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To cite this article: Juan I. Vanzolini, Juan A. Galantini, Juan M. Martínez & Liliana Suñer (2017): Changes in soil pH and phosphorus availability during decomposition of cover crop residues, Archives of Agronomy and Soil Science, DOI: [10.1080/03650340.2017.1308493](https://doi.org/10.1080/03650340.2017.1308493)

To link to this article: <http://dx.doi.org/10.1080/03650340.2017.1308493>



Accepted author version posted online: 20 Mar 2017.
Published online: 30 Mar 2017.



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Changes in soil pH and phosphorus availability during decomposition of cover crop residues

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ABSTRACT

The aim of this study was to determine the effect of winter cover crop (CC) residues on soil pH and phosphorus (P) availability. Three incubation assays were performed in pots using two CC: vetch (V) (*Vicia villosa* Roth.) and oats (Oa) (*Avena sativa* L.). Soil samples were taken from 10 sites at 0–20-cm depth. The rate of residues were 0 (D0), 10 (D1), 20 (D2), 30 (D3), and 40 (D4) g dry matter kg⁻¹ soil and the soil sampling was after 10, 20, 30, 60, 90, and 120 days of incubation. Soil pH, extractable P (Pe), and soil organic matter (SOM) and its fractions were determined. The pH increase was correlated with the rate applied (D1 < D2 < D3 < D4). No differences were found for pH comparing V and Oa residues with low residue rates. Soil pH changes were dependent from initial pH and SOM fractions in different soils across the incubation period. The multiple regression models showed that the pH changes were dependent on initial pH level and SOM fractions with a high R² (0.81). CC residues and its quantities produced different changes on pH – especially at the beginning of the incubation – which influenced the P availability.

ARTICLE HISTORY

Received 16 November 2016
Accepted 14 March 2017

KEYWORDS

Residue decomposition; soil organic matter fractions; vetch; alkalization

Introduction

Soil pH is one of the main factors in determining soil fertility and it may be affected by crop and residue management. There are contradictory results regarding cropping effects on the direction and magnitude of pH changes. Some authors have suggested that accumulation of fresh organic matter may be one of the causes of soil acidification (Tang et al. 1999), particularly in soils under legume crops. This acidification is mainly attributed to the imbalance between carbon (C) and nitrogen (N) cycles, in the short and long term.

Plant roots take up cations and anions from the soil solution to satisfy their growth requirements. The specific plant requirements and the soil solution composition determine the relative amount of ions. In most cases, plants take up more cations than anions and release protons to maintain the charge balance. During biological N₂ fixation by legumes, the proton excretion by roots is closely related to organic anion accumulation (malate, citrate, and oxalate) in plant tissues. Mengel and Steffens (1982) proposed that the proton release by plants increased the pH in plant cells, which stimulates the synthesis of organic anions. However, Mengel (1994) suggested that organic anions accumulated in plants are a source of potential alkalinity, which is likely to cause an increase in soil pH when they are decomposed by soil microorganism activity. Organic anion concentration may be calculated as the difference in charges between cations and inorganic

anions (Equation (1)), known as concentration of excess cations (EC), as described by Yan and Schubert (2000):

$$\text{Alkalinity} = (\text{K}^+ + \text{Ca}^{2+} + \text{Mg}^{2+} + \text{Na}^+) - (\text{H}_2\text{PO}_4^{4-} + \text{SO}_4^{2-} + \text{Cl}^-). \quad (1)$$

The incorporation of plant materials increase soil pH, mainly by reactions between H^+ and added organic matter, and via ammonification and decarboxylation processes during decomposition (Yan et al. 2006). Several studies have shown that residues from dicotyledonous plants typically have higher concentrations of organic anions and a greater alkaline effect than grass residues (Yan & Schubert 2000; Paul et al. 2001; Xu & Coventry 2003; Xu et al. 2006a).

On the other hand, Tang and Yu (1999) reported that the direction and magnitude of pH changes depend on the concentration of organic anions and N in the added plant material and the initial soil pH. The incorporation of plant material containing high N-levels may modify the N-cycle in the soil and therefore produce variations in soil pH. The processes involved in the N-cycle and their effect on soil pH were described by Bolan and Hedley (2003). The potential for pH to change also varies between residues with different quality (Pocknee & Sumner 1997; Tang & Yu 1999); the highest pH change was obtained from residues with a high N-content or fertilized residues (Schomberg et al. 1994).

Soil characteristics may influence the dynamics of residue decomposition, thus modifying the effect the residue may have on soil chemical or physical properties. The degree of pH changes is directly related to the soil–residue relationship, and it depends on the initial soil pH (Xu et al. 2006a; Wang et al. 2012). In moderately acid soils, incorporation of residues with a low concentration of EC (alkalinity) caused the decrease on soil pH (Tang & Yu 1999). However, in soils with low initial pH, which they incubated with legume residues, the increase of pH was observed (Tang et al. 1999).

Paul et al. (2001) found that incorporation of particulate organic matter (POM) into the soil may cause changes in the short term. The soil POM content varies with crop sequences (Galantini et al. 2002), management systems (Migliarina et al. 2000; Duval et al. 2013), and water availability; tending to decline when water is available during the fallow period (Martínez et al. 2017), and to increase during the crop cycle (Galantini & Rosell 2006).

When cover crops (CCs) are included in no-tillage (NT) systems, residues accumulate on the soil surface and their nutrient content – which is usually high – is stratified at the surface level (Duval et al. 2016). Changes in soil pH may affect the balance of the various forms of certain nutrients, as well as their availability to plants, especially phosphorus (P) (Lindsay 1979).

With CC implementation under NT, non-removal of residues may cause changes of considerable magnitude on the soil pH, thus affecting the extractable P (Pe) that could be the more labile P fraction available for plant. Some authors (Xu et al. 2006a; Wang et al. 2016) have studied the effects of crop residues on pH, and others (Zheng et al. 2004; Alamgir & Marschner 2013) have studied their effects on P availability dynamics. This may be of great importance for the nutrition of the subsequent crop (Suñer et al. 2014); however, there is no information on the extent of these changes, or the factors that may affect them.

The hypothesis was that CC residues have an impact on soil pH and affects the P availability, which could be different in accordance to the soil characteristics.

The aims of this study were (i) to assess the effects of applying different rates of vetch (V) residues on soil pH and Pe in soils with different initial pH values; and (ii) to compare them to the effects of oats (Oa) residue incorporation.

Materials and methods

Soil sampling

The soil sampling was performed in 10 sites located in the southwest of the Argentine Pampas. The samples were collected at a 0–20-cm soil depth. Three sampling areas of about 50 m² were selected in each site; they were representative of the fields to reduce spatial variability. A composite soil sample (16

and 20 soil cylinders) was collected from each sampling area (replications) at each site. After being air-dried, they were passed through a 2-mm sieve and fully homogenized. The soil classification (IUSS Working Group WRB 2015) is shown in Table 1. In order to assess the effects of V residue incorporation on pH and Pe, three incubation assays were performed. For each experiment, the dynamics of soil pH and Pe changes over time was analyzed by comparing the values obtained at the beginning of incubation against the ones obtained after 10, 20, 30, 60, 90, and 120 days.

Chemical and physical analyses

The soil samples were air-dried, sieved (<2 mm), and chemically analyzed for the following parameters: soil organic carbon (SOC) by dry combustion using a Leco C automatic analyzer (Leco Corporation, St Joseph, MI); pH in a soil-water suspension of 1:2.5; extractable P (Pe) by Bray-Kurtz I (0.025 mol L⁻¹ HC1 and 0.03 mol L⁻¹ NH₄F, pH 2.6) (Bray & Kurtz 1945). Soil organic matter (SOM) was estimated by multiplying the SOC values by the 1.724 factor (Nelson & Sommers 1982). The SOM fractions were determined by physical fractionation (Duval et al. 2013). The physical fractionation of SOM was performed by wet sieving (Cambardella & Elliott 1992; Duval et al. 2013). Briefly, 50 g of soil previously air-dried and sieved were dispersed in 120 mL glass containers, and mixed with 100 mL of distilled water. Ten glass beads (5 mm diameter) were added to increase aggregate destruction and reduce potential problems created by sand (Cambardella & Elliott 1992). After dispersion soil suspension was sieved through two connected sieves: 100 microns and 53 microns of diameter. Sieves were, moved back and forth and soil retained in the top of the sieves was sprinkled with distilled water until the water at the bottom sieve was clear to the naked eye. Three fractions were obtained: one with a particle size less than 50 microns, containing clay, silt, and the mineral-associated organic carbon (MOC) fraction; an intermediate fraction of 53–100 microns, containing very fine sands and fine particulate organic carbon (fPOC); and a coarse fraction of 100–2000 microns, containing the rest of the sands and the coarse POC (cPOC). Silt + clay content was estimated by the difference between the FF content (<53 microns) minus its organic matter, assuming a 58% of C content (MOC/0.58) (Duval et al. 2013). The analytical data of the sampled sites are summarized in Table 1.

Cover crop residues

The residues were obtained from the dry matter (DM) of V (*Vicia villosa* Roth) at 50% flowering, and oats (*Avena sativa* L.) (Oa) at flowering stage. The samples were collected prior to herbicide application, stove-dried (60°C), and then ground in a Thomas-Wiley mill (Model 4) through a 1-mm mesh. They were chemically characterized in terms of N concentration, alkalinity (EC), and the

Table 1. Soil characteristics and properties of the soils used in the different experiments.

| Soil | Location | Soil classification ^a | pH | Pe (mg kg ⁻¹) | S + c (%) | SOM | SOM fraction | | |
|----------------|--------------|----------------------------------|----------|------------------------------|--------------|---------|------------------------------|----------|----------|
| | | | | | | | MOC (g kg ⁻¹) | cPOC | fPOC |
| A ₁ | Ascasubi | Haplic Kastanozem | 7.0(0.2) | 30(4.6) | 25.6(2.1) | 19(1.1) | 8.3(0.4) | 1.3(0.4) | 1.5(0.2) |
| A ₂ | Ascasubi | Haplic Kastanozem | 7.0(0.1) | 25(8.0) | 23.7(4.0) | 19(0.8) | 7.3(0.8) | 2.4(0.6) | 1.3(0.3) |
| C ₁ | Cabildo | Haplic Kastanozem | 7.1(0.2) | 43(5.2) | 20.7(1.8) | 16(0.5) | 7.4(0.9) | 1.2(0.3) | 0.9(0.1) |
| C ₂ | Cabildo | Haplic Kastanozem | 8.0(0.4) | 8(1.2) | 23.9(2.2) | 12(1.1) | 6.3(0.4) | 1.0(0.4) | 1.0(0.2) |
| C ₃ | Cabildo | Haplic Kastanozem | 6.5(0.2) | 7(0.9) | 22.9(5.0) | 13(1.0) | 6.2(0.8) | 0.9(0.4) | 0.8(0.3) |
| C ₄ | Cabildo | Haplic Kastanozem | 6.3(0.2) | 30(6.4) | 34.2(2.6) | 20(1.8) | 10.4(1.0) | 1.2(0.7) | 2.1(0.6) |
| C ₅ | Cabildo | Haplic Kastanozem | 6.7(0.3) | 8(2.6) | 35.5(4.1) | 17(0.8) | 8.9(1.0) | 0.9(0.3) | 1.7(0.4) |
| C ₆ | Cabildo | Haplic Kastanozem | 7.2(0.2) | 6(1.0) | 27.1(1.6) | 19(2.1) | 5.4(1.3) | 1.0(0.4) | 0.8(0.2) |
| Cg | Cagliero | Calcic Vertisol | 7.2(0.1) | 13(2.2) | 17.8(0.9) | 11(0.8) | 6.8(0.9) | 2.4(0.8) | 1.5(0.4) |
| O | Tte. Origone | Calcic Vertisol | 7.4(0.2) | 5(0.8) | 13.0(2.1) | 12(1.4) | 5.6(0.4) | 2.5(0.9) | 1.2(0.3) |

^aWorld Reference Base for Soil Resources, IUSS Working Group WRB (2015). Values in brackets indicate the standard deviation. Pe, extractable phosphorus; S + c, silt plus clay content; SOM, soil organic matter; MOC, mineral-associated organic carbon; POCf and POCc, fine (50–100 µm) and coarse particulate organic carbon (100–2000 µm), respectively.

C:N ratio (Xu et al. 2006b). The chemical residue composition was described in Table 2. The application rate was determined on the basis of the production of increasing DM. The rates of residue used in the different experiments were: 0, 10, 20, 30, and 40 g DM kg⁻¹ soil, denominated as D0, D1, D2, D3, and D4, respectively.

Long-term laboratory incubation

Briefly, 40 g of air-dried soil (four replicates) was placed in a 100-mL plastic container (7 cm high and 5 cm wide), with two 5-mm diameter holes were drilled into each container lid to facilitate the aerobic exchange. Then, the CC residues were thoroughly mixed within the soils and then wetted to field capacity at the start of incubation. In order to restore microbial activity, the soils were preincubated at 25°C and at field-holding capacity for 10 days in the darkness (Xu et al. 2006a). Soil total porosity (TP) of the air-dried soil was determined (Klute 1986), and a soil mass percentage of 60% of TP was estimated by mass difference. The soils were incubated for 120 days at 25°C. The water content in the container was maintained periodically by weight at 60% of TP across the incubation.

Effects of residue application rate

For analyzing the effect of V residue rates only two soils were used. Soils A₁ and C₁ were incubated with different rates of vetch residues: D0, D1, D2, D3, and D4. The experimental design was fully randomized with three replications. The sampling was performed after 10, 20, 30, 60, 90, and 120 days of incubation. Also, soil inorganic N (NO₃-N plus NH₄-N) was determined by steam distillation (Mulvaney 1996). The experiment was carried out in a split-plot design, where the soil type was the main plot and the amount of residue was the subplot.

Residue quality effects

For analyzing the differences between CC residue quality (V and Oa) only two soils were used. Soils A₁ and C₁ were incubated with two levels (D1 and D4) of Oa residue, and they were compared to the pH changes obtained after V incorporation. The treatments were defined as: control (D0), V, and Oa. The experimental design was completely randomized design with three replications. The sampling was performed after 10, 60, and 120 days of incubation. Soil samples were air-dried, homogenized in a mortar, and then analyzed.

Residue effects on different soils

Ten soils (A₁, A₂, C₁, C₂, C₃, C₄, C₅, C₆, C_g, O) were incubated with three V residue rates (D0, D1, and D4). The experimental design was completely randomized design with three replications. In this experiment, three sampling times were used: 10, 60, and 120 days of incubation. Then, each soil sample was air-dried, homogenized in a mortar, and then analyzed.

Statistical analysis

A three-way analysis of variance (ANOVA) was used to test the differences between residue application rates, residue quality, and effects of residue in different soils. When a significant

Table 2. Chemical composition of the residues used in incubations.

| Residue | C | N | S | P | Na | Mg | Ca | K | Cl | EC | |
|---------|-----|-----|----|-----|-----|-----|-----|------|------|-----|-----------------------|
| | C:N | | | | | | | | | | (g kg ⁻¹) |
| Vetch | 41 | 4.0 | 10 | 2.8 | 3.2 | 1.3 | 2.8 | 14.8 | 38.3 | 7.7 | 1625 |
| Oats | 42 | 2.3 | 18 | 2.2 | 2.7 | 1.7 | 1.3 | 4.1 | 31.6 | 4.6 | 927 |

EC, alkalinity.

interaction was detected, a one-way ANOVA was performed in accordance to the aims of each experiment. Mean test values were compared using the least significant difference with a significance level of 0.05 probability level. Multiple regressions were performed to find a model that could describe the effects of V residue incorporation on soil pH and Pe. All data were analyzed using Infostat statistical software (Di Rienzo et al. 2013).

Results and discussion

Effects of residue application rate

The results showed a soil–rate–time interaction ($p < 0.05$), so the data were separately analyzed for each soil. However, the pH in both soils showed a significant rate–time interaction; a rate–time interaction was found in A_1 , but not in C_1 . In the case of significant interactions, the results were analyzed in terms of the application rate effects observed at each sampling time.

The initial pH was 7.0 for A_1 and 7.1 for C_1 , and during the incubation period the parameter decreased ($p < 0.05$) in both soils. This is in agreement with the results obtained by Paul et al. (2001), who observed a soil pH decline in incubated soils with no residue incorporation. They attributed this pH decrease to the soil N mineralization during incubation, which was followed by nitrification. In general, residue incorporation at the lowest rate (D1 and D2) into soil A_1 caused the decrease ($p < 0.05$) of soil pH, but at end of the incubation period it was the same as the control treatment ($p > 0.05$). High rates of residue (D3 and D4) increased the pH in A_1 ; when incubation was over, however, only D_4 resulted in a pH significantly higher than the control (0.3 units). Residue incorporation in C_1 increased soil pH, from 0.4 to 2.0 depending on the rate of application. This effect disappeared with time incubation in D1 (20 days) and D2 (120 days). However, the pH in C_1 was significantly higher ($p < 0.05$) than the control after D3 and D4 applications (0.6 and 1.0 units, respectively) at the end of the incubation period. Owing to the pH decrease in the control treatment (D0) during the incubation period and in order to standardize the changes, alterations in the pH (Δ pH) during that period were described in Figure 1(a,c). As mentioned above, laboratory incubation studies showed that incorporation of organic anions from plant material into the soil results in a rapid pH increase, followed by a gradual pH decline (Hoyt & Turner 1975; Yan et al. 1996; Tang et al. 1999; Butterly et al. 2012). In this experiment, soil pH increased almost immediately in A_1 and C_1 , even though the extent was different (Figure 1(a,c)). The increase of initial pH was correlated with the rate applied, so the value was higher when the quantity of added residue was increased ($D1 < D2 < D3 < D4$).

In A_1 , initial pH increase following residue incorporation was lower than in C_1 . The slight pH rise in A_1 at the highest residue rate may be attributed to a high SOM content in the soil. Probably, there was a strong activity of decomposing microorganisms in A_1 and it managed to stabilize the pH faster. The pH decrease with D1 and D2 after 30 days of incubation was attributed to the nitrification of mineralized N of the residue and the subsequent release of H^+ (Figure 1(a)).

In C_1 , the average initial pH rose by 1.9 units when the soil was treated with the highest rate (D3 and D4). This result may be attributed to the lower SOM content and to the microbial activity, increased pH following release of anions within the residue. On the other hand, application of D1 and D2 in C_1 did not alter the final soil pH (Figure 1(c)).

Residue decomposition and microbial processes which hydrolyze organic N also play a key role in altering soil pH. Ammonification, the process that converts organic N into NH_4^+ ions, consumes protons. On the other hand, nitrification, the process by NH_4^+ ion is oxydized to NO_3^- , and releases protons. These processes generate, in theory, one mol of H^+ for every mol of N transformed. Both ammonification and nitrification are likely to be affected by the initial soil pH, but the latter is more sensitive to low pH levels than ammonification (Robson & Abbot 1989). Even when a pH increase occurred at the beginning of incubation, all treatments showed a tendency towards a decreasing soil pH over time. This gradual pH decline during incubation was attributed to the nitrification reaction of the residue, depending on the initial soil pH conditions (Xu et al. 2006a; Wang et al. 2016).

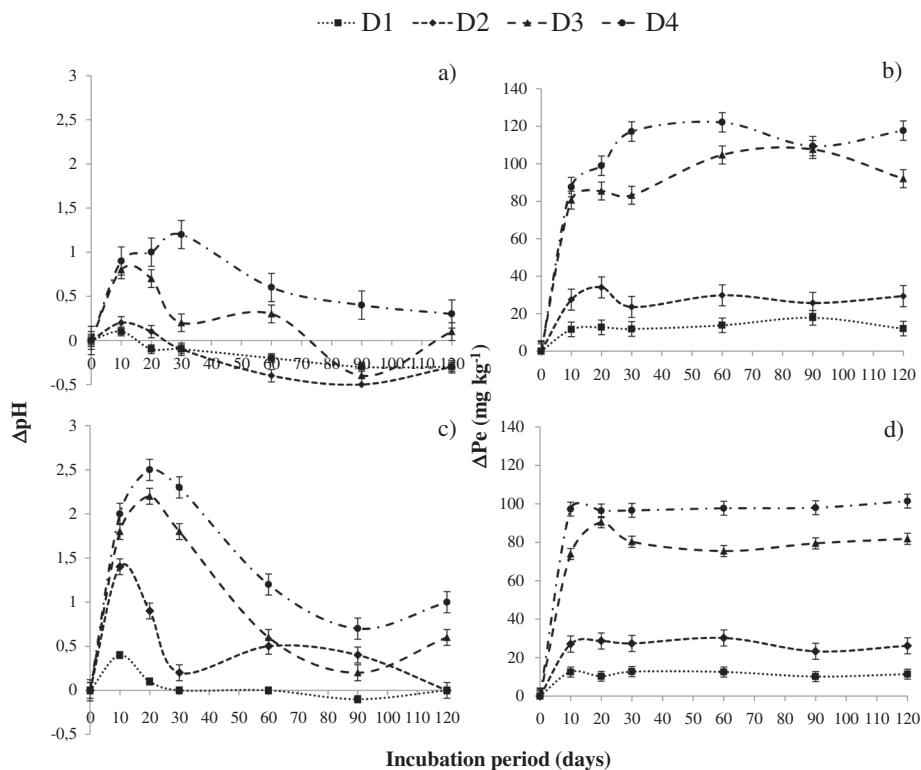


Figure 1. Changes in pH (left) and Pe (right) with different vetch application rates (D1, D2, D3, D4) over a 120-day incubation period for A₁ (a; b) and C₁ (c; d). Vertical bars indicate the standard deviation.

Alkalinity release (decomposition of organic anions) from added V residues and ammonification residue N resulted in a pH increase, whereas nitrification of residue N resulted in a pH decline. Xu and Coventry (2003) found that incorporation of alkalinity and ammonification of organic N are the two main factors leading to a pH increase, whereas nitrification favors the pH decline. These authors state that the balance between these reactions determines the final soil pH. The association/dissociation of organic compounds may also play a role in pH changes, depending on the initial soil pH. The overall effect on soil pH after incorporation of plant residues would therefore depend on the extent of each process under the given conditions (Yan & Schubert 2000).

In A₁, the ammonification process was not very significant over the 120-day incubation period (Figure 2). Concentration of NH₄⁺ in soil A₁ with the application of D1 remained unchanged as compared with the control. Application of D4 produced a slight increase in concentration of NH₄⁺ in the soil. For this reason, it may be inferred that, due to the small alteration in NH₄⁺ levels, the pH change seen during the first days of incubation of A₁ occurred because of the release of organic anion from V residues.

In C₁, the initial ammonification process of residue N was more significant, and it became evident in the strong initial pH increase. During incubation, NH₄⁺ levels became lower. At the same time, an increase in NO₃⁻ concentration occurred, indicating ammonia nitrification, thus declining the soil pH. The processes previously described showed some effects of residue incorporation on soil pH. Both anion release and the mineralization reactions of the N contained in the residue altered the pH.

The initial Pe levels in both soils were 30 mg kg⁻¹ for A₁ and 43 mg kg⁻¹ for C₁. Upon examining the results, a rate–time interaction ($p < 0.05$) was found and the effect of each residue rate was separately analyzed. In general, both in A₁ and C₁, Pe levels were not altered in the controls during

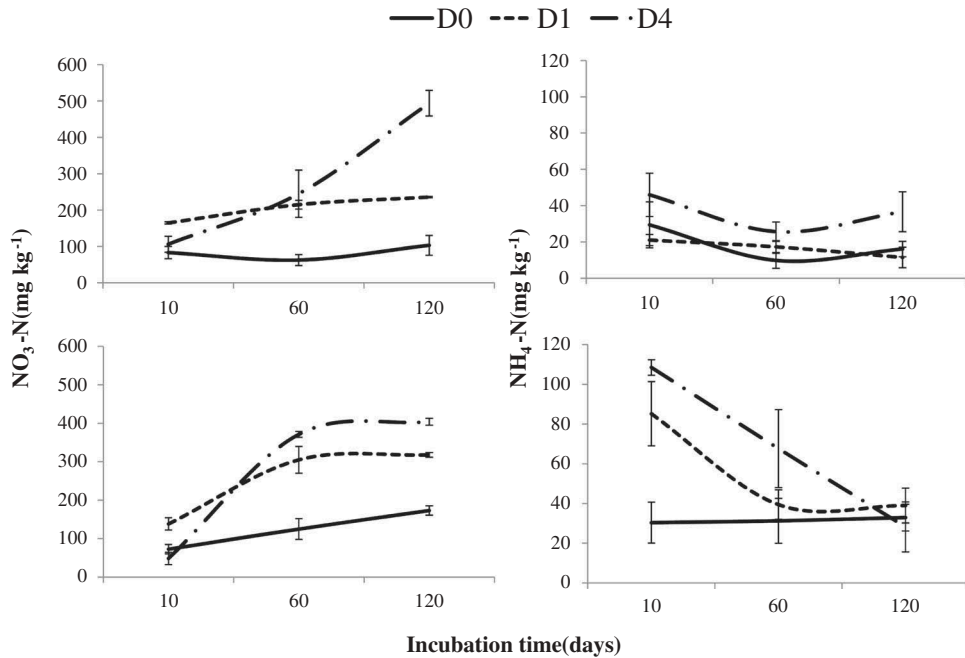


Figure 2. Concentrations of inorganic N ($\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$) during the incubation period of soils A_1 (a; b) and C_1 (c; d).

incubation, but they did go up as the amount of V residue was increased (Figure 1(b,d)). However, the incorporation of V residues increased P availability in the soil. These residues contained $3.29 \text{ g P kg}^{-1} \text{ CC}$, meaning that they added P into the soil after decomposing. There was some evidence, however, that changes in Pe may be related to pH changes.

The study showed that the increase of residue application increase soil pH and then tended to equal the initial value. The degree of this change was depending on residue rate and it was highest in soil with low SOM, where residue decomposition was faster.

Residue quality effects

The ANOVA of the whole data showed a significant soil–time–residue interaction for the pH and Pe variables, since the results from each soil showed differences considering the type of residue (V and Oa) and rate applied. Consequently, the results were assessed for each soil separately. In A_1 , a triple interaction (rate–time–residue) was found and, in order to analyze the results, the application rate and the incubation time were fixed; the differences in the both CC residues were observed. In C_1 , there were single interactions (rate–time and rate–residue), so the analysis was performed by comparing the results of each residue in terms of rate and time.

Once incubation was completed for soil A_1 , significant differences ($p < 0.05$) between residues were shown by D1 (data not shown). After Oa residue addition, pH levels in the incubated soil were higher than with V residue incorporation. Other authors, however, have found that legumes have a greater alkalization capacity over grass plants, although this may be due to the low amount of added residue. With D4 rate, V residues caused the soil pH level to rise higher than Oa residues did during the 120-day incubation period. This means that the alkalization capacity of legume residues becomes noticeable when application level is high. Application of D1 in C_1 – the soil with lower SOM content – did not result in significant differences between the both residue types. In contrast, the rate D4 in C_1 produced significant differences ($p < 0.05$) in soil pH with V and Oa residues.

Decomposition of Oa residues decreased pH in comparison with V, but it did not decrease below the control treatment level.

In the short term, it could be concluded that the soil pH behavior was similar when the application rate of both residues were low. However, the alkalization capacity of legume residues becomes evident when the residue rates were high and the changes were sharper in the soil with lower SOM content (Figure 3).

As to the change observed in Pe, higher levels produced after application of the lowest residue rate were similar comparing the two CC residues under study (Table 3). However, when the highest rate was applied, the Pe change was greater for V than for Oa (Figure 3). In this case, the decomposition rate of the residues may have been dissimilar due to the differential quality characteristics of grass and legume plants. Rapid decomposition of V residues not only modifies soil pH but also favors decomposition of native SOM by incorporating N and converting organic into inorganic P.

Residue effects on different soils

Analysis of the overall data indicated a soil–rate–time interaction ($p < 0.05$); the results were examined for each soil in particular, taking into account the changes on soil pH and Pe at each sampling time. The lowest residue rate did not result in pH changes after the 120-day incubation period, such as in C₁, C₂, C₃, C₅, O, and C_g soils. Nevertheless, when the highest rate was applied, the pH change was different for each soil. In C₁ and C₃, the final pH following incubation was greater than the initial pH. In soils A₁, C₄, and C₆ with low application rates, post-incubation pH levels were lower than the initial pH levels. In the case of the first two soils, applications of the highest rate of residue increase the pH. However, in C₆ a decrease in the final pH also occurred, as compared with the initial pH.

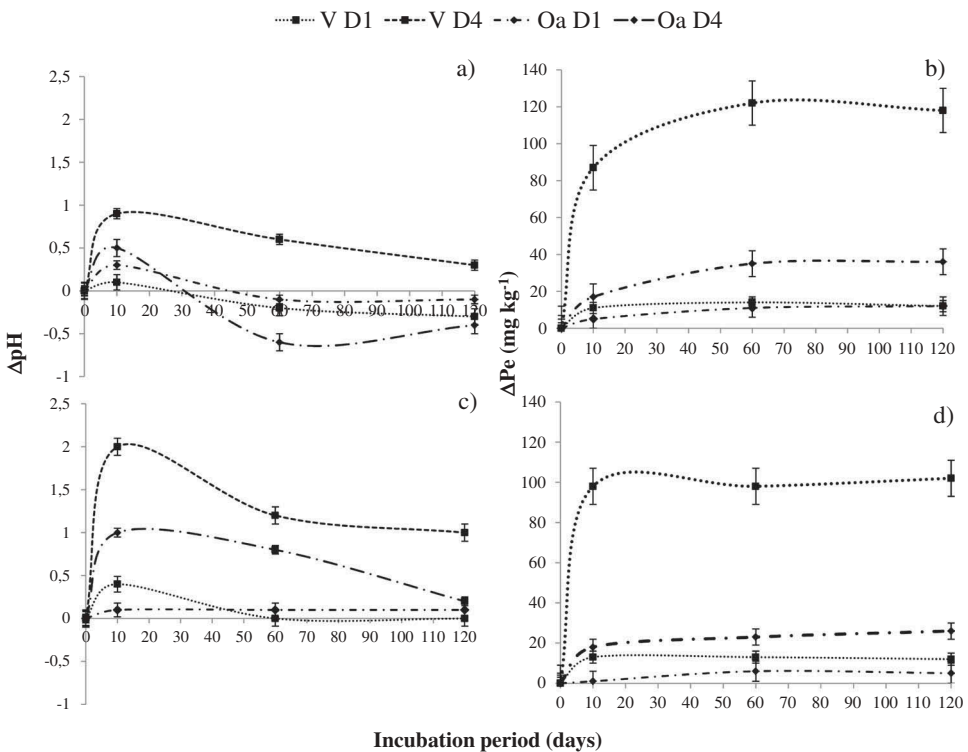


Figure 3. Changes in pH (left) and Pe (right) during incubation with application of two rates (D1 and D4) of vetch and oats residues (V and Oa) for soils A₁ (a; b) and C₁ (c; d). Vertical bars indicate the standard deviation.

Table 3. Changes in pH and Pe (mean \pm standard deviation) during incubation (10, 60, and 120 days) for soils A₁ and C₁ following application of three rates (D0, D1, and D4) of vetch (V) and oats (Oa) residues.

| Soil | Variable | Residue type | Rate | Incubation time (days) | | |
|----------------|---------------------------|--------------|------|------------------------|---------------|---------------|
| | | | | 10 | 60 | 120 |
| A ₁ | pH | Control | D0 | 6.5 \pm 0.2 | 6.3 \pm 0.2 | 6.2 \pm 0.1 |
| | | | D1 | 6.6 \pm 0.1 | 6.1 \pm 0.2 | 5.9 \pm 0.1 |
| | | Vetch | D4 | 7.4 \pm 0.1 | 6.9 \pm 0.3 | 6.5 \pm 0.1 |
| | | | D1 | 6.8 \pm 0.2 | 6.2 \pm 0.1 | 6.1 \pm 0.2 |
| | | Oat | D4 | 7.0 \pm 0.2 | 5.7 \pm 0.2 | 5.8 \pm 0.1 |
| | | | D1 | 5.5 \pm 0.1 | 4.9 \pm 0.2 | 4.9 \pm 0.2 |
| C ₁ | pH | Control | D0 | 5.4 \pm 0.3 | 4.8 \pm 0.1 | 4.8 \pm 0.1 |
| | | | D1 | 5.8 \pm 0.1 | 4.8 \pm 0.1 | 4.8 \pm 0.1 |
| | | Vetch | D4 | 7.4 \pm 0.2 | 6.0 \pm 0.1 | 5.8 \pm 0.2 |
| | | | D1 | 5.5 \pm 0.1 | 4.9 \pm 0.2 | 4.9 \pm 0.2 |
| | | Oat | D4 | 6.4 \pm 0.3 | 5.6 \pm 0.2 | 5.0 \pm 0.1 |
| | | | D1 | 25 \pm 1.0 | 31 \pm 3.8 | 33 \pm 1.9 |
| A ₁ | Pe (mg kg ⁻¹) | Control | D0 | 20 \pm 3.2 | 20 \pm 5.1 | 21 \pm 2.8 |
| | | | D1 | 31 \pm 0.9 | 34 \pm 2.8 | 33 \pm 1.9 |
| | | Vetch | D4 | 107 \pm 5.0 | 142 \pm 6.3 | 139 \pm 8.9 |
| | | | D1 | 25 \pm 1.0 | 31 \pm 3.8 | 33 \pm 1.9 |
| | | Oat | D4 | 37 \pm 5.2 | 55 \pm 5.4 | 57 \pm 5.6 |
| | | | D1 | 39 \pm 3.1 | 42 \pm 4.2 | 41 \pm 3.9 |
| C ₁ | Pe (mg kg ⁻¹) | Control | D0 | 39 \pm 3.1 | 42 \pm 4.2 | 41 \pm 3.9 |
| | | | D1 | 52 \pm 5.0 | 55 \pm 8.1 | 53 \pm 6.3 |
| | | Vetch | D4 | 137 \pm 6.1 | 140 \pm 8.9 | 143 \pm 7.5 |
| | | | D1 | 40 \pm 4.9 | 48 \pm 6.3 | 46 \pm 3.1 |
| | | Oat | D4 | 57 \pm 6.1 | 65 \pm 4.2 | 67 \pm 3.9 |
| | | | D1 | 40 \pm 4.9 | 48 \pm 6.3 | 46 \pm 3.1 |

On the basis of the data from the 10 soils under study, multiple regressions showed that the soil pH changes at low V residue rates was related with the initial soil pH, fPOC, and MOC. These relationships were significant ($p < 0.01$) at the beginning ($R^2 = 0.81$) and at the end of the experiment ($R^2 = 0.73$), but not in the middle time of incubation ($p > 0.05$).

At high rates of V residues, the initial pH change was related to the initial soil pH and MOC, however the coefficient of determination was scarce ($R^2 = 0.43$). After that time (60 and 120 days), the pH variation was associated with three factors: the initial pH, fPOC, and MOC, showing a high R^2 (>0.80).

Considering the Pe changes, no model was found to describe these changes during the first 60 days of incubation. Only one relationship was found at 120 days incubation, and the associated parameters were the SOM fractions content, that is, MOC and the cPOC with a $R^2 = 0.87$, these fractions appear to be the most variable (Suñer & Galantini 2015; Duval et al. 2016). When the highest residue rate was applied on the three incubation times, there was a strong relationship between Pe change and the SOM content and texture (silt plus clay), resulting in a very high R^2 (0.94).

Extractable P in soils where the lowest residue rate was applied did not rise over 10–15 mg P kg⁻¹. This trend was similar with the highest residue rate, however, the Pe increased over 100 mg kg⁻¹ in soils A₁ and C₁ the Pe (data not shown).

The CC residue incorporation caused changes in soil pH, and the magnitude and direction depended on the initial soil properties – especially soil organic fractions – and the amount of added residue. Soil reactions to residue decomposition were variable, and such variability was related to the capacity of the soil to restore its pH level.

Changes in Pe were related to the amount of P in the added residue (Alamgir et al. 2012). Considering the dynamics of soil nutrients, however, it would be wrong to assume that the Pe measured at the different incubation times comes alone from residue. Part of the changes in P availability in the soil may also be attributed to the variations observed in pH. Although P in the added residues may become available during decomposition, the presence of residue in soil may have a negative effect on the growth of the following crop (Mat Hassan et al. 2012). Briefly, high application of residue increased soil pH, which tended to the initial value with the time. Soil Pe increased, depending on residue rate and soil initial Pe. This increase was initially sharp and then Pe level was stable along time of the experiment.

These incubation experiments differ from the real systems, where plant residues are left on the surface. In this case, residues are subject to suffer losses through decomposition and erosion, and therefore varying the supply of cations/anions and N. However, they may cause the soil pH to change through the incorporation of legume residues and the pH may thus alter the P dynamics in the soil. These changes are likely to take place in the thin layer that is modified in soils under NT, and might have cumulative effects if the management is repeated over time.

Conclusions

The decomposition of vetch residues modifies soil pH in the short term and then it tends to the initial condition. This change was depending on residue rate application, initial pH, and soil organic fractions content, being higher in low SOM soil, because the residue decomposition was faster. Pe was sharply increased by the residue application and then tended to be stable with time. This increase could be related to initial pH, which modified the P forms equilibriums. These results are important to be considered when P availability to the crops is evaluated.

Disclosure statement

No potential conflict of interest was reported by the authors.

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