Canola production and effect on soil chemical properties in response to different residue levels from three biannual crop rotations

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**ABSTRACT**

Conservation agriculture using crop rotations and residue management is increasingly accepted in conventional agricultural systems. However, the effects on crop productivity and soil properties of different rotations, levels of use, and residue management have yet to be fully understood. Our study considered the effect of three previous crops (bread wheat, durum wheat, and corn) and four levels of residue incorporation (0%, 50%, 100%, and 200%) in a split plot design with four replicates on canola production parameters and soil chemical properties at the end of this crop. Production parameters and soil chemical properties were mostly affected by the previous crop and less by the residue incorporation rates under the conditions of this experiment; however, neither of these factors affected grain yield (ranging from 4.0 to 4.8 Mg ha⁻¹). Canola residue production was higher (9.7%) after the corn crop, regardless of the residue incorporation rate, but the harvest index was lower after this crop. Most of the soil chemical properties were also affected, revealing increased organic matter and exchangeable K when the previous crop was corn and decreased concentrations of the cations with basic reaction when the previous crop was durum wheat.

**Highlights**

- Bread wheat and durum wheat residue incorporation did not affect the grain yield of the canola crop.
- Canola residue production was positively affected by corn residue incorporation at different rates.

**Introduction**

The use of crop rotations with residue incorporation at different levels is an increasingly common technique in agriculture (Hiel et al., 2018; Karunakaran & Behera, 2016; Motazedian et al., 2019). It has benefitted soil fertility (Hirzel et al., 2020; Naab et al., 2017; Virk et al., 2019), decreased water and nutrient requirements in the next crop rotation (Aulakh et al., 2012; Selim, 2019), mitigated erosive effects, and increased conservation of soil resources (Blanco-Canqui & Lal, 2009; Selim, 2019; Stella et al., 2019). It has also lowered pathogen pressure in the following crop (Kerdraon et al., 2019), reduced greenhouse gas emissions associated with the burning of residues or the exclusion of residues from the soil (Liu et al., 2019; Malhi et al., 2006; Yang et al., 2015). However, the use of crop rotations with residue incorporation can result in significant differences in soil properties, yield and nutritional composition of the following crop (Brar et al., 2013; Hiel et al., 2018; Hirzel et al., 2019, 2020; Liu et al., 2019; Rong et al., 2018; Virk et al., 2017). Furthermore, the decomposition of the residue in the soil is carried out by the microbial biomass (mainly by enzymatic activities that allow the use of C, N, and other nutrients in the residue as a substrate for its metabolism). Its activity depends on some characteristics of the residue such as size, quantity, depth of incorporation, and C:N ratio (Rong et al., 2018; Wei et al., 2015; Zhao et al., 2016).

In a study conducted on wheat-pea rotation with wheat residue on surface, both soil organic carbon and total nitrogen in the top 10 cm soil profile was higher compared to the conventional system (Awale et al., 2018).

For a field experiment with three crops (winter wheat, faba bean, and corn cultivated) for six cropping seasons, using different tillage systems (reduced tillage at 10 cm depth vs. conventional tillage with ploughing at 25 cm depth), were reported effect positives on soil chemical properties (Hiel et al., 2018). They also used different residue management strategies (amount of crop residue returned to the soil and incorporation vs. exportation of residues), and showed that the main differences on soil chemical properties were mostly from the tillage practice and less from the restitution or removal of residues.
Hirzel et al. (2020) conducted experiments with two-year crop rotations (canola-corn and bean-corn) with different residue incorporation rates of canola or bean and showed that the residue incorporation rate did not affect corn grain yield. However, all canola residue levels increased soil pH and Mg, and the highest residue level reduced soil S. In addition, the soil P concentration increased proportionally with the bean residue level, and the highest bean residue level (19.0 Mg ha⁻¹) increased soil S.

Along the same lines, Swanepoel et al. (2019) conducted an experiment for two consecutive seasons with a canola crop and three wheat residue levels (high, intermediate, and low at 5.1–6.4, 4.3–5.3, and 1.5–1.9 Mg ha⁻¹, respectively) and two tillage systems (tine openers and disc openers). They indicated that the residue level of the previous crop affected the initial plant population and biomass production up to 60 days after sowing without affecting the yield of the last crop, and concluded that canola can tolerate some level of residue. However, low yields were obtained, which fluctuated between 0.9 and 1.3 Mg ha⁻¹. These authors also indicated that canola would perform best when located in a rotation sequence following a low residue-producing crop or a crop that has been grazed or harvested for biomass with relatively little residue left on the field.

Residue characteristics had been shown to affect soil microbial biomass (Rong et al., 2018). These authors demonstrated that the 13–24 cm straw length, 10–17 cm burial depth, and the 370–650 g m⁻² amount of straw were the most effective to improve soil microbial functional diversity and enzyme activity among 23 evaluated treatments.

There are few reports short-term rotations with different residue incorporation levels on both the canola crop (Brassica napus L.) yield and soil chemical properties at the end of the crop. Therefore, the objective of the present study was to determine the effect of three crop rotations and four levels of residue on grain yield, residue and dry matter production, harvest index of canola, and soil chemical properties at the end of the crop in the third year of a long-term biannual crop rotation.

**Material and methods**

The experiment was conducted for three consecutive seasons from 2016–2019 at the Santa Rosa Experimental Station (36°31’ S; 71°54’ W), INIA-Quilamapu, Chillán, Chile. The soil is volcanic (Melanoxerand). There is a temperate Mediterranean climate characterized by a hot dry summer and cold wet winter. Precipitation was concentrated in winter and spring with values of 605, 563, and 730 mm for the 2016, 2017, and 2018 seasons, respectively. The mean temperature was 12.8, 13.2, and 13.4°C and annual evaporation was 1,023, 1,041, and 980 mm for the 2016, 2017, and 2018 seasons, respectively.

**Experiment management**

The design of this long-term experiment consists of biannual rotations with three crop combinations: canola-bread wheat, canola-durum wheat, and canola-

![Figure 1. Canola plot for the biannual rotation experiment.](image-url)
corn in which residues of the previous crop are incorporated at rates of 0%, 50%, 100%, and 200%; the basic design has been maintained over time. Given this basic design, the present article focuses on the cultivation of canola as the third crop in this biannual rotation (2018–2019 season) (figure 1).

At the start of the biannual rotation experiment, lime was applied at the rate of 3000 kg ha\(^{-1}\) prior to sowing canola in April 2016 to correct soil acidity (Table 1). There were three previous crops before canola: 1) bread wheat cv. Pandora-INIA sown on 5 July 2017 and harvested on 20 January 2018, 2) durum wheat cv. Queuele-INIA sown on 20 July 2017 and harvested on 27 January 2018, and 3) corn cv. DK-469 (Dekalb) sown on 25 October 2017 and harvested on 22 April 2018.

The experimental unit was a 40 m long and 14 m wide (560 m\(^2\)) plot with 0.2, 0.2, and 0.7 m inter-row spacing for bread wheat, durum wheat, and corn, respectively. Nitrogen, P (P\(_2\)O\(_5\)), and K (K\(_2\)O) fertilization rates were 240, 120, and 120 kg ha\(^{-1}\) in bread wheat and durum wheat and 350, 120, and 120 kg ha\(^{-1}\) in corn in accordance with soil chemical properties (Table 1). In the three crops, P and K were applied 100% at sowing, while N was applied 15%, 45%, and 40% at the sowing, tillering, and flag leaf stages in bread wheat and durum wheat and 40% at sowing and 60% at the six leaves stage in corn. 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 in all crops, based on the soil chemical analysis (Table 1), with magnesium sulfate, zinc sulfate, and calcium borate fertilizers. Once the three crops were harvested, the residues were incorporated at rates of 0%, 50%, 100%, and 200% (April 2018) in the same experimental unit, and the plot was divided into four split-plots 20 m long and 7 m wide (140 m\(^2\)). Residue production was 8.0, 8.5, and 16.4 Mg ha\(^{-1}\) for bread wheat, durum wheat, and corn, respectively. The machinery used to grind and incorporate residues were a replaceable mulcher (Tornado 310, Maschio Gaspardo, Campodarsego, Italy) and a compact disk harrow (Rubin 9, Lemken GmbH and Co. KG, Alpen, Germany), respectively.

The canola (Brassica napus L.) crop ‘Imminent-SIS’ was sown on 25 May 2018 and harvested on 15 January 2019. The inter-row spacing in the canola crop was 0.7 m. Irrigation was applied to the canola crop at the flowering stage. Total weed control was carried out and disease control was not necessary. Nitrogen, P (P\(_2\)O\(_5\)), and K (K\(_2\)O) fertilization rates were 160, 120, and 80 kg ha\(^{-1}\). Phosphorus and K were applied 100% at sowing, while N was applied 50% at sowing and 50% at the 60% covering 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.

Canola 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 above ground residue. Grain and tissue samples were oven-dried at 70°C for 72 h. In addition, the harvest index was determined as the relationship between grain production and the sum of grain and above ground residue production (total dry matter production).

Soil analysis

Composite samples were collected manually from the 0–20 cm soil depth for each treatment on the same day.
canola was harvested. 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 (Sadzawka et al., 2006). Soil inorganic N (NO₃⁻-N and NH₄-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 NaHCO₃ (Olsen P) by the molybdate-ascorbic acid method. Exchangeable Ca, Mg, K, and Na were determined by 1 M NH₄OAc extraction followed by flame spectroscopy: absorption (Ca and Mg) and emission (K and Na). Soil exchangeable Al concentration was found with 1 M KCl extraction by absorption spectroscopy. Sulfur (SO₄²⁻) 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 (three crops) and the split plot was the residue level (four levels) with four replicates. Results were analyzed by ANOVA and mean were separated using 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 separately the effects of the treatment. In addition, a Pearson correlation analysis was performed for the soil chemical properties under analysis.

**Results**

**Soil chemical properties before sowing the canola crop**

The post-harvest chemical properties of the soil for the bread wheat, durum wheat, and corn crops were similar (p > 0.05) (Table 1), and without limitations for the canola crop. The increase in pH and Ca concentration from the start of the experiment in 2015 (Table 1) was due to lime application. Small variations in the other soil properties were observed from the start of the crop rotations to the end of the third season (Table 1); these were not attributed to the different crop rotations because there was no significant effect of the previous crop on the soil chemical properties before sowing the canola crop (p > 0.05) (Table 1).

**Significance analysis**

The analysis of significance (Table 2) showed a greater effect of the previous crop and limited effects of the residue level and the interaction between both factors.

**Table 2.** Significance testing of canola grain yield, residue and dry matter production, harvest index, and soil chemical properties after the canola crop harvest as affected by three previous crops and incorporation of four residue levels.

| Parameter               | Trait       | Previous crop (C) | Residue level (R) | C × R interaction |
|-------------------------|-------------|-------------------|-------------------|-------------------|
| Crop                    | Yield       | NS                | NS                | NS                |
|                         | Residue     | *                 | NS                | NS                |
|                         | Dry matter production | *          | NS                | NS                |
| Soil chemical properties | Harvest index | *              | *                 | *                 |
|                         | pH          | NS                | NS                | NS                |
|                         | Organic matter | **        | *                 | NS                |
|                         | Nitrogen concentration | **    | NS                | NS                |
|                         | Phosphorous concentration | **              | NS                | NS                |
|                         | Calcium concentration | *                | NS                | NS                |
|                         | Magnesium concentration | **              | NS                | NS                |
|                         | Potassium concentration | **          | NS                | NS                |
|                         | Sodium concentration | **           | NS                | **                |
|                         | Aluminum concentration | NS         | NS                | NS                |
|                         | Sulfur concentration | **        | NS                | *                 |

*Significant at p < 0.05; **Significant at p < 0.01; NS: nonsignificant.

The previous crop affected both the residue and total dry matter production and the harvest index in the canola crop (p < 0.05); it also affected most of the analyzed soil chemical properties and the effect was highly significant (p < 0.01) (Table 2). The soil Ca concentration was significantly affected (p < 0.05) by the previous crop, while the Al concentration was not (p > 0.05) (Table 2). The residue incorporation level had a significant effect on the harvest index, soil organic matter content (p < 0.05), and K content (p < 0.01) (Table 2). The previous crop × residue interaction

**Table 3.** Canola grain yield, residue and dry matter production, and harvest index as affected by three previous crops and incorporation of four residue levels.

| Previous crop | Residue level (%) | Grain yield (Mg ha⁻¹) | Residue production (Mg ha⁻¹) | Dry matter production (Mg ha⁻¹) | Harvest index (Mg ha⁻¹) |
|---------------|-------------------|-----------------------|-----------------------------|--------------------------------|------------------------|
| Bread wheat   | 0 4.3 Aa          | 10.6 Ba               | 14.9 Ba                     | 28.8 Ab                        |
|               | 50 4.3 Aa         | 9.5 Ba                | 13.8 Ba                     | 30.9 Aa                        |
|               | 100 4.4 Aa        | 10.3 Ba               | 14.7 Ba                     | 29.9 Aa                        |
|               | 200 4.3 Aa        | 10.6 Ba               | 15.0 Ba                     | 28.8 Ab                        |
| Durum wheat   | 0 4.0 Aa          | 9.6 Ba                | 13.6 Ba                     | 29.6 Aa                        |
|               | 50 4.1 Aa         | 9.6 Ba                | 13.7 Ba                     | 29.7 Aa                        |
|               | 100 4.8 Aa        | 11.1 Ba               | 15.9 Ba                     | 30.1 Aa                        |
|               | 200 4.5 Aa        | 11.1 Ba               | 15.6 Ba                     | 29.1 Aa                        |
| Corn          | 0 4.5 Aa          | 11.7 Aa               | 16.2 Aa                     | 27.9 Ba                        |
|               | 50 4.5 Aa         | 11.2 Aa               | 15.7 Aa                     | 28.5 Aa                        |
|               | 100 4.6 Aa        | 11.1 Aa               | 15.8 Aa                     | 29.5 Aa                        |
|               | 200 4.6 Aa        | 11.0 Aa               | 15.6 Aa                     | 29.4 Aa                        |

Different uppercase letters in the same column indicate differences between previous crops as a mean of the four incorporated residue levels according to Tukey’s test (p < 0.05).

Different lowercase letters in the same column for the same previous crop indicate differences between residue level treatments according to Tukey’s test (p < 0.05).
only affected the harvest index, soil S concentration (p < 0.05), and soil Na concentration (p < 0.01).

**Production parameters in the canola crop**

Canola grain yield was not affected by the evaluated treatments (p > 0.05) (Table 2) and fluctuated between 4.0 and 4.8 Mg ha⁻¹ (Table 3). Canola residue production varied between 9.5 and 11.7 Mg ha⁻¹ (Table 3), and the highest mean values for the previous crop effect were obtained after the corn crop (p < 0.05) (Table 3), which increased 9.7% compared with the values for the other crop rotations. The total dry matter production of canola ranged from 13.6 to 16.2 Mg ha⁻¹ (Table 3), and the highest mean values were also obtained as the effect of the previous crop after corn (p < 0.05) (Table 3), an increase of 7.8% compared to the other crop rotations. The harvest index in canola fluctuated between 27.9% and 30.9% (Table 3), and the highest mean values as the effect of the previous crop were obtained after bread wheat and durum wheat (p < 0.05). The effect of the interaction between the previous crop and the residue incorporation level on the harvest index (Table 2) occurred when the previous crops were bread wheat and corn (Table 3). After bread wheat, the highest harvest index value in canola was achieved with 50% incorporation of the previous crop residue, surpassing the treatments with no residue incorporation or with 200% bread wheat residue (p < 0.05) (Table 3). After the corn crop, the higher harvest index values in canola were reached with the incorporation of 100% and 200% of the previous crop residue, outperforming only the control without residue incorporation (p < 0.05) (Table 3).

**Soil chemical properties after canola crop harvest**

On an average, the previous crop effect after corn exhibited the highest contents of both soil organic matter and K (p < 0.5) after the canola crop harvest (Table 4). The highest concentration of both available N and P were reached after corn, surpassing only the values obtained durum wheat crop (p < 0.05) (Table 4). When canola was cultivated after durum wheat, there were lower values of both soil Ca and Mg concentrations after the canola crop was harvested (p < 0.05) (Table 3).

The previous crop × residue level interaction on soil Na concentration occurred when canola was cultivated after corn (Table 4). In this case, the highest Na concentration was obtained when 200% of the corn residue was incorporated, outperforming only the control without residue incorporation (p < 0.05) (Table 4). For the soil S concentration after the canola crop harvest, the previous crop × residue level interaction occurred when canola was cultivated after bread wheat and durum wheat (Table 4). After bread wheat, the highest soil S concentration was reached when 200% of the residue was incorporated, surpassing only the control without residue incorporation (p < 0.05) (Table 4). After durum wheat, the highest soil S concentration was obtained in the control without residue incorporation, outperforming only the treatment with 100% residue incorporation of the previous crop (p < 0.05) (Table 4).

**Correlations between soil chemical properties determined at canola crop harvest**

Following canola harvest, the soil chemical properties exhibited many correlations greater than 50% with

| Previous crop | Residue level (%) | pH | MO % | N mg kg⁻¹ | P mg kg⁻¹ | Ca cmol kg⁻¹ | Mg cmol kg⁻¹ | K cmol kg⁻¹ | Na cmol kg⁻¹ | Al cmol kg⁻¹ | S mg kg⁻¹ |
|---------------|-------------------|----|------|-----------|-----------|-------------|-------------|-------------|-------------|-------------|-----------|
| Bread wheat   | 0                 | 6.01Aa | 10.2 Ba | 11.3ABa | 23.4ABa | 5.65Aa | 0.47Aa | 0.50 Ba | 0.06Aa | 0.05Aa | 42.1ABb |
|               | 50                | 6.02Aa | 10.5 Ba | 11.9ABa | 21.9Ab | 5.76Aa | 0.49Aa | 0.56 Ba | 0.06Aa | 0.04Aa | 43.4ABab |
|               | 100               | 6.00Aa | 10.6 Ba | 8.7Ba | 21.8Aa | 5.12Aa | 0.37Aa | 0.56 Ba | 0.05Aa | 0.04Aa | 49.2ABab |
|               | 200               | 6.01Aa | 10.6 Ba | 11.5ABa | 22.0Aa | 5.55Aa | 0.44Aa | 0.74 Ba | 0.06Aa | 0.04Aa | 52.6ABa |
| Durum wheat   | 0                 | 5.97Aa | 9.7 Ba | 9.1 Ba | 21.2 Ba | 4.75 Ba | 0.31 Ba | 0.40Cc | 0.03Ca | 0.04Aa | 67.0Aa |
|               | 50                | 6.05Aa | 10.3a | 8.4Ab | 22.6 Ba | 4.63 Ba | 0.34 Ba | 0.43Cbc | 0.02Ca | 0.03Ba | 54.5Ab |
|               | 100               | 6.13Aa | 10.3 Ba | 7.5 Bb | 18.1 Ba | 4.63 Ba | 0.34 Ba | 0.52Cba | 0.03Ca | 0.03Aa | 39.2Ab |
|               | 200               | 6.06Aa | 10.3 Ba | 63Bb | 18.0 Ba | 4.69 Ba | 0.34 Ba | 0.61Ca | 0.03Ca | 0.04Aa | 62.7Ab |
| Corn          | 0                 | 6.00Aa | 10.5a | 11.3Ba | 21.8Aa | 5.23Aa | 0.36Aa | 0.61Aa | 0.03Bb | 0.04Aa | 32.4Ba |
|               | 50                | 6.01Aa | 10.7a | 12.7Aa | 22.7Aa | 5.06a | 0.38a | 0.73Aa | 0.04Bb | 0.05Aa | 38.9Ba |
|               | 100               | 5.99Aa | 11.3Aa | 13.8Aa | 26.4Aa | 5.48a | 0.46Aa | 0.84Aa | 0.04Bb | 0.06Aa | 45.5Ba |
|               | 200               | 6.12Aa | 11.7Aa | 15.6Aa | 24.3Aa | 6.09Aa | 0.48Aa | 0.90Aa | 0.07 Bb | 0.04Aa | 42.8Ba |

Different uppercase letters in the same column indicate differences between previous crops as the mean of the four incorporated residue levels according to Tukey’s test (p < 0.05).

Different lowercase letters in the same column for the same previous crop indicate differences between residue level treatments according to Tukey’s test (p < 0.05).
Table 5. Post-harvest soil chemical properties of the canola crop that showed a correlation greater than 50% and statistical significance for the harvest date.

| Soil chemical properties | Correlation value (R) | Significance value (p < 0.01)** |
|--------------------------|-----------------------|--------------------------------|
| pH                       | Calcium 0.82          | **                             |
| pH                       | Magnesium 0.68        | **                             |
| pH                       | Aluminum -0.85        | **                             |
| pH                       | Sulfur -0.70          | **                             |
| Nitrogen                 | Magnesium 0.52        | **                             |
| Nitrogen                 | Potassium 0.51        | **                             |
| Nitrogen                 | Sodium 0.64           | **                             |
| Phosphorus               | Aluminum 0.56         | **                             |
| Potassium                | Calcium 0.57          | **                             |
| Potassium                | Magnesium 0.62        | **                             |
| Potassium                | Sulfur -0.55          | **                             |
| Calcium                  | Magnesium 0.90        | **                             |
| Calcium                  | Aluminum -0.67        | **                             |
| Calcium                  | Sulfur -0.73          | **                             |
| Magnesium                | Sodium 0.60           | **                             |
| Magnesium                | Aluminum -0.59        | **                             |
| Magnesium                | Sulfur -0.76          | **                             |
| Aluminum                 | Sulfur 0.58           | **                             |

a significant effect (p < 0.01) (Table 5). Soil pH was usually positively correlated with the exchangeable Ca and Mg concentrations in the soil, and was negatively correlated with both exchangeable Al and available S concentrations in the soil (Table 5). Available N exhibited positive correlations with exchangeable Mg, K, and Na concentrations in the soil (Table 5). Available P was positively correlated only with the exchangeable Al concentration in the soil (Table 5). In general, there was a positive correlation between the K, Ca, and Mg cations in the soil (Table 5). Exchangeable Ca and Mg concentrations in the soil were negatively correlated with both soil exchangeable Al and available S in the soil (Table 5). The exchangeable Mg concentration in the soil was positively correlated with the exchangeable Na concentration in the soil (Table 5). Finally, there was a positive correlation between soil exchangeable Al and available S (Table 5).

Discussion

Grain, residue, and total dry matter production in canola

In contrast to our results for canola grain yield, other authors (Govaerts et al., 2005; Hirzel et al., 2019; Pandiaraj et al., 2015) have described significant effects of the previous crop on the grain yield of the following crop. In a review of canola crops, Assefa et al. (2018) suggest that water supply, balanced nutrition, early planting (for both winter and spring types) at a shallow depth (10–19 mm), high seeding rate (6 kg ha−1), and different rotations (canola every 3 or 4 years) are among the best management practices to increase yields. They indicate neither a greater nor lesser effect on grain yield of any crop before canola. Nevertheless, there was an effect of the previous crop on residue and total dry matter production and the canola harvest index, which concurs with findings mentioned by some authors evaluating total dry matter production of crops such as corn and durum wheat in different crop rotations (Hirzel et al., 2017; Retamal-Salgado et al., 2017). Other authors (Butterly et al., 2013; Hirzel et al., 2020; Kazemeini et al., 2014) have also reported the effects of the previous crop and the residue level on soil chemical properties at the end of the crop.

Grain yield was normal for the area under study (Hirzel et al., 2019) and is within the yield range mentioned by Assefa et al. (2018). This yield was much higher than values reported by Swanepoel et al. (2019) in their experiment with canola using three residue levels (high, intermediate, and low at 5.1–6.4, 4.3–5.3, and 1.5–1.9 Mg ha−1, respectively) and two tillage systems in the Mediterranean climate of the Western Cape of South Africa (soil with low organic matter and high bulk density). The difference in yield and soil physicochemical properties, is largely due to the availability of irrigation, given that there is a direct relationship between canola grain yield and crop water consumption (Assefa et al., 2018; Swanepoel et al., 2019). Similar to the indicated by Swanepoel et al. (2019), our result showed lack of the effect of the residue incorporation level on canola yield.

As for residue production and the contribution of these residues to the production of the total dry matter, the highest values obtained after the corn crop can be associated with a higher amount of organic C incorporated with the corn residue and the subsequent effect on soil physicochemical properties (Li et al., 2018). These effects can also be associated with differences in the nutritional contribution of previous crop residue or to the effect of residue composition on soil biomass, which can stimulate the increased activity of beneficial soil microorganisms with positive effects on the productivity of the following crop (Kumar et al., 2018; Urra et al., 2018; Zhang et al., 2018). The highest residue and total dry matter production after the corn crop negatively affected the harvest index because there were no differences in grain yield associated with the previous crop. However, the differences in the harvest index as the effect of the previous crop × residue level interaction were inconsistent when canola was cultivated after bread wheat or corn. One would have expected a higher harvest index with the lower residue rates because a greater nutrient supply associated with the incorporation of increasing residue rates could promote more vigorous plant growth (Selim, 2019). The increase in the harvest index in canola with the highest incorporation rates of corn residue can
be associated with a rapid nutrient supply from the corn crop (0.97%, 0.14%, 0.83%, 0.21%, 0.11%, and 0.06% of N, P, K, Ca, Mg, and S, respectively [Hirzel et al., 2020]). The corn crop was harvested at the end of summer and incorporated under temperature and soil moisture conditions that were favorable for soil biomass activity (Rong et al., 2018), and for the subsequent mineralization and nutrient supply available in the next canola crop. Corn residue had a C:N ratio that was lower than wheat residue; this could have promoted mineralization and nutrient supply from the corn residue (Fiorini et al., 2018).

**Soil chemical properties at canola crop harvest**

The effect of the previous crop on increased organic matter and K concentration is associated with the residue rate, as in the case of the corn crop, due to its supply of C and K (Hirzel et al., 2020). However, given the greater amount of residue applied when the previous crop was corn, an increase in the other evaluated soil nutrients would have been expected at the end of the canola crop, which was only partially observed in the concentrations of available N and P and exchangeable Ca and Mg. In the case of the P, Ca, and Mg nutrients, this can be explained by their moderate (Mg) to high (P and Ca) initial concentrations in the soil and by lime application at the start of the experiment of long-term biannual rotations, which makes it difficult to achieve a significant increase associated with the supply of nutrients with residue incorporation. As for N, determining available N is not a suitable indicator of the N reserve in the active pool or total soil N; low values of less than 20 mg kg\(^{-1}\) are normally obtained in this type of soil at the end of a crop cycle (Hirzel et al., 2020). However, after corn residue incorporation it was possible to obtain a higher concentration of available N in the soil, although not significant, associated with a lower C:N ratio of corn residue compared with bread wheat residue (Fiorini et al., 2018). The lower soil Ca and Mg concentrations when the previous crop was durum wheat could be explained by a greater effect of soil acidification after durum wheat residue incorporation; however, soil pH at the time of the canola harvest was similar to the three previous crops.

Another reason could be a greater extraction of Ca and Mg by the canola crop when it was sown after residue incorporation of durum wheat compared with residue incorporation of bread wheat and corn. Nutrient concentrations in the canola plant in each crop rotation were not determined. Hirzel et al. (2020) have reported effects of the previous crop on changes in nutrient concentration in the grain and residue of an indicator crop (bread wheat) in the same study area. A lower concentration of base cation reactions in the soil (Ca, Mg, K, and Na) are usually generated when canola is cultivated after durum wheat; this effect could be explained by soil acidification and cation exchange reactions with elements such as (H\(^+\)) and Al (Al\(^{3+}\) and Al\(^{2+}\)) (Fageria & Nascente, 2014). However, soil pH was statistically equal after each previous crop. The effects of each type of residue on the soil microbial biomass and the reactions of this biomass with basic reaction nutrients could be studied because the type of incorporated residue generates changes in the soil microbial community (Kerdraon et al., 2019). The lower soil S concentration when canola was cultivated after corn can also be related to the S requirements of the microbial biomass associated with the decomposition of corn residue (Kerdraon et al., 2019), which was not evaluated in this experiment. The effects of the previous crop \(\times\) residue level interaction on the concentrations of soil Na and S are directly related to the residue rate used when canola was cultivated after corn (Na) or after bread wheat (S), and there was an erratic effect in the S concentration when canola was cultivated after durum wheat. A higher residue rate generates a greater supply of all the nutrients both for the following crop and to increase soil bioavailable reserves (Hirzel et al., 2020; Selim, 2019).

**Soil chemical property relationship**

Regarding the correlations between soil chemical properties, it was expected that there would be positive correlations between pH and the elements Ca and Mg (Havlin et al., 1999; Kunito et al., 2016; De Vargas et al., 2019) and between base cation reactions (Ca, Mg, K, and Na) (Fageria et al., 2014; Fageria & Nascente, 2014; De Vargas et al., 2019). This would occur when fertilization is adjusted to the soil chemical properties and there are negative correlations between pH and Al concentrations or between base cation reactions and Al (Fageria & Nascente, 2014; Kunito et al., 2016; De Vargas et al., 2019). However, the negative correlation between pH and S obtained under this experimental condition cannot be generalized to all soils because the highest or lowest concentration of soil available S depends on several soil formation factors (Havlin et al., 1999). For volcanic soils, such as the one used in the present experiment and for other soils, a negative correlation between the exchangeable Al and P concentrations would have been expected (Rampim et al., 2013); however, there is more evidence of a negative correlation between available P and extractable Al in the soil (Agbenin, 2003; Havlin et al., 1999). The negative correlations found between the S concentration and base
cation reactions (Ca, Mg, K) are associated with the negative correlation between pH and the S concentration; in this soil, this can be explained by the S requirement of the microbial biomass in the mineralization processes of the nutrients supplied with residue incorporation (Havlín et al., 1999; Kerdraon et al., 2019). Likewise, the positive correlation between exchangeable Al and available S can be caused by the increased bioavailable concentration of both nutrients when soil pH decreases (Fageria & Nascente, 2014; Havlín et al., 1999; Kunito et al., 2016). The positive correlations between the available N concentration and the K, Mg, and Na concentrations can be caused by the proportional increase of these nutrients associated with the residue rate in use and the nutrient content of these residues (Hirzel et al., 2020).

Conclusions

Under the conditions of the present experiment, the bread wheat, durum wheat, and corn crops and their residue incorporation rates did not affect the grain yield of the canola crop. Canola residue production was positively affected by corn residue incorporation at different rates. The canola harvest index was negatively affected by the corn crop, but the values obtained presented an increase directly proportional to the corn residue level incorporated.

The use of different crops and their residue incorporation levels before the canola crop affected most of the soil chemical properties. We have highlighted the increase in organic matter and exchangeable K when the previous crop was corn and a decrease in the concentration of base cation reactions when the previous crop was durum wheat.

Finally, the production parameters and soil chemical properties in the canola crop were mostly affected by the previous crop and to a lesser extent by the residue incorporation rates.

Disclosure statement

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References

Agbenin, J. (2003). Extractable iron and aluminum effects on phosphate sorption in a savanna Alfisol. Soil Science Society of America Journal, 67(2), 589–595. https://doi.org/10.2136/sssaj2003.5890

Assefa, Y., Vara Prasad, P. V., Foster, C., Wright, Y., Young, S., Bradley, P., Stamm, M., & Ciampitti, I. A. (2018). Major management factors determining spring and winter canola yield in North America. Crop Science, 58(1), 1–16. https://doi.org/10.2138/cropsci2017.02.0079

Aulakh, M. S., Manchanda, J. S., Garg, A. K., Kumar, S., Dercon, G., & Nguyen, M. L. (2012). Crop production and nutrient use efficiency of conservation agriculture for soybean-wheat rotation in the Indo-Gangetic Plains of Northwestern India. Soil and Tillage Research, 120, 50–60. https://doi.org/10.1016/j.still.2011.11.001

Awale, R., Machado, S., & Rhinhart, K. (2018). Soil carbon, nitrogen, pH, and crop yields in winter wheat-spring pea systems. Agronomy Journal, 110(4), 1523–1531. https://doi.org/10.1016/j.agrisonj.2017.07.0371

Blanco-Canqui, H., & Lal, R. (2009). Crop residue removal impacts on soil productivity and environmental quality. Critical Reviews in Plant Sciences, 28(3), 139–163. https://doi.org/10.1080/07352680902776507

Brar, B. S., Singh, K., Dheri, G. S., & Kumar, B. (2013). Carbon sequestration and soil carbon pools in a rice-wheat cropping system: Effect of long-term use of inorganic fertilizers and organic manure. Soil and Tillage Research, 128, 30–36. https://doi.org/10.1016/j.still.2012.10.001

Butterly, C. R., Baldock, J. A., & Tang, C. (2013). The contribution of crop residues to changes in soil pH under field conditions. Plant and Soil, 366(1–2), 185–198. https://doi.org/10.1007/s11104-012-1422-1

De Vargas, J., Dos Santos, D. R., Camotti, M., Schaefera, G., & Bolzan, P. (2019). Application forms and types of soil acidity corrective: Changes in depth chemical attributes in long term period experiment. Soil and Tillage Research, 185, 47–60. https://doi.org/10.1016/j.still.2018.08.014

Fageria, N., & Nascente, A. (2014). Management of soil acidity in South American soils for sustainable crop production. Advances in Agronomy, 128, 221–275.

Fageria, N. K., Moreira, A., Moraes, L. A. C., & Moraes, M. F. (2014). Influence of lime and gypsum on yield and yield components of soybean and changes in soil chemical properties. Communications in Soil Science and Plant Analysis, 45(3), 271–283. https://doi.org/10.1080/00103624.2013.861906

Fiorini, A., Boselli, R., Amaducci, S., & Tabaglio, V. (2018). Effects of no-till on root architecture and root-soil interactions in a three-year crop rotation. European Journal of Agronomy, 99, 156–166. https://doi.org/10.1016/j.eja.2018.07.009

Govaerts, B., Sayre, K. D., & Decker, J. (2005). Stable high yields with zero tillage and permanent bed planting? Field Crops Research, 94(1), 33–42. https://doi.org/10.1016/j.fcr.2004.11.003

Havlín, J. L., Tisdale, S. L., Nelson, W., Havlín, J., & Beaton, J. (1999). Soil fertility and fertilizers. An introduction to nutrient management 6th ed. Prentice-Hall.

Hiel, M., Barbieux, S., Pierreux, J., Olivier, C., Lobet, G., Roisin, C., Garné, S., Colinet, G., Bodson, B., & Dumont, B. (2018). Impact of crop residue management on crop production and soil chemistry after seven
years of crop rotation in temperate climate, loamy soils. PeerJ, 6, e4836. https://doi.org/10.7717/peerj.4836

Hirzel, J., Retamal-Salgado, J., Walter, I., & Matus, I. (2017). Cadmium accumulation and distribution in plants of three durum wheat cultivars under different agricultural environments in Chile. Journal of Soil and Water Conservation, 72(1), 77–88. https://doi.org/10.2489/jswc.72.1.77

Hirzel, J., Undurraga, P., León, L., Panichini, M., Carrasco, J., Carrasco, J., & Matus, I. (2019). Different residues affect wheat nutritional composition. Journal of Soil Science and Plant Nutrition, 20(1), 75–82. https://doi.org/10.1007/s42729-019-00102-2

Hirzel, J., Undurraga, P., León, L., Panichini, M., González, J., Carrasco, J., & Matus, I. (2020). Maize grain production, plant nutrient concentration and soil chemical properties in response to different residue levels from two previous crops. Acta Agriculturae Scandinaivaca, Section B - Soil & Plant Science, 70(4), 285–293. https://doi.org/10.1080/09064710.2020.1725619

Karunakaran, V., & Behera, U. K. (2016). Tillage and residue management for improving productivity and resource-use efficiency in soybean (Glycine max)-wheat (Triticum aestivum) cropping system. Experimental Agriculture, 52(4), 617–634. https://doi.org/10.1017/S0014479715000289

Kazemeini, S. A., Bahrami, M. J., Pirasteh-Anosheh, H., & Mehdi, S. M. (2014). Maize growth and yield as affected by wheat residues and irrigation management in a no-tillage system. Archives of Agronomy and Soil Science, 60(11), 1543–1552. https://doi.org/10.1080/03650340.2014.896457

Kerdraon, L., Balesdent, M., Barret, M., Laval, V., & Sabout, F. (2019). Crop residues in wheat-oilseed rape rotation system: A pivotal, shifting platform for microbial meetings. Microbial Ecology, 77(4), 931–945. https://doi.org/10.1007/s00248-019-01340-8

Kumar, M., Kundu, D. K., Ghorai, A. K., Mitra, S., & Singh, S. R. (2018). Carbon and nitrogen mineralization kinetics as influenced by diversified cropping systems and residue incorporation in Inceptisols of Eastern Indo-Gangetic Plain. Soil and Tillage Research, 178, 108–117. https://doi.org/10.1016/j.soiltell.2017.12.025

Kunito, T., Isomura, I., Sumi, H., Park, H.-D., & Toda, H. (2016). Aluminum and acidity suppress microbial activity and biomass in acidic forest soils. Soil Biology & Biochemistry, 97, 23–30. https://doi.org/10.1016/j.soilbio.2016.02.019

Li, Z., Lai, X., Yang, Q., Yang, X., Cui, S., & Shen, Y. (2018). In search of long-term sustainable tillage and straw mulching practices for a maize-winter wheat-soybean rotation system in the Loess Plateau of China. Field Crops Research, 2017, 199–210. https://doi.org/10.1016/j.fcr.2017.08.021

Liu, Z., Gao, T., Liu, W., Sun, K., Xin, Y., Liu, H., Wang, S., Li, G., Han, H., Li, Z., & Ning, T. (2019). Effects of part and whole straw returning on soil carbon sequestration in C3-C4 rotation cropland. Journal of Plant Nutrition and Soil Science, 182(3), 429–440. https://doi.org/10.1002/jpln.201800573

Malhi, S. S., Lemke, R., Wang, Z. H., & Chhabra, B. S. (2006). Tillage, nitrogen and crop residue effects on crop yield, nutrient uptake, soil quality, and greenhouse gas emissions. Soil and Tillage Research, 90(1–2), 171–183. https://doi.org/10.1016/j.still.2005.09.001+1

Motazedian, A., Kazemeini, S. A., & Bahrami, M. J. (2019). Sweet corn growth and grain yield as influenced by irrigation and wheat residue management. Agricultural Water Management, 224, 105748. https://doi.org/10.1016/j.agwat.2019.105748

Naab, J. B., Mahama, G. Y., Yahaya, I., & Prasad, P. V. V. (2017). Conservation agriculture improves soil quality, crop yield, and incomes of smallholder farmers in North Western Ghana. Frontiers in Plant Science, 8, 996. https://doi.org/10.3389/fpls.2017.00996

Pandiaraj, T., Selvaraj, S., & Ramu, N. (2015). Effects of crop residue management and nitrogen fertilizer on soil nitrogen and carbon content and productivity of wheat (Triticum aestivum L.) in two cropping systems. Journal of Agricultural Science and Technology, 17, 249–260. http://jast.modes.acổi/article-23-2448-en.html

Rampim, L., Lana, M. C., & Fradolosso, J. F. (2013). Available phosphorus and sulphur, exchangeable aluminium and remaining phosphorus in rhodic eutroch submitted to gypsum cultivated with wheat and soybean. Semina. Ciências Agrárias, 34(4), 1623–1638.

Retamal-Salgado, J., Hirzel, J., Walter, I., & Matus, I. (2017). Bioaccumulation and bioaccumulation of cadmium in the straw and grain of maize (Zea mays L.) in growing soils contaminated with cadmium in different environment. International Journal of Environmental Research and Public Health, 14(11), 1399. https://doi.org/10.3390/ijerph14111399

Rong, G., Ning, Y., Cao, X., Su, Y., Li, J., Li, L., Liu, L., & Zhou, D. (2018). Evaluation of optimal straw incorporation characteristics based on quadratic orthogonal rotation combination design. Journal of Agricultural Science, 156(3), 367–377. https://doi.org/10.1007/s42729-019-01340-8

Sadzawka, A., Carrasco, M. A., Grez, R., Mora, M. L., Flores, H., & Neaman, A. (2006). Métodos de análisis recomendados para los suelos de Chile. Revisión 2006. Serie Actas INIA Nr 34. Instituto de Investigaciones Agropecuarias (INIA).

Selim, M. M. (2019). A review of advantages, disadvantages and challenges of crop rotations. Egyptian Journal of Agronomy, 41(1), 1–10. https://doi:10.21608/AGRO.2019.6606.1139

Stella, T., Mouratidou, I., Gaiser, T., Berg-Mohnicke, M., Wallor, E., Ewert, F., & Nendel, C. (2019). Estimating the contribution of crop residues to soil organic carbon conservation. Environmental Research Letters, 14(9), 094008. https://doi.org/10.1088/1748-9326/ab395c

Swanepoel, P. A., le Roux, P. J. G., Agenbag, G. A., Strauss, J. A., & MacLaren, C. (2019). Seed-drill opener type and crop residue load affect canola establishment, but only residue load affects yield. Agronomy Journal, 111(4), 1658–1665. https://doi.org/10.2134/agronj2018.10.0695

Urra, J., Mijangos, I., Lanzén, A., Lloveras, J., & Garbisu, C. (2018). Effects of corn stover management on soil quality. European Journal of Soil Biology, 88, 57–64. https://doi.org/10.1016/j.ejsobi.2018.06.005

Virk, H. K., Singh, G., & Manes, G. S. (2019). Nutrient uptake, nitrogen use efficiencies, and energy indices in soybean under various tillage systems with crop residue and nitrogen levels after combine harvested wheat. 1–11. Journal of Plant Nutrition. https://doi.org/10.1080/01904167.2019.1683190

Virk, H. K., Singh, G., & Sharma, P. (2017). Effect of tillage, crop residues of preceding wheat crop and nitrogen levels on biological and chemical properties of soil in the soybean-wheat cropping system. Communications in Soil Science and Plant Analysis, 48(15), 1764–1771. https://doi.org/10.1080/00103624.2017.1395446

Wei, T., Zhang, P., Wang, K., Ding, R., Yang, B., & Nie, J. (2015). Effects of wheat straw incorporation on the availability of soil
nutrients and enzyme activities in semiarid areas. *Plos One*, 10(4), e0120994. https://doi.org/10.1371/journal.pone.0120994
Yang, H. S., Yang, B., Dai, Y. J., Xu, M. M., Koide, R. T., Wang, X. H., Liu, J., & Bian, X. M. (2015). Soil nitrogen retention is increased by ditch-buried straw return in a rice-wheat rotation system. *European Journal of Agronomy*, 69, 52–58. https://doi.org/10.1016/j.eja.2015.05.005
Zhang, L., Wang, J., Fu, G., & Zhao, Y. (2018). Rotary tillage in rotation with plowing tillage improves soil properties and crop yield in a wheat-maize cropping system. *Plos One*, 13(6), e0198193. https://doi.org/10.1371/journal.pone.0198193
Zhao, S., Li, K., Zhou, W., Qiu, S., Huang, S., & He, P. (2016). Changes in soil microbial community, enzyme activities and organic matter fractions under long-term straw return in North-Central China. *Agriculture, Ecosystems & Environment*, 216, 82–88. https://doi.org/10.1016/j.agee.2015.09.028