Volcanic ash soils in Andean ecosystems: unravelling organic matter distribution and stabilisation

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Citation for published version (APA):
1 Description of the research area

Location of study area and study sites

The Ecuadorian Andes consists of two mountain ranges trending northeast-southwest, called the Western Cordillera and the Eastern Cordillera, separated by the Inter Andean valley (Sauer 1971). Our study sites are located in the nature protection area of Estacion Biologica Guandera in northern Ecuador near the border with Colombia, Figure 1.1 and Table 1.1. Guandera is situated in the Eastern Cordillera on the western flanks facing the Inter Andean valley and has a (semi-) natural UFL at approximately 3650 m a.s.l. Since pre-Columbian times, the Inter Andean valley has been the most densely populated part of the country and deforestation in the Inter Andean valley has therefore been particularly severe. Guandera contains unique remnants of native tropical montane forest and páramo ecosystems representative of the ‘Tropical Andes’ biodiversity hotspot (Myers 2000) and its continued preservation is of key importance.

Figure 1.1  Map of study area and study sites. ● = study site; ■ = village or town (courtesy of J.P. Lesschen).
Table 1.1 Description of study sites

<table>
<thead>
<tr>
<th>Site</th>
<th>Altitude(^a) [m a.s.l.]</th>
<th>Coordinates(^b)</th>
<th>Slope ([%])</th>
<th>Aspect ([])</th>
<th>Soil type</th>
<th>Current vegetation</th>
</tr>
</thead>
<tbody>
<tr>
<td>G11</td>
<td>3330</td>
<td>N 0°35'12&quot;/ W 77°42'37&quot;</td>
<td>8</td>
<td>260</td>
<td>Andosol</td>
<td>Forest patch</td>
</tr>
<tr>
<td>G1</td>
<td>3501 ± 9 (n = 20)</td>
<td>N 0°35'27&quot;/ W 77°42'1&quot;</td>
<td>3</td>
<td>270</td>
<td>Histosol</td>
<td>Forest</td>
</tr>
<tr>
<td>G2</td>
<td>3520 ± 9 (n = 14)</td>
<td>N 0°35'27&quot;/ W 77°42'1&quot;</td>
<td>8</td>
<td>290</td>
<td>Histosol</td>
<td>Forest</td>
</tr>
<tr>
<td>G4</td>
<td>3616 ± 12 (n = 12)</td>
<td>N 0°35'53&quot;/ W 77°41'41&quot;</td>
<td>9</td>
<td>250</td>
<td>Andosol</td>
<td>Forest just below UFL</td>
</tr>
<tr>
<td>G5a</td>
<td>3697 ± 9 (n = 9)</td>
<td>N 0°35'41&quot;/ W 77°41'36&quot;</td>
<td>13</td>
<td>280</td>
<td>Cambisol</td>
<td>Forest patch</td>
</tr>
<tr>
<td>G5b</td>
<td>3694 ± 13 (n = 9)</td>
<td>N 0°35'41&quot;/ W 77°41'35&quot;</td>
<td>8</td>
<td>280</td>
<td>Andosol</td>
<td>Páramo</td>
</tr>
<tr>
<td>G6</td>
<td>3790</td>
<td>N 0°35'46&quot;/ W 77°41'30&quot;</td>
<td>10</td>
<td>280</td>
<td>Andosol</td>
<td>Páramo</td>
</tr>
<tr>
<td>G7</td>
<td>3860</td>
<td>N 0°35'48&quot;/ W 77°41'25&quot;</td>
<td>8</td>
<td>270</td>
<td>Andosol</td>
<td>Páramo</td>
</tr>
<tr>
<td>G10</td>
<td>3905</td>
<td>N 0°35'50&quot;/ W 77°40'45&quot;</td>
<td>11</td>
<td>240</td>
<td>Andosol</td>
<td>Páramo</td>
</tr>
<tr>
<td>G9</td>
<td>3990</td>
<td>N 0°35'34&quot;/ W 77°39'52&quot;</td>
<td>9</td>
<td>0</td>
<td>Andosol</td>
<td>Páramo</td>
</tr>
</tbody>
</table>

\(^a\) Altitudes from altimeter, n = 1 unless stated otherwise
\(^b\) GPS coordinates in WGS 1984

We selected an altitudinal transect from 3330 to 3990 m a.s.l. intersecting the current UFL (Figure 1.2), starting with a site in a forest patch surrounded by agricultural lands (G11), followed by sites currently covered by continuous forest (G1 and G2), a site just below the UFL (G4), a site in a forest patch above the UFL (G5a) and 5 sites currently covered by páramo vegetation (G6, G7, G9, G10) of which one was located next to the forest patch (G5b). Furthermore, a small mire (G15) and a peat bog (G8) were selected specifically for paleoecological analysis, which was the topic of a separate PhD thesis within the RUFLE project and will not be further discussed here. Two main findings of the RUFLE project are that site G5a has been only relatively recently (~50 years) colonised by forest vegetation (Jansen et al. 2008), while G1 and G2 have been forested for longer time periods of at least 500 years (Bakker et al. 2008).

Figure 1.2 Altitudinal transect of study sites at the nature protection area of Guandera Biological Station (courtesy of M. Moscol Olivera). Sites G8 and G15 were specifically selected for pollen analysis and not used in this thesis.
Climate

Guandera has a typical humid tropical alpine climate. Equatorial temperatures do not show large seasonal variation (Sarmiento 1986). Large daily air temperature fluctuations are typical for tropical alpine environments and are poetically described as “winter every night, summer every day” by Hedberg (1964). Night frost may occur year round, with frequencies depending on altitude. Precipitation patterns vary with the movement of the Intertropical Convergence Zone and depend on distance to the Pacific Ocean, altitude and exposition. Mean annual precipitation in Guandera is around 1900 mm. In general, seasonal variation in precipitation is small (Bader 2007) and therefore the soil climate is perudic. Soil temperature at 30 cm, representative of the mean annual temperature, was on average 9.1 ± 0.5 °C at forest sites and 9.7 ± 0.4 °C at páramo sites (isomesic), which is similar to data reported by Bader (2007). Soil temperature did not show a lapse rate with altitude, probably because forest vegetation and high air humidity in the páramo buffer the temperature. Daily air temperature fluctuations at the UFL in Guandera are much larger in páramo (up to 30 °C) than in forest (up to 15 °C), as discussed by Bader (2007).

Geology

Volcanism in Ecuador and southern Colombia is part of the ‘Northern Volcanic Zone’, extending from 5°N to 2°S (Stern 2004). In the neighbouring Amazonian basin, back-arc volcanoes are situated (Barragan et al. 1998). The northern part of the Ecuadorian Andes is characterised by Cenozoic volcanic rocks (Hörmann & Pichler 1982). The volcanic rocks of the Western Cordillera belong to a calc-alkaline andesite dacite series, while the volcanic rocks in the Eastern Cordillera are members of the andesite dacite rhyodacite series (Hörmann & Pichler 1982; Stern 2004). Volcanoes in the region of the study area that have been active over the last thousands of years are Cerro Negro, Chiles, Soche and Azufral, while Cumbal erupted during historic times (Droux & Delaloye 1996; Instituto Geofisico 2006). Additionally, explosive eruptions of the more distant volcanoes Cuicocha and Quilotoa might have reached the area (personal communication Hall 2006).

Eruptions of andesitic magma generally produce limited amounts of volcanic ash that are distributed locally by the dominant S-SE-E winds of the Inter Andean valley, while more siliceous magma types generate large quantities of ash that may be transported over much larger distances eastwards in the stratosphere (Hall & Mothes 1994). Tephra deposits show lateral and vertical variations in particle size and mineralogy. The largest and heaviest particles fall nearest to the source, while smaller and lighter particles fall at increasing distances (Shoji et al. 1993). Therefore, the mineralogical assemblage of volcanic ash is often not representative of the source magma. However, Hall & Mothes (1994) demonstrated that the mineralogical assemblage of pumice in contrast is representative of the source magma, and that most Ecuadorian volcanoes possess a typical mineralogical assemblage that varies little between eruptions. The mineralogy of pumice encountered in
the different (rhyo-) dacitic tephra deposits in which the studied volcanic ash soils were formed closely resembles that of the Soche volcano with at least one known eruption, containing feldspar, amphibole, quartz and biotite. The occurrence of pumice of large size (up to 3 cm) implies a nearby source and because the study area is directly west of Soche volcano, it is likely that the tephra deposits in the study area are of Soche origin (personal communication M. Hall 2006).

Vegetation

The vegetation in Guandera is described in detail by Moscol Olivera & Cleef (2008a and 2008b). The tropical montane forest has a structure and composition characteristic for mountainous equatorial regions, being characterised by a reduced tree stature, canopy trees with dense compact crowns, small coriaceous leaves and a high proportion of epiphytic biomass of bryophytes, ferns, bromeliads, orchids and other vascular species (Keese et al. 2007). The transition from forest to páramo is abrupt, probably indicating at least some human influence (Laegaard 1992), but the forest still contains trees with a considerable diameter at breast height (dbh) of 70 cm. Although occupying only 10 % of Ecuador, the tropical montane forests contain half of the country’s species (Keese et al. 2007). The dominant species in the Guandera forest include Clusia flaviflora Engl., Weinmannia cochensis Hieron. and Ilex colombiana Cuatrec. Aboveground biomass of a similar Clusia forest at 3059 m a.s.l. in southern Ecuador was estimated between 7.4 and 15.6 kg m⁻² (Leuschner et al. 2007) with a leaf litter production of 263 ± 44 g m⁻² y⁻¹ and a root litter production of 2084 ± 177 g m⁻² y⁻¹ (Röderstein et al. 2005).

Páramo refers to the tropical montane grasslands encountered between the UFL and the snow limit in the equatorial Andes. The páramo forms an altitudinal belt extending from northern Peru to northern Costa Rica (Luteyn 1992) and occupies 5 % of the land area in Ecuador thus representing 25 % of the total Andean páramo surface (Mena Vasconez et al. 2001). The Guandera páramo is characterized by bunchgrasses of Calamagrostis effusa (Kunth) Steud. and stem rosettes of Espeletia pycnophylla Cuatrec., the latter only occurring from northern Ecuador - including our study area - and further north. Aboveground biomass in a similar páramo ecosystem at 4100 m a.s.l. in Colombia was 3.5 kg m⁻² with approximately 1.7 kg m⁻² leaf litter and a belowground biomass of 1.2 kg m⁻² (Hofstede & Rossenaar 1995).

Soils

Authorative reviews concerning the properties of volcanic ash soils are presented by Theng (1980), Mizota & Van Reeuwijk (1989), Shoji et al. (1993) and Dahlgren et al. (2004). Characteristic chemical and physical soil properties and soil classification according to the World Reference Base (WRB) for soil resources developed by the FAO (2006) of the soils in the study area are discussed in more detail in this section.
Soil profile descriptions according to the FAO (1990) guidelines are presented in Appendix II. Figure 1.3a and 1.3b show typical soil profiles under forest and páramo vegetation respectively. The forest soils characteristically had ectorganic horizons with a combined thickness of up to 100 cm, classifying as Folic horizons according to the World Reference Base (FAO 2006). Roots were generally concentrated in these ectorganic horizons. Such thick ectorganic horizons (Wilcke et al. 2002) with rooting (Soethe et al. 2006) are characteristic for tropical montane forest. Contrary, ectorganic horizons barely exceeded 1 cm in the páramo profiles and litter was mostly present as hanging dead material within the tussock grasses or on the stem rosettes, while roots were concentrated mainly in the mineral topsoil. These traits are indeed typical for páramo vegetation (Hofstede & Rossenaar 1995). C/N ratios of forest litter (~88 mass ratio) and páramo litter (~87) were similar, C/N ratios in the other ectorganic horizons of the forest sites were lower (~39).

Based on the mineral soil horizon sequence, we generally identified at least two tephra deposits in the field (on average ~50 cm thick), recognizable as a ‘current soil’ and a ‘paleosol’. Beneath this paleosol an ‘unweathered ash’ was present that could either belong to the paleosol or represent a separate preceding tephra deposition and thus could constitute an additional immature or strongly truncated paleosol. Most soils had a placic horizon, which may be ascribed to the strong textural contrast hindering drainage of the otherwise well drained soils.

Figure 1.3  a) Forest soil profile (G1)  b) Páramo soil profile (G7)
The horizon sequence based on the field observations can be summarised as O – Ah – AB or Bw – 2Abh – 2Bs b – 2 or 3 Bcb. The number of tephra deposits is often underestimated in the field as soil formation following tephra deposition may overprint preceding deposits (Buurman et al. 2004). In Chapter 3 the conclusive tephra stratigraphy and corresponding soil horizonation is unravelled. Therefore, Chapter 2 refers to field horizons while in Chapter 4 to 6 horizon naming is according to this unravelled tephra stratigraphy.

Chemical and physical soil properties are presented in Appendix III and in Chapter 3 and 5, the methodology is described in these chapters, unless specifically mentioned here. In general, organic carbon contents were very high (> 6 mass %) and soil pH was acidic (pH$_{\text{CaCl}_2}$ = 4.2 ± 0.3) throughout the current soil and paleosol, while the unweathered ash contained less organic carbon (0.9 ± 1.2 %) and had a higher pH$_{\text{CaCl}_2}$ (5.1 ± 0.4). The C/N ratio was on average 21 ± 4 throughout the soil profiles. The crystalline clay fraction throughout the soil profile contained predominantly Al-hydroxy interlayered minerals and clay sized primary minerals (albite, amphibole, cristobalite and quartz) and only trace amounts (if any) of kaolinite, illite and halloysite. Allophane was absent in the current mineral topsoils, but allophane content in the current subsoils was on average 4.4 ± 2.6 % and increased to 9.5 ± 4.0 % in the paleosol. The pH as measured in 1 M NaF (1:50 w/v) exceeded 9.5 throughout the mineral soil, indicating the presence of (amorphous) hydroxide groups (Fieldes & Perrott 1966). In the current soil and paleosol, pH$_{\text{KCl}}$ was always higher than pH$_{\text{CaCl}_2}$ demonstrating the presence of dominant positive variable charge rather than permanent negative charge, which is typical for volcanic ash soils and related to amorphous constituents. The effective CEC measured at ambient soil pH in 1 M KCl or 1 M NH$_4$Cl (w/v 1:5) is 67 ± 44 mmol$_e$kg$^{-1}$ in the current soil and 41 ± 10 mmol$_e$kg$^{-1}$ in the paleosol, with a base saturation of only 13 ± 7 % in the current soil and 17 ± 10 % in the paleosol. Exchangeable acidity (H$^+$ and Al$^{3+}$ extractable with 1M KCl) amounted to 60 ± 44 mmol$_e$kg$^{-1}$ in the current soil and 35 ± 31 mmol$_e$kg$^{-1}$ in the paleosol.

Dry bulk density was low (< 0.90 g cm$^{-3}$) throughout the current soil and paleosol and higher in the unweathered ash (> 0.90 g cm$^{-3}$). Porosity was high (76 ± 8 %) in representative páramo topsoil samples of site G7 and G9 and in a forest subsoil sample of site G11. The density of the solid phase in these samples was 1.9 ± 0.1 g cm$^{-3}$ (as determined with a pycnometer) reflecting the high SOM content. Gravimetric water content was 163 ± 57 % at saturation point (15 kPa or pF 2.2) and still 46 ± 13 % at wilting point (1500 kPa or pF 4.2). Soil structure was massive, consistency was (very) friable when moist and non to slightly sticky when wet. Moreover, the soils showed thixotropic behaviour, i.e. the soil changes from a plastic solid into a liquid under pressure.

Mineral topsoils of both forest and páramo sites generally showed Vitric properties rather than Andic properties according to the WRB classification (FAO 2006), because the (Al$_o$ + ½ Fe$_o$, subscript ‘o’ indicates oxalate extractable) content, indicative for the degree of weathering, did not exceed 2.0. Since all other diagnostic criteria for Andic properties were fulfilled, e.g. low dry bulk densities (≤ 0.90 g cm$^{-3}$) and high P retention (≥ 85 %), and because
the \((\text{Al}_p + \frac{1}{2} \text{Fe}_p)\) content did approach or exceed 2.0 in the subsoils, we consider the Vitric properties on the verge of maturing into Andic properties. In accordance we decided to apply the prefix qualifier Andic rather than Vitric in the soil classification. More specifically, the current soils possess Aluandic properties because \(\text{Al}_p/\text{Al}_b\) (subscript ‘p’ indicates pyrophosphate extractable) exceeded 0.5, indicating the dominance of Al-humus complexes. Contrary, the paleosol generally showed Silandic properties with an \(\text{Al}_p/\text{Al}_b\) ratio below 0.5, pointing towards the predominance of amorphous minerals. Andosols with Aluandic properties in the mineral topsoil are also referred to as ‘non-allophanic’, while those with Silandic properties in the mineral topsoil are called ‘allophanic’ (Takahashi & Shoji 2002). The unweathered ash beneath the paleosol had Vitric properties. Additionally, all páramo soil profiles contained an Umbric surface horizon because of their low base saturation.

Shoji et al. (1993) mentioned the influence of vegetation in creating either Fulvic (forest) or Melanic (grassland) Andosols and this vegetation effect was also present in our study area. At the forest sites, the diagnostic criteria for Fulvic horizons were not met sensu strictu, because of the absence of unambiguous Andic properties in the mineral topsoils. However, we argue that classification as Fulvic horizon is still justified because of the clear development towards Andic properties. In order to fulfil the cumulative thickness requirement of 30 cm, Ah and Bw horizons were grouped, which is allowed because both horizons fulfil the supplementary diagnostic criteria of either having a melanic index greater than 1.7 or having a Munsell colour chroma exceeding 2. In most páramo sites, the diagnostic criteria for Melanic horizons were clearly met, despite the Vitric nature of the mineral topsoils, because average \((\text{Al}_p + \frac{1}{2} \text{Fe}_p)\) content of the Ah horizon did closely approach or exceed 2.0. Accordingly, we added the qualifier Melanic to the páramo soils. The forest patch soil (G5a) has a Melanic horizon, although at the top of the Ah horizon the melanic index slightly exceeded 1.7 indicating transformation towards a Fulvic horizon, probably as a result of the relatively recent recolonisation by forest.

Forest soils with thick ectorganic horizons (> 25 cm) keyed out as Histosol or Cambisol rather than Andosol in the WRB classification, but to enable easy comparison we used the list of Andosol qualifiers also for these soil types during classification. Additional specifiers ‘Endo-’ or ‘Bathy-’ indicate that the diagnostic feature started at a depth greater than 50 cm or 100 cm respectively, while specifier ‘Thapto-’ indicates the presence of buried layers with a cumulative thickness of 30 cm within 100 cm from the soil surface. Concluding, the forest patch surrounded by agricultural land (G11) is a Folic, Hemic, Aluandic, Fulvic Andosol (Dystric, Placic, Thixotropic). Forest soils (G1, G2) classify as Folic, Hemic, Endo/Bathyaluandic, Endo/Bathyfulvic Histosols. The forest site just below the UFL (G4) has a Folic, Hemic, Aluandic, Fulvic, Thaptaluandic, Andosol (Thixotropic, Colluvic, Dystric), and the forest patch soil (G5a) is a Folic, Hemic, Aluandic, Endomelanic Cambisol (Hyperhumic, Thixotropic, Dystric). The páramo soils (G5b, G6, G7, G9, G10) classify as Aluandic, Melanic, Umbric Andosols (Thixotropic).