	0.55	0.87
Interaction CR * RL	0.77	0.80
Interaction Y * CR * RL	0.64	0.87

Table 4. Significance testing for the soil chemical properties as affected by two crop rotations with four residue incorporation levels after six year of evaluation.

Soil properties	Crop rotation (CR)	Residue level (R)	CR × R Interaction
pH	0.70	0.13	0.91
Organic matter	0.91	0.27	0.65
Available N	< 0.01	0.92	0.28
Available P	< 0.01	0.71	< 0.01
Exchangeable Ca	< 0.01	< 0.01	0.12
Exchangeable Mg	< 0.01	< 0.01	0.10
Exchangeable K	< 0.01	< 0.01	0.04
Exchangeable Na	0.14	0.24	0.66
Exchangeable Al	0.62	0.09	0.65
Available S	< 0.01	0.16	0.26

Table 5. Soil chemical properties as affected by two crop rotations, as average of four residue incorporation levels.

Soil properties	Canola – durum wheat	Bean – durum wheat
pH	6.00 a	5.99 a
OM, g kg^{-1}	82.3 a	81.8 a
Available N, mg kg^{-1}	10.3 b	17.7 a
Available P, mg kg^{-1}	17.2 a	14.4 b
Exchangeable Ca, $cmol_+$ kg^{-1}	3.49 b	5.15 a
Exchangeable Mg, $cmol_+$ kg^{-1}	0.37 b	0.48 a
Exchangeable K, $cmol_+$ kg^{-1}	0.42 b	0.49 a
Exchangeable Na, $cmol_+$ kg^{-1}	0.06 a	0.07 a
Exchangeable Al, $cmol_+$ kg^{-1}	0.05 a	0.05 a
Available S, mg kg^{-1}	46.0 a	28.7 b

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

Table 6. Soil chemical properties as affected by four residue level, as average of two crop rotations.

Soil properties	Residue level (%)			
	0	50	100	200
pH	5.94 a	5.98 a	6.03 a	6.04 a
OM, g kg^{-1}	80.1 a	78.1 a	82.3 a	87.7 a
Available N, mg kg^{-1}	13.8 a	13.8 a	13.6 a	14.9 a
Available P, mg kg^{-1}	16.0 a	16.5 a	15.5 a	15.3 a
Exchangeable Ca, $cmol_+$ kg^{-1}	3.63 b	4.29 ab	4.98 a	4.39 ab
Exchangeable Mg, $cmol_+$ kg^{-1}	0.39 b	0.39 b	0.45 ab	0.48 a
Exchangeable K, $cmol_+$ kg^{-1}	0.37 c	0.42 bc	0.50 ab	0.54 a
Exchangeable Na, $cmol_+$ kg^{-1}	0.06 a	0.07 a	0.05 a	0.06 a
Exchangeable Al, $cmol_+$ kg^{-1}	0.07 a	0.05 a	0.04 a	0.04 a
Available S, mg kg^{-1}	41.8 a	37.3 a	35.5 a	34.6 a

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

Table 7. Soil Phosphorous and Potassium as affected of the interaction crop rotation and residue level.

Crop rotation	Soil properties	Residue level (%)			
		0	**50**	**100**	**200**
Canola – Durum wheat	Available P, mg kg^{-1}	19.5 a	19.4 a	15.9 ab	14.0 b
	Exchangeable K, cmol$_{+}$ kg^{-1}	0.35 b	0.42 ab	0.47 a	0.45 ab
Bean – Durum wheat	Available P, mg kg^{-1}	12.5 b	13.5 ab	15.0 ab	16.6 a
	Exchangeable K, cmol$_{+}$ kg^{-1}	0.40 c	0.42 bc	0.52 ab	0.62 a

For each crop rotation different letters in the same row indicate differences between residue incorporation levels according to Tukey's test ($p < 0.05$).

Table 8. The Pearson's correlation for the soil chemical properties at the finish of the experimental time (n = 32).

Soil chemical propety	OM	N	P	Ca	Mg	K	Na	Al	S
pH	-0,38*	-0.34	-0.48**	0.43*	0.42*	0.36*	-0.03	-0.92**	-0.56**
OM		0.32	0.41*	-0.02	0.08	-0.08	0.07	0.36*	0.17
N			-0.14	0.40*	0.57**	0.37*	0.18	0.10	-0.36*
P				-0.29	-0.34	-0.11	0.07	0.61**	0.67**
Ca					0.76**	0.60**	0.11	-0.44*	-0.79**
Mg						0.75**	0.08	-0.47**	-0.75**
K							-0.001	-0.40*	-0.54**
Na								0.04	-0.23
Al									0.62**

OM, organic matter
N, available nitrogen
P, available phosphorous
Ca, exchangeable calcium
Mg, exchangeable magnesium
K, exchangeable potassium
Na, exchangeable sodium
Al, exchangeable aluminium
S, available shulpur
*, significant at p<0.05
**, significant at p<0.01

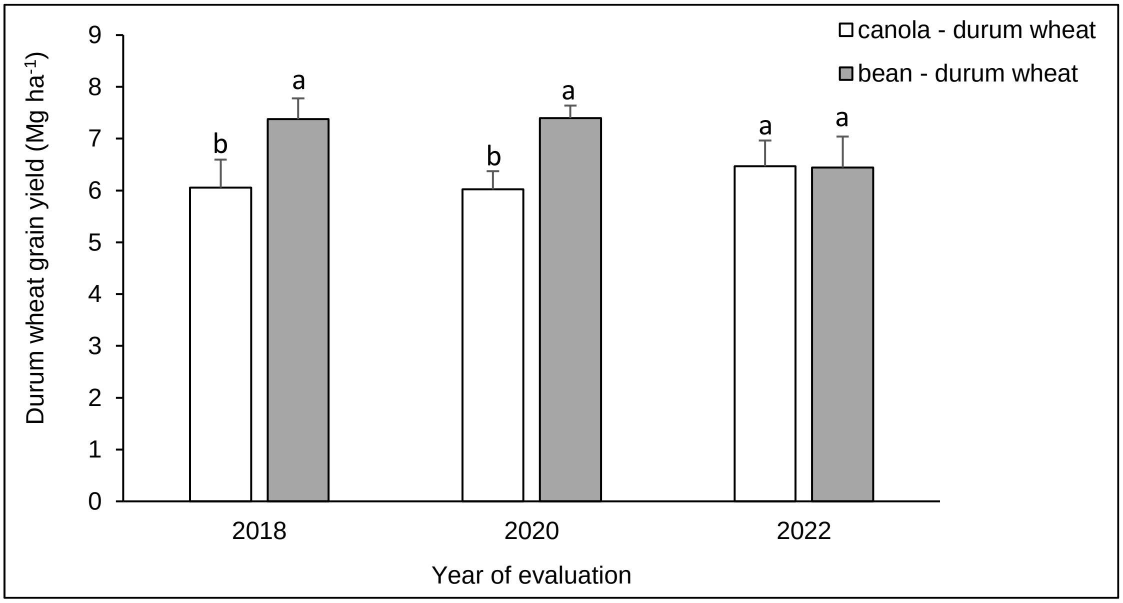

Figure 1. Durum wheat grain yield during three cycles of two biannual crop rotations (after of canola or bean).

Different letters above the bars indicate differences in the same year of evaluation according to Tukey's test ($p < 0.05$). Whiskers correspond to the standard error for each bar.

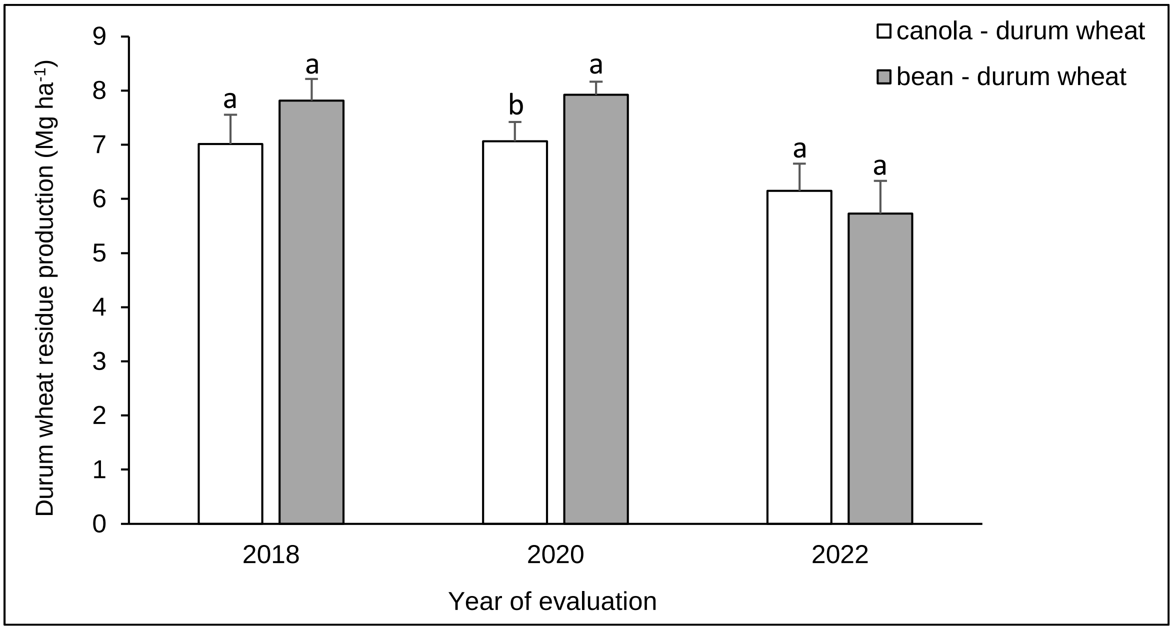

Figure 2. Durum wheat residue production during three cycles of two biannual crop rotations (after of canola or bean).

Different letters above the bars indicate differences in the same year of evaluation according to Tukey's test ($p < 0.05$). Whiskers correspond to the standard error for each bar.

Discussion

The soil used in this study (Table 1) presented an adequate level of fertility for the cultivation of durum wheat, except for its acidity, which was corrected with the liming applied prior to the first planting cycle. The sowing and harvest dates of durum wheat cultivar were accordingly of the study area (Table 2), and with similar yields as indicated by Hirzel and Matus [7] obtained in the same area (5.38 to 7.65 Mg ha^{-1}) (Figure 1) but slightly lower compared with another productive areas in Chile [21].

The effect of bean as a pre-crop on grain yield compared to canola can be explained by the benefits of legumes on the contribution to the soil of compounds of lower molecular weight that contribute to increase the microbial biomass [25-28], as well as for the contribution of nutrients for the following crop [29-31]. In the case of durum wheat, Woźniak et al. [3] also reported a positive effect of including a legume in the rotation (pea crop), with a 37% increase in yield compared to rotations with only cereals.

In our experiment, a positive effect of bean cultivation would have been expected in the three rotation cycles, however the different climatic condition of the last season, with more precipitation and less evaporation, and evapotranspiration (gas exchange) may have decreased the productivity of durum wheat cultivation [19].

The production of residues also had a beneficial effect of the use of beans as pre-cultivation, but only in the second cycle. The absence of differences in the first and third rotation cycle can be explained by a shorter chronological cultivation time between sowing and harvest during these two cycles, decreasing on the one hand the production of carbohydrates and also the location of these in the residue [19], masking the positive effect of using bean as pre-culture.

In general, the use of different crop rotations in our experiment generated production differences in durum wheat, highlighting the use of the legume (bean) as a pre-crop, which has been reported by several authors [3-5,30,32]. The incorporation of different levels of residues in our experiment had no effect on the production of durum wheat, different from papers of this and other plant species [4,33-34].

In relation to the chemical properties of the soil, the bean-durum wheat rotation generated a positive effect on the available N and exchangeable Ca and Mg, which is attributed to the biological fixation of N from the bean and additional contribution of N to the soil [31,35-37], as well as the lower nutrient extraction of this species associated with its lower biomass production compared to cultivation of canola [17,38]. The canola-durum wheat rotation generated a higher concentration of available S, which is associated with the extraction capacity of this nutrient from the soil by canola and the subsequent contribution with the decomposition of its roots [17,39].

Sarker et al. [33] found that residue incorporation of canola in crop rotations with wheat, stimulated the mineralization of soil organic matter, with an increase in available S. In general, the concentration of available S at the end of the three rotation cycles was greater than the initial value, associated with the fertilization and the entry of residues into the soil. The highest dose of residue had an effect only on some of the chemical properties of the soil (exchangeable Ca, Mg and K), associated with the nutritional composition of these residues, in which the contribution of these cations stands out given the allometric distribution of Ca, K and Mg towards bean and canola residues [39-40]. The absence of differences in the concentration of available N, P and S can be explained by the lower contribution of these nutrients in bean and canola residues [39-40], as well as by organizational processes or immobilization of these nutrients associated with the contribution of carbon with the residue [41-42]. At the same time, the volcanic soil in which this experiment was carried out has a high P fixation capacity, which reduces the possibility of increasing the concentration of available P [39,43]. Regarding OM, a significant increase would have been expected with the use of a higher dose of residue, however the annual contribution of carbon (C) with the input of residue is low in relation to the high OM content of this soil, therefore requires many years of organic carbon application to generate changes in the OM content [10,44]. As a general condition of the soil in which this experiment was carried out, a decrease in the OM content was observed with respect to the initial value, which can be explained by the performance of traditional tillage, environmental conditions, irrigation management and nitrogen fertilization, which favor the soil C mineralization process.

The interaction of crop rotation and residue level affected in a different way the concentration of available P in the soil, with an increase in concentration when using the highest dose of residue in the bean-durum wheat rotation, which is associated with the P content in the residue and its mineralization in the soil. This was also observed with the lowest doses of residues but was not statistically significant. For the canola-durum wheat rotation the result was different, with a decrease in available P when using the highest dose of residue, which can be explained by the immobilization of the applied P associated with the greater mass of C incorporated into the soil with the higher dose 33,39. However, in general, a higher concentration of available P was achieved in the canola-durum wheat rotation, associated with the greater contribution of P with the mass of canola residue [17,38] and the distribution of P towards canola residue (51%) [45]. In relation to the exchangeable K, in both rotations an increase was obtained with the addition of higher doses of residue, however the dose of residue that achieved the highest concentration in the soil was different in both rotations. For the canola-durum wheat rotation there was an erratic effect between the doses of 100 and 200% of residue, having expected a higher concentration of exchangeable K with the use of the highest dose of residue, associated with the contribution of this nutrient with the residues incorporated for 6 years of rotation [39-40].

Regarding the correlations between chemical properties of the soil, it is normal to expect a positive correlation between pH and exchangeable Ca, Mg and K (basic reaction cations), given the effect of decreasing H^+ protons by increasing the pH with the liming carried out at the beginning of the year, and with the consequent replacement of these protons in the cation exchange sites [39,46-47]. At the same time, it was also expected to find a negative correlation between pH and exchangeable Al, due to the effect explained above. The increase in soil pH generates a greater oxidation potential and with it, a decrease in available S associated with mineralization processes and subsequent leaching, as well as immobilization processes in the microbial biomass whose activity is benefited by increases in pH [39]. Positive correlations between exchangeable basic reaction cations were also expected in this experiment, given their contribution with liming, annual fertilization, and the input of residues with high recycling of cations [39-40,46-47]. At the same time, a negative correlation between basic reaction cations and exchangeable Al was also expected. The practice of liming or application of basic reaction nutrients stimulates both greater microbial biomass activity and oxidation of soil OM, which is why a negative correlation between pH and OM was expected [39,48]. Thomas et al. [49] also reported negative correlation ($R = -0.88$, $p<0.01$) between pH and organic C of a Luvisol soil from the semi-arid zone of southern Australia. For available N, a positive correlation was observed with the exchange bases Ca, Mg and K, as well as the addition of these bases with liming and fertilization stimulates greater bacterial activity in the soil with greater OM mineralization and supply of N [39]. OM is a source of P reserve in the soil, which explains a positive correlation. In the same way, a positive correlation between OM and exchangeable Al was expected, given that in volcanic soils like the one used in this study, alumino-allophane and alumino-allophane-humic compounds are formed, capturing carbon in the aluminum present in the amorphous clays of the soil [39,43,50]. On the other hand, Takahashi and Dahlgren [43] have also described the relationship between P and Al found in this experiment, explained by the chemical interactions between both elements. The relationship found between available P and S can be explained by its structural role in soil OM and its subsequent mineralization [39,48]. The negative correlation between the exchange bases Ca, Mg and K with the available S can be explained by the increase in soil pH (increase in the concentration of bases) and its effect on the lower availability of S, previously explained. Finally, the positive relationship between exchangeable Al and available S can be explained by the structural role of both elements in soil OM, and their subsequent availability through chemical or biological processes such as pH change and mineralization, as well as by the adsorption of $S\text{-}SO_4^{2-}$ on Al oxides [39,48].

Conclusion

The pre-crop used in each biannual rotation affected the grain yield and residue production of durum wheat in interaction with the rotation cycle, highlighting the positive effect of bean in a few of these cycles. However, the level of residue incorporated did not affect the production of grain or residue of durum wheat. On the other hand, some chemical properties of the soil were affected by the crop rotation and the level of residue after the three biannual rotation cycles, highlighting a higher concentration of available N and exchangeable Ca, Mg and K in the bean-durum wheat rotation, and a higher concentration of available S in the canola-durum wheat rotation. In general, by increasing the residue dose, a directly proportional increase was achieved in the concentrations of exchangeable Ca, Mg and K. In turn, the concentrations of available P and exchangeable K showed interaction with the crop rotation and the level of residue highlighting an opposite effect of the residue level on the available P in each rotation, with an increase in concentration with increasing the dose of residue in the bean-durum wheat rotation and a decrease in concentration in the canola-durum wheat rotation. Finally, the chemical properties of the soil presented positive and negative correlations associated with the management of liming, fertilization and nutrients mostly present in the incorporated waste.

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