agriculture

Article

Spatial Variability of Soil Acidity and Lime Requirements for Potato Cultivation in the Huánuco Highlands

Kenyi Quispe [1], Sharon Mejía [1], Carlos Carbajal [1], Lidiana Alejandro [1], Patricia Verástegui [1] and Richard Solórzano [1,2,*]

[1] Dirección de Supervisión y Monitoreo en las Estaciones Experimentales Agrarias, Instituto Nacional de Innovación Agraria (INIA), Av. La Molina 1981, Lima 15024, Peru; k.quispe1008@gmail.com (K.Q.); sharon.mejia.m29@gmail.com (S.M.); cmcarbajal@gmail.com (C.C.); lalejandro@inia.gob.pe (L.A.); patymarve@gmail.com (P.V.)

[2] Facultad de Ciencias Ambientales, Universidad Científica del Sur (UCSUR), Lima 15067, Peru

* Correspondence: investigacion_labsaf@inia.gob.pe

Abstract: Soil acidity is a major limiting factor for potato production in Peru's high Andean region. This study aims to predict the spatial variability of soil acidity as a fundamental tool for recommending site-specific liming treatments and to identify the physical–chemical characteristics most closely related to soil acidity. The soil samples were collected from five locations in the province of Pachitea, Huánuco. Descriptive statistics, principal component analysis (PCA), and Pearson correlation analysis were used to identify the soil properties contributing most to total variance and those most strongly correlated with soil acidity. The ordinary geostatistical kriging method evaluated the predictive accuracy for 23 soil properties and liming requirements over a 28,463 ha area, at a spatial resolution of 10 m. Results showed that the Plaza Punta and Buenos Aires locations had more degraded acidic soils, with frequencies between 55% and 100% above the general mean (30.94 ± 24.87%) and the critical threshold (25%) for potato cultivation. Variables such as exchangeable calcium percentage (ECP), Ca^{2+}, Mg^{2+}, sand content, and organic matter strongly correlated with soil acidity, while exchangeable H^+ and ECP were the main contributors to the total variance. Geostatistical analysis revealed that Mg^{2+} and Ca^{2+} had the highest R^2 values (0.87 and 0.76, respectively), indicating a strong fit between observed and predicted values in the spatial analysis of soil acidity. It is concluded that the agricultural dolomite requirements in the localities of Plaza Punta and Buenos Aires exhibit high spatial predictability. Additionally, the analysis of diverse soil physicochemical properties is emphasized as critical for determining precise application rates.

Keywords: soil fertility; soil acidity; geostatistical interpolation; spatial analysis

Citation: Quispe, K.; Mejía, S.; Carbajal, C.; Alejandro, L.; Verástegui, P.; Solórzano, R. Spatial Variability of Soil Acidity and Lime Requirements for Potato Cultivation in the Huánuco Highlands. *Agriculture* **2024**, *14*, 2286. https://doi.org/10.3390/agriculture14122286

Academic Editor: Lorenzo Barbanti

Received: 17 October 2024
Revised: 6 December 2024
Accepted: 9 December 2024
Published: 13 December 2024

1. Introduction

Potato has a vital role in global food security, with an annual worldwide production of approximately 374.07 million tons, making it the sixth most important crop after sugarcane, maize, wheat, rice, and oil palm [1]. Peru is the leading potato producer in the Andean region, with a total output exceeding 6 million tons [1]. This crop supports the livelihoods of over 700,000 families, most of whom are engaged in small-scale farming, contributing 10.1% to the country's gross value of agricultural production (GVP) [2]. The Huánuco region stands out regarding cultivated area and production [2] and is one of the key centers of potato diversity [3,4]. However, Huánuco is among Peru's poorest regions, with some of the highest extreme poverty levels [2]. It ranks as one of the most food-insecure areas, with a vulnerability index of 0.54, where values closer to 1 signify greater vulnerability [5]. This issue is further compounded by soil conditions, such as acidity, which significantly limit crop production in the region.

Soil acidity is one of the major constraints to crop production globally [6]. In South America, acidic soils account for 52% of the total agricultural area [7]. In Peru, pH values in the central Andes range between 4.2 and 4.6, classifying these soils as strongly acidic [8]. Acidic soils are typically characterized by severe deficiencies in essential nutrients like phosphorus, calcium, magnesium, and molybdenum while exhibiting toxic levels of aluminum, iron, and manganese [9]. These degraded, low-fertility soils exacerbate the vulnerability of native potato agroecosystems in the high Andean regions of Peru.

Several studies highlight that the integrated use of inorganic and organic fertilizers and liming amendments significantly enhances the physicochemical properties of acidic soils [10]. Specifically, liming raises soil pH to optimal levels, increases the availability of exchangeable calcium (Ca^{2+}) and magnesium (Mg^{2+}), and reduces phosphorus immobilization [11]. This practice also improves the soil's physical and biological quality, increasing crop productivity [12].

However, soil properties and nutrient concentrations often fluctuate across crop fields due to the varying effects of soil-forming factors [13]. As a result, fertilizer applications can create areas of nutrient excess or deficiency [14]. In regions with excessive fertilizer levels, leaching can lead to water contamination, while insufficient fertilizer dosages can limit crop yields [15]. In this context, the use of soil fertility maps allows for the precise programming of variable doses of fertilization and liming, using geostatistical methods for predicting the spatial variation in soil properties [16].

The present study aims to predict the spatial variation in lime requirements for potato cultivation across five locations in the Pachitea province, Huánuco, Peru. The geostatistical interpolation method, Ordinary Kriging (OK), was employed to accurately assess the spatial variability of soil properties and generate characterization maps. Additionally, the study seeks to identify the physicochemical characteristics most strongly associated with soil acidity. Pearson correlation analysis and principal component analysis (PCA) were conducted on 23 soil physicochemical properties to achieve this.

2. Materials and Methods

2.1. Study Area

The study area is situated in the Peruvian highlands, specifically in the villages of Huarichaca, Chagragoto, Rumichaca, Plaza Punta, and Buenos Aires, located in the districts of Umari, Chaglla, Molino, and Panao, within the province of Pachitea, Huánuco region (Figure 1). The area experiences an average annual precipitation of 865.31 mm and a mean annual relative humidity of 78.46%. Minimum temperatures range from 9 °C in June to 5 °C in August, while maximum temperatures vary between 25 °C in September and 24 °C in November. These historical averages were calculated using data from the Chaglla meteorological station (9°50′49.9″ S; 75°54′54.0″ W; 2800 m.a.s.l.) managed by the National Service of Meteorology and Hydrology of Peru (SENAMHI) as shown in Figure 2.

2.2. Soil Sampling and Analysis

The R software version 4.4.1 [17] was used to determine the sampling points through the sample function from the sp package [18]. The R script generated the sampling coordinates by integrating a raster layer with high-resolution satellite imagery (e.g., Sentinel-2) as the base map, and stratified sampling was selected as the method. Ninety soil samples were collected at a depth of 30 cm from fields managed by native potato growers.

A total of 90 soil samples, taken from a depth of 0–30 cm, were analyzed at INIA's Soil, Water, and Foliar Laboratories network. The variables assessed were part of a comprehensive soil characterization using established reference methodologies. Soil texture (sand, silt, and clay percentages) was determined using the Bouyoucos hydrometer method [19]. The pH was measured following EPA guidelines [20], while electrical conductivity (EC) was determined using the saturation extract method [21]. Organic matter content (OM) was analyzed using NOM-021-RECNAT-2000 [19] and total nitrogen (N) using ISO standards [22]. Available phosphorus for both neutral and acidic soils was measured using the Bray and Kurtz method [19], and available potassium (K), according to Bazán Tapia [23]. Exchangeable cations (H^+, Al^{+3}, Ca^{+2}, Mg^{+2}, K^+, and Na^+) were also quantified [19]. Bulk density

(BD) values were obtained from the global digital soil mapping system, SoilGrids [24], with a spatial resolution of 250 m, focusing on the 15–30 cm depth. The data were retrieved in TIFF format from the SoilGrids database and processed using QGIS to extract the relevant values.

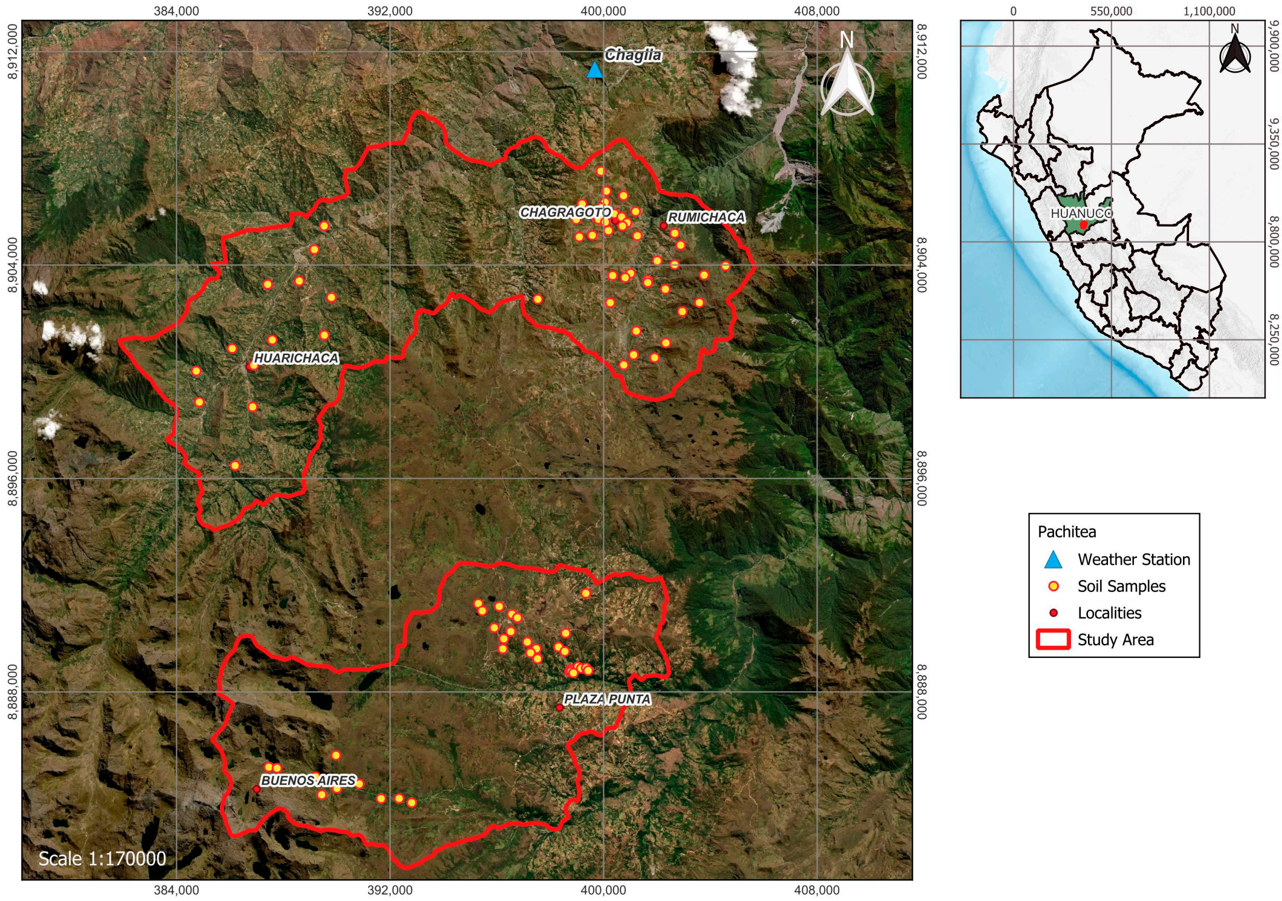

Figure 1. Soil monitoring locations in Pachitea province, Huánuco, Peru.

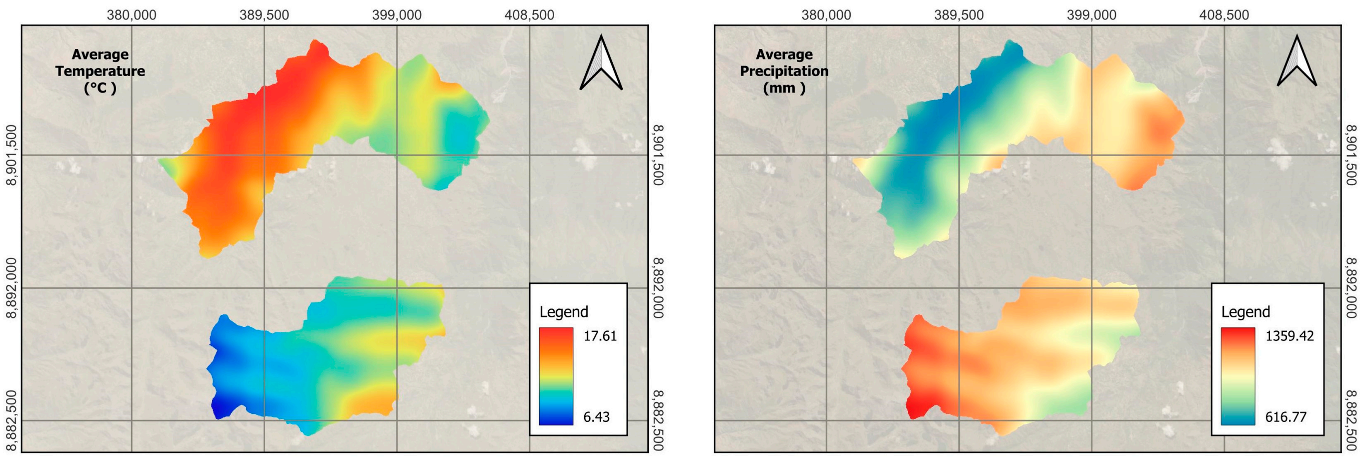

Figure 2. Average temperature and average precipitation in the study area.

2.3. Estimation of the Liming Requirement for Soils

According to Havlin [25], calculations were made to estimate liming requirements.

$$CEC_{\text{mEq } 100\text{g}^{-1}} = \left(Ca^{+2} + Mg^{+2} + K^{+} + Na^{+} + H^{+} + Al^{+3}\right)_{\text{mEq } 100\text{g}^{-1}} \quad (1)$$

$$TSW_{\mathrm{t\ ha^{-1}}} = BD_{t\ m^{-3}} \times 0.3_m \times 10000_{m^2} \quad (2)$$

$$EAP_{\%} = \frac{\left(H^{+} +\ Al^{+3}\right)_{\mathrm{mEq\ 100g^{-1}}}}{CEC_{\mathrm{mEq\ 100g^{-1}}}} \quad (3)$$

$$LR_{\mathrm{kg\ ha^{-1}}} = \frac{(EAP_{\%} - PAS_{\%}) \times CEC_{\mathrm{mEq\ 100g^{-1}}} \times TSW_{\mathrm{t\ ha^{-1}}} \times 2.8}{550} \quad (4)$$

$$DR_{\mathrm{kg\ ha^{-1}}} = \frac{(EAP_{\%} - PAS_{\%}) \times CEC_{\mathrm{mEq\ 100g^{-1}}} \times TSW_{\mathrm{t\ ha^{-1}}} \times 2.8}{300} \quad (5)$$

$CEC_{\mathrm{mEq\ 100g^{-1}}}$ refers to the effective cation exchange capacity, determined by summing the exchangeable bases in acid soils. $TSW_{\mathrm{t\ ha^{-1}}}$ indicates the topsoil weight at a depth of 30 cm that is suitable for potato cultivation. EAP (%) represents the exchangeable acidity percentage, calculated as the ratio of the soil's exchangeable acidity to the effective CEC. $LR_{\mathrm{kg\ ha^{-1}}}$ denotes the agricultural lime requirement, determined based on the mEq·100 g^{-1} of calcium necessary to neutralize the EAP up to the permissible acidity saturation (PAS) for potato crops. A threshold of 25% PAS is considered optimal for potato cultivation [26], and agricultural lime with a calcium oxide (CaO) content of 55% is used. For the agricultural dolomite requirement (DR), a CaO content of 30% is considered. Application of DR is recommended for plots where the percentage of exchangeable magnesium in the soil is less than 10% [27].

2.4. Statistical Analysis

In RStudio, various tools and libraries are used to generate graphs that facilitate the statistical analysis of soil properties. First, for the description of the statistical analysis, basic functions such as summary() and boxplot() were used, as well as the ggplot2 package [28], allowing the creation of more sophisticated and customizable visualizations. Later, in the principal component analysis (PCA), the prcomp() function was used to perform the analysis and ggbiplot() to visualize the results [29], providing a clear representation of the relationships between the variables and the principal components. Finally, for the Pearson correlation analysis, the cor() function was used to calculate the correlations between the variables, complemented with scatter plots generated by ggplot2 and the pairs() function to visually observe the relationships.

2.5. Geostatistical Interpolation

Understanding spatial variability through the appropriate geostatistical semivariogram model is essential for mapping and delineating the spatial variability of soil fertility, thereby optimizing fertilization programs [30]. A geostatistical analysis of the soil analysis results from the 90 georeferenced sampling points was performed. These correspond to the bulk density, the percentage of sand, silt and clay, pH, electrical conductivity (EC), organic matter (OM), available P and K, effective cation exchange capacity (CEC), concentration of exchangeable cations (H^{+}, Al^{+3}, Ca^{+2}, Mg^{+2}, K^{+} and Na^{+}), and liming requirement. Spatial interpolations were performed using the Ordinary Kriging (OK) method. All aspects of the procedure were facilitated by the spatial and geostatistical tools of the SAGA software version 9.4, package such as the creation of variograms and the implementation of the Kriging model, ensuring an accurate and efficient estimation [31]. Subsequently, the interpolated maps were exported using the QGIS software version 3.34, with the aim of visualizing and analyzing spatial data effectively [32].

2.6. Model Validation

The nugget (C0), sill (C0 + C), range (R), and sill–nugget ratio (PSV), shown in the Equation (6), are key parameters in the semivariogram analysis that describe the spatial autocorrelation of the data. These parameters are derived from fitting the semivariogram model for geostatistical interpolation [33].

$$PSV = \frac{Sill - Nugget}{Sill} = \frac{C}{C0 + C} \quad (6)$$

The semivariogram model is selected based on criteria such as the root mean square error (RMSE) and the coefficient of determination (R^2) [33]. Ideally, the chosen model should exhibit RMSE values close to zero and R^2 values close to one, shown in the Equation (7), as these indicate the accuracy and quality of the model, respectively [34]. The kriging interpolations for each soil property were cross-validated using the leave-one-out method [35].

$$RMSE = \sqrt{\frac{1}{n}\sum_{I=1}^{n}[Z_1(x_i) - Z_2(x_i)]^2} \quad (7)$$

where n represents the number of samples and $Z_1(x_i)$ and $Z_2(x_i)$ represent the predicted and observed values at site i, respectively.

3. Results

3.1. Descriptive Statistics for Soil Acidity

The pH values ranged from 3.9 to 5.8, with a mean of 4.69 ± 0.39 (Table 1). The exchangeable acidity percentage (H^+ + Al^{+3}) varied between 0% and 72.75%, yielding a mean of 30.94 ± 24.87% (Table 1). The variance for pH was 0.16, while the exchangeable acidity percentage (EAP) exhibited a variance of 618.73, indicating a high dispersion of potential acidity data within narrow pH ranges (Table 1). All locations displayed mean pH values below the critical threshold (5.5) necessary for optimal potato crop growth. Plaza Punta and Buenos Aires were identified as the most degraded sites, characterized by pH values below the overall mean (Figure 3).

Regarding the potential acidity of the soils, the localities of Buenos Aires, Plaza Punta, Chagragoto, and Rumichaca exhibit EAP that exceeds the overall mean of 30.94 ± 24.87% (Figure 4). However, only the localities of Buenos Aires and Plaza Punta have averages that surpass both the general mean and the critical threshold (25%) for potato cultivation. Among these, the acid soils in Plaza Punta were the most degraded, showing a frequency of 100% of the data above the critical value. In contrast, the acid soils of Huarichaca were the least degraded, with 85% of the data falling below the critical threshold (Figure 4).

Table 1. Descriptive statistics of soil's physicochemical properties in the study area.

Parameter	Min	Max	Mean	Median	Var	Sd
Sand (%)	42.00	94.00	70.75	70.00	157.06	12.53
Silt (%)	1.00	37.00	15.52	15.42	43.38	6.59
Clay (%)	0.27	35.00	13.77	11.00	80.11	8.95
pH	3.90	5.80	4.69	4.60	0.16	0.39
OM (%)	1.00	32.90	9.16	7.40	47.32	6.88
EC ($dS \cdot m^{-1}$)	0.01	0.80	0.09	0.06	0.01	0.11
P ($mg \cdot kg^{-1}$)	0.00	478.98	41.60	26.30	3494.27	59.11
K ($mg \cdot kg^{-1}$)	29.99	616.00	183.70	169.80	12,267.40	110.76
CEC ($cmol^+ Kg^{-1}$)	2.85	22.33	7.96	7.30	14.72	3.84
H^+ ($cmol^+ Kg^{-1}$)	0.00	4.90	1.49	1.40	1.23	1.11
Al^{+3} ($cmol^+ Kg^{-1}$)	0.00	3.40	0.55	0.30	0.55	0.74
Acidity ($cmol^+ Kg^{-1}$)	0.00	7.80	2.04	1.80	3.25	1.80
Ca^{+2} ($cmol^+ Kg^{-1}$)	0.62	16.56	3.91	3.10	10.49	3.24
Mg^{+2} ($cmol^+ Kg^{-1}$)	0.17	4.23	1.27	0.85	1.15	1.07
K^+ ($cmol^+ Kg^{-1}$)	0.04	1.65	0.58	0.51	0.11	0.33
Na^+ ($cmol^+ Kg^{-1}$)	0.00	1.80	0.16	0.10	0.06	0.25
ECP (%)	11.63	78.99	44.57	45.95	364.56	19.09
EMP (%)	3.40	31.41	14.12	12.74	58.35	7.64
EPP (%)	0.36	21.68	8.15	6.61	22.10	4.70
ESP (%)	0.00	21.49	2.22	2.01	8.07	2.84
EAP (%)	0.00	72.75	30.94	27.82	618.73	24.87

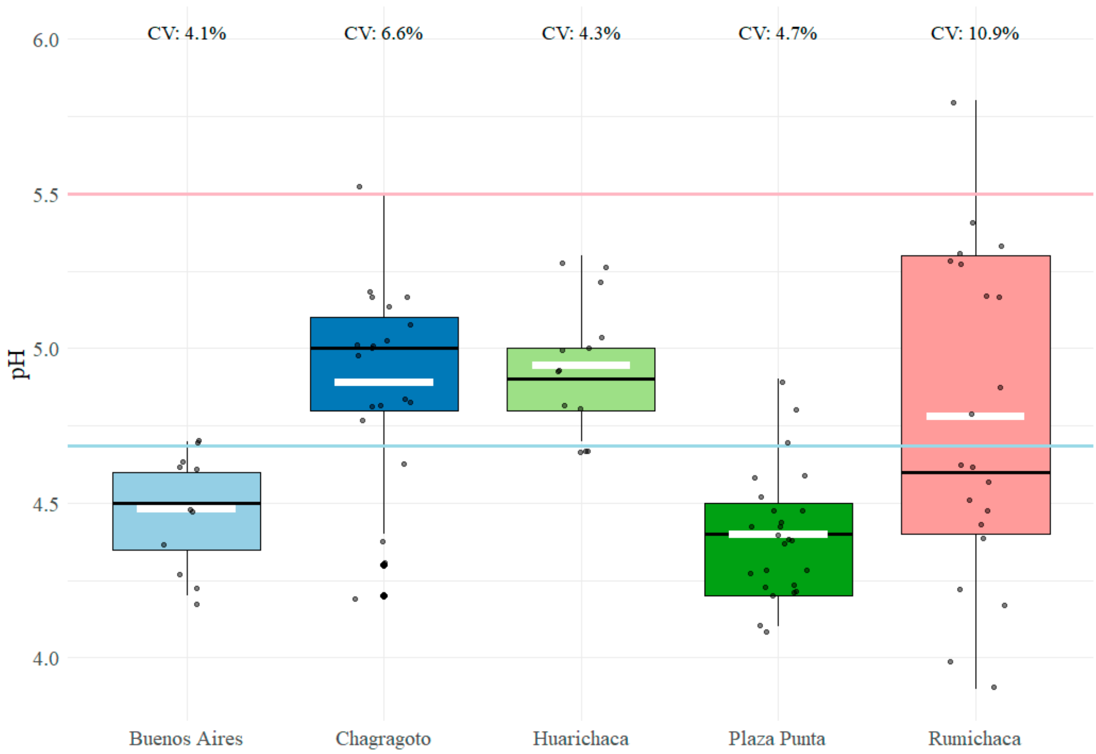

Figure 3. Descriptive statistics of soil pH in the localities of Buenos Aires, Chagragoto, Huarichaca, Plaza Punta and Rumichaca, belonging to the province of Pachitea, Huánuco, Peru. Pink line: critical pH level of potato crops; Blue line: general average of the pH values of the 5 localities evaluated; White line: average pH value of each locality.

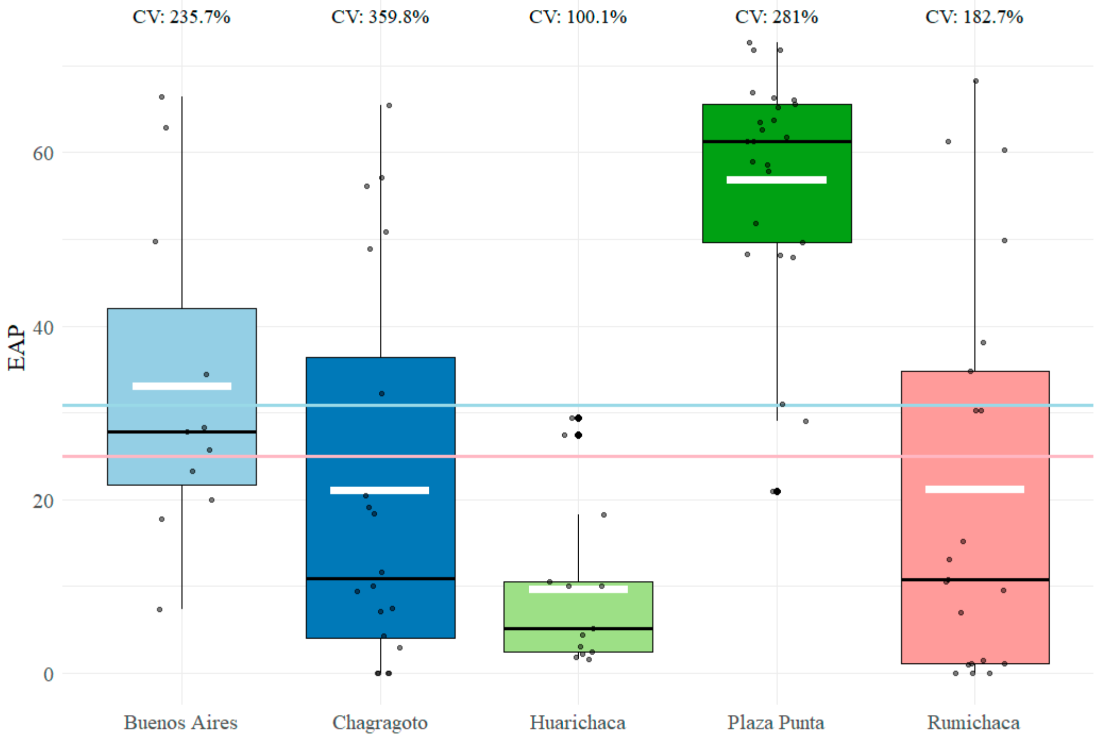

Figure 4. Descriptive statistics of exchangeable acidity percentage (EAP) of soil pH in the localities of Buenos Aires, Chagragoto, Huarichaca, Plaza Punta and Rumichaca, belonging to the province of Pachitea, Huánuco, Peru. Pink line: critical pH level of potato crops; Blue line: general average of the pH values of the 5 localities evaluated; White line: average pH value of each locality.

3.2. Principal Component Analysis of Soil Properties

Principal component analysis (PCA) was conducted on 21 soil physicochemical characteristics (Table 1). As shown in Figure 5, the first two components account for 59% of the variance across the five studied locations. The biplot indicates that the variables contributing the most to the variance explained by Component I are exchangeable H^+, exchangeable acidity percentage (EAP), and exchangeable calcium percentage (ECP). The soils in Plaza Punta and Buenos Aires show a stronger association with exchangeable acidity (H^+ + Al^{+3}), sand percentage, and organic matter (OM), which reflect a greater need for liming. Plaza Punta soils, in particular, exhibit high EAP and an inverse relationship with the exchangeable magnesium percentage (EMP) and cation exchange capacity (CEC), indicating a higher requirement for dolomite. Conversely, the variance related to acidity is not associated with the soils from Chagragoto and Huarichaca, which have higher pH, ECP, and bulk density (BD) values, indicating no liming requirement. However, the Rumichaca soil variance has no clear relationship with the studied physicochemical variables.

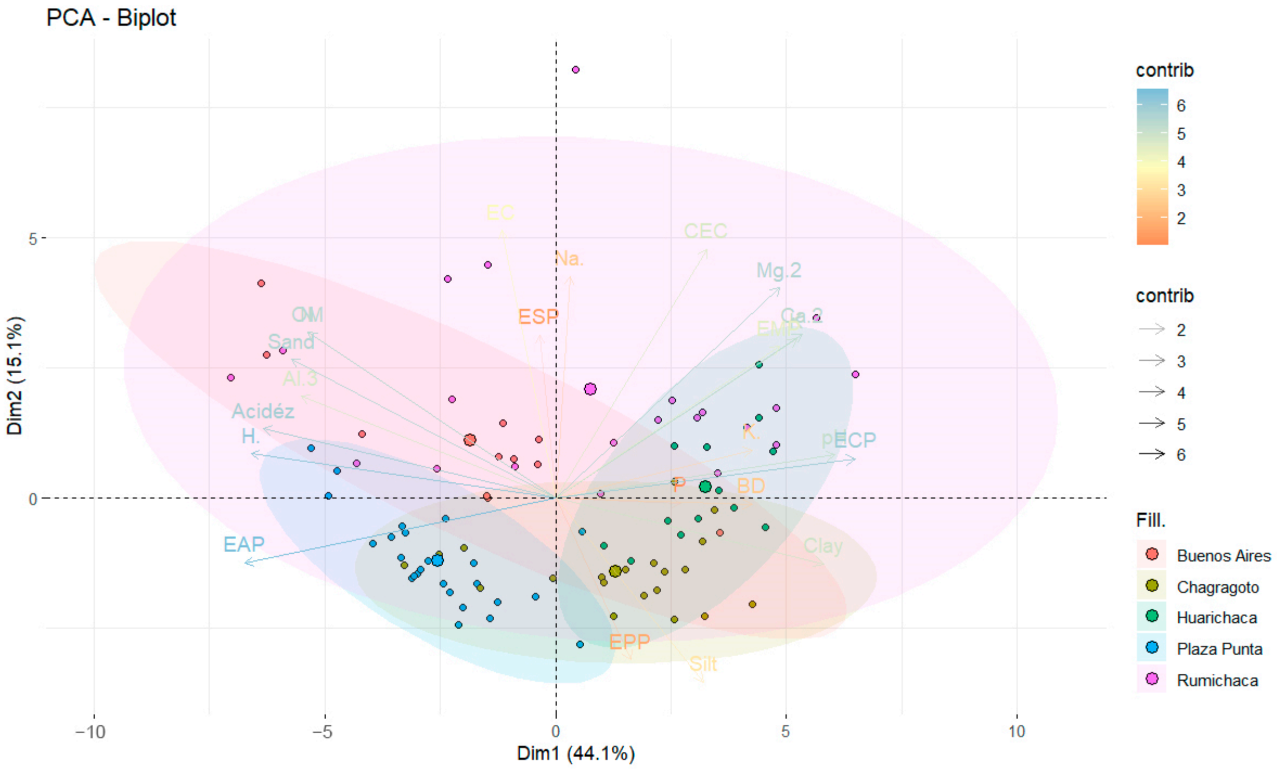

Figure 5. Principal component analysis (PCA) of the soil's physicochemical properties in five Pachitea, Huánuco, Peru locations.

3.3. Pearson's Correlation Analysis of Soil Properties and Their Relationship with Soil Acidity

Pearson correlation analysis was conducted for the 23 evaluated variables (Figure 6). The most strongly correlated variable with soil pH is the exchangeable calcium percentage (ECP), with a positive correlation of 0.77. Additionally, there is a significant negative correlation between ECP and both the exchangeable acidity percentage (EAP) and exchangeable H^+, with correlation values of −0.96 and −0.84, respectively. The exchangeable magnesium percentage (EMP) also shows a strong negative correlation with EAP, reaching a value of −0.74. Increasing ECP and EMP can reduce exchangeable H^+ concentrations and raise soil pH. Furthermore, a noteworthy positive correlation exists between soil acidity with the sand percentage and organic matter (OM), with values of 0.63 and 0.71, respectively. Several variables also exhibit a high positive correlation with pH, including exchangeable Mg^{+2}, Ca^{+2}, K^+, clay content, available K, and bulk density (BD), with respective values of 0.52, 0.65, 0.66, 0.59, 0.66, and 0.50. These relationships are critical, as soils with higher sand content and high OM levels require larger lime doses. In contrast, treatments that integrate different exchangeable bases and improve soil bulk density will enhance the effectiveness of liming on acidic Andean soils.

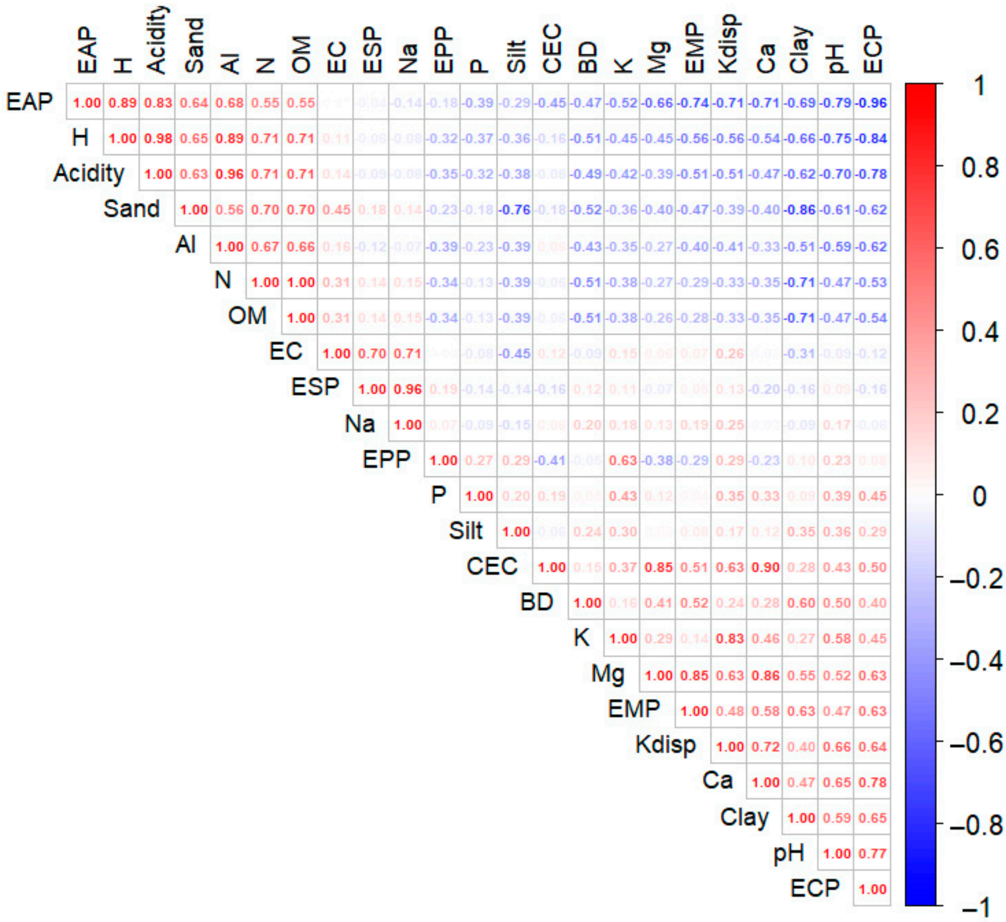

Figure 6. Pearson correlation matrix among soil fertility parameters.

3.4. Spatial Variation in Soil Acidity in the Localities of Plaza Punta and Buenos Aires

Table 2 presents the parameters of the semivariogram models obtained using the Ordinary Kriging (OK) interpolation method and the cross-validation results based on RMSE and R^2 values for model evaluation. The linear and exponential semivariogram models provided the best parameterization for predicting unknown values of the soil parameters under study. In the locations of Plaza Punta and Buenos Aires, the soil physicochemical variables with the highest spatial predictability were Al^{+3} (mEq·100 g^{-1}), Ca^{+2} (mEq·100 g^{-1}), Mg^{+2} (mEq·100 g^{-1}), exchangeable calcium percentage (ECP), and exchangeable acidity percentage (EAP), with R^2 values of 0.60, 0.76, 0.87, 0.57, and 0.53, respectively. These R^2 values indicate a strong correlation between observed and predicted values in unsampled areas. Notably, Ca^{+2} (mEq·100 g^{-1}) and Mg^{+2} (mEq·100 g^{-1}) emerged as significant variables for explaining the variance in the soils' physicochemical properties in the PCA. Both variables show high negative correlations with EAP at −0.71 and −0.66, respectively. Furthermore, they exhibited significant R^2 values in the prediction of spatial variability. Based on these findings, spatial variation maps were produced for EAP (Figure 7), Ca^{+2} (Figure 8), and Mg^{+2} (Figure 9), as these characteristics play a crucial role in explaining soil acidity and liming requirements.

3.5. Spatial Variation in Soil Acidity in the Localities of Huarichaca, Chagragoto, and Rumichaca

Table 3 presents the parameters of the semivariogram models derived using the Ordinary Kriging (OK) interpolation method alongside the cross-validation results based on RMSE and R^2 values for evaluation. The semivariogram models with Linear and Gaussian parameterization proved to be the most suitable for predicting unknown values of the studied soil parameters. In the localities of Chagragoto, Huarichaca, and Rumichaca, the soil physicochemical variables with the highest spatial predictability were bulk density ($g \cdot cm^{-3}$), exchangeable magnesium percentage (EMP), and exchangeable potassium percentage (EPP), with R^2 values of 0.79, 0.54, and 0.54, respectively. These values indicate a strong alignment between observed and predicted data in non-sampled areas, reflecting a high model fit. Notably, EMP (%) and EPP (%) emerged as significant variables in explaining the variance of the soil's physicochemical characteristics in the principal component analysis (PCA). They showed strong negative correlations of −0.74 and −0.18 with exchangeable acidity percentage (EAP). Additionally, these variables exhibited substantial R^2 values for predicting spatial variability. Consequently, spatial distribution maps were generated for bulk density (Figure 10), magnesium (Figure 11), and potassium (Figure 12), which are crucial for understanding soil acidity and liming requirements (Figure 13) for these locations.

3.6. Liming Requirement

Figure 13 illustrates the spatial variation in liming requirements for the localities of Plaza Punta and Buenos Aires, where calcium (Ca^{2+}) and magnesium (Mg^{2+}) levels exhibited a significant correlation with observed and predicted values (R^2 values of 0.76 and 0.87, respectively) (Figure 14a). Both variables also showed strong positive correlations with soil pH, with correlation coefficients (R) of 0.64 and 0.51, respectively. Furthermore, linear regression analysis indicates that the observed values of Ca^{2+} closely align with the predicted liming requirements (Figure 14b).

Table 2. Semivariogram models for the soil properties in the localities of Plaza Punta and Buenos Aires.

Soil Property	Model	Nugget (C0)	Sill (C0 + C)	Range (m)	PSV (C/C0 + C)	Cross-Validation	
						[1] R^2	[2] RMSE
pH	Exponential	0.0045	0.0387	7155.83	0.1161	0.20	0.1582
P ($mg \cdot kg^{-1}$)	Gaussian	1.3691	2.3057	7155.83	0.5938	0.11	1.2467
K ($mg \cdot kg^{-1}$)	Gaussian	1.7494	0.1700	7155.83	10.2925	0.26	1.1112
EC ($dS \cdot m^{-1}$)	Linear	0.0000	0.0000	7155.83	0.0000	0.36	0.0388
OM (%)	Cubic	0.3263	0.5905	7155.83	0.5526	0.31	0.6909
H^+ ($cmol^+ Kg^{-1}$)	Gaussian	0.2938	2.0557	7155.83	0.1429	0.43	0.6984
Al^{+3} ($cmol^+ Kg^{-1}$)	Linear	0.0000	0.0000	7155.83	0.0000	0.60 *	0.2301
Acidity ($cmol^+ Kg^{-1}$)	Linear	0.0000	0.0000	7155.83	0.0000	0.46	0.4068
CIC ($cmol^+ Kg^{-1}$)	Linear	0.0000	0.0000	7155.83	0.0000	0.51	0.4446
Ca^{+2} ($cmol^+ Kg^{-1}$)	Gaussian	0.0343	0.1405	7155.83	0.2442	0.76 *	0.2280
Mg^{+2} ($cmol^+ Kg^{-1}$)	Linear	0.0000	0.0000	7155.83	0.0000	0.87 *	0.1170
K^+ ($cmol^+ Kg^{-1}$)	Linear	0.0234	0.0000	7155.83	0.0000	0.38	0.2630
Na^+ ($cmol^+ Kg^{-1}$)	Linear	0.0000	0.0000	7155.83	0.0000	0.69	0.0411
BD ($g \cdot cm^{-3}$)	Linear	0.0008	0.0000	7155.83	0.0000	0.44	0.0416
EAP (%)	Linear	0.0000	0.0000	7155.83	0.0000	0.53 *	0.6665
ECP (%)	Linear	0.0000	0.0000	7155.83	0.0000	0.57 *	0.5826
EMP (%)	Linear	0.1844	0.0000	7155.83	0.0000	0.44	0.5295
EPP (%)	Linear	0.1844	0.0000	7155.83	0.0000	0.44	0.5295
ESP (%)	Linear	0.0000	0.0000	7155.83	0.0000	0.42	0.3157
Liming ($t \cdot ha^{-1}$)	Linear	0.0975	0.0000	7155.83	0.0000	0.52 *	0.5972

[1] Coefficient of determination; [2] root mean square error. * Selected variables with higher R^2, due to a high fit degree between the observed and predicted values, are shown with uppercase asterisks.

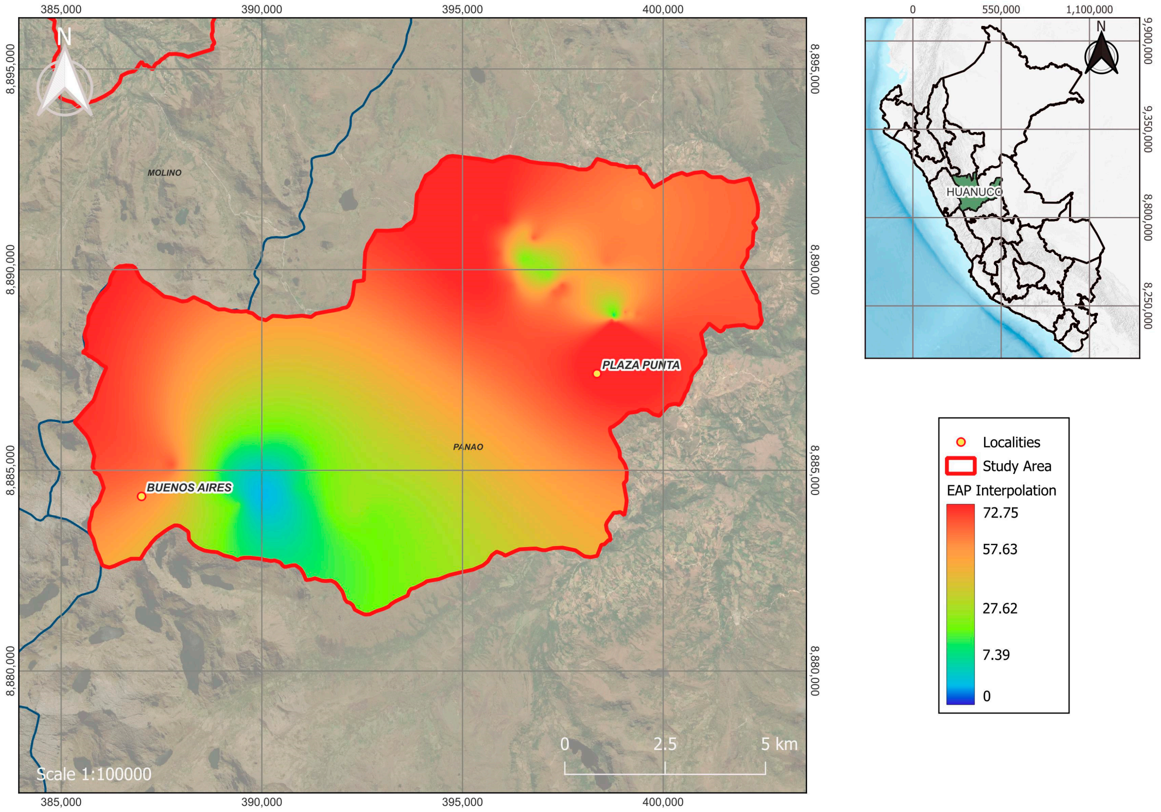

Figure 7. Soil exchangeable acidity in the communities of Pachitea.

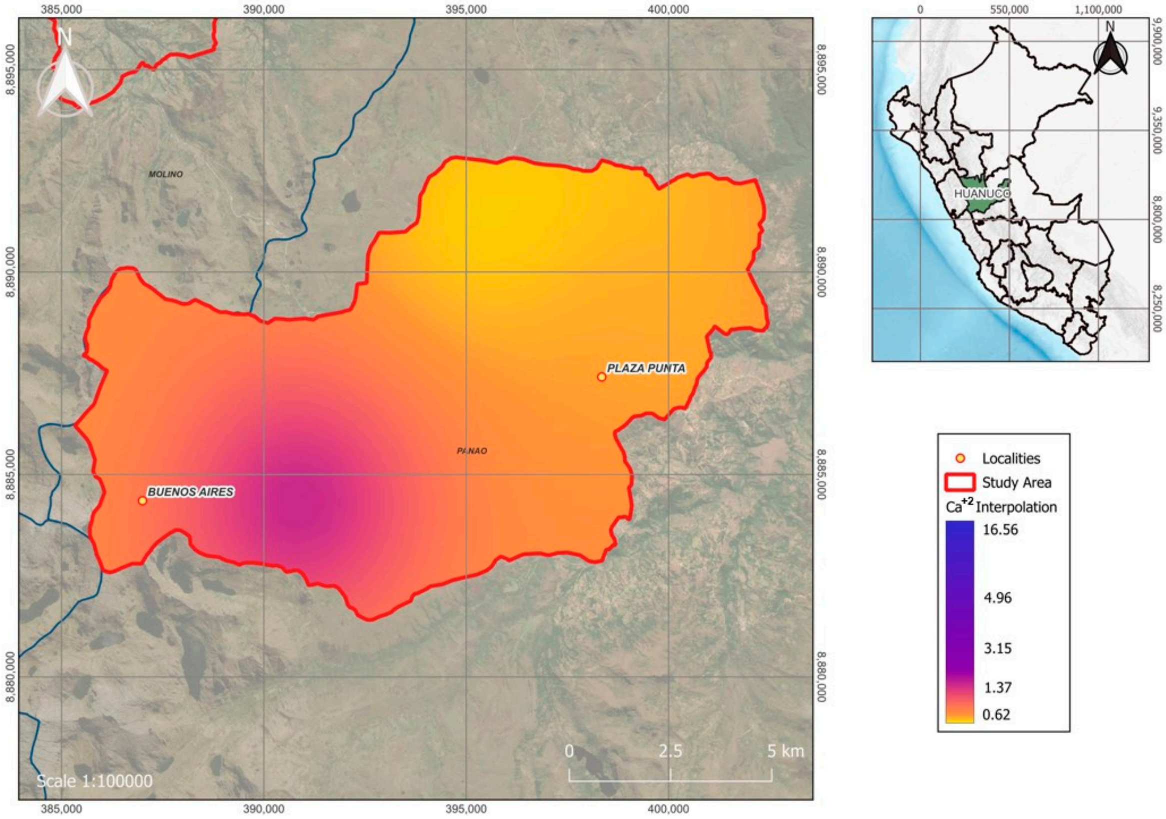

Figure 8. Soil exchangeable calcium in the communities of Pachitea.

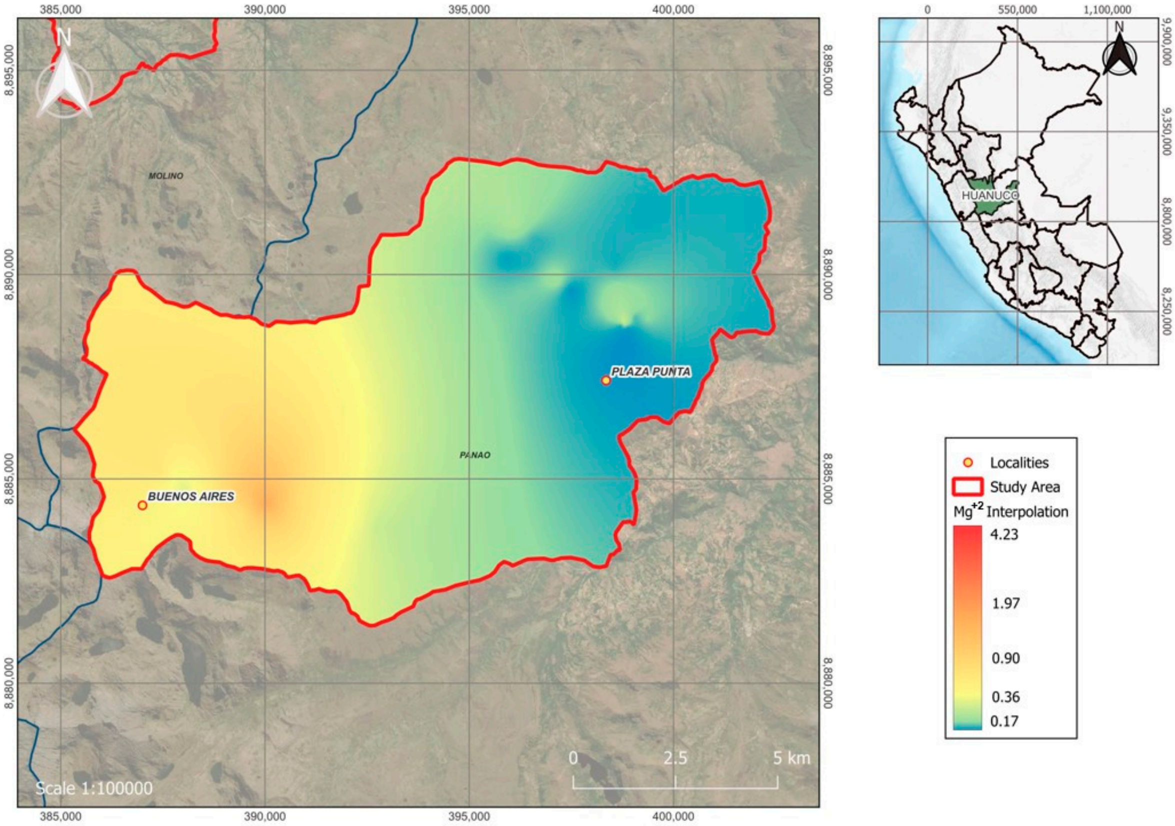

Figure 9. Soil exchangeable magnesium in the communities of Pachitea.

Table 3. Semivariogram models for the soil properties in the localities of Huarichaca, Chagragoto, and Rumichaca.

Soil Property	Model	Nugget (C0)	Sill (C0 + C)	Range (m)	PSV (C/C0 + C)	Cross-Validation	
						[1] R^2	[2] RMSE
pH	Exponential	0.0307	0.0505	11,349.19	0.6075	0.11	0.2096
P ($mg \cdot kg^{-1}$)	Linear	0.0000	0.0000	11,349.19	0.0000	0.27	1.3337
K ($mg \cdot kg^{-1}$)	Linear	0.0000	0.0000	11,349.19	0.0000	0.22	1.4363
EC ($dS \cdot m^{-1}$)	Linear	0.0000	0.0000	11,349.19	0.0000	0.51	0.0669
OM (%)	Linear	0.0000	0.0000	11,349.19	0.0000	0.45	0.5599
H^+ ($cmol^+$ Kg^{-1})	Linear	0.1870	0.0000	11,349.19	0.0000	0.37	0.5132
Al^{+3} ($cmol^+$ Kg^{-1})	Linear	0.0000	0.0000	11,349.19	0.0000	0.32	0.4610
Acidity ($cmol^+$ Kg^{-1})	Linear	0.0000	0.0000	11,349.19	0.0000	0.36	0.6046
CIC ($cmol^+$ Kg^{-1})	Linear	0.0000	0.0000	11,349.19	0.0000	0.43	0.6176
Ca^{+2} ($cmol^+$ Kg^{-1})	Gaussian	0.4994	0.3408	11,349.19	1.4656	0.39	0.7875
Mg^{+2}($cmol^+$ Kg^{-1})	Power	0.0883	0.0000	11,349.19	0.0000	0.18	0.3680
K^+ ($cmol^+$ Kg^{-1})	Linear	0.0558	0.0000	11,349.19	0.0000	0.39	0.4773
Na^+ ($cmol^+$ Kg^{-1})	Linear	0.0000	0.0000	11,349.19	0.0000	0.28	0.2053
BD ($g \cdot cm^{-3}$)	Gaussian	0.0009	0.0042	11,349.19	0.2180	0.79 *	0.0267
EAP (%)	Linear	2.1710	0.0000	11,349.19	0.0000	0.16	1.7022
ECP (%)	Linear	1.1814	0.0000	11,349.19	0.0000	0.28	1.1638
EMP (%)	Linear	0.0000	0.0000	11,349.19	0.0000	0.54 *	0.4758
EPP (%)	Linear	0.0000	0.0000	11,349.19	0.0000	0.54 *	0.4758
ESP (%)	Spherical	0.0684	0.6601	11,349.19	0.1036	0.22	0.7406
Liming ($t \cdot ha^{-1}$)	linear	0.7501	0.0000	11,349.19	0.0000	0.30	1.0868

[1] Coefficient of determination; [2] root mean square error. * Selected variables with higher R^2, due to a high fit degree between the observed and predicted values, are shown with uppercase asterisks.

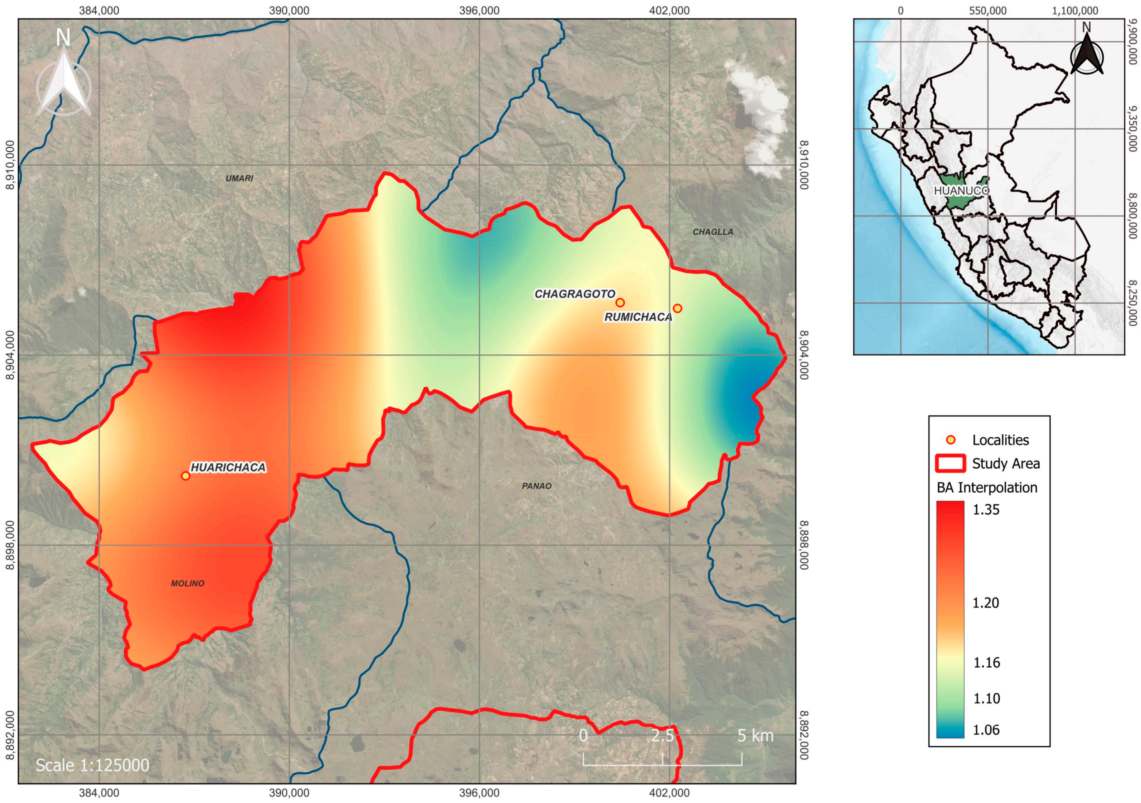

Figure 10. Soil bulk density in the communities of Pachitea.

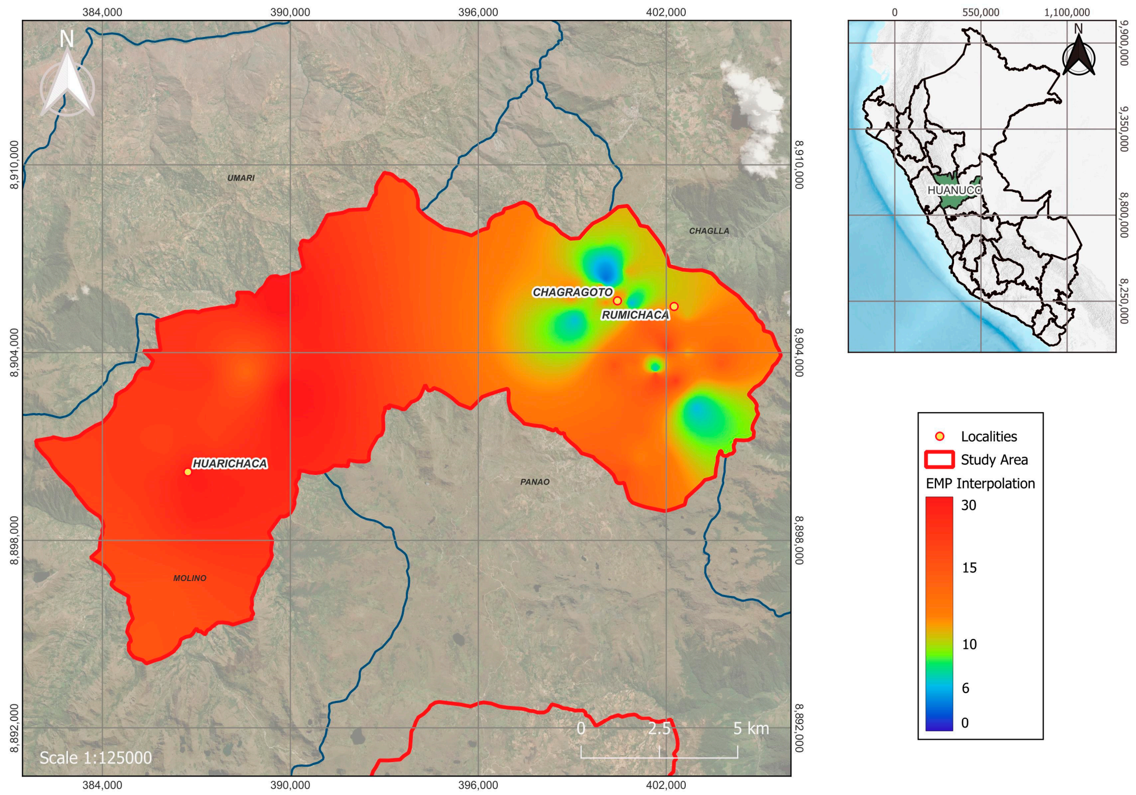

Figure 11. Soil's exchangeable magnesium percentage in the communities of Pachitea.

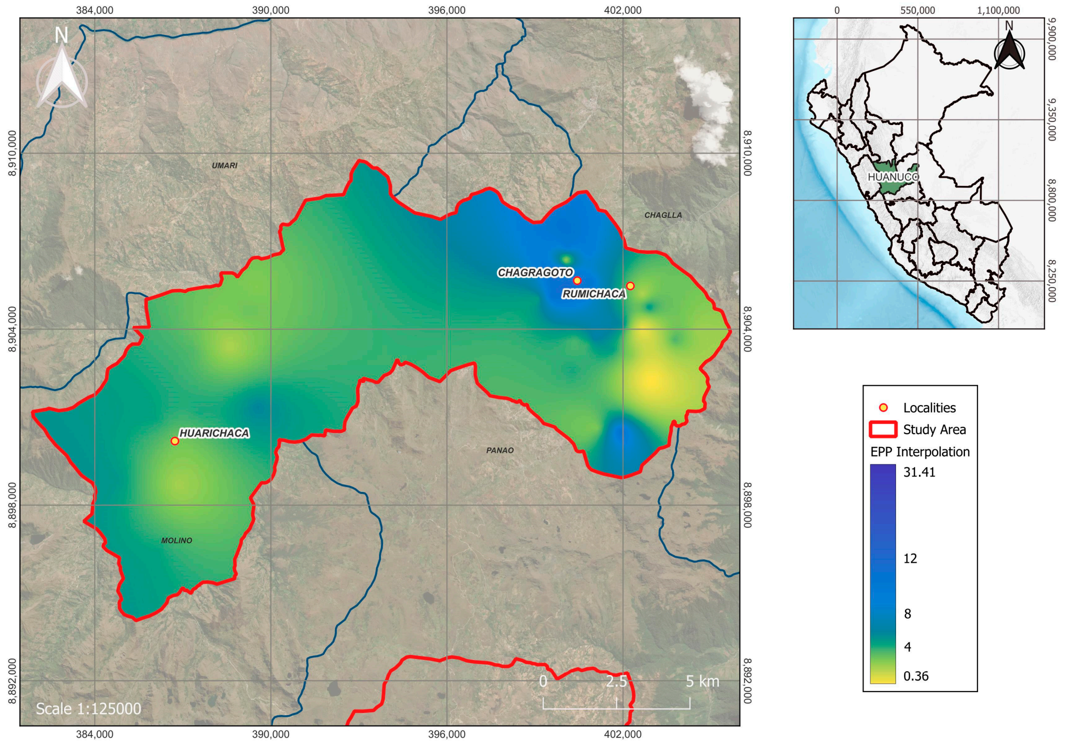

Figure 12. Soil's exchangeable potassium percentage in the communities of Pachitea.

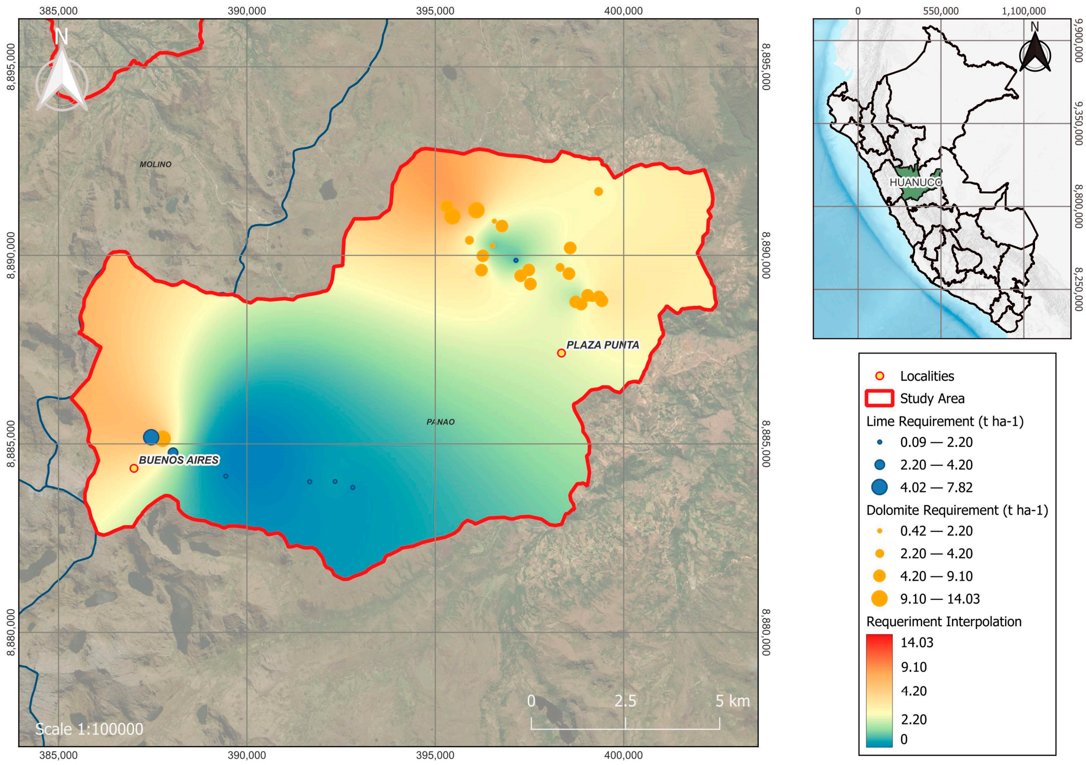

Figure 13. Liming requirement in the communities of Pachitea.

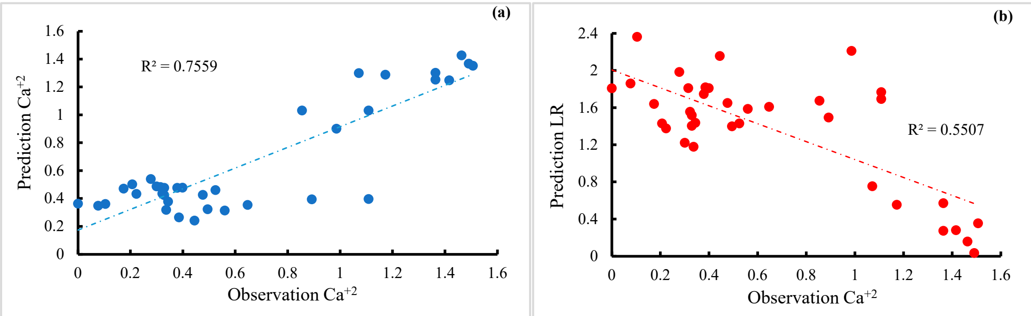

Figure 14. Linear regression analysis between (**a**) observed and predicted values of exchangeable calcium; (**b**) observed values of exchangeable calcium predicted values of liming requirement (LR).

The spatial variation map of soil acidity identifies five zones with differing requirements for lime and dolomite (Figure 13). Specifically, 34.07% of the areas necessitate liming with dolomite, while 18.68% require agricultural lime. In Plaza Punta, the liming requirement averages 5.1 ± 2.8 t·ha^{-1}, predominantly in regions with a higher demand for agricultural dolomite (Figure 13). In contrast, Buenos Aires has an average liming requirement of 3.4 ± 5.5 t·ha^{-1}, primarily in areas with moderate needs for agricultural lime. Rumichaca shows a liming requirement of 2.5 ± 4.4 t·ha^{-1}, more commonly found in regions with elevated agricultural lime needs (Figure 13). Chagragoto exhibits an average requirement of 1.6 ± 2.8 t·ha^{-1}, typically in areas with higher demands for agricultural dolomite. Finally, the locality of Huarichaca has liming values of 0.1 ± 0.3 t·ha^{-1}, which are more prevalent in areas with low requirements for agricultural lime.

4. Discussion

4.1. Soil Acidity in Potato Cultivation and Its Relationship with the Soil Physicochemical Properties

Potatoes are a crop with high nutritional demands, particularly for macronutrients. It requires 1.7 kg of nitrogen (N), 0.7 kg of phosphorus (P), and 3.15 kg of potassium (K) per ton of production [36]. However, when grown in acidic soils with pH levels below 5.5, potatoes experience severe nutrient deficiencies at the leaf level [37]. Furthermore, high exchangeable aluminum (Al^{3+}) concentrations in acidic soils have been reported to be toxic to potato growth [38]. Elevated levels of potential soil acidity ($Al^{3+} + H^{+}$), ranging from 20% to 25%, hinder root cell division and respiration, increase cell wall rigidness, and interfere with calcium and magnesium uptake and transport [39,40]. In this study, the soils from the five potato-producing localities exhibited average pH values of 4.69 ± 0.39 and an exchangeable acidity percentage of 30.94 ± 24.87%, creating limiting conditions for crop growth and development.

To address this issue, it is essential to prioritize liming in fertilization plans for potato crops to raise soil pH [41]. In this study, neutralizing the potential acidity method to a critical threshold of 25% for potato cultivation estimated an average liming requirement of 2.78 ± 3.77 t·ha^{-1}. Furthermore, principal component analysis revealed that variables related to soil acidity, such as EAP and ECP, accounted for the most variance among the 23 physicochemical characteristics evaluated. These findings highlight significant spatial variability in the severity of acid soil degradation across Pachitea province.

The localities of Plaza Punta and Buenos Aires exhibit the lowest pH values (4.41 ± 0.2 and 4.48 ± 0.18, respectively), which can be attributed to high rainfall intensity, with mean annual precipitation of 1035.33 mm and 1159.37 mm, respectively. Elevated rainfall enhances the chemical weathering of soil clay minerals and introduces significant amounts of acid pollutants, such as SO_2 and nitrogenous compounds (NO, NO_2, and N_2O) [27]. Likewise, they increase the leaching of exchangeable bases through the soil profile, which is favored in soils with high percentages of sand, characteristic of the localities of Plaza Punta and Buenos Aires (77.67 ± 7.83 and 74.73 ± 13.10%) [42]. However, the soils in Plaza Punta have lower cation exchange capacity (CEC) than those in Buenos Aires (4.8 ± 1.17

and 7.99 ± 1.98 mEq·100 g^{-1}, respectively). This difference in CEC explains the variation in the severity of soil potential acidity between both localities. Plaza Punta has the highest exchangeable acidity percentage (EAP) (56.91 ± 13.49%) among the five localities and the highest liming requirement (5.1 ± 2.8 t ha^{-1}).

Differences in the severity of soil acidity and its negative impact on fertility potential between localities are likely due to mineralogical variations [43]. Soils rich in gibbsite (aluminum hydroxides) tend to have low CEC values, ranging from 1 to 4 mEq·100 g^{-1}, while soils rich in kaolinite (1:1 phyllosilicates) typically have higher CEC values, between 4 and 15 mEq·100 g^{-1} [44]. This suggests that Plaza Punta soils may be high in gibbsite, whereas Huarichaca, Buenos Aires, and Chagragoto soils, with CEC values of 9.6, 8, and 6.2 mEq·100 g^{-1}, respectively, are more kaolinite-rich. Gibbsite is a secondary mineral formed in soils experiencing intense 2:1 and 1:1 chemical weathering of aluminosilicates [45], which likely explains these mineralogical differences.

The results obtained in the Pearson correlation analysis suggest that the source of soil acidity is strongly linked to both clay and organic matter content. The clay percentage shows a strong negative correlation with exchangeable acidity percentage (EAP) (−0.71), while organic matter content is highly positively correlated with exchangeable soil acidity (0.71). This indicates that the dominant pedogenic processes responsible for soil acidity in these areas are clay illuviation and organic matter accumulation. The accumulation of organic matter is due to the low average annual temperatures of the province of Pachitea, the lowest being in the towns of Plaza Punta and Buenos Aires (8.45 and 6.45 °C, respectively). Likewise, in these localities there are percentages of organic matter of 10.64 ± 5.4 and 18.99 ± 7.59%, higher than the percentage values of organic matter in Huarichaca, Chagragoto, and Rumichaca (3.75, 5.25, and 9.31%, respectively). This characteristic reveals that high Andean soils with a higher percentage of organic matter are more acidic due to the release of H^+ into the soil solution; however, the effect of rainfall on the chemical weathering of clay minerals has a greater impact on the potential acidity of the soil [46].

The positive effect of liming on potato crops is likely attributed to the soil's increased CEC, resulting from a higher density of pH-dependent variable charges [39]. Thus, agricultural lime turns out to be the most economical and viable amendment for soils with pH less than 5.5, since it increases potential soil fertility and crop yield by up to 36% [47]. Likewise, in potato cultivation, it is reported that soil pH values below 4.9 generate Al and Mn toxicity, and severe P, K, Ca and Mg deficiencies [37]. In addition, it has been confirmed that it is possible to increase potato yields on strongly acidic ultisols by raising the soil pH with dolomitic lime or by applying calcium and magnesium phosphate fertilizers without altering the pH [48]. This highlights the critical role of calcium and magnesium fertilization in managing acidic soils. In our study, Ca^{2+} (mEq·100 g^{-1}) and Mg^{2+} (mEq·100 g^{-1}) were the key variables in reducing soil acidity, showing a strong negative correlation with exchangeable soil acidity (−0.71 and −0.66, respectively) concerning the exchangeable acidity percentage (EAP). These findings suggest that the mass effect on the cation exchange of H^+ and Al^{3+} ions for Ca^{2+} and Mg^{2+} is the most critical factor in acidic soil management [27].

In this context, recommended liming doses ranging from 2 to 14 t·ha^{-1} are expected to enhance the soil's potential fertility. It is also likely that treatments aimed at increasing pH-dependent charges will improve the physicochemical properties of acidic high Andean soils. Several studies support the importance of these agricultural practices. Bordoloi et al. [49] highlight that applying 0.4 t·ha^{-1} of agrarian lime, supplemented with 1 t·ha^{-1} of vermicompost, increased soil pH from 4.54 to 5.12, reducing fertilizer usage by 50% and boosting potato yields by 36–54%.

4.2. Spatial Variability in Soil Acidity and Liming Requirement

Geostatistical analysis using semivariogram models and the Ordinary Kriging (OK) method enables precise identification of soil variables with the highest spatial predictability related to soil acidity [16]. Key indicators like the coefficient of determination (R^2) and root mean square error (RMSE) are critical in evaluating the fit of these models between observed and predicted values in unsampled areas [50]. Models with R^2 values approaching 1 and low RMSE indicate a superior fit, making them effective tools for soil management in acidic soil regions and facilitating the optimization of practices such as liming and fertilization [51].

Several key variables have been identified in predicting soil acidity, with Ca^{2+} and Mg^{2+} being the most influential in determining the spatial variability of soil fertility, particularly in the localities of Buenos Aires and Plaza Punta. These exchangeable cations are strongly correlated with soil acidity, allowing for the generation of precise maps for agricultural management using geostatistical methods like Ordinary Kriging [52]. R^2 values ranging from 0.70 to 0.85, along with low RMSE in predictions for Ca^{2+} and Mg^{2+}, are adequate for accurately forecasting soil fertility and acidity levels. Additionally, variables like bulk density and exchangeable potassium percentage (EPP) have proven to be critical in acidic soils found in grazing areas, with significant spatial model adjustments, particularly in the localities of Huarichaca, Chagragoto, and Rumichaca. This suggests that the relevance of predictive variables can vary depending on climatic conditions, land use, the extent of acid soil degradation, and other soil properties [53].

5. Conclusions

The spatial prediction of soil acidity indicates a higher agreement between observed and predicted acidity values in the localities of Plaza Punta and Buenos Aires (R^2 = 0.57 and RMSE = 0.59) compared with the localities of Rumichaca, Chagragoto, and Huarichaca (R^2 = 0.30 and RMSE = 1.10). Principal component analysis (PCA) reveals that the variability in soil acidity in Plaza Punta and Buenos Aires is primarily explained by variations in the sand percentage and soil organic matter content. Similarly, these localities exhibit a strong agreement between observed and predicted values for exchangeable Ca^{2+} (R^2 = 0.76 and RMSE = 0.23) and Mg^{2+} (R^2 = 0.87 and RMSE = 0.12). These results demonstrate a high predictability of the spatial variation in agricultural dolomite requirements in Plaza Punta and Buenos Aires based on observed exchangeable calcium and magnesium levels.

This research underscores the significant variability in the severity of degraded acidic soils in the Pachitea province, Huánuco, Peru. These findings provide a foundation for developing optimal and sustainable fertilization strategies tailored to the potato agroecosystem in the high Andean mountains of Peru. Furthermore, soil fertility maps generated through geostatistical approaches are invaluable tools for farmers, researchers, and policymakers, enabling improved soil management practices, optimized liming requirements, and enhanced potato crop productivity. The applied methodological framework effectively demonstrates the strong spatial dependence of the studied soils.

Author Contributions: Conceptualization, K.Q., P.V. and R.S.; methodology, K.Q., L.A. and R.S.; software, S.M. and C.C.; validation, R.S. and L.A.; formal analysis, K.Q. and S.M.; investigation, K.Q., and S.M.; writing—original draft preparation, K.Q. and S.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Institute of Agricultural Innovation (INIA) project "Mejoramiento de los servicios de investigación y transferencia tecnológica en el manejo y recuperación de suelos agrícolas degradados y aguas para riego en la pequeña y mediana agricultura en los departamentos de Lima, Áncash, San Martín, Cajamarca, Lambayeque, Junín, Ayacucho, Arequipa, Puno y Ucayali" CUI 2487112.

Institutional Review Board Statement: Ethical review and approval were waived for this study due to not applicable for studies not involving humans or animals.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. FAO. *Una Guía Sobre El Día Internacional de La Papa de 2024*; FAO: Rome, Italy, 2024.
2. MIDAGRI Presentó Marco Orientador de Cultivos (MOC) de La Campaña Agrícola 2024/2025—Noticias—Ministerio de Desarrollo Agrario y Riego—Plataforma Del Estado Peruano. Available online: https://www.gob.pe/institucion/midagri/noticias/1010824-midagri-presento-marco-orientador-de-cultivos-moc-de-la-campana-agricola-2024-2025 (accessed on 9 October 2024).
3. Velásquez, D. Estrategias Campesinas de Conservación in Situ de Recursos Genéticos En Agroecosistemas Andinos de La Sierra Del Perú: Cajamarca y Huánuco. Master's Thesis, Universidad Nacional Autónoma de México, Mexico City, Mexico, 2009.
4. Egúsquiza, B.R. *La Papa: Producción, Transformación y Comercialización. Proyecto Papa Andina CIP-COSUDE*; International Potato Center: Lima, Perú, 2000; ISBN 978-9972-9347-2-8.
5. Documento Para Discusión Perú: Evaluación de La Seguridad Alimentaria Ante Emergencias (ESAE), 2021—Midis. Available online: https://evidencia.midis.gob.pe/esae-seguridad-alimentaria-2021-documento-discusion/ (accessed on 10 October 2024).
6. Sadeghian, S. La acidez del suelo una limitante común para la producción de café. *Av. Técnicos Cenicafé* **2016**, *466*, 1–12.
7. Sanz, J.; Zeigler, R.; Sarkarung, S.; Molina, D.; Rivera, M. Sistemas Mejorados Arroz-Pasturas Para Sabana Nativa y Pasturas Degradadas En Suelos Ácidos de América Del Sur. In *Sistemas Agropastoriles en Sábanas Tropicales de América Latina*; CIAT-EMBRAPA: Cali, Colombia, 1999; pp. 234–244, ISBN 958-694-010-1.
8. Garay Canales, Ó.; Ochoa Acevedo, Á. *Primera Aproximación Para La Identificación de Los Diferentes Tipos de Suelo Agrícola En El Valle Del Río Mantaro*; Instituto Geofísico del Perú: Lima, Perú, 2010; ISBN 978-612-45795-2-3.
9. Ayarza, M.A. Efecto de Las Propiedades Químicas de Los Suelos Ácidos En El Establecimiento de Las Especies Forrajeras. In *Establecimiento y Renovación de Pasturas: Conceptos, Experiencias y Enfoque de la Investigación*; CIAT: Veracruz, México, 1991; pp. 161–185, ISBN 958-9183-26-3.
10. Conradi, E., Jr.; Gonçalves, A.C., Jr.; Seidel, E.P.; Ziemer, G.L.; Zimmermann, J.; de Oliveira, V.H.D.; Schwantes, D.; Zeni, C.D. Effects of Liming on Soil Physical Attributes: A Review. *J. Agric. Sci.* **2020**, *12*, 278. [CrossRef]
11. Bizarro, H.; Fernando, A. Uso de La Cáscara de Huevo Molida Como Material Encalante En Suelos Ácidos Del Perú. 2018. Available online: https://hdl.handle.net/20.500.12996/3563 (accessed on 16 October 2024).
12. Quinto Carhuancho, C.E. Propiedades Físicas, Químicas y Biológicas Del Suelo Bajo La Influencia de Tres Sistemas de Uso de La Tierra En El Distrito José Crespo y Castillo, Leoncio Prado. Bachelor's Thesis, Universidad Nacional Agraria de la Selva, Tingo María, Perú, 2016.
13. Balta-Crisólogo, R.A.; Rodríguez-Del Castillo, Á.M.; Guerrero-Abad, R.; Cachique, D.; Alva-Plasencia, E.; Arévalo-López, L.; Loli, O. Absorción y concentración de nitrógeno, fósforo y potasio en sacha inchi (*Plukenetia volubilis* L.) en suelos ácidos, San Martín, Perú. *Folia Amazónica* **2015**, *24*, 23. [CrossRef]
14. Cotrina-Cabello, V.R.; Alejos-Patiño, I.W.; Cotrina-Cabello, G.G.; Córdova-Mendoza, P.; Córdova-Barrios, I.C. Efecto de Abonos Orgánicos En Suelo Agrícola de Purupampa Panao, Perú. *Centro Agrícola* **2020**, *47*, 31–40.
15. Arce Zapata, A. *Desarrollo Del Mercado de Fertilizantes Compuestos En El Perú y Su Impacto En Cultivos Tradicionales de La Selva Peruana*; Universidad Nacional Agraria La Molina: Lima, Perú, 2021.
16. Chen, S.; Lin, B.; Li, Y.; Zhou, S. Spatial and Temporal Changes of Soil Properties and Soil Fertility Evaluation in a Large Grain-Production Area of Subtropical Plain, China. *Geoderma* **2020**, *357*, 113937. [CrossRef]
17. R Core Team. R A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, 2018—Vienna—References—Scientific Research Publishing. Available online: https://www.scirp.org/reference/ReferencesPapers?ReferenceID=2342186 (accessed on 10 October 2024).
18. Pebesma, E.J.; Bivand, R.S. Classes and Methods for Spatial Data in R. *R News* **2005**, *5*, 9–13.
19. Natural Resources and Environment Secretary. Mexican Official Standard. NOM-021-RECNAT-2000: Especificaciones de Fertilidad, Salinidad y Clasificación de Suelos. Available online: https://www.fao.org/faolex/results/details/es/c/LEX-FAOC050674/ (accessed on 10 October 2024).
20. U.S. Environmental Protection Agency Method 9045D: Soil and Waste pH. Revision 4. Available online: https://www.epa.gov/sites/default/files/2015-12/documents/9045d.pdf (accessed on 15 October 2024).
21. International Standard ISO 11265:1994. Soil Quality—Determination of the Specific Electrical Conductivity. Available online: https://www.iso.org/standard/19243.html (accessed on 10 November 2024).
22. International Standard ISO 11261:1995. Soil Quality—Determination of Total Nitrogen—Modified Kjeldahl Method. Available online: https://www.iso.org/standard/19239.html (accessed on 12 October 2024).
23. Bazán Tapia, R. *Manual de Procedimientos de los Análisis de Suelos y Agua con Fines de Riego*; Instituto Nacional de Innovación Agraria: La Molina, Peru, 2017.
24. Hengl, T.; Mendes De Jesus, J.; Heuvelink, G.B.M.; Ruiperez Gonzalez, M.; Kilibarda, M.; Blagotić, A.; Shangguan, W.; Wright, M.N.; Geng, X.; Bauer-Marschallinger, B.; et al. SoilGrids250m: Global Gridded Soil Information Based on Machine Learning. *PLoS ONE* **2017**, *12*, e0169748. [CrossRef]
25. Havlin, J.L. Soil: Fertility and Nutrient Management. In *Landscape and Land Capacity*; CRC Press: Boca Raton, FL, USA, 2020; pp. 251–265, ISBN 978-0-429-44555-2.
26. He, H.; Li, Y.; He, L.F. Aluminum Toxicity and Tolerance in Solanaceae Plants. *S. Afr. J. Bot.* **2019**, *123*, 23–29. [CrossRef]
27. Havlin, J.; Tisdale, S.; Nelson, W.; Beaton, J. *Soil Fertility and Fertilizers: An Introduction to Nutrient Management*, 8th ed.; Pearson: Upper Saddle River, NJ, USA, 2013; ISBN 978-0-13-503373-9.

28. Wickham, H. *Ggplot2-Elegant Graphics for Data Analysis*; Use R! Springer International Publishing: Cham, Switzerland, 2016; ISBN 978-3-319-24275-0.
29. Vu, V.Q.; Friendly, M.; Tavadyan, A. Ggbiplot: A Grammar of Graphics Implementation of Biplots. Available online: https://cran.r-project.org/web/packages/ggbiplot/index.html (accessed on 10 October 2024).
30. Tunçay, T. Comparison Quality of Interpolation Methods to Estimate Spatial Distribution of Soil Moisture Content. *Commun. Soil. Sci. Plant Anal.* **2021**, *52*, 353–374. [CrossRef]
31. Bock, M.; Böhner, J.; Köthe, R.; Conrad, O.; Köthe, R.; Ringeler, A. Methods for Creating Functional Soil Databases and Applying Digital Soil Mapping with SAGA GIS. In *RC Scientific and Technical Reports*; Office for Official Publications of the European Communities: Luxembourg, 2007; Volume 1, pp. 31–37.
32. Martínez, C.R. Modelado Geoestadístico de Fertilidad de Un Terreno Agrícola Mediante Mapas de Kriging Que Interpolan Los Datos de Análisis Químico de Suelos. *Prod. Agropecu. Desarro. Sosten.* **2021**, *9*, 63–84. [CrossRef]
33. Gallardo Correa, A. Geostadística. *Ecosistemas* **2006**, *15*, 48–58.
34. Fu, Y.; Song, J.; Guo, J.; Fu, Y.; Cai, Y. Prediction and Analysis of Sea Surface Temperature Based on LSTM-Transformer Model. *Reg. Stud. Mar. Sci.* **2024**, *78*, 103726. [CrossRef]
35. Fernández Villafañez, S. Métodos de Regresión y Clasificación Basados en Árboles. Master's Thesis, Universidad de Valladolid, Valladolid, España, 2022.
36. Burton, A. Influence of Solution Management Techniques on Nutrient Use Efficiency in Hydroponically Grown Salad-type Plants-ProQuest. Master's Thesis, North Carolina A&T State University, Greensboro, NC, USA, 2018.
37. Mugo, J.N.; Karanja, N.N.; Gachene, C.K.; Dittert, K.; Nyawade, S.O.; Schulte-Geldermann, E. Assessment of Soil Fertility and Potato Crop Nutrient Status in Central and Eastern Highlands of Kenya. *Sci. Rep.* **2020**, *10*, 7779. [CrossRef] [PubMed]
38. George, E.; Horst, W.J.; Neumann, E. Adaptation of Plants to Adverse Chemical Soil Conditions. In *Marschner's Mineral Nutrition of Higher Plants*, 3rd ed.; Elsevier: Amsterdam, The Netherlands, 2012; pp. 409–472. [CrossRef]
39. Cakmak, I.; Brown, P.; Colmenero-Flores, J.M.; Husted, S.; Kutman, B.Y.; Nikolic, M.; Rengel, Z.; Schmidt, S.B.; Zhao, F.-J. Micronutrients. In *Marschner's Mineral Nutrition of Plants*; Elsevier: Amsterdam, The Netherlands, 2023; pp. 283–385. ISBN 978-0-12-819773-8.
40. Rout, G.R.; Samantaray, S.; Das, P. Aluminium Toxicity in Plants: A Review. *Agronomie* **2001**, *21*, 3–21. [CrossRef]
41. Jovovic, Z.; Dolijanovic, Z.; Spalevic, V.; Dudic, B.; Przulj, N.; Velimirovic, A.; Popovic, V. Effects of Liming and Nutrient Management on Yield and Other Parameters of Potato Productivity on Acid Soils in Montenegro. *Agronomy* **2021**, *11*, 980. [CrossRef]
42. Du, L.; Zhang, Z.; Chen, Y.; Wang, Y.; Zhou, C.; Yang, H.; Zhang, W. Heterogeneous impact of soil acidification on crop yield reduction and its regulatory variables: A global meta-analysis. *Field Crops Res.* **2024**, *319*, 109643. [CrossRef]
43. McGahan, D.G.; Southard, R.J.; Zasoski, R.J. Mineralogical Comparison of Agriculturally Acidified and Naturally Acidic Soils. *Geoderma* **2023**, *114*, 355–368. [CrossRef]
44. Kome, G.K.; Enang, R.K.; Tabi, F.O.; Yerima, B.P.K.; Kome, G.K.; Enang, R.K.; Tabi, F.O.; Yerima, B.P.K. Influence of Clay Minerals on Some Soil Fertility Attributes: A Review. *Open J. Soil Sci.* **2019**, *9*, 155–188. [CrossRef]
45. Bhattacharyya, T.; Pal, D.K.; Srivastava, P. Formation of Gibbsite in the Presence of 2:1 Minerals: An Example from Ultisols of Northeast India. *Clay Miner.* **2000**, *35*, 827–840. [CrossRef]
46. Guo, C.; Shabala, S.; Chen, Z.H.; Zhou, M.; Zhao, C. Aluminium tolerance and stomata operation: Towards optimising crop performance in acid soil. *Plant Physiol. Biochem.* **2024**, *210*, 108626. [CrossRef]
47. Zhang, S.; Zhu, Q.; de Vries, W.; Ros, G.H.; Chen, X.; Muneer, M.A.; Zhang, F.; Wu, L. Effects of soil amendments on soil acidity and crop yields in acidic soils: A world-wide meta-analysis. *J. Environ. Manag.* **2023**, *345*, 118531. [CrossRef] [PubMed]
48. Lee, C.R.; MacDonald, M.L. Influence of Soil Amendments on Potato Growth, Mineral Nutrition, and Tuber Yield and Quality on Very Strongly Acid Soils. *Soil Sci. Soc. Am. J.* **1977**, *38*, 573–577. [CrossRef]
49. Bordoloi, P. Lime application for higher productivity of potato (*Solanum tuberosum* L.) and managing soil acidity in Ri-Bhoi District of Meghalaya. *Indian Res. J. Ext. Educ.* **2021**, *21*, 201.
50. Wang, Y.; Liu, G.; Zhao, Z. Spatial Heterogeneity of Soil Fertility in Coastal Zones: A Case Study of the Yellow River Delta, China. *J. Soils Sediments* **2021**, *21*, 1826–1839. [CrossRef]
51. Campisi, N.; Kulu, H.; Mikolai, J.; Klüsener, S.; Myrskylä, M. Spatial Variation in Fertility across Europe: Patterns and Determinants. *Popul. Space Place* **2020**, *26*, e2308. [CrossRef]
52. Trujillo-González, J.M.; Torres-Mora, M.A.; Ballesta, R.J.; Brevik, E.C. Spatial Variability of the Physicochemical Properties of Acidic Soils along an Altitudinal Gradient in Colombia. *Environ. Earth Sci.* **2022**, *81*, 108. [CrossRef]
53. Erraez, R.M.M.; Vásquez, E. Enmienda de Cal En Suelos Degradados Por La Ganadería En La Parroquia Panguintza, Cantón Zumbi, Provincia de Zamora Chinchipe. *Bosques Latid. Cero* **2023**, *13*, 49–67. [CrossRef]