How an advanced combination of soil science, biogeochemistry, and paleo-ecology helps Ecuadorian cloud forest management

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Abstract
Montane forest composition and specifically the position of the upper forest line (UFL) is very sensitive to climate change and human interference. As a consequence, reconstructions of past altitudinal UFL dynamics and forest species composition are instrumental to infer relationships between climate change and vegetation dynamics, and assess the impact of (pre)historic human settlement. We developed an innovative combination of techniques derived from soil science, molecular organic geochemistry, palynology, and vegetation ecology to reconstruct past forest dynamics from fossil pollen and biomarkers preserved in soils and peat deposits. Here we present the results of the first application of the new approach to reconstruct the natural position of the UFL in a biodiversity hotspot of montane rainforest in the Ecuadorian Andes where its location is highly disputed. Our results show that the current páramo vegetation above 3600 m in the area is a natural ecosystem rather than the product of deforestation. As a consequence, Kyoto Protocol triggered reforestation activities in this part of the Ecuadorian Andes should be limited to maximally 3600 m elevation. Aforestation at higher elevations will disturb the natural páramo ecosystem and affect the carbon storage potential of the soil.

Key Words
Reforestation, upper forest line dynamics, biomarker analysis, pollen analysis, pedogenesis.

Introduction
The highest parts of the tropical Andes in Ecuador consist of fragile ecosystems characterized by a high biodiversity. They are mainly inhabited by indigenous populations that entirely rely on subsistence use of the natural resources. The ecosystems in these high montane areas include páramo grasslands and humid montane rain (and cloud) forests, which originally covered large tracts from Venezuela to Peru. These ecosystems fulfill important environmental functions e.g. supply of drinking and irrigation water, biodiversity conservation, carbon storage, agricultural production and tourism. Over the past decades, population pressure on the systems in question has rapidly increased and agricultural land use has strongly expanded, often using inappropriate techniques and leading to rampant degradation. Natural upper montane forests have been widely replaced by either potato cultivation or tree plantations (Hofstede *et al.* 2002), and native páramo grasslands are over-exploited by grazing and burning. In many situations the intense land use is believed to have lead to a downward push of the upper forest line (UFL: defined as the elevation with the highest occurrence of continuous forest). However, upward movements of montane forest have also been attributed to global warming, particularly affecting mountain ecosystems (Price 1999). Contradictory results from fossil pollen analysis on the one hand and vegetation analysis on the other have resulted in scientific debate about the natural position of the UFL in the Ecuadorian Central Valley. In the Guandera Biological Station that protects one of the last remaining stretches of cloud forest in the Inter-Andean Central Valley, scientific estimates of the natural position of the UFL ranged from the present day position of approximately 3600 m a.s.l. *(above sea level)* to a hypothesized 4000 m a.s.l. (Laegaard 1992; Wille *et al.* 2002). Such uncertainty is severely hindering sustainable management of the remaining stretches of cloud forest, including reforestation projects under Kyoto Protocol CO_2 emission trade schemes. The main aim of the five year program “Reconstruction of the Upper Forest Line in Ecuador (RUFLE)” that was concluded in 2009, was to obtain better insight into forest dynamics in the Ecuadorian Andes in general under biotic and a-biotic pressures, and in particular to reconstruct the most likely natural position of the UFL in the northern Andes. To overcome the scientific uncertainty an interdisciplinary multi-proxy approach was chosen. In this

approach an innovative combination of techniques derived from soil science, molecular organic geochemistry, palynology, and vegetation ecology was set up to identify the spatio-temporal vegetation dynamics along series of altitudinal transects that cross current and past forest-páramo transitions.

Methods

The study area

The study area is part of the Guandera Biological Reserve in El Carchi province in northern Ecuador. The Reserve is located approximately 11 km from the town of San Gabriel in the Eastern Cordillera. It protects approximately 10 km^2 of high altitude páramo grassland as well as extensive areas of relatively undisturbed montane cloud forest. Most of the Andean forest is left between 3300 and 3640 m elevation. Above an altitude of 3640 m grass páramo dominates the landscape but some forest patches occur up to 3700 m altitude. The soils in the study area were formed in three distinct tephra deposits of Holocene age (Tonneijck *et al.* 2008). They consist of Histosols with andic properties at sites currently covered by continuous forest, Andic Cambisols in forest patches above the UFL and Andosols at the sites currently covered by páramo vegetation (Tonneijck *et al.* 2009). In addition to soils, two peat deposits in the area were sampled and analysed. Vegetation in the study area was thoroughly analysed and described as part of the project (Moscol Olivera and Cleef 2008a,b).

Soil analysis

All soils sampled were extensively described, chemically and physically analysed and ^{14}C dated (Tonneijck *et al.* 2008; Tonneijck and Jongmans 2008; Tonneijck *et al.* 2006). A micro-morphological assessment of bioturbation features formed an important part of the analyses with an aim of obtaining the chronostratigraphy of the soils (Tonneijck and Jongmans 2008). For this, thin sections were analysed using a Leitz M420 makrozoom microscope and a Leitz Wetzlar petrographic microscope. Thin sections were described following the micro-morphological terminology of Stoops (Stoops 2003). Abundance classes were as follows: very few (< 5%), few (5 – 15%), common (15 – 30%), frequent (30 – 50%), dominant (50 – 70%) and very dominant (> 70%).

Analysis of molecular biomarkers

In the biomarker approach, plant species typical for specific vegetation zones are examined for the presence of biomarkers, defined as plant-specific (combinations of) molecular components. The most likely candidates for application as biomarker to distinguish forest from non-forest vegetation were *n*-alkanes, *n*-alcohols and *n*-fatty acids in the carbon number range of C_{20}-C_{36} that uniquely occur in the wax layers of leaves and in roots of higher plants in varying combinations. Along the altitudinal transect the plant species responsible for the dominant biomass input in soils were sampled and several intact soil monoliths collected. The lipids from the plant and soil samples were extracted and analyzed with a combination of Accelerated Solvent Extraction (ASE) and gas chromatography-mass spectrometry (GC/MS) optimized for this purpose (Jansen *et al.* 2006a). Plant lipids were tested for unique combinations of *n*-alkanes, *n*-alcohols and *n*-fatty acids through cluster analysis using Ward's method (Jansen *et al.* 2006b). To unravel the mixed soil lipid signal with depth, a discrete linear model (VERHIB) was developed that describes the accumulation of lipids in the soil. By inversion the most likely vegetation composition leading to the mixed biomarker signal in the soil was derived (Jansen *et al.* 2009).

Fossil pollen analysis

From the same soil samples used to establish the biomarker signal, fossil pollen were extracted and analysed. In addition, the modern pollen rain in the area was sampled. All samples were processed using the standard pre-treatment including sodium pyrophosphate, acetolysis, and heavy liquid (bromoform) separation (Faegri and Iversen 1989). To calculate pollen concentration values, one tablet of exotic *Lycopodium* spores was added to each sample prior to processing. Pollen samples were mounted in glycerin gelatin and counted with a Zeiss microscope at 500x magnification. For identification, pollen morphological descriptions published by Bogotá *et al.* (1996) and Hooghiemstra (1984), and the modern pollen reference collection at Amsterdam laboratory were used. A minimum of 400 pollen grains from terrestrial taxa was counted for all samples. The data were plotted and cluster analysis was carried out with TILIA, TILIAGRAPH, CONISS and TG-view (Bakker *et al.* 2008).

Results

Figure 1 provides an example of the percentage forest cover (all forest species grouped together) as reconstructed from biomarkers and fossil pollen from a soil monolith at 3480 m a.s.l. in a site currently part of the continuous forest. From Figure 1 it is clear that fossil pollen and molecular biomarkers both point to the same trends in forest cover with time. However, important differences are also visible as for instance at 55 cm depth where the biomarkers indicate a much more pronounced shift in percentage forest cover that also peaks slightly earlier than indicated in the pollen record. The reason is that as a result of the wind blown dispersal of pollen, the pollen record yields a regional image of shifts in vegetation patterns. In contrast, due to their leaf origin, biomarkers provide a much more local picture. Most likely, the peak at 55 cm indicates a local phenomenon such as nearby páramo patches within the integral forest that also occur at present day (Moscol Olivera and Cleef 2008b) and are predominantly reflected in the local biomarker record. The steady and concurrent decline in percentage forest cover from 20 cm upward might be interpreted as a decline in UFL position, but given the distance of the site from the current UFL and the local nature of the biomarker record, it more likely reflects deforestation coupled with encroaching agricultural fields from the valley below the current forest. These results illustrate how the multi-proxy approach when we subsequently applied it in the complete sequence of soils and peat deposits, allowed for a reconstruction of past dynamics of forest vegetation patterns with unprecedented detail. A reconstruction where the regional scale vegetation dynamics obtained from fossil pollen and present day vegetation patterns e.g. (Bakker *et al.* 2008; Moscol Olivera and Cleef 2008a; Moscol Olivera and Cleef 2008b) was complemented with the local scale information yielded by biomarker analysis (Jansen *et al.* 2008; Jansen *et al.* 2009). Not only did this allow us to reconstruct the altitudinal shifts of the UFL over time, the combined data also provided detailed information about changes in forest composition over time, often at species level. The study of pedogenetic processes allowed for an assessment of the maximum attainable resolution of the fossil pollen and biomarkers preserved in soils. In addition, it provided the time frame for the vegetation reconstructions and served as proxy to distinguish between forest and páramo vegetation through its organic matter composition (Tonneijck and Jongmans 2008). From our combined results we infer that during the last 10,000 years the UFL in the study area did not reach altitudes above 3700 m.

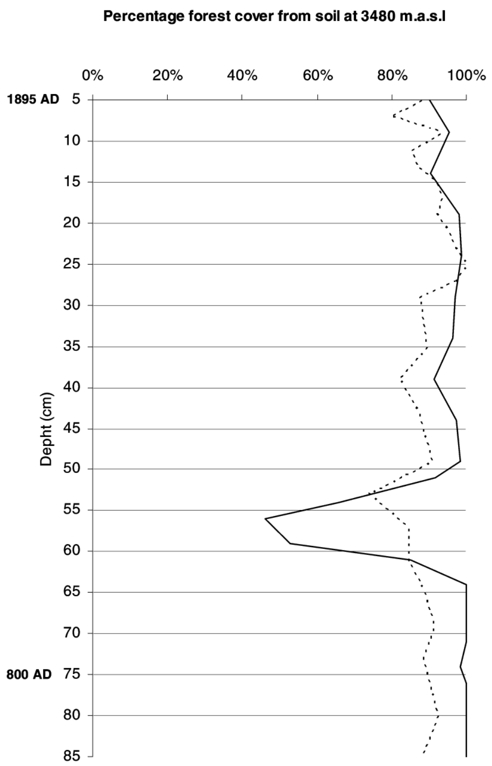

Figure 1. The percentage forest cover over time reconstructed from biomarkers (solid line) and fossil pollen (dotted line) from a soil monolith at 3480 m a.s.l. within the current integral forest at the Guandera research site.

Conclusion

We conclude that the multi-proxy approach developed offers a valuable new tool to reconstruct past forest dynamics in general and in particular UFL positions within areas with volcanic ash soils where its natural location is uncertain due to human interference, climate change or both. With respect to the uncertainty whether the present-day páramo vegetation in the Guandera Biological Station has a natural background or is the result of human induced deforestation, we conclude that the natural undisturbed UFL was below 3700 m and páramo vegetation above 3600 m is a natural ecosystem. As a consequence, Kyoto Protocol triggered reforestation activities in this part of the Ecuadorian Andes should be limited to maximally 3600 m elevation. Afforestation above 3600 m, in particular with exotic trees such as *Eucalyptus* and Mexican pine (mainly *Pinus patula* and *P. radiata*), should be strongly discouraged. Not only from a conservational point of view, but also because it will affect the carbon storage potential of the soil.

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