Heavy metals and pesticides in soils under different land-use patterns in neotropical high Andean Páramos

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ABSTRACT: Páramos are unique strategic ecosystems in the neotropical region, above the upper limit of closed forest and below the lower limit of perpetual snow in the tropical mountains of Central and South America. Their soils are of particular importance for water regulation and carbon storage; however, thousands of peasants develop agricultural activities such as potato cultivation and livestock farming in these areas. This research aimed to evaluate the possible heavy metals contents (arsenic, cadmium, mercury, and lead) and pesticide residues (348 in total) associated with potato cultivation and livestock farming activities in soils of Páramo ecosystems (Cruz Verde and El Verjón) in Cundinamarca, Colombia. Soil samples are from areas in the Páramo under potato crops and livestock farming, at two different altitudes: 3300 m a.s.l. (meters above sea level) and 2900 m a.s.l.; and then, the physical-chemical properties, heavy metals, and pesticide content were determined in each sample. The results showed that none of the soils evaluated exceeded the concentrations of heavy metals permitted by the normativity that was analyzed. On the other hand, we found the presence of the fungicide dimethomorph (0.27 mg kg\(^{-1}\)) in soils under potato crops at altitudes 1 and 2, fungicide metalaxyl (0.013 mg kg\(^{-1}\)) in soils under potato crops at altitude 1, and insecticide thiamethoxam (0.048 mg kg\(^{-1}\)) in soils under potato crops at altitude 2. Anyhow, the statistical analysis did not show significant heavy metals contents or pesticide residues in the Páramo soils associated with potato cultivation and livestock farming; nonetheless, there are significant impacts on five of the physicochemical properties of the soils under study (moisture, bulk density, organic carbon, cation exchange capacity, and phosphorus). Although soil physicochemical parameters properties were modified by soil potato crop and cattle raising, these land-use types did not cause relevant impacts heavy metals and pesticides, which could be due to the specific agricultural practices adopted in the area (Potato-pasture rotation system, with fallow periods of between 7 and 10 years). Finally, this study represents the first report on heavy metals and pesticide residues in Páramo soils.

Keywords: soil contamination, soil quality, environmental pollution, arsenic, cadmium.
INTRODUCTION

Páramos are unique strategic ecosystems that are located in the neotropical region above the upper limit of the closed forest and below the lower limit of perpetual snow in the tropical mountains of Central and South America. They are rich in endemic flora and fauna, with particular ecological functions related to hydrological supply, drinking water generation, hydrogeological regulation, and carbon storage (Díaz-Granados et al., 2005; Hofstede, 1997; Luteyn and Balslev, 1992).

Páramos are located in Colombia, along the three branches of the Andes mountain range, with the greatest extension of this ecosystem in the departments of Boyacá and Cundinamarca. Although the Páramos share similar biological, environmental, and climatic characteristics, the soils, vegetation, and anthropic intervention are different in each region, generating particular conditions in these biomes (Bernal-Cuesta, 2017).

Agricultural and livestock farming activities in the Páramo ecosystems have generated different impacts. Several studies have reported on the impacts of potato cultivation and livestock farming on the physicochemical properties, enzymatic activities, and microorganisms of the soils in the Páramo (Cañon-Cortazar et al., 2012); however, up to date and despite the permanent agricultural activities in these ecosystems, there are no studies on heavy metals and pesticides in the soils of Páramo ecosystems under potato cultivation and livestock. Páramo is of utmost importance given the consequences on the health of the ecosystems, human beings (as final consumers), and the biological processes of the soils.

Different studies have evaluated the concentration and bioaccumulation of heavy metals and pesticide residues generated due to agricultural activities, given the excessive or inadequate use of fertilizers or pesticides (Alves et al., 2016). Heavy metals can be leached and are not degradable in the environment (Martley et al., 2004; Alloway, 2013; Sidhu, 2016; Ashraf et al., 2019). Crops contaminated with heavy metals, either in the soil or irrigation water, can cause cancer and chronic diseases in the respiratory tract, heart, brain, and kidney (Ashraf et al., 2019).

In the case of pesticides, these are compounds that, depending on their nature, are stable to hydrolysis and photolysis, may be soluble and cause leaching into groundwater, may be resistant to microorganisms, and may also be able to persist for long periods not only in the soil, but also in water and air (FAO and WHO, 2007; Gondar et al., 2013; Bonmatin et al., 2015; Mohapatra et al., 2019; Simon-Delso et al., 2015). Their effects on human health are varied since they travel through the respiratory tract when inhaled in contaminated atmospheres; or through the ingestion of contaminated food either once or repeatedly, or even by contact with the skin, leading the individual to present both acute and chronic toxicity, and causing neurological and reproductive problems, and cancer, among others (del Puerto-Rodriguez et al., 2014). Thus, soil contamination by pesticides in agricultural areas around the world is well documented, such as the case of the study carried out by Silva et al. (2019), which reveals that the presence of mixtures of pesticide residues in soils are the rule rather than the exception, indicating that environmental risk assessment procedures should be adapted accordingly to minimize related risks to soil life and beyond.

The presence of heavy metals in the soil of the Páramos is of particular concern, possibly because of the traces that can be found in chemically synthesized fertilizers, which, due to their prolonged use on potato crops, can lead to an increase in their contents. Another concern is the residual nature of pesticides, mainly associated with conventional phytosanitary management with commercial pesticides of different toxicological categories, which are used on potato crops in the Páramo areas. On the other hand, and although in the Páramo livestock systems, livestock feeding is mainly done with the area’s pastures, it is important to mention that there are studies on what has been determined, for example, the contents of heavy metal (Cu, Zn, As, Cr, Cd and Pb) in animal feeds and manures,
finding that Animal manure is an important source of heavy metals to the environment in Northeast China (Zhang et al., 2012).

This study aimed to evaluate if there is a significant impact on the increase in the content of heavy metals and pesticide residues in the soils of the Páramo that have been intervened with potato cultivation and livestock farming. Additionally, we sought to evaluate if these impacts have any variation when analyzed at two different altitudes. The research hypothesis is that there is a significant increase in the heavy metals contents and pesticide residues in the soils of the Páramo due to the potato cultivation and livestock farming activities developed in the area. The present document can be taken as the first report that has been released on the presence of heavy metals and pesticide residues in the soils of the Páramo.

MATERIALS AND METHODS

Study area

This study was developed in the area between Páramo Cruz Verde and Páramo El Verjón, located in the department of Cundinamarca, Colombia (Figure 1). The average temperature in the area is 8 °C, and the main economic activities are potato (Solanum tuberosum), tomato (Solanum lycopersicum) and bean (Phaseolus vulgaris) cultivation, livestock farming, mining, and tourism (Alcaldía Municipal Choachi Cundinamarca, 2008). The agricultural practices developed in the area combine peasant knowledge together with the implementation of Green Revolution technologies. In this way, seeds are planted for a maximum of two consecutive years, followed by rest or fallow cycles of 7 to 10 years, implementing crop rotation systems with livestock, thus avoiding permanent grazing in the same area. However, conventional applications of chemically synthesized pesticides are carried out; namely, carbofuran (Furadan), parathion (Parathion), methamidophos (Monitor), Chlorpyrifos (Lorsban), profenofos (Curacron), mancozeb (Manzate), propinab + cymoxanil (Fitoraz), metalaxyl (Ridomil), hexaconzole (Anvil), and N:P:K-type fertilizers (Avellaneda-Torres et al., 2014).

Type of sampling

To identify the concentration of heavy metals and pesticide residues in Páramo soils, soil samples were collected from soils that had been used for potato cultivation, livestock

Figure 1. Map presenting where the study area is located.
farming, and Páramo-conservation (areas with the least possible anthropic intervention), in two altitudinal ranges, in the area between Páramo Cruz Verde and Páramo El Verjón, Colombia. Soil samples were taken after the potato crop was harvested in July 2018. Samples under the first altitudinal range were designated as C1, G1, and P1, corresponding to potato crop (3307 MASL), livestock (3246 MASL), and Páramo (3310 MASL), respectively. Samples from the second altitudinal range were designated C2, G2, and P2, corresponding to potato crop (2954 MASL), livestock (2938 MASL), and Páramo (2972 MASL), respectively.

The coordinates of the different study zones were: P1 (N 04° 35’ 41.5”- W 073° 59’ 09.2”), P2 (N 04° 37’ 08.1”- W 073° 57’ 59.3”), C1 (N 04° 35’ 35.8”- W 073° 59’ 08.8”), C2 (N 04° 37’ 11.1”- W 073° 58’ 02.7”), G1 (N 04° 35’ 48.6”- W 073° 58’ 44.3”), and G2 (N 04° 37’ 14.1”- W 073° 58’ 05.6”). After removing the vegetal layer covering the soil, the soil samples were collected in the layer of 0.00-0.20 m. For each land use and altitude, three 10 × 10 m observation quadrants were evaluated, and each quadrant consisted of 10 sub-samples collected in a zig-zag pattern, which were homogenized to obtain a composite sample, completing a total of three samples for each combination of land use and altitude. The collected samples were placed in properly labeled plastic bags and stored at -4 °C for physicochemical analysis and determination of heavy metals and pesticides; all analyses were performed in triplicate in the laboratory. In the case of pesticides, the samples were processed less than a week after their collection.

Physicochemical analysis

Physicochemical parameters of the soil were determined according to the procedures established by the IGAC (2006), using the following methods: moisture according to the gravimetric method, bulk density according to the paraffin-coated clod method, plasticity according to the Atterberg method, texture according to the Bouyoucus method, pH in water using the potentiometric method in soil-water ratio 1:1, percentage of organic carbon according to the Walkley Black method, boron by hot water extraction according to Berger and Truog (1939), and assimilable phosphorus by the Bray II method, cation exchange capacity, calcium, magnesium, potassium, and sodium chloride by extraction with ammonium acetate 1 mol L⁻¹, and exchangeable acidity by extraction with potassium chloride 1 mol L⁻¹ (Avellaneda-Torres et al., 2018).

Determination of heavy metals

Determination of heavy metals (arsenic, cadmium, mercury, and lead) was performed by inductively coupled plasma emission spectrometry prior extraction by closed digestion with a mixture of nitric acid: hydrochloric acid in a 7:1 ratio, respectively. The quantification was achieved by the external standard method. Final concentration spiked calibration curves were prepared between 5.0 and 50 µg kg⁻¹. The adjustment parameters in the equipment were: stabilization pump speed 100 rpm, analysis pump speed 50 rpm, stabilization time 5 s, nebulizer gas flow 0.5 L min⁻¹, and stabilization time for sample reading 30 s to control the analysis and the results generated, the analysis of calibration standards and linearity verification (r>0.995), method blank, duplicate calibration curve checkpoint (% RPD <30 %), analysis of a CRM (% recovery between 75 and 125 %), and a wash white (Julshamn et al., 2013; Mao et al., 2017).

Determination of organophosphorus-organonitrogen pesticides

On a sample of 10 g of soil, the researchers performed an extraction after adding salt and then ethyl acetate, stirring with ultraturrax for 1 min, and completing the process with ultrasonic extraction for 1 h. Subsequently, the sample was taken to a centrifuge at 5000 rpm for 5 min and after decantation, the supernatant was collected and the filtration with anhydrous residue grade sodium sulfate was carried out. The concentration process was performed in a rotary evaporator, quantitatively transferred to a 1 mL volumetric balloon, and subsequently placed in a vial for injection in the gas chromatograph.
Determination of organophosphorus and organonitrogen pesticides was carried out using an HP 6890 plus chromatograph connected to a capillary column (DB-5, 30 × 0.25 mm id × 0.25 μm), with shunt for parallel connection to micro-capture electronic detectors (μECD) and selective nitrogen-phosphorus detection (NPD). Previously, an ultrasound extraction with ethyl acetate was performed. An HP 7683B autosampler and a 15-meter guard column (Retention Gap) connected from the injector to the chromatographic column were used. The quantification of pesticides (cymoxanil, dimethoate, chlorothalonil, m-parathion, malathion, folpet, profenofos, oxadixyl, l-cyhalothrin, difenoconazole, cyproconazole, propiconazole, deltamethrin, methamidophos, monocrotophos, metalaxyl, dimethomorph, azoxystrobin, tebuconazole) was conducted through the external standard method. As a control of results, the standards of the calibration curve were analyzed, and their linearity was verified, a duplicate analysis of the sample was performed (maximum CV% allowed 20 %), the analysis of the fortified matrix was carried out (recovery percentages between 75 and 93 %), as well as an analysis of a white soil sample that had the same extraction treatment as the analysis sample to verify interferences and cross-contamination. Given the negative result, no confirmatory tests were performed.

**Determination of multi-residue pesticides**

Determination of multiple residues (328 pesticides) was carried out using liquid chromatography with T amden Mass Spectrometry (LC-MS/MS), with electrospray ionization detection, sim-mode acquisition, using two target ions and their relative abundance ratio. The extraction process was performed at low temperature (dry ice) and under the procedure guidelines given by the directives of the health and safety commission of the European Union (SANTE/11945/2015 E10), and the quantification by the standard addition method. The pesticides determined were selected based on pesticide use patterns in the area, conducting a search for their active ingredients and/or similar or associated chemical groups. The procedure was carried out at low temperature (dry ice), with solvents of different polarity; ethanol and acetonitrile in different proportions to avoid pesticide losses, and the binding of extracts after preconcentration. The quantification was conducted by the standard addition method, to compensate for the matrix effect and low recovery percentages of some pesticides. As a control of the results, the standards of the calibration curve for 10 % of the pesticides representative of the analysis were analyzed and their linearity was verified, a duplicate analysis of the sample (maximum CV% allowed 20 %) and the analysis of the fortified matrix (recovery percentages between 60 and 140 %) were performed, and an analysis of a white soil sample that had the same extraction treatment as the analysis sample was carried out to verify interferences and cross-contamination. Given the negative result, no confirmatory tests were performed.

**Statistical analysis**

Univariate analysis of data in which the variance was evaluated using the non-parametric Friedman method was performed, followed by a comparison of means using the Wilcoxon Test. A multivariate analysis of the data was also carried out using the principal component analysis, where possible interactions and relationships between variables were identified. Statistical analyzes were performed with a level of significance of p≤0.05, and using the R-Project program, version 3.4.2.

**RESULTS**

**Physicochemical parameters**

Gravimetric moisture results obtained categorize soils under Páramo and livestock farming as with very high moisture, and soils under cultivation as with high moisture
Regarding the plasticity index, all samples showed low plasticity (Sociedad Colombiana de la Ciencia del Suelo, 1991). On the other hand, the bulk density of all the soils under study is low (IGAC, 2006). Likewise, significant differences (p≤0.05) were found between the uses given to the soil in all the evaluated physical properties, finding that the moisture was significantly higher in the soils under Páramo, with respect to those used for potato cultivation and livestock farming, presenting the trend Páramo > livestock farming > potato crops. Likewise, the bulk density was significantly higher in soils under potato crops and livestock farming with respect to soils under Páramo, presenting the trend potato crops > livestock farming > Páramo. The only significant differences (p≤0.05) were found between the altitudes that were evaluated in the parameters of plasticity and bulk density, without finding a unique trend in terms of altitude.

Soils under Páramo showed significantly higher organic carbon content than the intervened soils, showing the following significant trend Páramo > livestock farming > potato crops (Figure 3). In the case of cation exchange capacity, the same trend was observed. In the case of phosphorus, there is a significant increase in soils under potato cultivation compared to the other two uses. According to the evaluated factors, the other parameters did not show statistically significant differences or any trend. There were no significant differences (p≤0.05) for any of the variables by altitude.

**Heavy metal**

According to the results shown in table 1, no significant differences (p≤0.05) were found in the arsenic contents related to land use or altitude. In Colombia, there is no legislation establishing permissible values for heavy metals in soils, so the results obtained were compared with the permissible limits of other countries with similar biogeographic conditions (Peru and Ecuador) and a third reference country (Spain). According to the Ministerio de Ambiente del Perú [Peruvian Ministry of Environment] (2012), of the Ministerio del Ambiente de Ecuador [Ministry of Environment of Ecuador] (2003), and the Consejería de Medio Ambiente de la Junta de Andalucía - España [Regional Ministry for Environment, Government of Andalusia – Spain] (1999), in the case of arsenic, the soils do not exceed the maximum values that are allowed according to the regulations consulted.

In the case of cadmium, no significant differences related to land-use or altitude were found (p≤0.05). The concentration of cadmium in test C2 is higher compared to the others. In this case, according to the Ministerio de Ambiente del Perú [Peruvian Ministry of Environment] (2012), the quality standard value in agricultural land is 1.4 mg kg⁻¹.

According to the Ministerio del Ambiente de Ecuador [Ministry of Environment of Ecuador]...
(2003), the maximum value for cadmium in agricultural land is 2 mg kg\(^{-1}\). In the case of the Consejería de Medio Ambiente de la Junta de Andalucía - España [Regional Ministry for Environment, Government of Andalusia – Spain] (1999), they establish that the limit values for agricultural soils are 2 mg kg\(^{-1}\) in acidic soils and 3 mg kg\(^{-1}\) in neutral and basic soils, within the reference level. Therefore, according to the regulations consulted in the case of cadmium, the maximum permitted values are not exceeded.

No presence of mercury was found above the detection level of the method (0.20 mg kg\(^{-1}\)) in any of the soils under study, so the regulatory requirements were not exceeded in any of the cases. Finally, on the subject of lead, no significant differences were detected (p≤0.05) in terms of the use or altitude of the evaluated soils. In the case of Ministerio de Ambiente del Perú [Peruvian Ministry of Environment] (2012), they consider a concentration of 70 mg kg\(^{-1}\) as the standard value for Pb. According to the Ministerio...
del Ambiente de Ecuador [Ministry of Environment of Ecuador] (2003), the maximum content allowable for Pb in agricultural soils is 100 mg kg\(^{-1}\). According to the Consejería de Medio Ambiente de la Junta de Andalucía - España [Regional Ministry for Environment, Government of Andalusia – Spain] (1999), for agricultural soils, they determine a limit value of 100 mg kg\(^{-1}\) in acid soils and 200 mg kg\(^{-1}\) in neutral and alkaline soils, within the reference level. Thus, the results did not exceed the maximum values allowed according to the regulations consulted in the case of Pb.

**Pesticides**

From the 348 pesticides evaluated in the soil under study, only the compounds dimethomorph (sum of isomers), metalaxyl and thiametoxam (listed in Table 2) were reported in the amounts indicated. Soils P1 and P2 of the Páramo show no residue of any pesticides found in the other land uses (Table 2); this also occurs in the livestock farming soil, G1. On the other hand, the potato crop soils have the same dimethomorph content at both altitudes. Additionally, traces of this same compound are observed in the livestock farming soil, G2, but in smaller amounts. To a lesser extent, metalaxyl was found in the soils under potato crops at altitude 1, and thiamethoxam in soils under potato crops at altitude 2.

**PCA**

According to figure 4a, there is a correlation among the thiamethoxam, dimethomor, cadmium, and lead, with soils under potato crops at altitude 2. Likewise, it is observed that soils under potato crops at altitude 1 have a correlation with metalaxyl content.

| Table 2. Pesticides identified by LC-MS / MS in soils under Páramo, potato cultivation, and cattle farming |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                  | C1              | C2              | G1              | G2              | P1              | P2              |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| **Dimethomorph (sum of isomers)** | 0.27Aa+0.01     | 0.27Aa+0.01     | ND              | 0.037Aa+0.002   | ND              | ND              |
| **Metalaxyl**   | 0.013Aa+0.0007  | ND              | ND              | ND              | ND              | ND              |
| **Thiamethoxam (A)** | ND              | 0.048Aa+0.002   | ND              | ND              | ND              | ND              |

* The different lowercase letters on the bars represent statistically significant differences between land uses (p≤0.05). ** The different uppercase letters on the bars represent statistically significant differences between heights (p≤0.05). ND: not detected.

**Figure 4.** Analysis of principal components relating the physicochemical variables, heavy metals, and pesticides of soils under the Páramo, potato cultivation, and cattle farming (a); and individual map of the uses of the soils under Páramo, potato cultivation, and cattle farming (b).
It is observed that Páramo soils have the highest correlation with high organic matter contents, plasticity index, and good cation exchange capacity.

**DISCUSSION**

According to the regulations analyzed, none of the soils under study exceeded the permitted contents of heavy metals. Likewise, no significant differences were found between the different land uses and altitudes evaluated in relation to heavy metal content. Thus, the initial hypothesis that potato crops and livestock farming were generating significant increase in the content of heavy metals was not validated for the case study.

Regarding the residuality of pesticides in soils under potato crops at altitudes 1 and 2, we found fungicide dimethomorph (0.27 mg kg\(^{-1}\)); in potato crops at altitude 1, we found fungicide metalaxyl (0.013 mg kg\(^{-1}\)) and in potato crops at altitude 2, the insecticide thiamethoxam (0.048 mg kg\(^{-1}\)). These results contrast with the behavior of the soils under Páramo, where no residual of any of the pesticides evaluated was found. However, no statistically significant differences were found in pesticide content in relation to land use and the altitudes evaluated. Likewise, it is important to mention that according to the values the degradation of those pesticides on soil (DT50 typical aerobic in IUPAC Pesticide Properties Database http://sitem.herts.ac.uk/aeru/ppdb/en/search.htm) the detection seems compatible with the moment of soil collection (after potato cultivation), reporting 72.5 days for dimethomorph, 36 days for metalaxyl and, 50 days for thiamethoxam.

Similar to the present study, Liang et al. (2011) reported residues of the fungicide dimethomorph in soils under bell pepper crops, finding concentrations between 0.05-0.94 and 0.29-1.05 mg kg\(^{-1}\) for the years 2008 and 2009, respectively. The results obtained in this investigation are within these same ranges (0.27 mg kg\(^{-1}\)). According to the study developed by Kailani et al. (2019) on pesticide residuality in soils in Jordan, they found contents of metalaxyl fungicide between 1.44 and 2.66 mg kg\(^{-1}\), which compared to this research is higher than the results obtained in soils under potato crops (0.013 mg kg\(^{-1}\)).

Finally, as reported by He et al. (2016), soils under corn cultivation in China show concentrations of thiamethozam insecticide between 0.01 and 0.44 mg kg\(^{-1}\); values that represent higher concentrations compared to those obtained in soils under potato crops in the present study (0.048 mg kg\(^{-1}\)).

Within the study of pesticide residuals, it should be noted that to date, no guidelines have been found for monitoring pesticide residues in Latin American soils or in the European Union (Hofstede et al., 2003; Silva et al., 2019). Additionally, Colombian researchers evaluated the concentration and distribution of heavy metals (Cr, Ni, Pb, Cd, Hg, and Zn) and pesticides (organochlorine and organophosphorus) of agricultural soils in an Irrigation District (Martínez-Mera et al., 2019). In the study of Martínez-Mera et al. (2019), the presence of pesticides in the soils was not reported. In contrast, the content of heavy metals in the soils varied as follows Zn > Cr > Ni > Pb > Hg > Cd (Martínez-Mera et al., 2019). Another study in Colombia obtained leaching risk maps of the pesticides imidacloprid, lambda-cyhalothrin, and chlorpyrifos in agricultural soil under an onion (Allium cepa L.) crop in Tibasosa, Boyacá. Which found that lambda-cyhalothrin and chlorpyrifos have lower movement risks, thus reducing their risk of affecting groundwater and surface water. However, imidacloprid does present a greater risk of contamination of the aquifers and mobility, becoming a potential pollutant (Navarro et al., 2021). Despite, these studies have not been carried out on Páramo soils.

Furthermore, these results indicate that none of the pesticides found in the soils of the area exceed the toxicity levels reported by IUPAC for mammals for acute oral levels (Mammals - Acute oral LD\(_{50}\) - mg kg\(^{-1}\)), which are: 3900 for dimethomorph; 375 for metalaxyl; and 1563 for thiamethoxam (http://sitem.herts.ac.uk/aeru/ppdb/en/search.htm). However, new results on pesticide residues in the soils of the Páramo are invited.
According to these results and although there are pesticide residues in soils under potato crops, the hypothesis that agricultural activities in the area generate significant pesticide residues was not validated, so the differences between land-uses and altitudes that were evaluated were not statistically significant. Therefore, it can be analyzed that (despite the soil samples being taken after the potato crop was harvested) there is no evidence of significant impact in the content of heavy metals or pesticide residues associated with potato cultivation and livestock farming in the area. This can be explained by the fact that current agriculture and livestock farming practices in the area under study have specific land use patterns and local agricultural practices developed mainly in the Páramo, in contrast to other country areas where potato crops and livestock farming activities are developed.

These patterns or local uses of the land are a combination of practices inherited from the Green Revolution (mass application of agrochemicals) but also from traditional agricultural wisdom, such as the implementation of a potato-pasture rotation system, with long periods of fallow, in which the potato crop is planted for up to two cropping periods on the same soil and then rested on a pasture system for seven years or more, which allows crop rotation periods that mitigate potential impacts. Likewise, these specific agricultural practices of the area present a low intensity in relation to the number of cattle per hectare of land, finding a low density of cattle heads (0.24–0.36) per hectare of land (Avellaneda-Torres et al., 2018). Additionally, these livestock systems do not receive industrial or commercial food or feed; their feeding is fundamentally based on the consumption of grasses in the area, which do not receive a chemical fertilization process for their growth. These practices correspond to patterns of peasant family agriculture or subsistence agriculture, which present behaviors different from those of commercial agriculture developed at lower altitudes in relation to those of the Páramo, in which there are no rest periods, but rather an intensive use of the soil and if processes of chemical fertilization of pastures can be presented, as well as feeding of livestock with external commercial products.

Moreover, these practices correspond to patterns of peasant family agriculture or subsistence agriculture, which present different behaviors from those of commercial agriculture in the potato-grazing systems developed at lower altitudes in relation to those of the Páramo.

Five of the physicochemical parameters of the soils evaluated (gravimetric moisture, bulk density, organic carbon, cation exchange capacity, and phosphorus) showed significant differences due to the activities of potato cultivation and livestock farming. In the case of gravimetric moisture, organic carbon, and cation exchange capacity, they were higher in Páramo soils, which demonstrates the conservation of this ecosystem by maintaining the natural vegetation that protects moisture, as well as the maintenance of organic matter and cation exchange capacity. On the other hand, soil bulk density increased under potato crops and livestock farming, which is explained by the trampling activities of cattle and mechanical work in the sowing of the crop that increase soil compaction. Likewise, the phosphorus content is higher in soils under potato crops, which corresponds to the application of phosphorus fertilizers that modify the natural content of phosphorus in the soil (Hofstede, 1997; Martínez et al., 2008; Llambí et al., 2012).

These results are partially consistent with those reported by Avellaneda-Torres et al. (2018), who indicated that organic carbon, cation exchange capacity, calcium, potassium, and NH₄ were modified by potato cultivation and livestock farming activities in the Páramo areas of Los Nevados National Natural Park. We agree with arguments that gravimetric moisture, organic carbon, and cation exchange capacity reflect the advantages of Páramo soils that still retain their native vegetation, thus conserving moisture. In contrast, cultivated soils showed lower moisture because they were more...
exposed to sunlight and air. Similarly, there is greater soil compaction in the cultivated areas due to cattle trampling and potato cultivation activities, in a potato-pasture rotation system.

CONCLUSIONS

No significant content of heavy metals or significant residual pesticides was found in Páramo soils associated with potato cultivation and livestock farming in the area under study. This behavior is attributed to the specific practices developed in the area in which, although there is an application of chemically synthesized agricultural supplies, there is also the implementation of a potato-pasture rotation system, with long periods of fallow. In this system the potato crop is planted for up to two cropping periods on the same soil and then rested on a cattle pasture system for seven years or more. This system also presents a low intensity in relation to the number of cattle per hectare of land, and the pastures (main cattle feed) do not present chemical fertilization. Finally, this study represents the first report on heavy metals and pesticide residues in Páramo soils.

SUPPLEMENTARY DATA

Supplementary data to this article can be found online at https://www.rbcsjournal.org/wp-content/uploads/articles_xml/1806-9657-rbcs-46-e0210135/1806-9657-rbcs-46-e0210135-suppl01.pdf.

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