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Analysis of Soil Quality through Aerial Biomass Contribution of Three Forest Species in Relict High Andean Forests of Peru

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ABSTRACT

The biomass that accumulates on the forest floor and its subsequent decomposition play an important role in maintaining the productivity of different terrestrial ecosystems by constituting the main nutrient flow to the soil. The objective of the study focused on analyzing the nutrient contribution to the soil derived from the aboveground biomass of three native forest species in relict forests of the Central Peruvian Sierra with socioeconomic and environmental relevance. Using random delineation methods, soil samples were collected at 20-30 cm depth, which were subjected to physical, chemical, and biological analyses, developing the determination of a Soil Quality Index (SQI). The results highlight that forests of Polylepis racemosa and Alnus acuminata significantly exhibit a higher SQI, with values of 0.66 and 0.58, respectively, compared to Escallonia resinosa, with the forestless system being of lower quality with an SQI of 0.28. The relict forests, Dorado, Colpar, and Talhuis, presented the highest SQIs (0.53, 0.52, and 0.48), while Saño obtained the lowest SQI with 0.39, with no significant differences among them. The forests of Polylepis racemosa and Alnus acuminata showed a superior soil structure, higher organic matter content, moisture retention, and microbial biomass compared to other analyzed systems.

Keywords: **Soil quality, relict forests, nutrient recycling, biomass, coverage**

INTRODUCTION

The assessment of aboveground biomass and litterfall in forest ecosystem productivity is fundamental as they constitute the main source of nutrients for the soil (Vitousek, 1984). These processes represent approximately 80% of the total nutrients returned to the soil through tree detritus decomposition (Ramírez-Correa *et al*., 2007), playing a crucial role in soil conservation. However, human activities have led to a marked regression of these ecosystems, subsequently replacing them with other land uses (Liu *et al*., 2022). Although Peru has an extensive area of forests covering 72 million hectares, only 0.22 are found in the Sierra as Andean forests, representing just 0.31% (LABOR, 2020). These Andean forests, classified as "relicts" due to their low representativeness in terms of surface area, high fragmentation, and limited accessibility, are part of Peru's fragile ecosystems (MINAM, 2016).

Assessing the quality and conservation status of both soils and forest ecosystems is crucial given their importance as a foundation for maintaining environmental quality (Lozano-Baez *et al*., 2021; Muñoz-Rojas, 2018). Soils provide support to terrestrial ecosystems, nutrients to plants, and harbor abundant biodiversity (Coleman *et al*., 2018; De Deyn & Kooistra, 2021). Soil quality determines the ability of soils to fulfill these functions; in particular, forest production largely depends on soil quality, as soils in good condition promote plant growth, water retention, and nutrient availability (Chavarin-Pined *et al*., 2021; Suárez *et al*., 2021).

Soil quality can be assessed through physical, chemical, and biological indicators. While a greater number of indicators provide a more comprehensive and complete evaluation, it is necessary to define a minimum set of optimal data to construct an index that can be representative, called the Soil Quality Index (SQI). The SQI is a measurement tool that provides information about the properties, processes, and characteristics of the soil (Begazo & Jave, 2018). This is how these soil properties can be used as analysis mechanisms to detect trends and determine whether current management systems conserve, improve, or degrade the soil (De *et al*., 2022; Maurya *et al*., 2020; Yuan *et al*., 2020). The balanced interaction among these properties creates a quality soil environment conducive to sustainable activities such as conservation, restoration, agroecology, among others (Duddigan *et al*., 2020a, 2020b; Hatten & Liles, 2019; Horváth *et al*., 2021).

Conserving forests with native species is considered important for maintaining the health and productivity of forest ecosystems. Additionally, they provide a range of essential ecosystem services such as water regulation, climate regulation, carbon capture, and biodiversity conservation (Fredericksen, 2021; Isabel *et al*., 2020). To assess the sustainability of forest soils, it is necessary to consider a series of factors, such as the physical, chemical, and biological quality of the soil, where the nutrient contributions of native species are an important factor to consider when selecting them for environmental projects (Kezik & Acar, 2016; Page-Dumroese *et al*., 2021).

Native forests are composed of trees with diverse nutritional requirements, each uniquely contributing to the soil component. Therefore, it is crucial to understand these nutrient contributions to the soil to ensure the development and persistence of these trees. Consequently, identifying the differential nutrient contributions of different species becomes essential to guarantee the vitality and resilience of forest plantations in the future, where this approach ensures the continuity of ecosystem services provided by these forests (Lorenz & Lal, 2010; Teben'kova *et al*., 2020).

The native species *Alnus acuminata*, *Polylepis racemosa*, and *Escallonia resinosa* are relevant for their ecological and economic value in the high Andean zones of Peru. For example, *Alnus acuminata* is a pioneer tree that contributes to the restoration of degraded soils due to its ability to fix atmospheric nitrogen, thus improving soil fertility (Weng *et al*., 2004); *Polylepis racemosa* comprises endemic trees of the Andes, providing habitat for biodiversity and helping regulate the climate through carbon capture, while *Escallonia resinosa* is a tree of economic importance in the area for its role in honey production and other non-timber forest products (Pariente *et al*., 2016; Rossi *et al*., 2018). The integration of these three native species provides both ecological and productive opportunities in forest plantations, which could easily enhance the ecosystems they are immersed in. They are relevant for their ecological and economic value in the Central Sierra of Peru.

Although there are studies on the function of these Andean forests, their importance in the dynamics of nutrient contributions to the soil component is still poorly understood. Therefore, this study aims to evaluate the soil quality of relict forests through the return of nutrients from the aboveground biomass and litterfall of three native species from the central Sierra of Peru: *Alnus acuminata, Polylepis racemosa*, and *Escallonia resinosa*, in order to promote the conservation and reforestation of these species in regional and national policy. Additionally, it represents a contribution to achieving the goals of the Sustainable Development Objectives

(SDGs) related to the conservation of biological diversity and terrestrial ecosystem services (Veidemane, 2019).

MATERIALS AND METHODS

Study area

The study was conducted in native relict forests located in the province of Huancayo, Junín region, in the central highlands of Peru (Figure 1). Four sampling sites were selected: the forest patch called El Dorado in the Paccha annex of the El Tambo district, where plots of Polylepis racemosa and Alnus acuminata were evaluated at an elevation of 3653 meters above sea level at geographic coordinates (11°58'59.4" S ; 75°11'51.9" W); the forest patch called Colpar in the Quilcas district with plots of *Alnus acuminata* and *Polylepis sp*. at 3509 meters above sea level at location (11°54'11.9" S ; 75°15'26.1" W); the patch of Escallonia resinosa forest in the San Pedro de Saño district at 3600 meters above sea level at (11°54'12" S ; 75°14'28.1" W); and the *Escallonia resinosa* forest in the Talhuis annex of the Pucará district at 3608 meters above sea level at coordinates (12°10'6.6" S ; 75°6'32.7" W). In each sampling site, plots of mature relict forests of each of the three target species were considered, under similar climatic conditions.

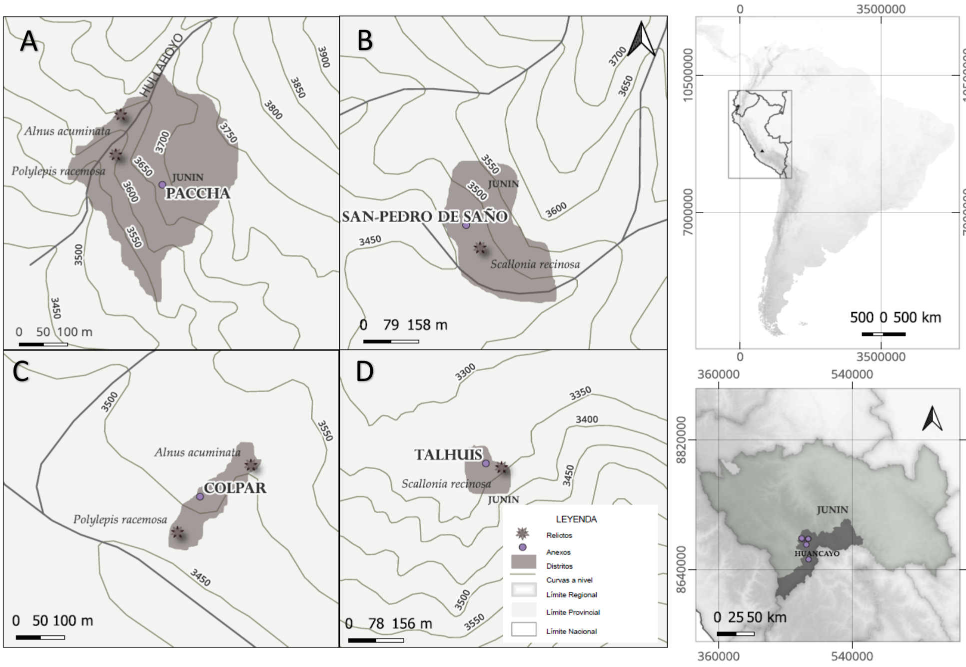


Figure 1. Location map in WGS 84 - Zone 18 S showing the high Andean relict forests a) El Dorado b) Saño c) Colpar d) Talhuis

Sampling and soil characterization

During the field phase, sampling areas were delimited by selecting representative sites in each geographic unit according to the soil maps of the study plots to identify soil variations. Additionally, simple random sampling was conducted using a grid, collecting samples in areas with higher tree density to ensure equiprobability and statistical representativeness (Smith *et al*., 2017).

Subsamples were obtained at a uniform depth of 20-30 cm as this is the relevant arable layer for assessing fertility (Tahir *et al*., 2016). A total of 30 subsamples were collected, which were homogenized to obtain composite samples of 1 kg each, placed in ziplock bags for subsequent laboratory analysis.

The physical, chemical, and biological characterization of the samples was analyzed at the Soil Laboratory of La Molina (LASPAF). The evaluated indicators included: organic matter, bulk density, moisture, pH, electrical conductivity, total nitrogen, phosphorus, available potassium, cation exchange Capacity (CEC), and microbial biomass. Standardized methods such as Walkley-Black, Olsen, electrometry, turbidimetry, gravimetry, among other standardized and validated protocols, were applied to evaluate these indicators.

For each soil condition and measured attribute, the mean value of the repetitions was obtained. The comparison of means was performed using the ANOVA statistic and the Tukey test (0.05), after verifying the homoscedasticity and normality of the values to be evaluated.

Physical, chemical, and biological indicators

The selection of soil indicators to be evaluated in the laboratory phase was justified by the need to establish a minimum set of indicators that characterize soil quality comprehensively and efficiently. Various researchers (Doran *et al*., 2015; Hailu & Chambers, 2012; Huisa, 2020; Karlen *et al*., 2015; Larson & Pierce, 1991; Seybold *et al*., 1997; Vocciante *et al*., 2017), have proposed that, instead of measuring every soil property, it is more practical to identify those key attributes that are sensitive to changes in soil functions. While this minimum set does not encompass all relevant properties for every region, it helps prioritize the most significant indicators at the local level and assess their relationship with critical soil and vegetation properties in a given context.

The indicators considered to determine soil quality are: a) soil organic matter (fundamental for fertility); b) Physical properties such as structure (allows evaluation of root movement and availability of water and nutrients, preventing compaction and facilitating better tillage), stability (ability to retain nutrients and water, as well as control erosion), bulk density, and water retention capacity (regulate soil porosity, workability, and water reserves in the soil (Fu *et al*., 2021) c) Chemical properties such as pH (modifies nutrient availability for organisms), electrical conductivity that can limit plant and microbial growth, and levels of nitrogen, phosphorus, and potassium indicating soil fertility and nutrient loss risk; d) Biological properties regarding carbon and nitrogen of microbial biomass that reveal the activity and potential of microorganisms for nutrient mineralization (Fujita *et al*., 2019).

Soil Quality Index

Before proceeding to define the calculation of the Soil Quality Index (SQI) and associated values, the methodology proposed by Cantú *et al*. (2009), was used. For this, it is necessary to define the maximum (lmax) and minimum (lmin) limits of the selected indicators. Therefore, the measurements of the indicators were converted to a dimensionless scale based on the critical values of the proposed indicators.

Since there is no single method for establishing maximum and minimum limits or classification ranges for soil quality, in this study, classes for forest soil were defined based on various criteria such as theoretical concepts of soil quality, predominant soil type in the area, ideal fertility conditions, availability of key nutrients, maximum feasible yields according to current conditions, limiting climatic factors, and the previous experience of researchers who have worked in this region or locality, as well as local, national, and international literature (Cantú *et al*., 2007, 2009; Cruz, 2019; Huisa, 2020). The integration of these theoretical and practical considerations related to local soil and agroforestry characteristics allowed for the establishment of classification ranges relevant to the biophysical and productive context of the study area.

With the maximum and minimum limits established, a representative value of each indicator was obtained for each sampling subunit. To do this, a weighted average was calculated according to the proportion of each type of management in the total area. Subsequently, the indicators were normalized to a scale from 0 to 1, where 0 represents the worst condition and 1 the best in terms of soil quality, regardless of the absolute values, according to the methodology of Cantú *et al*. (2009) and Prieto *et al*. (2013).

There are two situations: when the maximum value of the indicator (lmax) corresponds to the best quality, the calculation is:

$$Vn = (lm - lmin)/(lmax - lmin) \qquad (1)$$

If lmax represents the worst quality, the calculation is:

$$Vn = 1 - \ (lm - lmin)/(lmax - lmin) \qquad (2)$$

Where Vn represents the normalized value, lm is the measurement of the indicator, Vmax is the maximum value of the indicator, and lmin is the minimum value of the indicator. It is important to note that not all indicators will have the highest value (lmax) as indicative of better quality. For example, electrical conductivity is considered optimal at values close to 0.5 mS/cm, which corresponds to lmin. Finally, a Soil Quality Index (SQI) was established by averaging the normalized values of all the indicators evaluated. For the interpretation of the SQI, a transformation scale into five qualitative classes of soil quality was used, ranging from 1 to 5 (Table 1).

TABLE 1

Soil Quality Index by Scale and Class of Value

Soil Quality Index	**Scale**	**Class**
Very High	0.8-1.00	1
High Quality	0.6-0.79	2
Moderate Quality	0.4-0.59	3
Low Quality	0.20-0.39	4
Very Low Quality	0.00-0.19	5

Source: (Cantú *et al*., 2009)

RESULTS AND DISCUSSION

Soil sample characterization

In Table 2, the results of soil sample characterization collected through test pits in different relict forests for various native species are observed. These results and characterizations are crucial for understanding the composition and soil conditions in the habitats of these species, which can provide valuable information for conducting ICS processes.

TABLE 2

Soil sample characterization results

Sample	Species	Bulk Density g.cm-1	Organic Matter %	pH	Electrical Conductivity mS/cm	Total Nitrogen %	Available Phosphorus ppm	Available Potassium ppm	CIC meq/100g	Microbial Biomass mg kg -1	Moisture Content %	Sampling area
Test pist 1	*Alnus Acuminata*	1.10	9.65	4.78	0.76	0.46	4.90	595	18.40	226.59	41.03	Dorado
Test pist 2	*Alnus Acuminata*	1.26	6.21	4.36	0.43	0.34	1.20	113	16.00	311.95	25.31	Colpar
Test pist 3	*Alnus Acuminata*	0.72	15.72	4.03	0.76	0.76	5.30	236	32.00	277.84	60.95	Dorado
Test pist 4	*Alnus Acuminata*	1.13	9.38	3.87	0.55	0.48	1.50	152	20.80	393.41	44.38	Colpar
Test pist 5	*Alnus Acuminata*	1.10	13.24	4.58	0.48	0.62	2.90	488	25.12	252.43	55.79	Dorado
Test pist 6	*Alnus Acuminata*	1.29	9.65	4.21	0.45	0.52	3.90	238	20.16	323.28	35.34	Colpar
	Media	1.10	10.6	4.31	0.6	0.53	3.28	303.7	22.1	297.6	43.8	
Test pist 1	*Polylepis sp.*	1.13	10.62	6.54	0.14	0.40	4.6	555	24.00	805.27	42.31	Dorado
Test pist 2	*Polylepis sp.*	0.80	18.48	7.53	0.52	0.78	32.6	898	38.40	390.63	59.90	Colpar
Test pist 3	*Polylepis sp.*	1.11	9.31	6.01	0.08	0.41	3.4	201	23.36	528.74	48.96	Dorado
Test pist 4	*Polylepis sp.*	0.88	18.48	6.34	0.23	0.70	12.2	177	37.12	507.19	70.42	Colpar
Test pist 5	*Polylepis sp.*	1.11	9.17	5.89	0.18	0.42	2.4	533	22.72	568.39	48.43	Dorado
Test pist 6	*Polylepis sp.*	1.19	10.34	6.99	0.24	0.37	4.5	134	24.00	359.71	38.36	Colpar
	Media	1.04	12.73	6.55	0.23	0.51	10.0	416.33	28.27	526.66	51.40	
Test pist 1	bare ground	1.29	3.10	4.86	0.05	0.22	2.5	91	16.32	211.40	26.88	Dorado
Test pist 2	bare ground	1.28	2.55	5.10	0.08	0.15	1.8	107	11.52	59.06	25.77	colpar
Test pist 3	bare ground	1.29	2.41	4.49	0.05	0.19	1.3	51	14.40	122.45	24.28	Dorado
Test pist 4	bare ground	1.35	1.45	5.31	0.09	0.13	1.6	71	8.32	54.42	22.19	colpar
Test pist 5	bare ground	1.27	3.03	4.62	0.03	0.21	2.8	69	12.32	206.30	19.89	Dorado
Test pist 6	bare ground	1.28	2.90	5.07	0.09	0.15	4.5	112	9.60	20.91	23.57	colpar
	Media	1.29	2.57	4.91	0.07	0.18	2.42	83.50	12.08	112.42	23.76	
Test pist 1	*Escallonia resinosa*	0.83	7.19	4.91	0.41	0.3	2.70	142	16.00	226.59	41.03	Saño
Test pist 2	*Escallonia resinosa*	0.99	2.22	4.86	0.14	0.12	5.40	78	10.08	311.95	25.31	Saño
Test pist 3	*Escallonia resinosa*	1.03	1.28	4.82	0.15	0.06	4.10	62	7.36	277.84	60.95	Saño
Test pist 4	*Escallonia resinosa*	0.81	10.61	5.27	0.26	0.41	9.20	511	23.20	393.41	44.38	Talhuis
Test pist 5	*Escallonia resinosa*	0.96	5.31	5.13	0.19	0.31	7.30	369	16.64	252.43	55.79	Talhuis
Test pist 6	*Escallonia resinosa*	1.03	4.1	5.00	0.12	0.25	6.10	258	15.04	323.28	35.34	Talhuis
	Media	0.94	5.1	5.00	0.21	0.24	5.80	236.67	14.72	297.6	43.8	
Test pist 1	bare ground	0.87	5.17	5.09	0.05	0.24	3.7	147	12.80	211.40	26.88	Saño
Test pist 2	bare ground	0.96	2.42	5.14	0.04	0.17	4.3	108	9.60	59.06	25.77	Saño
Test pist 3	bare ground	0.99	2.02	5.09	0.03	0.13	3.2	87	9.12	122.45	24.28	Saño
Test pist 4	bare ground	0.93	5.91	4.95	0.23	0.34	6.2	148	14.40	54.42	22.19	Talhuis
Test pist 5	bare ground	1.1	2.22	5.05	0.08	0.17	4.6	75	12.00	206.30	19.89	Talhuis
Test pist 6	bare ground	1.09	2.02	5.09	0.06	0.15	3.9	62	11.84	20.91	23.57	Talhuis
Media		0.99	3.29	5.07	0.08	0.20	4.32	104.50	11.63	112.42	23.76	

Note: Results of 30 soil samples at 20-30 cm depth

Maximum and minimum values

In Table 3, maximum and minimum values for various indicators were established in different ways. For certain attributes, especially those related to optimal conditions, thresholds calculated from values observed in local soils were considered. On the other hand, for indicators such as bulk density, organic matter, pH, and available phosphorus, the minimum value was defined as the average of values measured in reference soils, while the maximum value was based on maximum measurements observed in the region, as indicated by some authors (Barahona, 2012; Cierto *et al*., 2022; Romaní, 2020). For moisture content, available potassium, total nitrogen, and cation exchange capacity (CEC), calculations were based on theoretical concepts related to soil quality and ideal fertility conditions in the region, as described in Barahona (2012) and Dionisio (2012). Regarding microbial biomass, its evaluation was carried out considering specific characteristics of areas adjacent to the study forests and supported by local bibliographic information (Hinostroza *et al*., 2021).

TABLE 3

Maximum and Minimum Values of Indicators

Indicators	U.M	Maximum value *	Minimum value *
Bulk Density	g cm^{-3}	1.50	0.6
Organic Matter	%	13	1
pH	-	7	4
Electrical Conductivity	mS/cm	1	0.05
Total Nitrogen	%	0.7	0.1
Available Phosphorus	ppm	11	2
Available Potassium	ppm	500	100
Cation Exchange Capacity	meq/100g	40	5
Microbial Biomass	mg kg^{-1}	550	10
Moisture Content	%	60	10

* Note: Maximum and minimum values resulting from the application of equations 1 and 2.

Soil quality indicators

From the evaluation of soil quality, considering a minimum set of recommended indicators and the specific normalized values obtained for each of the studied relict forests, Soil Quality Indices (SQIs) have been developed. This index provides a tool for comparing soil quality in different contexts, specifically for the forests of *Alnus acuminata*, *Polylepis racemosa*, *Escallonia resinosa*, and the soil without forest cover. The results of the SQIs for each indicator are presented in Table 4 and reveal significant variation in soil quality among these study areas.

The indicator exhibiting the lowest average SQI value corresponds to the species *Escallonia resinosa*, with an SQI of 0.51. According to the evaluation scale shown in Table 4, this value suggests moderate soil quality or class 3. This situation is comparable and observable with the species *Alnus acuminata*, which also records an SQI of 0.58, also in class 3. In contrast, the native species *Polylepis racemosa* obtains an SQI of 0.66, indicating high soil quality or class 2. This value is supported by high values in soil quality indicators in the sampled forests. These high estimates in organic matter, moisture content, phosphorus, potassium, and microbial biomass are regularly generated by the roots, leaves, and branches that fall and provide organic matter to the soils, fertilizing them and increasing their volume and water absorption capacity, forming fertile soils. Additionally, the soils in the patches of native relict forests of *Polylepis racemosa* are characterized by slightly acidic pH (less acidic than the other species), high levels of organic matter, and limited nutrient availability, a situation also reported by Cuyckens & Renison (2018).

In contrast, the soil without forest cover presents low results in the SQI, with a value of 0.28. This value effectively reflects the lack of forest cover and suggests poor soil quality, highlighting the importance of preserving and restoring forest cover in these ecosystems. The presence of cover would represent a positive impact on soil quality by protecting it from erosion, maintaining moisture, enriching it with organic matter, and fostering biological diversity. The loss of this cover often results in a lower soil quality index in those areas, as also supported by Cantú *et al*. (2007) and Nyeck *et al*. (2018).

All forest species maintain acceptable values of bulk density, consistent with reports by Nel *et al*. (1984) and Salter (1940), indicating good porosity, aeration, and root penetration, factors favorable for tree growth. Regarding electrical conductivity, it is the *Escallonia resinosa* cover that presents the highest values in this indicator, corresponding to high concentrations of salts, possibly acquired from human activities such as the release of pollutants, as the sampling of this species was conducted in patches of forests heavily visited for leisure and local tourism activities.

Similarly, Table 4 shows significant differences between the soil without cover regarding the species of *Alnus acuminata* and *Polylepis racemosa*, but not regarding *Escallonia resinosa*. Additionally, the three native species do not present significant differences among themselves according to the Tukey test (p<0.05).

TABLE 4

SQI by indicator for each native forest species

Indicators	SQI values			
	Alnus acuminata	*Polylepis racemosa*	*Escallonia resinosa*	Bare Soil
Bulk Density	0.44	0.51	0.62	0.40
Organic Matter	0.80	0.98	0.34	0.16
pH	0.90	0.15	0.80	0.73
Electrical Conductivity	0.58	0.19	0.83	0.49
Total Nitrogen	0.72	0.68	0.24	0.15
Available Phosphorus	0.14	0.89	0.42	0.15
Available Potassium	0.51	0.79	0.34	0.02
Cation Exchange Capacity	0.49	0.66	0.28	0.20
Microbial Biomass	0.53	0.96	0.53	0.19
Moisture Content	0.68	0.83	0.68	0.28
SQI	0.58 a	0.66 a	0.51 ab	0.28 b

Different letters within each experimental site represent significant differences ($p < 0.05$).

Table 5 shows the Soil Quality Index (SQI) values for each evaluated forest. The remnants of Dorado and Colpar relict forests presented the highest SQI values with 0.53 and 0.52 respectively, while the Saño forest had the lowest SQI value with 0.39. These results are related to the low indicators of organic matter, available potassium, available phosphorus, and cation exchange capacity (CEC) found in Saño. Considering that potassium and phosphorus are essential macronutrients for plants, their low levels can limit the vigor and productivity of the forest. The availability of potassium and phosphorus depends on soil reserves and organic matter input, the latter being a key attribute due to its influence on multiple soil properties as supported by Gregorich *et al.* (2011). The results suggest that the Saño forest presents limitations in terms of nutrient reserves and inputs, determining its lower quality index, which leads to reduced cation exchange capacity activity. Therefore, it is necessary to investigate the specific causes of the deficiencies observed at this site compared to forests with similar characteristics, as these soils require special attention to improve their quality and fertility. Particularly, it was in the Saño forest where soil samples were taken with *Escallonia resinosa* coverage, where a low SQI value was also observed, registering a value of 0.51.

Additionally, statistically, there are no significant differences in the mean SQI among the evaluated native forest patches ($p<0.05$).

TABLE 5

SQI by Patch of Native Relict Forest

Indicators	IQS Values			
	Dorado	Colpar	Saño	Talhuis
Bulk Density	0.42	0.38	0.62	0.57
Organic Matter	0.62	0.65	0.20	0.34
pH	0.64	0.53	0.81	0.77
Electrical Conductivity	0.76	0.74	0.91	0.89
Total Nitrogen	0.52	0.50	0.12	0.29
Available Phosphorus	0.15	0.57	0.21	0.47
Available Potassium	0.53	0.31	0.01	0.34
Cation Exchange Capacity	0.46	0.45	0.17	0.30
Microbial Biomass	0.64	0.48	0.35	0.37
Moisture Content	0.62	0.57	0.48	0.47
SQI	0.53 a	0.52 a	0.39 a	0.48 a

ANOVA test, there are no significant differences in at least one group of pooled data ($p < 0.05$).

Regarding the soil without forest cover, it presents a Soil Quality Index (SQI) of 0.28, corresponding to level 4 or low quality as shown in Figure 2a. This suggests that forest cover improves and maintains a direct relationship between soil health and the present forest species, increasing and maintaining some vital indicators of soil quality at ideal levels.

Similarly, there is little difference in the average Soil Quality Index (SQI) for each studied forest (Figure 2b), where a higher SQI generally suggests better soil quality, while a lower SQI may indicate less favorable soil quality. All four forests exhibit moderate soil quality, although the Saño forest soil is on the edge of low-quality soil (Wavrek *et al.*, 2023) argue that these data are useful for understanding variability in soil quality among different forests and may be crucial for decision-making in forest management and soil conservation, especially when aiming to conserve native species sensitive to changes in their indicators.

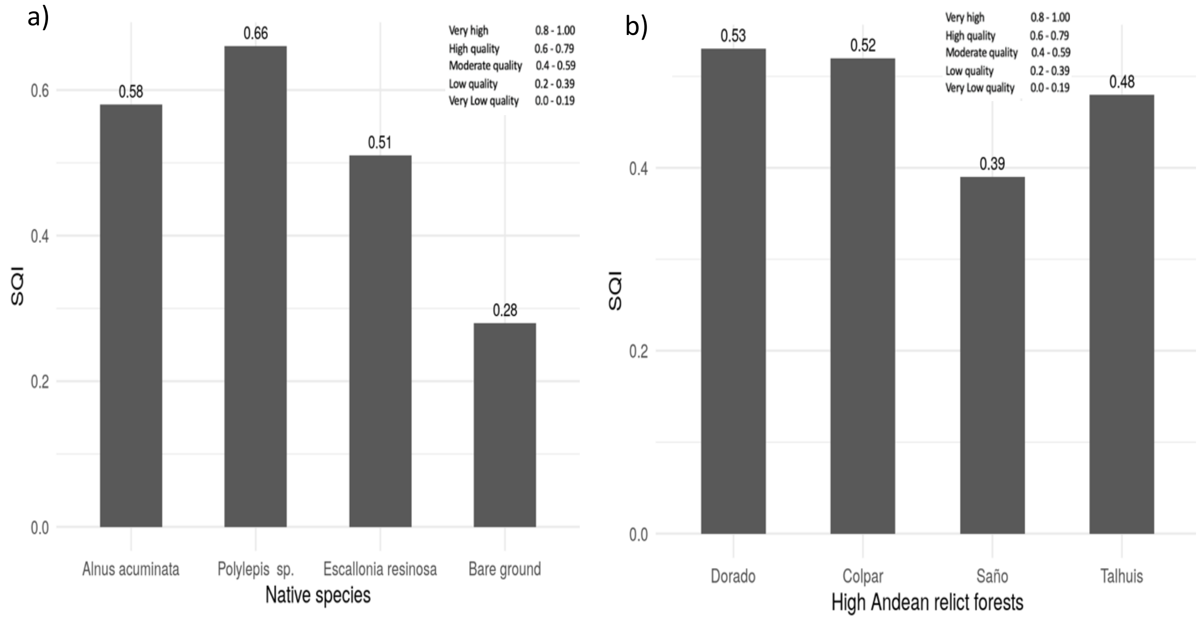
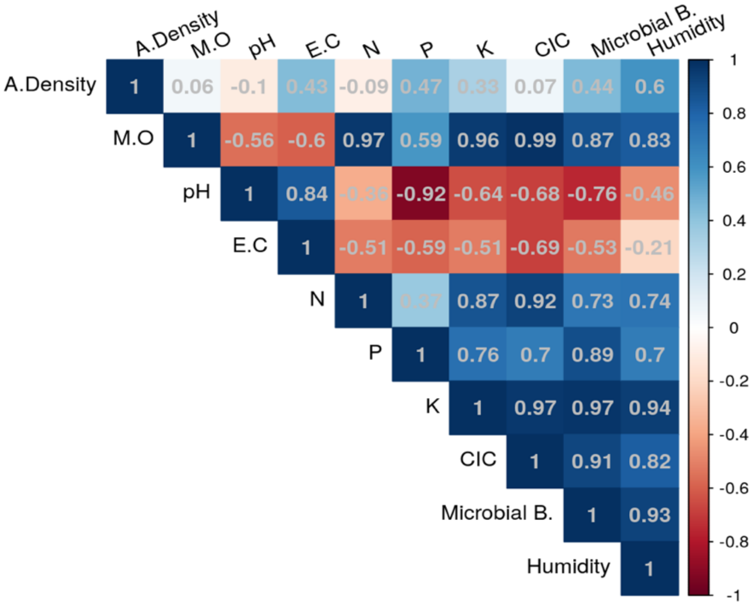


Figure 2. Soil Quality Index (SQI) by native forest species (a) and high-Andean relic forest (b).

The correlation matrix (Figure 3) unveils the relationships between the variables, and the closer the correlation value is to 1, the stronger the relationship. In this case, we highlight a revealing example; the strong positive correlation (0.93) between humidity and microbial biomass. This indicates that as humidity levels increase, so do the values of microbial biomass. This positive association suggests a direct and strong connection between these two indicators, which could indicate higher microbial activity under conditions of increased soil humidity, as revealed by Gerke (2022).

On the other hand, the indicators of potassium and pH reveal a significant negative correlation (-0.92), indicating a close to -1 inverse relationship. This implies that as the soil pH becomes more basic, the concentration of potassium decreases. This strong negative correlation suggests that an increase in soil pH basicity is closely related to a decrease in potassium availability for plants. Furthermore, this has important implications for soil management, as lower potassium availability can negatively affect plant growth, underscoring the importance of maintaining soil pH within the optimal range for nutrient absorption by plants, a postulate shared by Yin *et al*. (2021) regarding surfaces with pine forests.



	A.Density	M.O	pH	E.C	N	P	K	CIC	Microbial B.	Humidity
A.Density	1	0.06	-0.1	0.43	-0.09	0.47	0.33	0.07	0.44	0.6
M.O		1	-0.56	-0.6	0.97	0.59	0.96	0.99	0.87	0.83
pH			1	0.84	-0.36	-0.92	-0.64	-0.68	-0.76	-0.46
E.C				1	-0.51	-0.59	-0.51	-0.69	-0.53	-0.21
N					1	0.37	0.87	0.92	0.73	0.74
P						1	0.76	0.7	0.89	0.7
K							1	0.97	0.97	0.94
CIC								1	0.91	0.82
Microbial B.									1	0.93
Humidity										1

Figure 3. Correlation Matrix among Soil Quality Index (SQI) Indicators.

A significant correlation is highlighted between organic matter and cation exchange capacity, with a very strong correlation of 0.99. This indicates a solid and positive relationship between the amount of organic matter in the soil and its ability to retain and release nutrients, which is fundamental for soil fertility and productivity. This is also noted by Palm *et al*. (2001) in their work on nutrient availability to assess soil fertility.

A solid and negative correlation is also highlighted between pH and microbial biomass indicators, with a correlation value of -0.76. This indicates a significant inverse relationship between soil pH and the amount of microbial biomass present. In other words, as soil pH becomes more basic, microbial biomass tends to decrease, which may influence the microbial activity of some species sensitive to this change in this indicator, based on similar work and results by Tian *et al*. (2008). There are also many additional analyses among the indicators; however, the ones already shown are the most significant for the research objective.

CONCLUSION

The characterization of physical, chemical, and biological indicators allowed for the assessment of soil quality based on aboveground biomass input under different native forest coverages in the central highlands of Peru. In this regard, the Soil Quality Index (SQI) found significantly higher values in forests of *Polylepis racemosa* and *Alnus acuminata* compared to *Escallonia resinosa* and soil without coverage. Furthermore, these first two species are associated with improvements in key soil properties such as organic matter content, cation exchange capacity, and microbial biomass.

The results further support the positive role of conserving native forests such as Dorado and Colpar, dominated by *Polylepis racemosa* and *Alnus acuminata*, in maintaining soil quality and fertility in high Andean ecosystems. However, further ecological studies are needed to understand the specific mechanisms through which these native species contribute to improving the chemical, physical, and biological properties of the soil.

This study also underscores the utility of soil quality indices based on a minimal set of indicators to assess the impact of different forest coverages generated by forest aboveground biomass on soil health. The findings have implications for future conservation and ecological restoration initiatives in the region by highlighting key native species for reclaiming degraded soils.

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