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Forest Site Classification in the Southern Andean Region of Ecuador: A Case Study of Pine Plantations to Collect a Base of Soil Attributes

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Received: 30 October 2017; Accepted: 29 November 2017; Published: 2 December 2017

Abstract: Forest site classification adapted to the respective site conditions is one prerequisite for sustainable silviculture. This work aims to initiate the forest site classification for pine plantations in the southern Andean region of Ecuador. Forest productivity, estimated by the dominant height of 20-year-old trees (DH_{20}), was related to data from climate, topography, and soil using 23 plots installed in pine plantations in the province of Loja. Forest site productivity was classified as: low (class C: 13.4 m), middle (class B: 16.6 m), and high (Class A: 22.3 m). Strong determinants to differentiate the forest site classes were: the short to medium term available Ca and K stocks (organic layer + mineral soil standardized to a depth of 60 cm), soil acidity, the C:N ratio, clay and sand content, forest floor thickness, altitude, and slope. The lowest forest productivity (Class C) is mainly associated with the lowest short to medium term available K and Ca stocks. Whereas, in site classes with the highest forest productivity, pines could benefit from a more active microbial community releasing N and P, since the soil pH was about 1 unit less acidic. This is supported by the lowest forest floor thickness and the narrowest C:N ratio.

Keywords: exotic forest species; forest floor; forest productivity; *Pinus patula*; plant available nutrient stocks; tropical Andes

1. Introduction

Ecuador is a country that is in the top 10 list of countries with the greatest loss of primary forest area between 1990 and 2015 [1], and until recently, exhibited the highest deforestation rate in South America [2]. In South America, afforestation programs were mainly developed based on the use of exotic species with the early aim of wood production, but later changed into non-wood forest products and for environmental protection [3]. In Ecuador, the use of exotic species for afforestation programs has been implemented on a large scale since the beginning of the previous century [4,5]. A common feature is that they have been established without intensive base line studies [6]. In the

Andean region of Ecuador (Sierra Region), pines and eucalypts have been commonly used for plantations [7–9]. The effects of these plantations give evidence of reductions in environmental quality in Ecuador [5,10–13], and often, they have been shown to be financially non profitable [6,14]. All these studies have been mainly carried out in the central and northern part of Ecuador in areas that belong to the humid tropical alpine environments known as Páramos [15], with a special emphasis on hydrological aspects. For the southern Andean region, where there is a contrast among the wet eastern side of the Andes, the drier Andean valleys, and the western side [16], there is still scarce knowledge on the impacts of pine plantations on soil properties and on the controlling effects of site conditions on tree productivity. The effects on soil functionality as a strong determinant of forest productivity have not yet been investigated [17]. Therefore, it is necessary to establish a site classification that reflects the tree growth affected by ecological factors under different conditions [18].

The site classification could become a strategy tool for site evaluation and the consequent formulation of site-specific policies and management recommendations [19] for Ecuador. Until now, those aspects have not been sufficiently established by governmental regulations in Ecuador [20], in spite of the influence of several organizations, either national or international, e.g., PNUMA, which has promoted the importance of the sustainable management of forests in Ecuador [21] and CLIRSEN & SENPLADES (national institutions) which have worked in the project "Generation of geo-information for land management nationwide" (http://www.institutoespacial.gob.ec/proyecto-naciona/). However, during the last years, national programs have been developed for the conservation of forest lands and other critical ecosystems like Páramos and mangroves [22], or to improve the land use to cope with issues directly related to agricultural activities. Examples are the project "Zonificación Agroecológica del Austro" [23] and the study about Land Suitability for Cherimoya [24]. So far, there have been no programs that promote the restoration and/or rehabilitation of forest ecosystems, especially in zones of planted forests based on principles of forest site classification.

Forest site classification is defined as any form of classification system that stratifies biotic and/or abiotic land features using methods that aggregate, divide, sort, synthesize, and/or integrate into classes the different components of the forest environment (such as climate, topography, soil, and vegetation) [19]. But the effects of the different forest components depend on the scale [25]. The effect of the climate can be more important at a landscape and regional scale, whereas topography and soil can be more important at a local scale. For example, forest site classifications developed in Europe, Canada, and the United States developed over large extensions emphasize the effect of climate on forest productivity to differentiate the main categories (usually associated to specific vegetation) at the top level inside a hierarchical classification system. The lower levels depend on topographical attributes and finally on soil characteristics [26,27]. In smaller extensions, where the effect of climate in forest productivity is lower, some studies, for example, in China, in the Xiaoxing'an Mountain region [28] and Liangcheng County [29], have only highlighted the topography followed by soil effects on site productivity to derive their site classifications.

In forest environments, soils are developing together with trees due to the length of the forest life cycle [30]. Forest management also changes soil properties compared to natural unmanaged forest ecosystems in many cases [31]. Soil properties have been included in multifactor approaches (geocentric or phytogeocentric approaches) as one of the most important drivers for the determination of forest site classes. At the stand level, soil properties like nutrient status—despite their expensive and time-consuming acquisition—have been of the upmost importance to understand the direct relationship between soil and tree growth [32]. Nevertheless, the influence of a particular soil property or a group of them is dependent on the geographical position, for example, tropical forest soils have typically shown a low accumulation of P, K, and Ca [33]. Particularly, in the tropical southern Andean region of Ecuador—a region that shows a high variability in soils [34]—in pine plantations, a multiple cation deficiency has been detected [35]. This points to a high regional variability, leading to the assumption that forest productivity would be also diverse.

The present study aimed: (i) to characterize the site variability of the study region (based on environmental variables: climate, topography, and soil) in four pine plantation sites (*Pinus patula*); (ii) to identify the principal relations between the variables and forest productivity; and (iii) to initiate the construction of a classification protocol to be used and refined in future forest management planning and follow ups of conversion of plantations into mixed forest with native species.

2. Materials and Methods

2.1. Study Area

The study was carried out in the southern Andean region of Ecuador (Figure 1). In this area, four sites of pine (*Pinus patula*) plantations were selected and termed: Dos Puentes (DOS), Santiago (SAN), Villonaco (VIL), and Zamora-Huayco (ZAM). The selected plantations are inside a radius of 30 km from the provincial capital (Loja city) and their characteristics are summarized in Table 1.

The criteria for the selection of these sites were the following: (i) trees near to the commercial felling (the age ranges from 15 to 25 years in Ecuador); (ii) climatic variability among sites; and (iii) permission of the landowners for the establishment of inventory forest plots and soil sampling. The last point was the most challenging because many landowners of appropriate pine plantation sites did not grant access to their plantations. This limited the number of sites and the number of plots within one site.

In the four pine sites, it was possible to install a total of 23 sampling plots: six in DOS, three in SAN, seven in VIL, and seven in ZAM. The area of the plots was 576 m^2 (24 m × 24 m). Forest attributes and environmental variables (climatic, topographical, and soil variables) were taken from those plots, and the different attributes are described in Table 2.

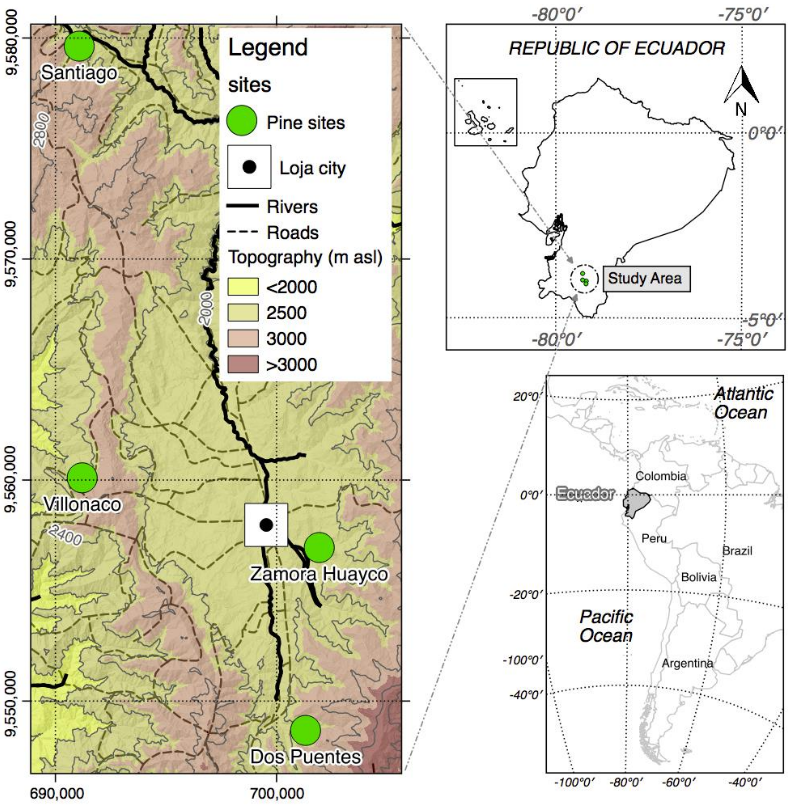

Figure 1. Location of the four sites of *Pinus patula* forest stands in the study region around Loja city in the south of Ecuador.

Table 1. Description of the pine plantation (*Pinus patula*) sites (DOS: Dos Puentes, SAN: Santiago, VIL: Villonaco, ZAM: Zamora-Huayco) included in this study.

	Site			
	SAN	**ZAM**	**DOS**	**VIL**
Forest				
Stand age (years) [a]	20	18	22	14
Climate				
Precipitation (mm year^{-1}) [c]	659	889	839	599
Temperature (°C) [c]	9.3	11.2	9.9	10.6
Potential Evapotranspiration (mm year^{-1}) [c]	1013	1053	1035	1043
Climate (Köppen) [e]	Humid temperate without dry season	Humid temperate without dry season	Humid temperate without dry season	Humid temperate without dry season
Terrain				
Geology [b]	Paleozoic metamorphics	Paleozoic metamorphics	Paleozoic metamorphics	Paleozoic metamorphics
Relief [d]	Medium hills	Irregular hillslopes	Irregular hillslopes	Irregular hillslopes
Altitude (m a.s.l.) [d]	2430	2234	2402	2324
Slope (%) [d]	30	41	41.5	44
Aspect [d]	North	North-West	North-West	North
Former land use [a]	pasture	pasture	pasture	remnant Andean shrubs

Sources: [a] Central Transfer Project "New Forests for Ecuador" (Günter & Mosandl, pers. comm.); [b] [36]; [c] [37]; [d] Deutsche Forschungsgemeinschaft 187 Research Unit 816 (RU 816) database 188 (www.tropicalmountainforest.org/); [e] [38].

Table 2. Set of environmental attributes for the forest site classification in this research.

Factor	Attribute	Measure
Forest	Dominant height of trees standardized to a plantation age of 20 years (DH_{20})	m
Climate	Precipitation (PRE)	mm year^{-1}
	Temperature (TEM)	°C
	Potential Evapotranspiration (PET)	mm year^{-1}
Topography	Slope (SLO)	percentage
	Aspect (ASP)	slope direction (intercardinal direction)
	Altitude (ALT)	m a.s.l.
Soil	*Morphological variables*:	
	Maximum root depth (MRD)	cm
	Dominant root depth (DRD)	cm
	Forest floor thickness (FFT)	cm
	Stoniness (STONES)	percentage
	Physical variables:	
	Bulk density (BD)	Mg m^{-3}
	Granulometry (CLAY, SILT, SAND)	percentage
	Chemical variables:	
	Base saturation (BS)	percentage
	Acidity (pH in water)	pH-value
	Soil organic carbon (SOC)	Mg ha^{-1}
	Cation exchange capacity (CEC)	cmol(+) kg^{-1}
	Total nutrients stocks: N, P, K, Ca, Mg, S, Fe, Mn, Zn, Cu, Ni, Na, Al	Mg ha^{-1}
	Plant available nutrient stocks *: P, Na, K, Ca, Mg, Al, Fe, Mn, NH_4-N, NO_3-N, TIN (Total Inorganic Nitrogen).	kg ha^{-1}

Table 2. *Cont.*

Factor	Attribute	Measure
	Total nutrient stocks ratios: N/P, N/K, N/Ca, N/Mg, TIN/P, TIN/K, TIN/Ca, TIN/Mg, C/N.	Ratio (stocks)
	Ratios of plant available nutrient stocks */total nutrient stocks: P */P, Na */Na, K */K, Ca */Ca, Mg */Mg, Al */Al, Fe */Fe, Mn */Mn, Ca */Mg *	Ratio (stocks)
	Contribution of the available nutrient stocks to the total nutrient stocks	percentage

Attributes were identified reviewing the following literature: Climatic attributes: adapted from [37]. Topographical attributes: DEM from Deutsche Forschungsgemeinschaft (DFG), available at the Research Unit 816 (RU 816) database. Forest attributes: field data from all plots measured by Dario Veintimilla (Central Transfer Project). Soil attributes: morphological getting from own field observations and physical and chemical determinations made in the laboratory (Laboratory of the Institute of Soil Science and Site Ecology, Technische Universität Dresden, Germany). *: plant available nutrient stocks.

2.2. Forest Attributes

Stand structural attributes were computed as following: (1) stem density (SD): the number of trees per unit area [39]; (2) basal area (BA): sum of the stem cross-sectional area at breast height per plot area [39]; (3) diameter at breast height (DBH): tree stem diameter at breast height of 1.3 m [39]; (4) quadratic mean diameter (QMD): diameter of the average basal area of the trees in the stand [40]; (5) stand height (SH): mean height of the three tallest trees in the plot [41]; (6) dominant height or height of dominant trees (DH): average height of a group of trees with the biggest diameter, 100 trees per hectare [39]; (7) stand volume (V): stand volume considering the stem over bark [39].

2.3. Enviromental Variables

2.3.1. Topographical and Climatic Attributes

Topographical attributes, slope and aspect, were computed from a Digital Elevation Model (DEM) with a 10 m resolution, of the Deutsche Forschungsgemeinschaft (DFG), available at the Research Unit 816 (RU 816) database (www.tropicalmountainforest.org/). For computation of slope and aspect, the Zevenbergen & Thorne algorithm of polynomial fitting (second order polynom) was applied [42], and implemented in the Morphometry library of SAGA [43] running in the QGIS environment [44]. To relate the forest data from plots of 24 m × 24 m to the topographical data (10 m × 10 m precision grid), the centroid value for every topographical attribute was computed from the grid topographical attribute values in the area of every forest plot using geometry tools implemented in QGIS.

Climatic attributes (Table 2) were obtained as follows: precipitation (PRE), temperature (TEM), and potential evapotranspiration (PET) belong to the average annual and they come from Ecuadorian national data, with a resolution of 2500 m [45]. To relate the grid climatic data to the forest and soil data, a correction was applied as follows: since PET shows a high correlation with altitude for the study area (correlation coefficient (r) = 0.88), it was adjusted via regression with the altitude data from the DEM per forest plot. Temperature (TEM) was corrected with the altitude data from the DEM of the study sites according to Fries et al. [46]. PRE data was not corrected and therefore, for the lack of spatial resolution compatibility with topography, forest, and soil data, it was not included for the forest site classification.

2.3.2. Soil Attributes

Soil Sampling

The soil morphological attributes (Table 2) come from the description of 23 soil profiles according to the "Guidelines for soil description" [47]. The soil classification (determination of the Reference Soil Groups) was based on IUSS Working Group WRB (2015) [48]. The hydro-physical and chemical attributes (Table 2) have been determined after a soil sampling campaign in the second semester of 2012. Soil samples were taken per horizon. For the sampling of the organic layers (Oi and OeOa), sampling frames (area of 546 cm^2) were used with three repetitions per layer. Soil samples from all mineral horizons of each soil profile were taken with Kopecky rings (volume: 100 cm^3). Six rings were used per horizon to form a composite sample. All samples were weighed at field moisture and then dried at 40 °C. Then, samples were stored in plastic bags and sent to Germany. The laboratory analysis started directly after the arrival of samples in October of 2012 in the Laboratory of the Institute of Soil Science and Site Ecology, Technische Universität Dresden, Germany.

Physical and Chemical Soil Attributes

Mineral soil samples were sieved (fine earth fraction: particle diameter <2 mm) and roots were separated. From the organic samples, roots were separated by hand. The stoniness was calculated as the coarse fraction (>2 mm) percentage of dried samples (40 °C) and the root content (mass percentage of roots <2 mm in diameter) was also derived from dried samples. The density of the fine earth fraction was determined by correcting the bulk density for the content of coarse-fragments (>2 mm) and of roots. Nutrient stocks were estimated according to Vesterdal et al. [49], using the bulk density of the fine earth fraction, the relative volume of the coarse fraction, the thickness of the horizons, and the nutrient concentration.

All stocks of nutrients in the mineral soil where normalized to a depth of 60 cm since this value represents the maximum of the dominant root depth of all soil profiles. Short to medium term available nutrient stocks were computed as the total nutrient stocks of the organic layer plus the easily available nutrient stocks concentrated in the upper part of the mineral soil layer (60 cm of depth) [50].

Soil texture was determined by sieving of the sand fraction and sedimentation of the silt and clay fraction [51]. Gravimetric water content was determined at 105 °C (from the 40 °C dried soil samples). For estimations of volumetric soil water content at field capacity (FC = water content at −33 kPa), wilting point (WP = water content at −1500 kPa), and the available water capacity (AWC = FC − WP), pedotransfer functions given by [52] were used. They are based on soil bulk density and sand content (for estimation of FC) and organic carbon content and clay content (for estimation of WP). Since the German system uses the particle size limits of: 2000 μm for sand, 63 μm for silt and 2 μm for clay [53], it was necessary to transform towards the system 2000 μm, 50 μm and 2 μm (2000-50-2), respectively, to apply the pedotransfer functions. This transformation was carried out by the Fredlund-type2 function described by [54] based on seven kinds of particles (German range of particle diameter in μm: coarse sand (2000-630), medium sand (630-200), fine sand (200-63), coarse silt (63-20), medium silt (20-6.3), fine silt (6.3-2), clay (<2)).

Amorphous (non-crystalline forms) iron, manganese, and aluminum was extracted with acid ammonium oxalate, while crystalline and amorphous forms of iron, manganese, and aluminum were extracted with dithionite-citrate-bicarbonate [55].

The soil pH of the soil samples was measured with a glass membrane electrode both in H_2O and 0.01 M $CaCl_2$ (soil:solution ratio = 1:2.5 for mineral soil and 1:10 for organic soil). The effective cation-exchange capacity (CEC) was analyzed by extraction with 0.5 M NH_4-Cl-solution [56]. Base saturation (BS) was calculated as the amount of basic cations of the total CEC in percent. A readily available amount of phosphorous (PO_4-P) was extracted with Bray I solution (0.03 M NH_4F + 0.025 M HCl) [57] and its concentration was measured by a continuous-flow auto analyzer (Skalar Analytic GmbH, Erkelenz, Germany). Dissolved organic carbon (DOC) and total dissolved nitrogen (TDN) were determined with 0.1 M KCl extract and filtration, and were measured by a multi-NC-analyzer (Analytik, Jena, Germany). Dissolved inorganic nitrogen (DIN) was determined as the sum of NO_3^--N and NH_4^+-N and these were extracted with 0.1 M KCl and filtration, before being measured with a continuous-flow auto analyzer (Skalar Analytik GmbH, Erkelenz, Germany). DON was calculated by subtracting DIN from the TDN.

Mineral and organic soil samples were finely ground for the subsequent analysis of total nutrients. Briefly, the determination of the organic soil carbon (SOC) and total nitrogen (TN) contents were made by dry combustion with a CNS-analyzer (vario EL, Elementar, Heraeus, Germany). The total amount of the other elements (P, K, Ca, Mg, S, Na, Al, Ba, Cu, Fe, Mn, Ni, Pb, Sr, Ti, V, Zn) was determined from aliquots of dried soil samples after acid digestion in a microwave ($HNO_3/HF/HClO_4$) [58] and measured with ICP-OES (CIROS-Spectro).

2.4. Statistical Analyses

To characterize the site variability (objective I), all variables were described by medians and median absolute deviations, since most data did not fulfill the assumptions of parametric tests (Shapiro-Wilk test, p-value < 0.05). Differences in environmental variables among sites were tested by the non-parametric Kruskal-Wallis test (p-value = 0.05) with the post-hoc Benjamini and Hochberg pairwise procedure (HB) [59].

To identify the principal relations between the variables and forest productivity (Objective II), data were processed in the following way:

(a) Reduction of the dimensionality of soil chemical data

Due to the large number of soil variables (see Table 2), data reduction was necessary, mainly in the soil chemical data because of their collinearity. The non-parametric technique of Classification and Regression Trees (CART) [60] was applied for the reduction of the dimensionality. CART is a less sensitive method to collinearity [61], is very useful in variable selection by accounting for the attribute importance [62], and is suitable for the analysis of unbalanced ecological data containing nonlinear relationships and missing values [63]. CART was applied using the height of dominant trees (DH) at a reference age of 20 years as a response variable. The height of dominant trees at a reference age has been used in our study because it is the most common indicator to measure site productivity in even-aged stands and therefore is an index of forest productivity widely used in forestry [64,65]. It is recommended for studies of site classification and stand productivity [66], basically because it is less dependent on stand density and thinning [67]. The DH data per plot was standardized at 20 years (DH_{20}) using a linear model based on the criteria of the mean annual increment (MAI) of tree height [39]. This linear standardization was used because the growth curve for pine (*Pinus sylvestris*) is approximately linear [68] in the considered growth interval between 14 and 22 years.

(b) Generation of forests site classes

Forest site classification was developed using Cluster and Partitioning Analysis [69]. A cluster analysis using the Ward's criterion was carried out with a database of the selected soil chemical variables by CART and the soil morphological and physical (see Table 2), climate, and topographical variables. Cluster and Partitioning Analysis was applied because it is a non-parametric method that has been used in several studies directly related to the generation of forest site classes and vegetation [28,29,70].

(c) Identification and assessment of the main relationships between environmental variables and forest productivity.

Partial Least Squares (PLS) regression was applied to identify the strength of the relationship between the environmental variables and forest site classification. PLS-regression analysis was used due to its capacity to work with strongly correlated data, noisy variables, missing values, and a larger number of variables than the sample size [71,72]. The standardized DH_{20} was also used to apply the PLS-regression and the validation of the PLS was developed by a K-fold cross-validation [73], and the final number of components was selected by a permutation test [74]. In the PLS regression, the importance of a variable in the relationship with the DH_{20} was determined by the use of a filter method based on a measure of variable importance in partial least projections known as variable importance in projection (VIP) [75]. Finally, Spearman correlation analysis was used to describe the relationships of the selected variables after the PLS-regression.

To achieve the objective III, statistical analyses were not required because it was based on the formulation of a basic site classification protocol for the study area.

All statistical analyses were applied using R-CRAN software [76]. QGIS [44] was used to create the location map.

3. Results

3.1. Characterization of Environmental Variables

3.1.1. Climate and Topography

Precipitation, temperature, and evapotranspiration were all statistically different among sites (Kruskal-Wallis test, $p < 0.05$), and ZAM showed the highest values for all the climatic parameters (Table 1). Topographical attributes: altitude, slope, and aspect, were also statistically different among sites (Kruskal-Wallis test, $p < 0.05$). Altitudinal differences among plots were approximately 300 m and plots in the SAN site were at the highest altitude. The slope of plots ranges from 9% to 54% and the VIL site showed the highest variability in plots. The sites exhibited statistical differences of aspect (Kruskal-Wallis test, $p < 0.05$), despite all of the plots showing an orientation between the North and West.

3.1.2. Soils

Physico-Chemical Soil Properties

Dominant soil types in the study area are Umbrisols followed by Cambisols, Regosols, and Gleysols (see Figure S1). The morphological characterization for the 23 soil profiles can be summarized as follows: soil depth was variable considering the total soil depth (including the organic O horizons and A-B-C mineral horizons) and ranges from 0.6 to more than 2 m. Differences in the horizon thickness between sites (Kruskal-Wallis test, $p < 0.05$) were detected with the exception of A horizons. Particularly, the ZAM site showed the highest thickness values for O and A, and the lowest for the B horizon. Meanwhile, for the C horizon, the SAN site showed the highest thickness values (see Figure S1).

In general, all soil profiles were acidic soils. The pH in the water of soil profiles (organic horizons + 60 cm of upper soil mineral layer (see Table S1) ranged from 4.6 to 5.2 (differences in values between pH in water and pH in 0.01 M $CaCl_2$ was on average 0.8) and the most acidic soils were Umbrisols. Soil weathering was variable among sites as indicated by the ratio of Fe_o/Fe_d (oxalate and dithionate-citrate extraction, data not shown), which varied from 0.12 to 0.47. The most weathered soils—associated with highly crystalline iron– belong to the VIL site (average profile ratio Fe_o/Fe_d = 0.12). This site is characterized by the dominance of Cambisols with a high percentage of sand and the lowest available water capacity (see Table S2). The less weathered soils (Umbrisols) occur at the ZAM and DOS sites (average Fe_o/Fe_d ratio for the profile of 0.42). In addition, the VIL site presented the lowest concentration of total dissolved nitrogen (TDN) between the study sites, showing an average value of 0.1 Mg ha^{-1} for the organic layer + 60 cm of the upper mineral soil layer (nitrogen is usually one of the most labile nutrients; data not shown). This is also an indicator of the stronger weathering processes that are happening in the soils of this site.

Soil Nutrient Stocks

Soil total nutrient and plant available nutrient stocks (easily available nutrients) varied significantly among sites. For the organic layer (horizons Oi + Oe/Oa), total macronutrients (TN, P, K, Ca, Mg, S) were more variable (based on the statistical differences) than micronutrients (Al, Fe, Mn, Cu, Na, Ni, Zn). However, the stocks were highest at ZAM with the exception of Ca, Mg, Al, Fe, and Mn, which were highest at SAN (Table 3). For the sites, the total nutrient stocks in this organic layer showed a trend in the following sequence: ZAM > DOS > SAN > VIL.

Table 3. SOC and soil total nutrient stocks in the organic layer (horizons Oi + Oe/Oa) for study sites (DOS: Dos Puentes, SAN: Santiago, VIL: Villonaco, ZAM: Zamora-Huayco).

Nutrient (Mg ha^{-1})	Site			
	SAN	ZAM	DOS	VIL
SOC	11.081 (0.16) b	26.736 (10.762) a	18.907 (3.93) ab	10.765 (4.133) b
TN	0.348 (0.033) b	0.685 (0.229) a	0.571 (0.129) a	0.272 (0.09) b
P	0.028 (0.001) ab	0.04 (0.017) a	0.029 (0.013) ab	0.016 (0.005) b
K	0.076 (0.009) bc	0.118 (0.062) a	0.095 (0.028) ab	0.048 (0.02) c
Ca	0.25 (0.02) a	0.052 (0.029) a	0.045 (0.007) a	0.08 (0.068) a
Mg	0.045 (0.02) a	0.03 (0.017) a	0.028 (0.008) a	0.033 (0.021) a
S	0.028 (0.002) bc	0.056 (0.021) a	0.044 (0.009) b	0.021 (0.008) c
Al	0.452 (0.077) a	0.251 (0.062) a	0.249 (0.132) a	0.169 (0.046) a
Fe	0.183 (0.042) a	0.102 (0.064) a	0.163 (0.056) a	0.086 (0.031) a
Mn	0.045 (0.03) a	0.008 (0.007) b	0.021 (0.014) ab	0.005 (0.004) b
Cu	0.0004 (0) b	0.0009 (0.0002) a	0.0006 (0.0002) ab	0.0004 (0.0002) b
Na	0.0091 (0.0051) a	0.012 (0.002) a	0.0086 (0.0046) a	0.0069 (0.0028) a
Ni	0.0003 (0) a	0.0008 (0.0004) a	0.0003 (0.0001) a	0.0003 (0.0001) a
Zn	0.0012 (0.0001) ab	0.0013 (0.0007) a	0.0012 (0.0005) ab	0.0006 (0.0003) b

Medians and median absolute deviations MAD in parenthesis. Within each row, different letters indicate significant differences (Benjamini and Hochberg pairwise procedure (HB) after Kruskal-Wallis test, $p < 0.05$). nDOS = 6; nSAN = 3; nVIL = 7; nZAM = 7.

For the mineral layer (standardized to a depth of 60 cm—horizons A + B + C), the variability (based on the statistical differences) of the total nutrient stocks was lower than the organic layer (see Table S3). In this layer, micronutrients were more variable than macronutrients. In the group of macronutrients, P presented the highest variability and VIL showed the highest P stocks. With regard to micronutrients, stocks of Fe, Mn, Na, and Ni were statistically different and the highest values were distributed among the sites (except ZAM) (see Table S3). The total nutrient stocks in this mineral layer showed the following trend: VIL > SAN > ZAM > DOS. The plant available nutrient stocks showed different trends compared to those of the total nutrients. In the organic (horizons Oi + Oe/Oa) (see Table S4) and mineral layer (standardized to a depth of 60 cm—horizons A + B + C) (Table 4), the plant available stocks of NH_4-N, Ca, Mg, and Mn where highest at SAN (although not always significant due to high variability). Plant available PO_4-P was highest at ZAM in the organic and mineral layer. In the organic layer, the highest amounts of available K and Al have been detected at ZAM (see Table S4), whereas in the mineral layer, the highest amounts occurred at SAN (Table 4). At DOS, the stocks of NO_3-N were the highest in the mineral soil, while those of Fe where high in the organic layer.

Table 4. Plant available nutrient stocks (exchangeable cations: NO_3^--N, NH_4^+-N, Bray—PO_4-P, K, Na, K, Ca, Mg, Al, Fe, Mn) in the mineral soil (standardized to a depth of 60 cm (horizons A + B + C)) for the study sites (DOS: Dos Puentes, SAN: Santiago, VIL: Villonaco, ZAM: Zamora-Huayco).

Nutrient (kg ha^{-1})	Site			
	SAN	ZAM	DOS	VIL
NO_3^--N	4.48 (4.17) ab	4.69 (4.34) ab	8.13 (7.97) a	1.61 (0.79) b
NH_4^+-N	51.67 (9.78) a	44.31 (18.3) ab	37.54 (6.28) ab	27.14 (10.73) b
PO_4-P	3.85 (0.65) a	27.91 (35.47) a	11.38 (10.8) a	11.08 (8.08) a
Na	14.33 (2.94) ab	22.25 (8.61) a	5.42 (1) c	10.62 (2.37) b
K	851.14 (83.72) a	192.44 (88.3) b	96.34 (12.23) c	166.47 (40.42) b
Ca	2245.51 (2460.26) a	114.79 (33.69) b	49.17 (14.07) c	91.42 (26.99) b
Mg	605.14 (738.28) a	9.51 (8.8) b	13.18 (3.5) ab	18.19 (16.75) ab
Al	5088.61 (1216.28) a	2964.51 (1472.39) a	1342.89 (615.01) b	1577.44 (852.61) b
Fe	79.95 (46.57) a	65.66 (39.46) a	93.38 (57.46) a	39.75 (10.41) a
Mn	17 (25.2) a	nd	4.73 (7.02) a	nd

Medians and median absolute deviations MAD in parenthesis. Within each row, different letters indicate significant differences (Benjamini and Hochberg pairwise procedure (HB) after Kruskal-Wallis test, $p < 0.05$). nDOS = 6; nSAN = 3; nVIL = 7; nZAM = 7. nd: not detectable.

3.1.3. Forest Stand Characteristics

There were differences between sites for all the structural attributes of the pine forest sites (Table 5). The SAN site presented the highest values for all attributes, except for stand density (SD) and basal area (BA), even though it was not the oldest forest stand. The ZAM site showed high values of forest attributes as well, but did not demonstrate clear relationships of stand attributes to age (Table 5). A clear relationship was only shown for VIL, the youngest stand, and presented the lowest values for all the attributes. For forest site classification, the dominant height of even aged plantations (20 years old) was taken (DH_{20}).

Table 5. Structural attributes of pine (*Pinus patula*) forest stands (DOS: Dos Puentes, SAN: Santiago, VIL: Villonaco, ZAM: Zamora-Huayco).

Forest Attribute	Site			
	SAN	ZAM	DOS	VIL
Stand age (years)	20	18	22	14
Stand Density (SD) (trees ha^{-1})	763.9 (0) b	1684 (797.9) a	729.2 (128.7) b	954.9 (77.2) a
Basal area (BA) (m^2 ha^{-1})	44.2 (2.7) a	47.3 (6.2) a	25.5 (3.1) b	17.1 (1.7) c
Diameter at breast height (DBH) (cm)	27.4 (0.9) a	19 (7.1) b	20.4 (0.3) ab	14.6 (1.5) c
Quadratic mean diameter (QMD) (cm)	27.7 (1.1) a	19.9 (7.4) b	21.3 (0.5) ab	15.3 (1.4) c
Stand height (SH) (m)	23.7 (1.3) a	17.8 (4.9) b	18 (1.8) b	10.3 (0.5) c
Dominant height (DH) (m)	22.3 (1.8) a	15 (1.7) b	15.9 (1.2) b	9 (0.4) c
Stand Volume (m^3 ha^{-1})	501.6 (71.7) a	401.2 (61.1) a	203.8 (23) b	75.2 (11.7) c
DH_{20} (m)	22.3 (1.8) a	16.6 (1.9) a	14.5 (1.01) b	12.9 (0.5) b

Medians with median absolute deviations in parenthesis. Within each row, different letters indicate significant differences (α = 0.05; BH post-hoc comparison after Kruskal-Wallis test). nDOS = 6; nSAN = 3; nVIL = 7; nZAM = 7.

3.2. *Forest Site Classification*

Three classes of forest sites were identified after the clustering procedure (Figure 2). The most productive class for 20-year-old plantations exhibited a dominant height of trees (DH_{20}) approximately 1.7 and 1.3 times higher than the low and medium class (Table 6). Although there were statistical differences in climatic conditions among forest site classes, they were not important, as indicated by the VIP value in the PLS-regression, or they were not significant in the correlation analysis with the forest productivity index (DH_{20}) (see Table S5).

The impact of topography on site productivity was only clear for the slope factor, obtaining the highest forest productivity in zones of a lower steepness (Table 6).

Taking into account the VIP values (VIP: variable influence in projection from the PLS-regression), the soil properties are the main source of variability among the forest site classes (accounting for 64% of the total variability). Despite most soil physical properties showing statistical differences among sites, a clear association of the highest forest productivity (class A) was only detected for maximum root depth and clay content (Table 6). Forest floor thickness and sand content was lowest in the high productivity forest site class (Table 6).

The importance of short to medium term available nutrient stocks was denoted by the VIP values—the higher the value, the higher the importance of the variable in the forest productivity PLS-regression. It can be highlighted that Ca, K, and Mg nutrient stocks were more important than P, but no more important than N stocks (Table 7). However, Ca and K nutrient stocks were the most statistically correlated with the forest stand productivity (DH_{20}) (see Table 7).

Based on tendencies of values of the variables of each forest site class and their statistical differences (see Table 6), together with the relationships between the dominant height of trees and the nutrient stocks (see Table 7), the forest site classes are defined in Table 8.

Table 6. Values of the main environmental variables selected after the CART algorithm for the three forest site classes of high, middle, and low productivity (class A, B and C). The dominant height of trees in 20-year-old plantations (DH_{20}) represents the productivity of each class.

Environmental Variables	Forest Site Class		
	A (DH_{20} = 22.3 m)	B (DH_{20} = 16.6 m)	C (DH_{20} = 13.4 m)
Temperature (TEM) (°C)	9 (0) b	12 (0) a	10 (1.48) b
Potential Evapotranspiration (PET) (mm y^{-1})	1038 (0) c	1050 (0) a	1040 (2.97) b
Aspect (decimal degrees)	360 (0) a	315 (0) a	315 (0) a
Slope (%)	30 (1.48) b	41 (5.93) ab	42 (4.45) a
Altitude (m a.s.l.)	2430 (13.34) a	2234 (16.31) c	2393 (48.93) b
Maximum root depth (MRD) (cm)	170 (14.83) a	100 (29.65) b	150 (44.48) a
Dominant root depth (DRD) (cm)	30 (0) a	50 (0) a	40 (14.83) a
Forest floor thickness (FFT) (cm)	3.6 (0.59) c	12 (5.29) a	7 (1.78) b
Stoniness (%)	18.38 (15.63) a	15.51 (9.74) a	28.76 (25.39) a
Bulk density (Mg m^{-3})	1.13 (0.1) b	1.33 (0.16) a	1.09 (0.17) b
Clay (%)	50.85 (5.13) a	19.45 (1.19) b	23.3 (7.41) b
Silt (%)	20.85 (3.11) c	45.35 (2.04) a	35.7 (10.23) b
Sand (%)	24.7 (1.85) b	35.65 (0.74) ab	39 (7.41) a
pH in water	5.41 (0) a	4.39 (0.36) b	4.64 (0.24) b
Base saturation (%)	68.48 (2.13) a	27.49 (12.85) b	33.95 (11.95) b
Short to medium term available nutrient stocks (Mg ha^{-1})			
N	0.41 (0.01) b	0.76 (0.25) a	0.51 (0.23) b
P	0.03 (0) b	0.07 (0.04) a	0.03 (0.01) b
K	0.93 (0.03) a	0.33 (0.21) ab	0.22 (0.05) b
Ca	2.48 (2.48) a	0.18 (0.03) b	0.14 (0.09) b
Mg	0.65 (0.76) a	0.04 (0.02) b	0.05 (0.02) b
Total Exchange nutrient stocks (Mg ha^{-1})	9.05 (4.53) a	3.46 (1.73) b	2.01 (0.85) c
Nutrient ratios			
N/P	4.61 (0.13) a	5.95 (0.35) a	4.01 (2.11) a
N/K	0.21 (0.11) a	0.1 (0.03) a	0.1 (0.07) a
N/Ca	2.02 (1.67) a	2.28 (2.94) a	6.81 (7.29) a
available/total stocks	1.17 (0.5) a	0.65 (0.25) a	0.34 (0.19) b
Ca/Mg	3.26 (0.47) ab	4.87 (2.33) a	2.25 (1.24) b
C/N	13.86 (1.11) b	23.18 (5.44) ab	22.45 (3.22) a
K *	0.08 (0.04) b	0.41 (0.16) a	0.34 (0.17) a

* Ratio of the short to medium term available K stocks concentrated in the organic layer with respect to the total depth (organic layer + the mineral (soil standardized to a depth of 60 cm)). Medians with median absolute deviations in parenthesis. Within each row, different letters indicate significant differences (α = 0.05; BH post-hoc comparison after Kruskal-Wallis test). nA = 3; nB = 7; nC = 13.

Table 7. Relationships between dominant height of trees (DH_{20}) and the short to medium term available nutrient stocks (organic layer and mineral soil down to 60 cm depth). Values correspond to the Spearman correlation coefficients (rho) and their associated *p*-values (VIP: Variable influence in Projection from the PLS-regression).

Nutrient Stocks	VIP	Spearman Correlation with DH_{20}	
		DH_{20} Cor	*p*-Value
Ca	0.04	0.58	0.004
K	0.08	0.52	0.012
Mg	0.04	0.30	0.159
N	0.07	0.22	0.317
P	0.00	0.28	0.195

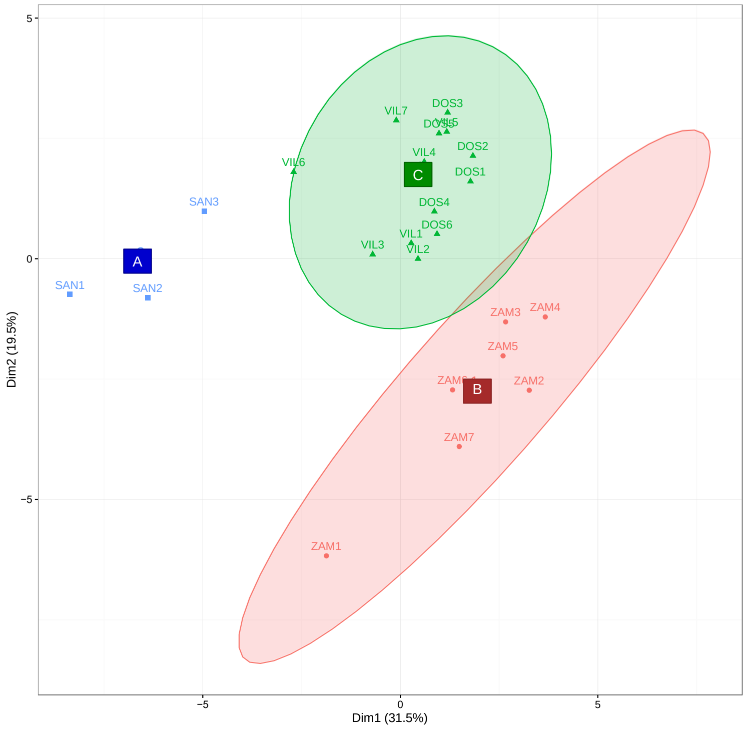

Figure 2. Site classification described by the three groups of forest productivity after the cluster analysis (factor map based in two dimensions of the clustering analysis explaining approximately the 43% of the total variability). Cluster analysis was based on analysis of soil, climate, and topographical variables. Cluster of the highest forest productivity = class A; cluster of medium forest productivity = class B; and cluster of the lowest forest productivity = class C.

Table 8. Definition of the forest site classes in the study area.

Forest Site Classes	Description
Class A: "High forest productivity" (dominant height of pine trees in 20 year old plantations approximately 22 m).	Sites with the highest soil fertility: short to medium term available nutrient stocks are highest with total exchangeable nutrient stocks of approximately 9 Mg ha^{-1}; particularly, Ca and K (2.5 and 0.9 Mg ha^{-1}, respectively). This is associated with two times higher clay contents (51%) and more than 10 fold lower concentration of H_3O^+. Stocks of short and medium term available macronutrients (N and P) are lower or similar to the other forest site classes. This together with the narrowest C:N ratio and the lowest forest floor thickness hints towards efficient nutrient cycling processes. In the study region this forest site class occurs in the highest altitude (around 2430 m a.s.l.) at slopes with the lowest steepness (30%).
Class B: "Middle forest productivity" (dominant height of pine trees in 20 year old plantations approximately 17 m).	Sites with middle soil fertility: the total exchangeable nutrient stocks are 2.6 times lower than in the forest site class of high productivity. The short to medium term available stocks of Ca and K show a notable decrease in comparison to the high forest site class (0.18 and 0.33 Mg ha^{-1}, respectively). In contrast, stocks of short and medium term available N and P as well as forest floor thickness are highest. The concentration of H_3O^+ is by tendency even higher than in the low forest productivity class. In the study region this site class is located at the lowest altitude in areas with slopes around 41%.
Class C: "Low forest productivity" (dominant height of pine trees in 20 year old plantations approximately 13 m).	Site with low soil fertility: the stocks of total available nutrients are approximately 4.5 times lower than in the forest site class of high productivity but 1.7 times lower than at sites of middle productivity. The short to medium term available stocks of Ca, K are the lowest (0.14 and 0.22 Mg ha^{-1}, respectively) whereas N and P stocks are slightly higher or similar to those in the high forest productivity class. The content of sand is highest in the soils with low forest productivity (39%). In the study region this site class occurs in areas with middle altitude and with the steepness similar to the sites of middle productivity (slope 42%).

3.3. Basic Protocol for Forest Site Classification in the South Andes

As an important result—in addition to the generation and analysis of forest site classes in the study area—is the presentation of a basic protocol for forest site classification for the Andes of the South of Ecuador. This protocol is synthesized in Figure 3, and can be used under the pointed conditions. In future forest management planning for the Andes, it can be adapted and refined.

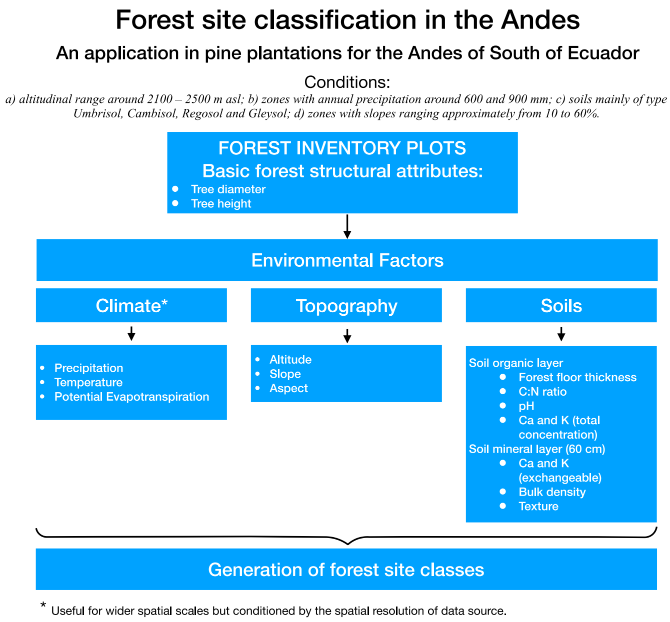

Figure 3. Synthesized protocol for forest site classification for pine plantations in the Andes of South of Ecuador.

4. Discussion

4.1. Effects of Climate and Topography on Forest Productivity

Several trends to serve in the classification of forest productivity in the investigated plantations were seen in the data set. Due to scale effects [77], because our study sites were between 8 and 32 km from each other, climate and topographical attributes were not stronger determinants [19,78–82] than soils for forest productivity. Additionally, the low number of study sites is a limitation of this work. However, the data present a useful collection of attributes for the construction of a protocol for forest site classification in the province of Loja.

At the sites with medium forest productivity, precipitation seems to be most important for determining the water status of the sites, probably related to the tendency of a slight increment of the evapotranspiration for this forest site class. In the forest class with the highest productivity, the deeply weathered soils with the highest maximum rooting depth and the highest clay content are most important regarding the amount of water available for plant growth. During drier periods—that usually happen from June to September in the study region [83]—the trees in the highest productivity class might also benefit from groundwater (since one of the soil profiles was classified as Gleysol). The lower degree of steepness in the forest class with the highest productivity will decrease surface runoff and increase water infiltration into the soils, thereby positively contributing to the water status. These results are in line with other studies where the slope has had an important role in site classification [29,78,84,85], and also slope has been recognized as an important variable, which has a direct effect on plant growth in the Andes of the south of Ecuador [86]. Future research should include a larger number of sites along a broader climatic gradient to address these issues systematically.

4.2. Effects of Soils on Forest Productivity

Soil was the main source for the generation of our site classification. The total stock of cation exchangeable nutrients (see Table 6)—directly related to the cation exchange capacity—has been the most influential soil property since it showed the highest positive correlation with the forest productivity (rho = 0.65; p-value < 0.001).

In order to assess the soil quality, it is necessary to know if the level of the short to medium term available nutrient stocks is low, medium, or high. However, for Ecuador (neither for the Andes), there is no information available regarding the assessment of the soil nutrient stocks for forest species. Therefore, soil nutrient stocks under pine were compared with those published by Wolff and Riek (1997) for forest soils of Germany with *Pinus sylvestris*. According to this information, the short to medium term available stocks of Ca, K, and Mg (considering the organic layer and the mineral soil layer—60 cm) range from very low to moderately high (Table 9).

Table 9. Short and medium term available nutrient stocks (organic soil layer + mineral soil standardized to a depth of 60 cm) rating for the forest site classes. Rating categories for pine plantations in Germany [50].

Rating	Wolff and Riek [50]			Forest Site Classes								
	Value Range (Mg ha^{-1})			A (DH$_{20}$ = 22.3 m)			B (DH$_{20}$ = 16.6 m)			C (DH$_{20}$ = 13.4 m)		
	K	Ca	Mg	K	Ca	Mg	K	Ca	Mg	K	Ca	Mg
Very low	<0.2	<0.2	<0.05					0.18	0.04		0.14	
Low	0.2–0.4	0.2–0.4	0.05–0.1				0.33			0.22		0.05
Moderate	0.4–0.6	0.4–0.8	0.1–0.2									
Medium	0.6–0.8	0.8–2.0	0.2–0.5									
Moderately high	0.8–1.2	2.0–4.0	0.5–1.0	0.93	2.48	0.65						
High	1.2–1.6	4.0–8.0	1.0–2.0									
Very high	≥1.6	≥8.0	≥2.0									

The highest and most significant correlation with the forest productivity was found for Ca and K in this study, leaving N and P in a second plane (Table 7), despite most forests across the globe showing N and P limitations [87]. Strong interactions between the Ca and K nutrition of trees are known. For example, a deficiency of Ca severely inhibited root growth in higher plants affecting the aboveground biomass [88] and the physiology of other cations, mainly K in pine trees [35]. In general, pine trees are adapted to the low nitrogen and phosphorous status, typically found in degraded soils. Due to the presence of an efficient mycorrhiza, the importance of N as a deficient nutrient is comparably low, which is supported by the local study of Breckle et al. [35] in *Pinus patula* plantations in Ecuador. Pine plantations established on abandoned agricultural fields showed increased levels of extractable nitrogen and phosphorus, due to the faster decomposition of organic matter by the newly established microflora and fauna [87]. The delivery of N and P to plants is highly dependent on soil microbial activity. In the present study, it is most likely that N and P cycling are fastest in forest class A with the highest pine productivity. The 2.6 to 4.5 times higher availability of Ca, together with a 10 times less acidic soil environment, might favor not only N fixation, but also the mineralization of soil organic matter and nitrification [89]. The faster turnover of pine litter in class A with the highest pine productivity is also indicated by the thinnest organic layer and the narrowest C:N ratio. Thus, the highest Ca availability improves the N availability in an indirect way via creating better living conditions for soil microorganisms [90]. In the forest site class B with medium pine productivity, the slowest organic matter decomposition, as indicated by the thickest organic layer, might be partly compensated for by the highest stocks of short to medium term available N. One explanation for the slow decomposition of organic matter in forest site class B might be the up-transport of Al from the mineral horizons to the organic layer via fungal hyphae [90]. According to the theory of Clarholm & Skyllberg [90], this is an important pH buffering process in soils with a pH below 4.5. Thereby the fungi keep the pH at a level sufficiently high for maintaining microbial activity. This is also the case when trees take up Ca for cell wall building. For a mycorrhiza fungi associated with loblolly pine, the capability to transport Al has been demonstrated [91]. In site class B, a significant increase in exchangeable Al stocks in the organic layer was detected (ZAM, Table S4) together with the lowest soil pH (Table S1). This increase in Al concentration might have changed the structure of soil organic matter by increasing the numbers of strong Al-bridges [90] and thereby slowing down organic matter decomposition [92].

4.3. Attributes Useful in a Future Protocol for Site Classification

In a future protocol for site classification in the southern Andean region of Ecuador, we can recommend a minimum data set as summarized in Figure 3. This minimum data set can be used under the following conditions: (a) altitudinal range around 2100–2500 m a.s.l.; (b) zones with annual precipitation around 600 and 900 mm; (c) soils mainly of type Umbrisol, Cambisol, Regosol, and Gleysol; (d) zones with slopes ranging from approximately 10% to 60%. These characteristics are associated with the bioclimatic formation of "Low Montane Dry Forest" in Ecuador according to Cañadas [93]. Beyond those conditions, especially above 2500 m a.s.l., the ecosystem changes [94], with Andisols as the dominant type of soil [95]. Andisols with pine plantations are highly distributed in the central and northern Andean region of Ecuador [96] and should be included [97] to generate a forest site classification for the Andes of Ecuador. Taking into account a stronger environmental gradient as in the present study, climate attributes have to be included, but the spatial resolution of climatic information—especially of precipitation—has to be considered due to the Ecuadorian Andes lack of a denser meteorological monitoring network [98]. The importance of precipitation for determining the water status was already obvious at our sites with medium forest productivity. However, in our study, the attributes slope and soil texture have been more useful. For example, the water status of sites with the highest productivity benefited from less steep slopes and a higher soil clay content. Future research should include further environmental parameters. Especially, data on soil microbial biomass and soil microbial activity will be helpful to describe nutrient fluxes in forest site classes and to assess the possible effects of forest management on nutrient cycling processes. However, the collection of such data is highly dependent on financial resources. Additionally, the effect of land use history in areas with pine plantations has to be considered; in the South of Ecuador, studies about soil fertility and nutrient cycling in a land-use sequence of forest-pasture-abandoned pasture provide evidence of pronounced changes on soil quality [99–101]. However, in our site classification, the nutrient stocks were important and not direct effects of the previous land use. The sites VIL and DOS have different former land uses but they belong to the same forest site class—Class C: low forest productivity.

4.4. Use of Forest Site Classification towards a Sustainable Silviculture in Ecuador

Site classification for the south of the Andean region of Ecuador has been developed as an example of ecological forest site classification in spite of the complexity of this landscape [102]. The findings of this work can be the start of an information tool for forest management planning and implementation of the conversion of pine forest into mixed forests with native tree species. Despite of the evidence of environmental damages caused by exotic plantations [5,10–13], there is also evidence that planted forests could offer several services if they are carefully managed. For example, with their adequate establishment, they can help to mitigate global warming by carbon sequestration in tree biomass, forest products, and soils. They serve as a source of amenity and recreation, alleviate deforestation, protect soil and water resources [3,103], improve the biodiversity by facilitation of the generation of native tree species at sites, and contribute to the dispersal and recovery of forest ecosystems by the establishment of those native species nuclei at the landscape scale [7,104]. One strategy for restoration and/or rehabilitation of the forest environments could be the establishment of mixed forests [105,106], with plantations of exotic tree species as an intermediate providing more suitable growth conditions for seedlings and saplings of native stands as compared to extreme conditions on abandoned pastures [107]. As an example of this approach, in the south of Ecuador, a project started to convert the presented pine plantations into mixed forests by thinning pine plantations and underplanting the native tree species *Cedrela montana* and *Tabebuia chrysantha*. Both species exhibit intensive mycorrhization after transplanting in the field [108] and are of a high timber value [109]. Further native species like *Alnus acuminata*, *Podocarpus oleifolius*, *Podocarpus sprucei*, *Lafoensio acuminata*, *Jacaranda mimosifolia*, *Cordia alliodora*, and *Triplaris cumingiana* also have a high potential in the south of Ecuador [109]. However, the effects of pine plantations on the success of the establishment of native tree species will vary with site conditions and the establishment of a forest site classification can help to develop site-specific measures to improve the effectiveness of forest conversion [109–111]. At sites with properties characteristic of the identified class C with the lowest pine productivity, thinning with the subsequent removal of pine trees will cause strong losses of nutrients, especially K and Ca. According to Berthrong et al. [112], pine plantations are responsible for losses of Ca and K from the soil by pine tree uptake and subsequent timber removal. Afforestation of abandoned land with pine plantations has decreased the stocks of soil exchangeable K. Thus, the uptake of Ca and K by pines seems to be very important for the whole soil nutrient status in the context of low nutrient stocks (as discussed in Section 4.2), as well as in the study area in the South of Ecuador. The removal of whole pine trees will further deplete the already low soil nutrient pool in the short-term and could endanger the success of the establishment of the planted native tree species and their use for forestry. Needles and thin branches that contain more K than the stem should be left in the field. Fertilization mainly based on K together with the addition of crushed, slow release limestone (as source of Ca and Mg) to increase soil pH by 1 unit will improve the establishment of native tree species. However, for liming, it is necessary to develop further research to determine the appropriate doses of lime and possible interactions between K and Ca [87]. Liming together with improved litter quality will enhance nutrient cycling in the medium term, resulting in higher forest productivity at former low productivity sites. After successful forest conversion, it can be expected that native forests sustain a higher soil nutrient concentration than pine plantations in the long-term (especially P, K, Ca, and Mg) [113] due to the faster turnover of detritus and a generally less intensive biomass use as associated with the management of those species. The data of the present study can be used as baseline values to assess the impacts of thinning and underplanting of native tree species on nutrient cycling processes. Furthermore, with our data on SOC stocks, a baseline exists for the assessment of changes in the carbon stocks under different scenarios of forest productivity, a topic very important for the payment of ecosystem services. Altogether, this could be a good start towards improved forest management in the southern Andean region of Ecuador.

5. Conclusions

The dominant height of pine trees (taken as a reliable measure for pine productivity) was highly dependent on stocks of exchangeable Ca and K (stored in the organic layer and the first 60 cm of mineral soil). Therefore, measuring stocks of N and P, which is common in many studies, did not improve forest site classification under the present soil acidic conditions. We assume that the fluxes of these macronutrients are most likely controlled by Ca and K availability and stocks and subsequent changes in the structure of soil organic matter and of the soil microbial community. However, the biogeochemical mechanisms behind this control, as well as the pathway of Ca and K functioning (nutritional vs. soil chemical), should be investigated in more detail. Further studies are needed to assess the possible effects of forest management practices on nutrient cycling processes and to implement dynamic indicators in forest site classification, as a supplement to state variables. One example is the investigation of the relationships between soil microbial biomass and activity, as proximate agents of the turnover process, and the fluxes and turnover of nutrients with litterfall in stands with exotic and native forest species.

The establishment of forest site classification represents the fundamental need to develop site-specific measures to improve the effectiveness of forest conversion to mixed stands with native tree species or to maintain pine plantations at sites with a high production potential. Thus, the site classification system is a valuable tool not only for ecological, but also for economic decisions.

Investments are more effective in stands of site class A than in site class B or C. Therefore, the site class systems help to decide where the money should be spent to generate the highest effects (forest conversion and/or biomass production). There is a high probability that other species also react to the site conditions in a similar way to the pine trees. Further studies can focus on relating the presented classification system to other native tree species by measuring their dominant height.

The presented data can contribute to an information tool for forest management planning. This, in turn, can help to implement sustainable silviculture in the region and serve as a positive example for other regions.

Supplementary Materials: The following are available online at www.mdpi.com/1999-4907/8/12/473/s1, Figure S1: Schematic distribution of soil profiles according to study sites (DOS: Dos Puentes, SAN: Santiago, VIL: Villonaco, ZAM: Zamora-Huayco). The y-axis represents the soil depth. Reference Soil Groups for study sites in parenthesis, Table S1: Soil acidity (pH_{H2O}) and base saturation (BS%) per site and horizon for the pine plantation (*Pinus patula*) sites (DOS: Dos Puentes, SAN: Santiago, VIL: Villonaco, ZAM: Zamora-Huayco) included in this study. Values represent mean with standard error in parenthesis for the organic layer (O horizon) and for the mineral soil horizons A-B-C (mineral topsoil: 0–60 cm). Different letters indicate significant differences between sites per soil horizon (Benjamini and Hochberg pairwise procedure (HB) after Kruskal-Wallis test, $p < 0.05$). nDOS = 6; nSAN = 3; nVIL = 7; nZAM = 7. Table S2: Soil hydrophysical attributes between the study sites (DOS: Dos Puentes, SAN: Santiago, VIL: Villonaco, ZAM: Zamora-Huayco) included in this study according to organic (horizons Oi + Oe/Oa) and mineral (A-B-C horizons) layers, Table S3: SOC and soil total nutrient stocks in the mineral soil standardized to a depth of 60 cm (horizons A-B-C) for the study sites (DOS: Dos Puentes, SAN: Santiago, VIL: Villonaco, ZAM: Zamora-Huayco), Table S4: Plant available nutrient stocks (exchangeable cations: NO_3^--N, NH_4^+-N, Bray—PO_4-P, K, Na, K, Ca, Mg, Al, Fe, Mn) in the organic layer (horizons Oi + Oe/Oa) according to study sites (DOS: Dos Puentes, SAN: Santiago, VIL: Villonaco, ZAM: Zamora-Huayco), Table S5: Factors of Variable Importance in the Projection (VIP) after the Partial Least Regression Analysis (variables selected after classification and regression trees). Additionally, relationships between dominant height of trees in 20 year old plantations (DH_{20}) and environmental variables according to Spearman correlation coefficients and their level of significance (*p*-value).

Acknowledgments: First, we would like to thank three anonymous reviewers for their valuable comments. This research was performed within the framework of the DFG project "New Forests for Ecuador" (Project DFG RU 816/2-T1, HA 4597/4-1). Partial funding was given by the UTPL (Universidad Técnica Particular de Loja) and SENESCYT (Secretaría de Educación Superior, Ciencia, Tecnología e Innovación del Ecuador). We are grateful to Peter Schad, who provided assistance in the soil classification. We would like to thank to Milton Ortega for his field assistance. We thank Manuela Unger, Thomas Klinger, Cristhian Vásquez, María Imaicela, Yelitza Carrión, and Jefferson González for their help in the laboratory. Costs to publish were supported by SENESCYT.

Author Contributions: U.H. and P.Q. conceived and designed the research; P.Q., D.V., and L.J. conducted the field-work; U.H., A.T., and P.Q. performed the laboratory work. P.Q. and U.H. analyzed the data; P.Q., L.J., A.T., S.G., R.M., and U.H. wrote the paper.

Conflicts of Interest: The authors declare that they have no conflict of interest.

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