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Impact of Pine Plantations on Soils and Vegetation in the Ecuadorian High Andes

A comparative study on the impact of pine plantations on soil and vegetation development was conducted in the Ecuadorian Andes (3000–4000 m). Pine plantations of different ages under different types of management were compared with extensively grazed páramo *grassland (the most common former land use) and natural forest (the formerly dominant vegetation in much of the life zone). No general impact of plantations was found, although some tendencies were identified that show that soils under pine plantations are drier and less organic. Moreover, the vegetation under pine plantations was similar to* páramo *grassland, though some examples of regeneration of Andean woody species were observed, as well as examples of plantations where understory was completely lacking. We concluded that the impact of pine plantations cannot be generalized but should be evaluated case by case while care is taken in implementing plantations until more knowledge is obtained about the effects on the ecosystem as a whole, especially considering their ecological importance.*

Keywords: *Pine plantations;* páramo*; vegetation; natural ecosystems; Andes; Ecuador.*

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Introduction

In the high Andean zone of Ecuador the vegetation of short and stunted Andean forests and *páramo* grasslands, which was widely dominant before establishment of human populations at high altitudes, has disappeared and many areas suffer from large-scale erosion (de Noni et al 1986; CESA 1992; Harden 1996). This is probably because of the great pressure exerted on the land by rural indigenous communities, most of which have limited resources (Hess 1990; Morris 1997). Considering the high economic and ecological value of the Andes, sustainable management of highland ecosystems is of vital importance (Ellis-Jones 1999). With this in mind several forestry programs were initiated with the aim of providing the inhabitants with timber and fuel and to protect and restore ecological values (Morris 1985, 1997).

Forestry activities in the Ecuadorian Andes are frequently concentrated at high altitudes (3000–4000 m), where there is less competition with agricultural land use (Morris 1985; Brandbyge 1992). At present, the land is mostly used for small-scale agriculture and extensive grazing on *páramo* grassland. The latter is a type of open grassland vegetation consisting of large tussock grass, low shrubs, and herbs and is the dominant vegetation type above the original upper forest line (ca 3600–4000 m), but it tends to invade lower areas when the forest is destroyed (Laegaard 1992; Hofstede et al 1998). Site conditions at this altitude are marked by relatively high net precipitation (500–3000 mm/y), low temperatures (2–10°C mean annual temperature), frequent occurrence of fog, and soils developed in recent volcanic ashes (Andisols; see Colmet-Daage 1980; Espinosa 1991; Luteyn 1999). In these soils, decomposition of organic matter (OM) is slow because of the low temperatures, high humidity, low pH, and specific properties of Andisols (formation of strong organomineral complexes). These soils have a high water retention capacity, a strong capacity to fix phosphorus (P), and a high organic matter (OM) content as a result of slow decomposition, whereas bulk density, pH, and P availability are generally very low (Wada 1985; Hofstede 1995; Poulenard 2000).

In tree plantations in the Ecuadorian Andes, mostly exotic tree species (*Eucalyptus* spp, *Pinus* spp) are used because they grow rapidly and because forestry experience with native tree species is limited (Brandbyge and Holm-Nielsen 1986; Hofstede et al 1998). Moreover, pine-based forestry programs are still promoted, using arguments such as the future demand for timber, the social acceptance of exotic species, and the possible ecological benefits of forest plantations in general. One of the main justifications for forestry programs in the Andean countries is to conserve soils and to regulate the hydrology (Galloway 1986; Evans 1992). However, in many (mountain) regions of the world, exotic tree plantations are subject to serious criticism because of their negative impact on water balance, soil fertility, and native biodiversity (Lundgren 1978; Bosch and Hewlett 1982; Evans 1992; Fahey and Jackson 1997).

No comprehensive study has been done on the environmental impact of tree plantations in the fragile ecosystems of the northern Andes, where they are planted at higher altitudes than elsewhere. Nevertheless, various authors have expressed concern, based on field observations, evidence from elsewhere, and logical reasoning (Cavelier 1994; Luteyn 1999; Sarmiento 2000). Exotic tree plantations may trigger negative impacts that are even more dramatic in the high Andes than elsewhere because of the special characteristics of young volcanic soils at high altitudes. Pine trees absorb high amounts of water, leading to drier soils under plantations. This implies an irreversible process of disintegration of the organomineral complexes, by which organic material becomes available for decomposition

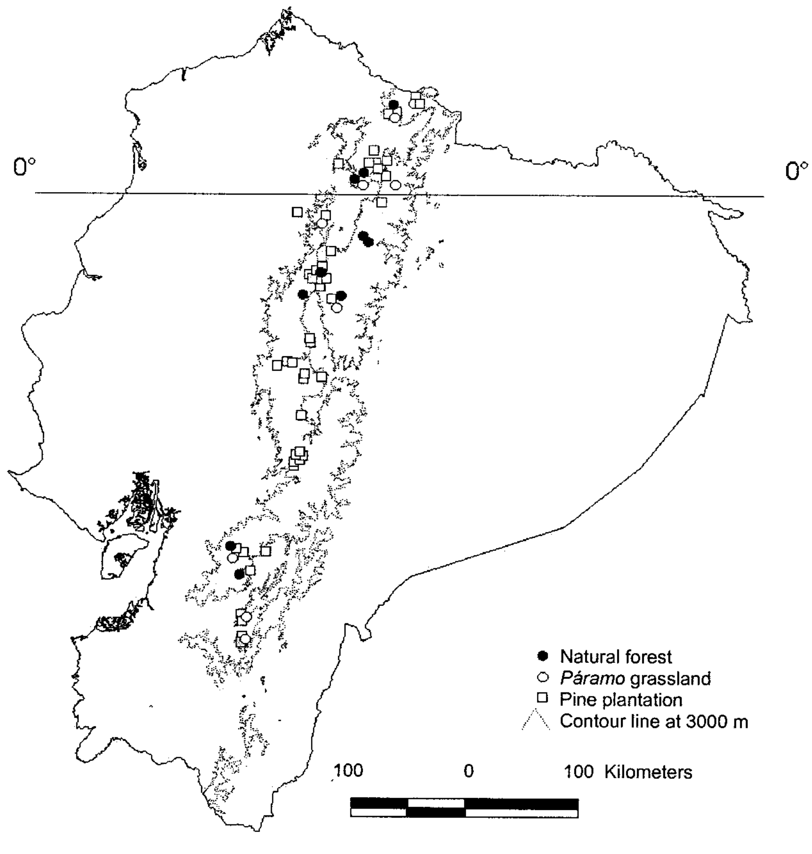

FIGURE 1 Map of Ecuador showing the location of the study sites. (Map by Pool Segarra)

(Wada 1985; Van Reeuwijk 1989). As a result, OM content will probably decline, because higher OM input will not compensate higher rates of decomposition, for pine litter only breaks down with difficulty. Therefore, under pine plantations in the high Andes, the characteristic properties of Andisols might change, resulting in the expected lower moisture content as well as higher P availability and bulk density of the soils (Cortés et al 1990). Disturbance of the hydrological properties of the soils is of particular concern because high-altitude ecosystems are of strategic importance for the regulation of the hydrological system of the productive and densely populated inter-Andean valleys.

Moreover, because of the change in soil conditions and the closed, uniform pine tree canopy, the vegetation in the undergrowth is likely to be dramatically altered, with a particular effect on typical *páramo* elements (Balslev and de Vries 1991). However, justification for tree plantation in the high Andes includes the reasoning that the plantation alters microclimatic conditions, favoring the regeneration of forest elements (Brandbyge 1992).

The aim of this study is to provide decision makers with a broad set of field data, originating from the complete range of pine plantations in the Ecuadorian Andes, which might support the theory about the negative impact of exotic tree plantations on high Andean natural ecosystems. From December 1996 to May 1997, we studied the soils and vegetation of a broad series of pine plantations in the high Andes, focusing on different age categories, forest management types, regions (general physiographical setting), elevations, and previous land use types. We compared them with (mostly extensively grazed) *páramo* grassland—the most frequent former land use—and with (remnants of) the natural Andean forest—the dominant vegetation type in the life zone studied before the establishment of human populations (Holdridge 1967; Laegaard 1992).

Methods

Forty-seven existing pine plantations (*Pinus radiata* and *P. patula*) were selected in the Ecuadorian Andes (Figure 1). The plantations were between 5 and 30 years old, distributed throughout the country (with the exception of the extreme south, where soils are not formed in volcanic ash) at altitudes between 3000 and 4000 m. Plantation management varied considerably, from no management to quite intensive management with repeated thinning and pruning. Three plantations were clear-cut 1–2 years before the study. Most plantations were planted over extensively grazed *páramo* grassland, but several other former land use types were included as well. Grazing was practiced on several plantations. Sites were selected on the basis of a plantation inventory by the Ecuadorian forest service (INEFAN) and with assistance in the field from INEFAN personnel and other local organizations.

TABLE 1 Arbitrary quantitative scale for texture, structure, and previous land use, for use in multivariate data analysis.

Class	Texture (scale 1–11)	Structure (scale 1–6)	Previous land use (scale 1–7)
1	Gravelly sand	Structureless	Eroded field or grassland
2	Sand	Weak subangular blocky	Agricultural field
3	Fine sand	Subangular blocky	Pasture
4	Loamy sand	Strong subangular blocky	Grazed tussock grassland
5	Sandy loam	Crumb	Tussock grassland
6	Sandy clay loam	Granular	Shrubland
7	Loam		Forest
8	Silty loam		
9	Clay loam		
10	Silty clay loam		
11	Clay		

Twelve extensively grazed *páramo* grassland sites adjacent to the plantations studied and 12 natural forest sites situated nearby were included as well. The composition of the *páramo* grassland sites was typical for slightly grazed tussock grassland: an almost complete, up to 1 m tall, tussock cover, some scattered shrubs, giant rosettes, and many small herbs, mostly typical *páramo* elements and a few indicators of grazing. The composition of the natural forests investigated was typical for the Andean treeline forest; they consisted of a thicket of gnarled, multistemmed trees between 6 and 12 m tall. The dominant genus is *Polylepis,* which can form almost monospecific stands but also grows in mixed stands. More detailed descriptions of these types of vegetation are given by Hofstede et al (1998) and Luteyn (1999).

Generally, 2 sampling units (SUs) were randomly selected within each plantation. If the plantation was very small or uniform, then only 1 SU was selected. We selected a total of 76 SUs in the 47 plantations. On *páramo* grassland and natural sites, only 1 SU was selected. The *páramo* grassland sites were always next to a series of studied plantations, to allow for proper comparison. The SUs were 10 × 20 m in size, parallel to the contour lines of the slope. General terrain characteristics were described for each SU. Estimates were made of the percentage cover of each vascular plant species, as well as the total cover and height of the vegetation strata and the percentage cover of the litter layer and bare soil. We studied soil temperature, structure and texture, thickness of the organic profile (litter, ferments and humus: LFH), and depth of the upper mineral soil horizon (A horizon) directly in the field.

Volumetric topsoil samples (0–10 cm) were taken in duplicate, each consisting of a bulked sample of 5 subsamples taken systematically over the SU. One additional volumetric soil sample, consisting of 3 subsamples, was taken at a depth of 30 cm. Analyses carried out showed a particular correlation with Andisol properties that may be affected by pine plantations. These include wet and dry bulk density, actual moisture content, available water content (defined as the difference in water retention capacity at field capacity and permanent wilting point), pH, OM content, total N content, available P, available potassium (K), and P-fixation capacity. The soil samples were not dried before analysis. Care was taken not to obtain topsoil samples during or immediately after rain events or during very dry periods, to avoid the influence of rainfall or dryness on actual moisture content. The comparability of the samples for actual moisture content was confirmed by a strong correlation between this value and water retention capacity at field capacity, as determined in the laboratory under standard conditions ($R^2 = 0.86$).

In order to detect the general trends in the complete data set, multivariate statistical analysis was applied to vegetation and soil data for all SUs (including *páramo* grassland and natural forests). Two-way indicator species analysis (TWINSPAN; Hill 1979) was used for the general grouping of the SUs based on soil characteristics. After this, a redundancy analysis (RDA, within the CANOCO computer package; Ter Braak 1991) was carried out to detect the environmental factors that determine the differences in soil composition. For this ordination analysis, several qualitative variables (management, grazing) were entered as dummy variables with values of 1 or 0. Other variables that could be considered as ordinal (soil texture, soil structure, and former land use) were arranged on a quantitative scale (Table 1). The location of the SUs entered the analysis as latitudes (UTM coordinates), in conformity with the north–south orientation of the Ecuadorian Andes. Afterwards, the observed trends were tested with direct

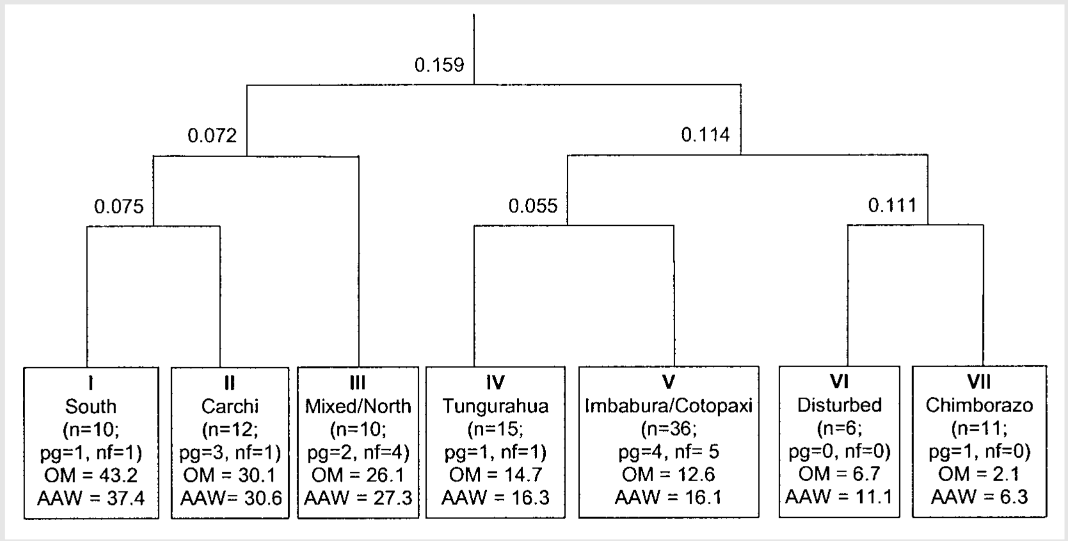

FIGURE 2 Groups of soil samples as identified by TWINSPAN analysis. Groups are named after the region where most of the samples were taken, except for group III (samples from 3 northern provinces) and group VI (samples from Imbabura and Cotopaxi with strong disturbance). The total number of samples per group (*n*) is presented in parentheses, as is the number of samples from the natural vegetation in the sampling units (pg, *páramo* grassland; nf, natural forest). To indicate the trends in environmental variables among groups, the average OM content (% dry weight) and the average available water content (AAW; in % dry weight) are presented. The numbers in the dendrogram represent the eigenvalue of the separations (range = 0–1).

statistical analysis of subsets of SUs and variables. TWINSPAN was applied to the vegetation data (percentage cover of all individual species and cover of litter and bare soil) to identify general vegetation types and to determine whether these differ between plantations and natural ecosystems. Trends identified by multivariate analysis were subsequently tested by correlation analysis and *t*-tests.

Results

The TWINSPAN analysis of the soil characteristics at all sites clearly identified different groups of samples, which, after visual analysis, could be attributed to different regions. This analysis did not differentiate between different types of land use, indicating that the difference between soils under pine plantation and natural vegetation (*páramo* grassland or Andean forest) was less than the general difference between soils from different regions (Figure 2). OM content and available water were the characteristics that determined most of the separations. TWINSPAN grouped the soil samples from left to right, arranged in a decreasing range of OM content and available water content.

The greatest difference in soil characteristics was found between the samples from groups VI and VII on one side and the rest of the groups on the other side. Group VII, containing samples from Chimborazo Province, had a very low OM content, a coarse texture, and little soil humidity and available water. Samples in group VI, which represented different regions, were all subjected to strong disturbance: 3 were taken at sites where a plantation was recently cut, 2 in very recent volcanic ashes, and 1 in a very intensively grazed pine plantation.

The RDA ordination analysis indicated that the soil characteristics differed between pine plantations, *páramo* grassland, and natural forest. In the resulting biplot the dummy environmental variables indicating the 3 land uses were put in 3 opposite quadrants (Figure 3), which means that the soils under plantations have compositions different from those under natural vegetation (*páramo* grassland and natural forest). The variables humidity, OM content, available water, and structure are arranged in the direction of the natural vegetation types (*páramo* grassland and, to a lesser extent, natural forest), which indicates that high values for these variables are associated with natural vegetation and low values with pine plantations. The variables pH and bulk density go in the opposite direction and are therefore likely to reach high values under pine plantations.

The arrangement of the TWINSPAN soil groups in the biplot confirms the importance of OM content for the grouping. Groups I and II are positioned on the right side of the diagram, around the position of OM content, whereas the OM-poor soils of groups VI and VII are on the left side. Several other variables are related to the second axis in the diagram (natural forest, latitude, nitrogen [N] and K content, and soil depth). However, the eigenvalue of this axis (0.047) is much lower than that of the first axis (0.206), which means that factors and variables related to the second axis are less important in explaining the variance between samples than present land use, texture, water, and OM content.

The trends identified by the ordination analysis were tested by correlation analysis. The trend observed in the influence of land use on soil characteristics was only statistically significant for a few characteristics (Table 2). Pine plantations had a significantly thicker

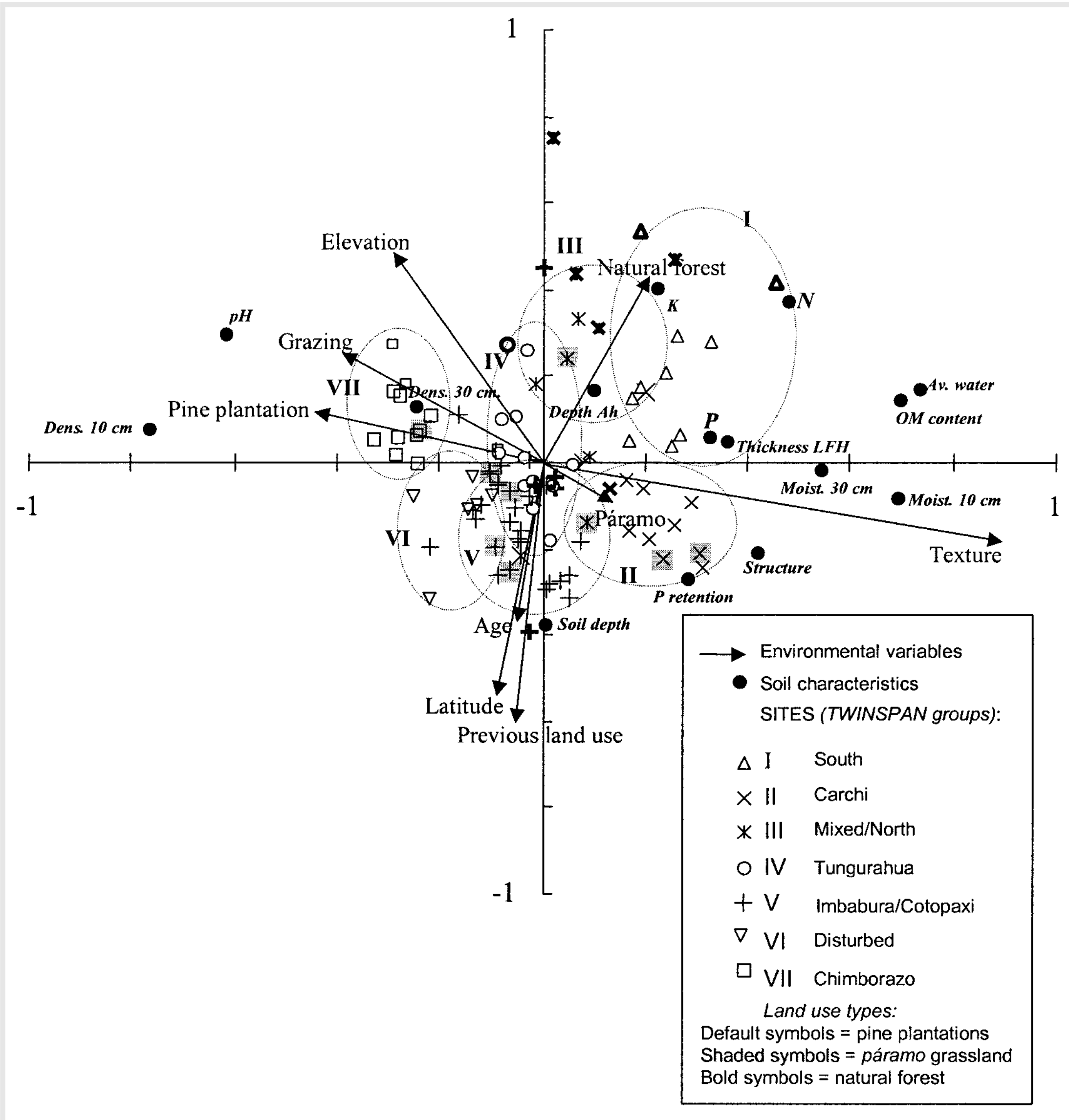

FIGURE 3 Distribution of environmental variables (arrows), soil characteristics (solid dots), and sampling units (symbols) over the first 2 axes of a biplot as a result of an RDA with CANOCO. Only the data with a significant relation ($P < 0.05$) to the axis are presented. The groups of sampling units (SUs) separated by TWINSPAN (Figure 1) are indicated by different symbols, and their distribution is indicated by circles. The eigenvalue of axis 1 = 0.206, of axis 2 = 0.047. Bold symbols represent SUs from natural forests, and shaded symbols are SUs from *páramo* grassland.

Soil characteristics[a]	Plantation	*Páramo*	Forest
Thickness organic profile (LFH, cm)[b]	4.76 A	1.46 B	7.59 C
OM content (%)	16.9 A	20.8 AB	24.9 B
Total N (%)	0.32 A	0.35 AB	0.47 B
Available P (mg/kg)	6.88 A	9.22 AB	11.8 B
Available K (mg/kg)	56.6 A	65.8 A	118.6 B
Available water (% dry weight)	18.2 A	22.9 B	31.0 B
Bulk density (0–10 cm, kg/m^3)	770 A	692 AB	568 B
Apparent humidity (10 cm, % dry weight)	54.5 A	80.2 B	85.9 B

[a]OM, organic matter.
[b]LFH, litter, ferments and humus.

TABLE 2 Average values of soil characteristics under pine plantations ($n = 71$), *páramo* grassland ($n = 12$), and natural forest ($n = 12$). Only characteristics that varied significantly among the land use types are presented (*t*-test, $P < 0.05$). Means sharing a letter were not separated statistically; in other words, if indicated by different letters (A, B, etc), they were significantly different.

TABLE 3 Average values of soil characteristics under grazed (n = 16) and ungrazed (n = 55) plantation sampling units. Only characteristics that varied significantly among the land use types are presented (t-test, P < 0.05). For the values of the classes for texture and structure, see Table 1.

Soil characteristics[a]	No grazing	Grazing
Thickness organic profile (LFH, cm)[b]	5.51	2.07
Texture (class)	5.79	3.75
Structure (class)	3.82	2.5
pH-H_20	4.94	5.67
OM content (%)	18.7	10.9
Total N (%)	0.35	0.21
Available K (mg/kg)	52.1	71.9
P retention (g/kg)	5.81	3.33
Available water (% dry weight)	19.8	12.4
Density (10 cm, kg/m^3)	695	1031
Humidity (0–10 cm, % dry weight)	61.6	30
Density (30 cm, kg/m^3)	792	1007

[a]OM, organic matter.
[b]LFH, litter, ferments and humus

litter layer and drier soils than did *páramo* grassland. Natural forest had more litter, OM content, and N, P, K, and moisture content and less soil density than did pine plantations. More significant differences existed between grazed and ungrazed pine plantations (Table 3). Plantations where cattle grazed the understory had a significantly thinner organic profile (LFH horizon) and lower OM content, total N, P retention, available water, and moisture content of the topsoil than did ungrazed plantations. pH and bulk density were higher with grazing (t-test, $P < 0.05$). No significant relationship existed between any of the soil variables and the age of the plantation or the presence of plantation management.

The TWINSPAN analysis of the vegetation of all the sites studied clearly separated most of the natural forests and the pine plantations with a woody understory (groups A and B) from the rest of the plantations and the *páramo* grassland vegetation (groups C–F; Figure 4). In a separation at a lower level, a group consisting of almost only natural forest samples (group A) was separated from samples taken in plantations with a woody understory (group B).

All the other vegetation groups identified contained samples with herbaceous ground cover. One group contained all the sites on the plantations and adjacent dry *páramo* grassland in Chimborazo province (F). The other groups (C–E) represented *páramo* grassland mixed with pine plantations with a tussock grassland understory. Characteristic species of these groups are typical *páramo* representatives. TWINSPAN did not clearly separate the *páramo* grassland sites from the pine plantations. This indicates that, in general, the vegetation in most pine plantations is not very distinct from extensively grazed *páramo* grassland and that the pine trees had not (yet) strongly affected the understory vegetation in many plantations. At the fourth level of separation the plantations with grazing (group C, including 1 grazed natural forest) were separated from the other sites with a herbaceous understory by the presence of pasture species.

In most plantation SUs (61 out of 76) no understory of woody plants was found. A lower canopy of regenerating native trees existed in 25 SUs in plantations. There was a significant positive relation between the age of the

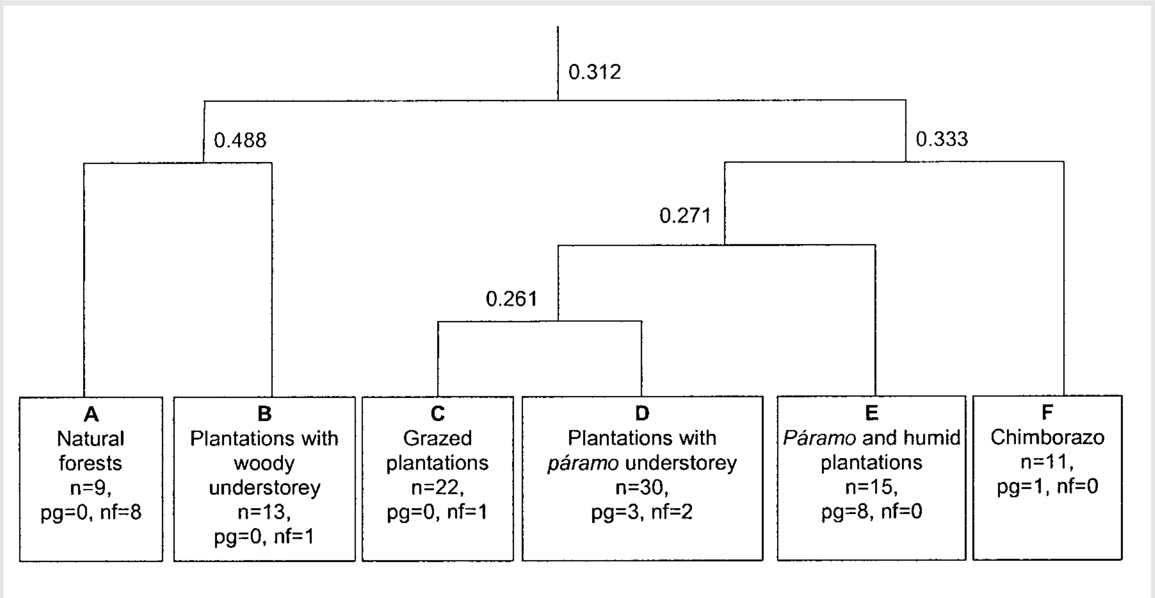

FIGURE 4 Groups of vegetation samples as identified by TWINSPAN analysis. Groups are named after the characteristics of land cover (except for group F, which included most of the samples taken from Chimborazo Province). The eigenvalue (range = 0–1) of the separations is presented, as well as the number of samples per group (n) and the number of samples from the natural vegetation in the sampling units (pg, *páramo* grassland; nf, natural forest).

plantation and the height of this lower canopy ($R^2 = 0.33$; F-test, $P < 0.01$). A weak but significant negative correlation between pine canopy cover and lower canopy cover was found ($r = -0.27$; F-test, $P < 0.01$), which points to a better development of the understory under a more open pine canopy. There was no relation between these factors and the management (thinning, pruning, or both) of the plantations. In the plantation SUs an average of 1.7 ± 0.23 (SE) tree species other than *Pinus* were found (including seedlings). On extensively grazed *páramo* grassland this amount was 1.3 ± 0.35 species and in natural forest 4.2 ± 0.44 species.

Discussion and conclusions

In a comparative study of the impact of pine plantations such as the present one, it is essential that the systems compared be clearly defined. We chose to compare pine plantations of different age with extensively grazed *páramo* grassland, which was the most common land use type prior to plantation establishment. We also included some natural forest SUs to compare the pine plantations with the dominant vegetation type at the altitudes studied before the establishment of human populations at these altitudes. Hence, we compared an artificial ecosystem (pine plantation) with 2 (semi) natural vegetation types. The effects of pine plantations on the environment would probably be found to be different if compared with other artificial ecosystems such as arable fields or pastures (Duncan 1995; León et al 1998).

The results of this study show that several soil types can be distinguished in the Ecuadorian high Andes, each with a characteristic set of properties. Soils formed in recent volcanic material have high actual moisture content and available water content, low bulk density, high OM content, N content, and P retention capacity, and fine textures. These soils have favorable hydrological properties and were found largely in natural ecosystems, particularly in the north of the country. Soils with less favorable properties (lower actual moisture content and available water content, lower bulk density, less OM and N content, lower P retention capacity, and a coarse texture) occurred especially in the drier parts of the central Ecuadorian Andes. They are connected with very recent and coarser ashes, lower precipitation, and (previous) inappropriate land use.

The present study clearly shows that the effect of *Pinus* plantations on the ecosystems of the high Andean zone of Ecuador cannot be generalized. These effects vary depending on the region (soils and climate), previous land use, and present management of the plantation. Nevertheless, a few general tendencies can be identified. Ordination analysis of the soil characteristics showed a trend of lower values for the complex of interrelated factors (moisture content, available water, OM content, P retention, and texture) in pine plantations as compared with natural ecosystems. Although this trend could only be partly confirmed by direct statistical analysis, it is clear that plantations almost never have a positive effect on soils and vegetation. Yet direct signs of soil degradation under pine plantations were not observed either. One specific phenomenon was found to be statistically significant: in pine plantations, soil moisture content and available water content were lower than in *páramo* grasslands. Lower soil moisture content might be explained by the higher levels of water use by rapidly growing exotic trees (Duncan 1995; Fahey and Jackson 1997).

Given the strong relation between soil moisture and OM content in high-altitude volcanic soils, it might be expected that plantations have less soil organic material in addition to lower moisture content. This was in fact observed as a tendency in the ordination analysis. However, although the average OM content in all pine plantations was lower than in natural ecosystems, the difference was not significant when tested by direct statistical analysis.

A small set of heavily disturbed plantations, including all harvested sites that were included in this study, had poor soil conditions similar to those in Chimborazo province. Although 3 postharvest sites is too small a number from which to draw well-founded conclusions, the results point to a dramatic impact of pine harvesting on the soils. This impact can be tempered by silvicultural techniques such as avoidance of heavy machinery or selective harvesting (Evans 1992; Waterloo 1994; Gayoso 1996). Unfortunately, these techniques are not commonly practiced in Ecuador.

The impacts of pine plantations on vegetation are somewhat easier to assess. We considered regenerated woody species and a high degree of total species richness in the plantation to be positive signs. The majority of the plantations had an understory that resembled *páramo* grassland with respect to species composition and woody species occurrence. Thus it might be concluded that the plantations so far have had no positive impact on the restoration of Andean forest elements. However, there were some examples of plantations with more abundant woody Andean forest elements. The latter group of plantations showed even greater species richness than did the adjacent *páramo* grassland. On the other hand, the soil on several plantations was almost completely covered by a thick layer of pine litter without undergrowth. Hence, it can be concluded that in some cases the effect of plantations is positive (woody understory), in other cases negative (no understory), but in most cases neutral (*páramo* grassland understory).

It was difficult to analyze conditions under which pine plantations had a positive impact on vegetation.

Although a relation was observed between the openness of the tree canopy and the structure of the understory, this could not be related statistically to age or management. Probably, the openness of the pine canopy was more closely related to phytosanitary problems than to management. Moreover, where plantations were managed, management was mostly ill planned and executed. It was also observed that where good regeneration occurs, the plantation was situated on grassland where some woody species were already present.

In general, grazing has a great impact on both vegetation and soils. In most cases the difference between grazed and ungrazed plantations is greater than the difference between ungrazed plantations and natural ecosystems. As a result of trampling, soils are denser, drier, less organic, and less acid. Grazing and trampling prevent the regeneration of woody species, and the understorey is transformed from tussock grassland into short, pasture-like grassland. This short vegetation provides less soil protection, and soils become drier and less organic (Hofstede 1995).

The effects of pine plantations and, hence, the arguments for or against planting exotic trees in the Ecuadorian Andes depend on physiographic and demographic factors. Morris (1997) suggests that a detailed evaluation of areas available for forestry activities is needed. Based on ecological and economic feasibility studies, areas should be identified where pine plantations are acceptable because of a great demand for firewood and other possible uses and where there is little ecological impact from such plantations when properly managed. On the other hand, other areas should be reserved for regeneration and protection of original vegetation and soil in order to conserve the hydrological properties of the Andes. The present study shows that in the latter areas, where mostly intact, highly organic soils occur, the establishment of pine plantations includes a risk of decreasing soil humidity, OM content, and plant diversity. Therefore, the establishment of plantations should be avoided until more knowledge is obtained about the effects on the ecosystem as a whole.

Forestry plans should be evaluated case by case, taking into account not only the site quality for the production of exotic trees but also the possible effects on ecosystems as well as the socioeconomic condition of the region. In all cases pine plantations do not seem to have an ecological justification but should be considered as a relatively low-impact agricultural crop. In a more detailed zonification, limited areas could be designed for wood production, considering the demand and the local market, and other, more natural areas could be protected to ensure the hydrological function of this ecosystem. In the long term, the hydrological value of the ecosystem might be economically more important than the profits from wood. Another recommendation is the development of integrated forestry techniques, including native tree species, which probably reduce possible negative impacts on the Andean ecosystems (Brandbyge and Holm-Nielsen 1986; Brandbyge 1992) and may form a sustainable alternative to massive plantations with exotics in the future.

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REFERENCES

Balslev H, de Vries T. 1991. Life forms and species richness in a bunch grass *páramo* on Mount Cotopaxi, Ecuador. *In:* Erdelen W, Ishwaran N, Muller P, editors. *Tropical Ecosystems: Systems Characteristics, Utilization Patterns, and Conservation Issues. Proceedings of the International and Interdisciplinary Symposium.* Saarbrücken, Germany: Verlag Josef Margraf, pp 45–58.

Bosch JM, Hewlett JD. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology* 55:3–23.

Brandbyge J. 1992. Planting of local woody species in the *páramo*. *In:* Balslev H, Luteyn JL, editors. *Páramo. An Andean Ecosystem Under Human Influence.* London: Academic Press, pp 265–274.

Brandbyge J, Holm-Nielsen LB. 1986. *Reforestation of the High Andes With Local Species.* Reports From the Botanical Institute. Aarhus, Denmark: University of Aarhus.
Cavelier J. 1994. Reforestation with the native tree *Alnus acuminata*: Effects on phytodiversity and species richness in an upper montane rain forest area of Colombia. *In:* Hamilton LS, Juvik JO, Scatena FN, editors. *Tropical Montane Cloud Forests. Proceedings of an International Symposium*. San Juan, Puerto Rico: East–West Centre, IHP, UNESCO, IITF, USFS, pp 78–85.
CESA (Central Ecuatoriana de Servicios Agrícolas). 1992. *El deterioro de los bosques naturales del callejón interandino del Ecuador.* Quito, Ecuador: Central Ecuatoriana de Servicios Agrícolas.
Colmet-Daage F. 1980. *Cartografía de los suelos en la Sierra Ecuatoriana y cartas derivadas. Metodos–Objetivos*. Martinique and Ecuador: MAG (Ministerio de Agricultura y Ganadería), PRONAREG (Programa Nacional de Regionalización, Ecuador), ORSTOM (Office de Recherche Scientifique & Technologique Outre-Mer).
Cortés A, Chamorro BC, Vega A. 1990. Cambios en el suelo por la implantación de praderas, coniferas y eucaliptos en un área aledaña al Embalse del Neusa (Páramo de Guerrero). *Investigaciones Instituto Geográfico Agustín Codazzi* 2(1):101–114.
de Noni G, Trujillo G, Viennot, M. 1986. L'érosion et la conservation des sols en Équateur. *Cahiers ORSTOM, Série Pédologie* 22(2):235–245.
Duncan MJ. 1995. Hydrological impacts of converting pasture and gorse to pine plantation, and forest harvesting. *Journal of Hydrology (New Zealand)* 34(1):15–41.
Ellis-Jones J. 1999. Poverty, land care and sustainable livelihoods in hillside and mountain regions. *Mountain Research and Development* 19(3):179–190.
Espinosa J. 1991. Los suelos volcánicos del Ecuador. *In:* Mothes P, editor. *El paisaje volcánico de la Sierra Ecuatoriana. Geomorfología, fenómenos volcánicos y recursos asociados.* Estudios de Geografía 4. Quito, Ecuador: Corporación Editora Nacional/Colegio de Geógrafos del Ecuador, pp 55–60.
Evans, J. 1992. *Plantation Forestry in the Tropics*. Oxford: Oxford University Press.
Fahey BD, Jackson RJ. 1997. Ecological impacts of converting native forests and grasslands to pine plantations, South Island, New Zealand. *Agricultural and Forest Meteorology* 84:69–82.
Galloway G. 1986. *Guía sobre la repoblación forestal en la Sierra Ecuatoriana*. Quito, Ecuador: MAG (Ministerio de Agricultura y Ganadería), USAID (The United States Agency for International Development).
Gayoso J. 1996. Costos ambientales en plantaciones de *Pinus radiata. Bosque* 17:15–26.
Harden CP. 1996. Interrelationships between land abandonment and land degradation: A case from the Ecuadorian Andes. *Mountain Research and Development* 16(3):274–280.
Hess CG. 1990. Moving up–moving down: Agro-pastoral land-use patterns in the Ecuadorian *páramos*. *Mountain Research and Development* 10(4):333–342.
Hill MO. 1979. *TWINSPAN: A Fortran Program for Arranging Multivariate Data in an Ordered Two-Way Table by Classification of Individuals and Attributes.* Ithaca, NY: Cornell University Press.
Hofstede RGM. 1995. The effects of grazing and burning on soil and plant nutrient concentrations in Colombian *páramo* grasslands. *Plant and Soil* 173(1):111–132.
Hofstede RGM, Lips J, Jongsma W, Sevink Y. 1998. *Geografía, ecología y forestación en la sierra alta del Ecuador.* Quito, Ecuador: Ediciones Abya Yala.
Holdridge LR. 1967. *Life Zone Ecology*. San José, Costa Rica: Tropical Science Centre.
Laegaard S. 1992. Influence of fire in the grass *páramo* vegetation of Ecuador. *In:* Balslev H, Luteyn JL, editors. *Páramo. An Andean Ecosystem Under Human Influence.* London: Academic Press, pp 151–170.
León T, Suárez A, Castañeda A. 1998. *Evaluación del impacto ambiental de las plantaciones forestales industriales: Componente de suelo y agua (Informe final, Fase II).* Bogota, Colombia: CONIF (Corporación Nacional de Investigación y Fomento Forestal), Ministerio del Medio Ambiente.
Lundgren B. 1978. *Soil Conditions and Nutrient Cycling Under Natural Forest and Forest Plantations in Tanzanian Highlands.* Reports in Ecology and Forest Soils 31. Uppsala, Sweden: Department of Forest Soils, Swedish University of Agricultural Sciences.
Luteyn JL. 1999. *Páramos. A Checklist of Plant Diversity, Geographical Distribution and Botanical Literature*. Memoirs of the New York Botanical Garden Volume 84. New York: The New York Botanical Garden Press.
Morris A. 1985. Forestry and land-use conflicts in Cuenca, Ecuador. *Mountain Research and Development* 5(2):183–196.
Morris A. 1997. Afforestation projects in highland Ecuador: Patterns of success and failure. *Mountain Research and Development* 17(1):31–42.
Poulenard J. 2000. *Les sols de páramo de l'Équateur sur couverture pyroclastique: diversité, genèse et propriétés physiques.* Nancy, France: Université Henri Poincaré, CNRS Centre National de la Recherche Scientifique), IRD (Institut de Recherche Pour le Développement).
Sarmiento FO. 2000. Restoration of Andean forests for conservation. *In:* Price MF, Butt N, editors. *Forests in Sustainable Mountain Development. A State of Knowledge Report for 2000.* IUFRO Research Series 5. Oxon, UK: CABI Publishing, pp 59–69.
Ter Braak CJF. 1991. *CANOCO: A FORTRAN Program for Canonical Community Ordination by [Partial] [Detrended] [Canonical] Correspondence Analysis, Principal Components Analysis and Redundancy Analysis (Version 3.12).* Wageningen, The Netherlands: DLO Agricultural Mathematics Group.
Van Reeuwijk LP. 1989. Andosols. *In:* Driessen PM, Dukdal R, editors. *Lecture Notes on the Major Soils of the World.* Wageningen, The Netherlands: Pudoc Scientific Publishers, pp. 47–54.
Wada K. 1985. The distinctive properties of Andosols. *Advances in Soil Science* 2:174–223.
Waterloo MJ. 1994. *Water and Nutrient Dynamics of* Pinus caribaea. *Plantation Forests on Former Grassland Soils in Southwest Viti Levu, Fiji*. Amsterdam: Vrije Universiteit.