

**Soil phosphorus fractions in an apple orchard with different weed managements**  
**Frações de fósforo no solo em pomar de macieira com diferentes manejos de plantas**  
**espontâneas**  
**Fracciones de fósforo en suelo de manzanos con diferentes manejos vegetales**  
**espontáneos**

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**Abstract**

The presence of weeds in apple orchards affects the dynamics of nutrients in the soil, including phosphorus (P). The objective of this study was to evaluate changes in distribution of P fractions in the soil of an apple orchard under different weed managements. The experiment was conducted in an apple orchard in the municipality of Urubici, Santa Catarina, Brazil. The following treatments were implemented in 2011: no weed management (NWM), desiccation of weeds in the apple-tree row (DR), and hoeing of weeds in the apple-tree row (HR). Soil samples of the 0-2.5, 2.5-5, 5-10, 10-15 and 15-20 cm layers were collected in the apple-tree rows at 24 months after the implementation of the experiment. The samples were subjected to chemical fractionation of P, obtaining the following fractions:  $P_{iAER}$ ,  $P_{iNaHCO_3}$ ,  $P_{ONaHCO_3}$ ,  $P_{iNaOH}$ ,  $P_{ONaOH}$ ,  $P_{iHCl}$ ,  $P_{iNaOH05}$ ,  $P_{ONaOH05}$ , and  $P_{residual}$ . The presence of weeds increased the contents of the following soil P fractions in the surface layers:  $P_{iAER}$ ,  $P_{iNaHCO_3}$ , and  $P_{ONaHCO_3}$ , which are bioavailable to plants. A higher proportion of organic forms of P in the soil was found when the weeds were hoed; these fractions can be mineralized and used for nutrition of apple trees when labile P forms are exhausted.

**Keywords:** *Malus domestica*; Biological P; Geochemical P; Nutrient cycling.

**Resumo**

A presença de vegetação espontânea nos pomares de macieira afeta a dinâmica dos nutrientes no solo, entre eles o fósforo (P). O estudo objetivou avaliar como diferentes manejos de

plantas espontâneas em pomares de macieira modificam a distribuição de frações de fósforo no solo. O experimento foi conduzido em um pomar de macieira no município de Urubici, Santa Catarina. Em 2011 foram implantados os tratamentos: sem manejo das plantas espontâneas (SM), dessecamento das plantas espontâneas na linha de plantio (DL) e roçada das plantas espontâneas na linha de plantio (RL). Após 24 meses da implantação do experimento, foram coletadas amostras de solo na linha de plantio das macieiras nas camadas de 0-2,5, 2,5-5, 5-10, 10-15 e 15-20 cm, e realizou-se o fracionamento químico de P, obtendo-se as seguintes frações:  $P_{iAER}$ ,  $P_{iNaHCO_3}$ ,  $P_{ONaHCO_3}$ ,  $P_{iNaOH}$ ,  $P_{ONaOH}$ ,  $P_{iHCl}$ ,  $P_{iNaOH05}$ ,  $P_{ONaOH05}$  e  $P_{Residual}$ . A presença de plantas espontâneas favoreceu o aumento dos teores de P no solo nas camadas superficiais nas frações  $P_{iAER}$ ,  $P_{iNaHCO_3}$ , e  $P_{ONaHCO_3}$  biodisponíveis às plantas. Quando as plantas espontâneas foram roçadas, houve maior proporção de formas orgânicas de P no solo, as quais podem ser mineralizadas e utilizadas na nutrição da macieira quando há depleção das formas de P lábeis.

**Palavras-chave:** *Malus domestica*; P biológico; P geoquímico; Ciclagem de nutrientes.

### Resumen

La presencia de vegetación espontánea en los manzanos afecta la dinámica de los nutrientes en el suelo, incluido el fósforo (P). El estudio tuvo como objetivo evaluar cómo diferentes manejos vegetales espontáneos en manzanos modifican la distribución de fracciones de fósforo en el suelo. El experimento se realizó en un huerto de manzanos del municipio de Urubici, Santa Catarina. En 2011 se implementaron tratamientos: sin manejo espontáneo de plantas (SM), desecación espontánea de plantas en la línea de plantación (DL) y siega de plantas espontáneas en la línea de plantación (RL). Luego de 24 meses de implantación del experimento, se recolectaron muestras de suelo en la línea de plantación de los manzanos en las capas de 0-2.5, 2.5-5, 5-10, 10-15 y 15-20 cm, y se realizó el fraccionamiento químico de P, obteniendo las siguientes fracciones:  $P_{iAER}$ ,  $P_{iNaHCO_3}$ ,  $P_{ONaHCO_3}$ ,  $P_{iNaOH}$ ,  $P_{ONaOH}$ ,  $P_{iHCl}$ ,  $P_{iNaOH05}$ ,  $P_{ONaOH05}$  y  $P_{Residual}$ . La presencia de plantas espontáneas favoreció el aumento del contenido de P en el suelo en las capas superficiales en las fracciones  $P_{iAER}$ ,  $P_{iNaHCO_3}$  e  $P_{ONaHCO_3}$  biodisponible para las plantas. Cuando se despejaron las plantas espontáneas, hubo una mayor proporción de formas orgânicas de P en el suelo, que se pueden mineralizar y usar en la nutrición de las manzanas cuando se agotan las formas lábiles de P.

**Palabras clave:** *Malus domestica*; P biológico; P geoquímico; Ciclo de nutrientes.

## 1. Introduction

The South region of Brazil has the largest apple (*Malus domestica*) plantation areas in the country due to its favorable climate characteristics to produce high-quality fruits. The planted area in the state of Santa Catarina (SC) in 2017 was 17,500 ha, with a production of 612,500 Mg and a mean yield of 35 Mg ha<sup>-1</sup> (IBGE, 2017). The Planalto Serrano is the largest apple producing mesoregion in the state, representing 71% of the total apple produced and a gross value of BRL (R\$) 353.5 million (Goulart Junior et al., 2017).

Apple orchards in SC are usually managed with presence of weeds, with predominance of white clover (*Trifolium repens*), red clover (*Trifolium pratense*), bahiagrass (*Paspalum notatum*), broadleaf dock (*Rumex obtusifolius*), and ryegrass (*Lolium multiflorum*) (Oliveira et al., 2016). However, the weeds are usually desiccated with herbicides, or hoed to facilitate the orchard management and reduce competition for water and nutrients, leaving the plant residues on the soil (Oliveira et al., 2016) to promote the cycling of nutrients, including phosphorus (P).

P is found in organic and inorganic forms in the soil, varying according to the chemical nature of the binder and the energy of the connection of this element in the soil (Brunetto et al., 2013). Most of the soils in the South region of Brazil are highly weathered, presenting high 1:1 (kaolinite) clay contents and Fe and Al oxides, which adsorb P with high energy (Fink et al., 2014), decreasing the availability of P to plants and affecting its dynamics in the soil, requiring the application of phosphate fertilizers.

The use of soil cover plants within and between the apple-tree rows should be adopted to increase the cycling of P in apple orchards; legumes, grass species, intercrops, or the maintenance of weeds can be used for this purpose. The use soil cover plants (planted or natural) has several benefits, such as protection against impacts by rainfall drops and erosive processes (Cardoso et al., 2012); it also increases soil organic matter contents and nutrient cycling, including P, and can modify soil P forms (Silva et al., 2017).

Soil P forms can be affected by the orchard weed management; weeds have different mechanisms to access less labile P forms in the soil, favoring the P cycling in the system (Casali et al., 2016). The management of these weeds varies according to cultural practices and age of the orchards, and are focused on avoiding interferences in the orchard production; the most common practices are hoeing, chemical desiccation, or waiting for natural senescence. Schmitt et al. (2017) compared soil P forms of two commercial apple orchards with weeds in the apple-tree rows and a native vegetation area and found that the distribution

of organic (Po) and inorganic (Pi) P forms in the apple orchard were similar to that of the native vegetation area, indicating a P accumulation in Po and Pi forms. This result is usually found for inorganic P forms; however, the presence of weeds in the study areas may have caused a conversion of Pi into Po due to the biomass production, i.e., when Pi is available for the development of these species, the mineralization of Po is not required, causing the accumulation of these organic P forms in the soil.

Therefore, the hypothesis investigated in the present study is that the weed management with permanence of weeds in the apple-tree rows by waiting for natural senescence or leaving them on the soil after hoeing increases the contents of organic P forms in the soil surface layers. Thus, the objective of this study was to evaluate the changes in the distribution of P fractions in the soils of an apple orchard under different weed managements.

## 2. Methodology

The experiment was conducted at a commercial apple orchard implemented in 2008 in the municipality of Urubici, SC, South region of Brazil (28°02'47.5"S 49°26'26.6"W, and altitude of 1000 m). The climate of the region is Cfb, presenting mean annual rainfall depths of 1,360 to 1,600 mm, mean maximum temperatures of 19.4 to 22.3 °C, and mean minimum temperatures of 9.2 to 10.8 °C. Cold temperatures, equal to or below than 7.2 °C, occur for 642 to 847 hours per year.

The soil of the orchard was classified as Humic Dystrudept (Cambissolo Humico; Santos et al., 2013) and presented the following characteristics in the 0.0-0.20 m layer before of the experiment implementation: 475 g kg<sup>-1</sup> of sand, 294 g kg<sup>-1</sup> of silt, and 231 g kg<sup>-1</sup> of clay; 46 g kg<sup>-1</sup> of organic matter; pH in water (1:1) of 5.8; exchangeable Al, Ca, and Mg of 0.0, 8.45, and 3.15 cmolc dm<sup>-3</sup>, respectively (extracted by KCl 1 mol L<sup>-1</sup>); 32.1 mg dm<sup>-3</sup> of available P and 243 mg dm<sup>-3</sup> of exchangeable K (extracted by Mehlich-1), 12.22 cmolc dm<sup>-3</sup> of effective cation exchange capacity (CEC); 16.38 cmolc dm<sup>-3</sup> of CEC at pH 7; and 74.6% of base saturation.

The orchard had two commercial apple varieties: Gala (70% of the area) and Fuji (30% of the area). The cultivar Fuji was used as pollinator, because only areas with plants of cultivar Gala were selected for the experiment. The orchard was conducted in a central leader planting system, with plants grafted on Marubakaido rootstocks, with 20-cm M9 filter, and density of 1,482 plants ha<sup>-1</sup> (4.5 m between rows and 1.5 m between plants).

The experiment was implemented in October 2011; 60 plants were selected and distributed in a randomized block experimental design, with four replications. Each treatment was composed of five plants per replication, and the area of the three central plants were considered for the evaluations. The treatments used were: no weed management (NWM), desiccation of weeds in the apple-tree rows (DR), and hoeing of weeds in the apple-tree rows (HR).

The hoeing and application of herbicides were done when the weeds had approximately 30-cm height. Eight applications of non-residual herbicide (active ingredient: potassium glyphosate) and 12 hoeing were done during the experiment. The weeds were cut at approximately 10 cm from the soil surface. The herbicide rate used in each desiccation was 50 mL for each 20 L of water, applying a solution volume of approximately 300 L ha<sup>-1</sup>. The predominant weeds in the orchard were: white clover (*Trifolium repens*), red clover (*Trifolium pratense*), bahiagrass (*Paspalum notatum*), and broadleaf dock (*Rumex obtusifolius*). Soil fertilization consisted of 50 kg ha<sup>-1</sup> of P<sub>2</sub>O<sub>5</sub> (triple superphosphate) and 200 kg ha<sup>-1</sup> of K<sub>2</sub>O (KCl), which were applied annually on the soil surface without incorporation.

Trenches of 40×40×40 cm were opened in the apple-tree rows, and soil samples from the layers of 0-2.5, 2.5-5, 5-10, 10-15, and 15-20 cm were collected in September 2013, corresponding to 24 months after the implementation of the experiment. The samples were air dried, ground, and passed through a 2-mm mesh sieve. They were then subjected to chemical fractionation of P, with sequential extractions as proposed by Hedley et al. (1982) and modified by Condron et al. (1985), obtaining the inorganic (Pi) and organic (Po) P fractions. Aliquots of 0.5 g of the dried soil were subjected to the following sequential extractions: anion exchange resin (Pi<sub>AER</sub>); NaHCO<sub>3</sub> 0.5 mol L<sup>-1</sup> (Pi<sub>NaHCO3</sub> and Po<sub>NaHCO3</sub>); NaOH 0.1 mol L<sup>-1</sup> (Pi<sub>NaOH</sub> and Po<sub>NaOH</sub>); HCl 1.0 mol L<sup>-1</sup> (Pi<sub>HCl</sub>); and NaOH 0.5 mol L<sup>-1</sup> (Pi<sub>NaOH05</sub> and Po<sub>NaOH05</sub>). The remaining soil was dried in an oven and subjected to digestion with H<sub>2</sub>SO<sub>4</sub> + H<sub>2</sub>O<sub>2</sub> + MgCl<sub>2</sub> (P<sub>Residual</sub>). The P from acid extracts was determined according to Murphy & Riley (1962), and the P from alkaline extracts were determined according to Dick & Tabatabai (1977). The P forms in the Hedley fractionation were grouped into geochemical-P and biological-P (Cross & Schlessinger, 1995). Geochemical-P is the sum of inorganic fractions plus P<sub>Residual</sub> (Pi<sub>AER</sub> + Pi<sub>NaHCO3</sub> + Pi<sub>NaOH</sub> + Pi<sub>NaOH05</sub> + Pi<sub>HCl</sub> + P<sub>Residual</sub>), and biological-P is the sum of organic fractions (Po<sub>NaHCO3</sub> + Po<sub>NaOH</sub> + Po<sub>NaOH05</sub>).

The data obtained were subjected to normality and homogeneity tests, following the assumptions of the analysis of variance. When the means presented significant differences between soil layers in the same treatment or between treatments in the same layer, they were

compared using the Scott-Knott test at 5% probability of error. The data obtained were also subjected to the Pearson's correlation analysis.

### 3. Results and Discussion

The weed management in the apple orchard changed the distribution of P fractions in the soil. In the soil surface layer (0-2.5 cm), the highest  $P_{iAER}$  contents were found in the treatments NWM and HR; and the  $P_{iAER}$  contents in the treatment DR were similar in all soil layers evaluated (Table 1). The highest  $P_{iNaHCO_3}$  and  $P_{ONaHCO_3}$  contents (0-2.5 cm) were found in NWM. The lowest  $P_{iNaHCO_3}$  contents (0-2.5 cm) were found in DR and HR, and the lowest  $P_{ONaHCO_3}$  was found in HR. In the 0-2.5 cm layer, the treatments NWM and HR presented, respectively,  $P_{iAER}$  contents 125% and 58% higher than the treatment DR.  $P_{iNaHCO_3}$  and  $P_{ONaHCO_3}$  found in NWM were, respectively, 129% and 26% higher than those found in DR.

**Table 1.** P fractions extracted by anion exchange resin ( $P_{iAER}$ ) and by the extractor  $NaHCO_3$  0.5 mol L<sup>-1</sup> ( $P_{iNaHCO_3}$  and  $P_{ONaHCO_3}$ ), in different soil layers of an apple orchard with different weed managements.

Layer (cm)	NWM	DR	HR	CV (%)
$P_{iAER}$ (mg kg <sup>-1</sup> )				
0-2.5	294.0 aA <sup>1</sup>	130.7 <sup>ns</sup> C	206.2 aB	12.2
2.5-5	115.0 bB	161.8 A	174.4 bA	7.6
5-10	60.0 cC	154.1 A	95.2 cB	12.3
10-15	75.1 cC	164.4 A	104.2 cB	11.4
15-20	83.6 cB	151.5 A	158.9 bA	15.3
CV (%)	13.3	11.9	11.8	
$P_{iNaHCO_3}$ (mg kg <sup>-1</sup> )				
0-2.5	120.4 aA	52.5 cB	41.4 bC	9.1
2.5-5	48.4 bB	41.9 dB	82.3 aA	12.6
5-10	41.4 bB	72.1 bA	77.4 aA	12.2
10-15	28.4 cB	69.7 bA	85.6 aA	19.5
15-20	27.5 cC	95.0 aA	66.3 aB	12.8
CV (%)	10.9	11.5	15.9	
$P_{ONaHCO_3}$ (mg kg <sup>-1</sup> )				
0-2.5	170.5 aA	134.9 aB	90.0 bC	8.1
2.5-5	119.1 bA	115.9 aA	128.7 aA	7.3
5-10	101.8 cC	116.2 aB	136.8 aA	7.7
10-15	86.8 dB	83.4 bB	136.5 aA	22.5
15-20	92.4 dA	98.6 bA	97.2 bA	14.3
CV (%)	7.1	18.3	9.4	

(1) Means followed by same lowercase letter in the columns or uppercase letters in the rows are not different by the Scott-Knott test at 5% probability of error; NWM = no weed management; DR = desiccation of weeds in the apple-tree rows; HR = hoeing of weeds in the apple-tree rows. Source : Authors.



$P_{iAER}$ ,  $P_{iNaHCO_3}$ , and  $P_{ONaHCO_3}$  are labile fractions that directly contribute to the supplying of P to plant nutrition, and are susceptible to transference processes in the environment (Schmitt et al., 2013). The highest P contents of these fractions found in the soil surface layers are due to the adsorption of this nutrient to more suitable connection sites for P, forming an internal sphere complex, because the remaining P is redistributed into fractions with lower connection energy (Rheinheimer & Anghinoni, 2001). In addition, the contents of these fractions are high in surface layers because of the P cycling (Brunetto et al., 2011), since species of soil cover plants can absorb P from the soil and incorporate it in their tissues, roots, and shoots. The residues of plants that were maintained in the apple tree crop (NWM) or hoed and left as soil cover (HR) can be decomposed, and part of the released P can be distributed into inorganic and organic fractions in the soil (Comin et al., 2017). The treatment DR, in which a broad-spectrum herbicide was used for desiccation of weeds, generated an interruption of the secondary metabolism of plants, causing their death; it accelerates the decomposition of the low amount of plant residues deposited on the soil, decreasing the soil protection and, consequently, accelerating the nutrient cycling, including P (Taiz & Zeiger, 2009).

The weeds species in the study area have different morphological characteristics, such as C to N ratio (C/N), and different physiological efficiency due to their C3 and C4 photosynthetic metabolisms, which are factors that directly affect the nutrient absorption. The bahiagrass (*Paspalum notatum*) found in the study area is a C4 plant that presents a higher physiological efficiency than C3 plants (Taiz & Zeiger, 2009), and is more efficient in the use of N in photosynthesis and in water absorption processes. C4 species such as *Amaranthus lividus* are more efficient in the use of atmospheric CO<sub>2</sub> and light energy, and have higher competitive ability than C3 plants (Vieira et al., 2010). These morphophysiological characteristics and strategies to access soil nutrients, including P, explain the higher contents of labile P forms in the soil surface layers of the treatments where the plants were maintained in the apple-tree row (NWM and HR). In addition, plants can absorb  $P_i$  by their roots and by mycorrhizal associations, or access  $P_o$  by enzymatic transformations specific to each type of phosphate ester (Aswitha et al., 2019; Wen et al., 2019).

The highest P contents in the  $P_{iNaOH}$  and  $P_{ONaOH}$  fractions were found in the in the 0-5 cm layer in the treatments NWM and DR, and in the 15-20 cm layer in the treatment HR (Table 2). The soil layers evaluated showed no significant differences for  $P_{iNaOH05}$  contents in NWM and DR, and for  $P_{ONaOH05}$  in DR (Table 2). The saturation of adsorbing sites in soil surface layers and the different root system of weeds affect the soil P dynamics. In the first



case, the decrease of functional groups that have high affinity for P causes migration of P to deep layers; and in the second case, there is better soil structuring and formation of galleries due to the macrofauna activity and decomposition of roots, favoring the flows of water and dissolved, particulate organic matter, which carry inorganic and organic P forms, causing the migration of P in the soil (Brunetto et al., 2013; Wang et al., 2019).

**Table 2.** P fractions extracted by the extractors NaOH 0.1 mol L<sup>-1</sup> (P<sub>INaOH</sub> and P<sub>ONaOH</sub>) and NaOH 0.5 mol L<sup>-1</sup> (P<sub>INaOH05</sub> and P<sub>ONaOH05</sub>), in different soil layers of an apple orchard with different weed managements.

Layer (cm)	NWM	DR	HR	CV (%)
P <sub>INaOH</sub> (mg kg <sup>-1</sup> )				
0-2.5	397.2 aA1	388.7 aA	286.5 bB	9.6
2.5-5	316.2 bB	403.1 aA	315.6 bB	10.8
5-10	287.9 bA	326.7 bA	331.8 bA	9.5
10-15	270.6 bB	377.8 aA	374.4 bA	16
15-20	269.0 bB	320.4 bB	531.6 aA	13.1
CV (%)	9.3	10.9	14.5	
P <sub>ONaOH</sub> (mg kg <sup>-1</sup> )				
0-2.5	124.7 aB	100.8 aC	215.4 bA	7.3
2.5-5	83.2 bA	92.8 aA	98.7 cA	11.8
5-10	61.2 cB	80.3 bA	74.9 dA	11.5
10-15	50.4 cB	74.0 bA	47.9 eB	23.2
15-20	54.5 cC	69.2 bB	238.2 aA	6.4
CV (%)	12.3	9	10	
P <sub>INaOH05</sub> (mg kg <sup>-1</sup> )				
0-2.5	166.5 nsA	145.9 nsB	137.0 bB	10.8
2.5-5	144.7 A	158.8 A	146.5 bA	9.1
5-10	141.2 A	141.7 A	142.3 bA	11.2
10-15	149.4 A	160.3 A	152.4 bA	14.5
15-20	173.5 B	144.7 B	266.1 aA	19.8
CV (%)	12.9	9.2	19	
P <sub>ONaOH05</sub> (mg kg <sup>-1</sup> )				
0-2.5	211.4 bB	219.1 nsB	295.5 aA	11
2.5-5	202.9 bA	202.5 A	224.2 bA	11.5
5-10	222.9 aB	232.3 B	274.2 aA	12.4
10-15	201.5 bA	216.8 A	239.7 bA	10.1
15-20	234.8 aA	217.8 A	105.7 cB	12.1
CV (%)	8	13.2	12.4	

(1) Means followed by same lowercase letter in the columns or uppercase letters in the rows are not different by the Scott-Knott test at 5% probability of error; NWM = no weed management; DR = desiccation of weeds in the apple-tree rows; HR = hoeing of weeds in the apple-tree rows. Source : Authors.

The  $P_{iNaOH}$ ,  $P_{ONaOH}$ ,  $P_{iNaOH05}$ , and  $P_{ONaOH05}$  contents represent the  $P_i$  related to oxides and silicate clays with intermediate energy of connection, and  $P_o$  from intermediately labile fractions (Cross & Schlessinger, 1995). These fractions contribute to the increase of more labile fractions and P availability to plants over time, as found by Tiecher et al. (2018), who evaluated the contribution of P fractions to the maintenance of P contents in the  $P_{iAER}$  fraction in soils with different management systems, in an experiment conducted for 23 years. They found that  $P_{ONaOH05}$  and  $P_{ONaOH}$  fractions do not significantly contribute to the  $P_{iAER}$  contents under absence of soil turning, but cause a cascade effect and increase the  $P_{ONaHCO3}$  fraction and, consequently, the  $P_{iAER}$ . In addition, Tiecher et al. (2018) found the same dynamics for inorganic fractions ( $P_{iNaOH05}$ ,  $P_{iNaOH}$ , and  $P_{iNaHCO3}$ ). These results indicate that P fractions with low lability in the soil, which do not directly contribute to plant nutrition, can be important for P cycling and assist in the maintenance of available P contents according to the consumption of more labile P forms.

The highest  $P_{iHCl}$  contents were found in the treatment HR in all soil layers evaluated (Table 3). The  $P_{iHCl}$  fraction is associated to the  $P_i$  that composes the calcium phosphates and is adsorbed to soil colloids by internal sphere complex (Leite et al., 2016). The higher  $P_{iHCl}$  contents found in HR can be due to the weed management used, since the cut of plant species causes physical stress, making the plants to increase their photosynthetic rates and synthesis of phytohormones, such as gibberellin (Hebert et al., 2019; Liu et al., 2019). In addition, the root exudation of organic acids, such as citric, malic, and oxalic acids, increases as a strategy to dissolve compounds that have P in their constitution, making P accessible and increasing its contents in the soil solution (Mora-macías et al. 2017; Wang et al., 2017).

**Table 3.** Inorganic P extracted by HCl 1.0 mol L<sup>-1</sup> (P<sub>HCl</sub>) and residual P (P<sub>Residual</sub>) in different soil layers of an apple orchard with different weed managements.

Layer (cm)	NWM	DR	HR	CV (%)
		P <sub>HCl</sub> (mg kg <sup>-1</sup> )		
0-2.5	19.4 aB	18.5 cB	129.1 aA	12.3
2.5-5	11.0 dC	17.0 cB	24.4 cA	7.6
5-10	15.7 bC	24.7 bB	35.0 cA	9.1
10-15	14.2 cB	24.6 bB	36.7 cA	35.1
15-20	18.1 aC	29.2 aB	95.5 bA	13.2
CV (%)	10.2	8.3	15.3	
		P <sub>Residual</sub> (mg kg <sup>-1</sup> )		
0-2.5	1546.4 dA	1546.4 aA	1176.2 aB	7.8
2.5-5	1733.9 cA	1452.7 aB	1082.5 bC	7.8
5-10	1996.3 aA	1340.2 aB	1124.7 bC	9.1
10-15	1827.6 bA	618.6 bB	141.9 cC	7.9
15-20	1621.4 dA	712.3 bB	80.3 cC	7.7
CV (%)	5.8	12.0	6.7	

(1) Means followed by same lowercase letter in the columns or uppercase letters in the rows are not different by the Scott-Knott test at 5% probability of error; NWM = no weed management; DR = desiccation of weeds in the apple-tree rows; HR = hoeing of weeds in the apple-tree rows. Source : Authors.

The P<sub>Residual</sub> contents were higher in the soil surface layers, except in the treatments NWM and DR, in which these contents were higher in the 5-10 cm layer (Table 3). The P<sub>Residual</sub> fraction represents recalcitrant inorganic and organic fractions that do not contribute to plant nutrition, except in cases of extreme deficiency of P in the soil (Gatiboni et al., 2005).

All P fractions were negatively correlated ( $p < 0.05$ ) with the P<sub>Residual</sub> contents in the treatment NWM, except for the P<sub>NaOH05</sub> and P<sub>HCl</sub> fractions (Table 4), indicating increases in the contents of more labile P fractions as the P<sub>Residual</sub> content is decreased. The treatment NWM also showed high positive correlations ( $p < 0.001$ ) for P<sub>AER</sub>, P<sub>NaHCO3</sub>, P<sub>NaHCO3</sub>, P<sub>NaOH</sub>, and P<sub>NaOH</sub> fractions (Table 4). Increases in the contents of some less labile fractions caused a cascade effect and increased the contents of more labile fractions, as also found by Tiecher et al. (2018). The maintenance of diverse weeds in the field enables these species to use different strategies to access the P in the soil, increasing its cycling (Casali et al., 2016).

**Table 4.** Pearson's correlation analysis for P forms ( $P_{iAER}$ ,  $P_{iNaHCO_3}$ ,  $P_{ONaHCO_3}$ ,  $P_{iNaOH}$ ,  $P_{ONaOH}$ ,  $P_{iNaOH05}$ ,  $P_{ONaOH05}$ ,  $P_{iHCl}$ , and  $P_{residual}$ ) in the soil of an apple orchard with different weed managements.

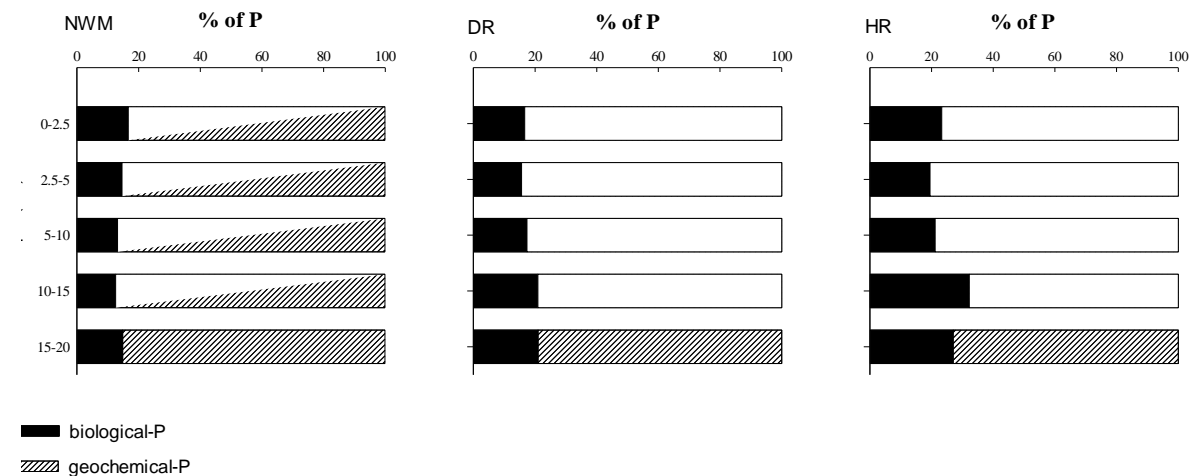
	$P_{iAER}$	$P_{iNaHCO_3}$	$P_{ONaHCO_3}$	$P_{iNaOH}$	$P_{ONaOH}$	$P_{iNaOH05}$	$P_{ONaOH05}$	$P_{iHCl}$	$P_{residual}$
NWM									
$P_{iAER}$	1								
$P_{iNaHCO_3}$	0.94***	1							
$P_{ONaHCO_3}$	0.93***	0.95***	1						
$P_{iNaOH}$	0.87***	0.83***	0.85***	1					
$P_{ONaOH}$	0.92***	0.92***	0.95***	0.88***	1				
$P_{iNaOH05}$	ns	ns	ns	ns	ns	1			
$P_{ONaOH05}$	ns	ns	ns	ns	ns	ns	1		
$P_{iHCl}$	0.45*	0.45*	ns	ns	ns	ns	ns	1	
$P_{residual}$	-0.60**	-0.44*	-0.45*	-0.44*	-0.43*	-0.51**	ns	ns	1
DR									
$P_{iAER}$	1								
$P_{iNaHCO_3}$	ns	1							
$P_{ONaHCO_3}$	-0.51**	ns	1						
$P_{iNaOH}$	ns	-0.54**	ns	1					
$P_{ONaOH}$	ns	0.71***	0.55**	0.63***	1				
$P_{iNaOH05}$	ns	ns	ns	ns	ns	1			
$P_{ONaOH05}$	ns	ns	ns	-0.49*	ns	ns	1		
$P_{iHCl}$	ns	0.86***	-0.45*	0.64***	0.78***	ns	ns	1	
$P_{residual}$	ns	0.69***	0.58**	ns	0.73***	ns	ns	0.70***	1
HR									
$P_{iAER}$	1								
$P_{iNaHCO_3}$	-0.52**	1							
$P_{ONaHCO_3}$	0.66***	0.82***	1						
$P_{iNaOH}$	ns	ns	ns	1					
$P_{ONaOH}$	0.67***	0.72***	0.89***	ns	1				
$P_{iNaOH05}$	ns	ns	-0.44*	0.71***	0.55**	1			
$P_{ONaOH05}$	ns	ns	ns	0.74***	ns	0.75***	1		
$P_{iHCl}$	0.62**	0.75***	0.79***	ns	0.85***	ns	ns	1	
$P_{residual}$	ns	ns	ns	0.69***	ns	-0.61**	0.68***	ns	1

NWM = no weed management; DR = desiccation of weeds in the apple-tree rows; HR = hoeing of weeds in the apple-tree rows. \* =  $0.05 \geq p\text{-value} > 0.01$ ; \*\* =  $0.01 \geq p\text{-value} > 0.001$ ; \*\*\* =  $p\text{-value} \leq 0.001$ ; ns = not significant correlation. Source: Authors.

The distribution of biological-P and geochemical-P fractions showed that the proportion of biological-P was higher in HR, with increases in the deeper soil layers (Figure

1). The mean percentages of biological-P found, considering all layers, were 27.1%, 29.9%, and 38.7% in the treatments NWM, DR, and HR, respectively.

**Figure 1.** Percentage distribution of geochemical-P ( $P_{iAER} + P_{iNaHCO_3} + P_{iNaOH} + P_{iNaOH05} + P_{iHCl} + P_{residual}$ ) and biological-P ( $P_{ONaHCO_3} + P_{ONaOH} + P_{ONaOH05}$ ) forms, in different soil layers of an apple orchard with different weed managements.



Source : Authors.

This result was due to the stress caused by the cut of weeds, which have mechanisms to resume metabolic activities and growth. This occurs because their root system, which has the functions of plant support and absorption of water and nutrient, also produces exudates that are used to access soil P (Monteiro et al., 2012). Yang et al. (2019) evaluated three weed species in a greenhouse experiment using different sources of P ( $P_o$  and  $P_i$ ) and found higher root development for organic P forms, denoting the increasing exudate production and the capacity of the species to access P in the soil.

#### 4. Final Considerations

The presence of weeds in the apple-tree rows increases soil P contents in more labile fractions, mainly in soil surface layers.

The hoeing of weeds increases the proportion of organic forms of P in subsurface soil layers (10-15; 15-20 cm).

The maintenance of weeds in the apple-tree rows, without desiccation or hoeing, should be a recommended practice for producers due to improvements in cycling of nutrients, including P, assistance in plant nutrition, and low environmental impact.

In this line of research, it is recommended to explore the physiology and mechanisms of weeds in accessing the less labile P fractions in the soil.

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