GENESIS, FERTILITY, AND ERODIBILITY OF VOLCANIC ASH SOILS

IN THE ANDES OF NORTHERN ECUADOR

by

FRANZ ZEHETNER

(Under the Direction of William P. Miller)

ABSTRACT

The volcanic ash soils of northern Ecuador have supported agricultural activities for thousands of years; however, at the dawn of a new millennium, the sustainability of agricultural production seems to be threatened on the slopes of volcano Cotacachi, where crop yields have been declining over the past decades. This study was undertaken as part of an interdisciplinary effort to devise a natural resource management plan and had the objective to characterize the soil resource of the area. Nature and culture in the studied Andean mountain environment are dominated by its verticality, and altitude is the master variable that governs soil development, determines the soils' susceptibility to runoff and erosion, and affects many aspects of soil fertility. At higher elevations, organic matter accumulates, amorphous constituents form, and the soils are Andisols. They have stable aggregate structure and show high infiltration capacity and resistance to erosion. However, their N- and P-supplying capacity may be impaired by slow mineralization of the former and strong sorption of the latter. At low elevations, organic matter contents are low, halloysite predominates clay mineralogy, and the soils are Inceptisols and Entisols. They exhibit lower infiltration capacity and are more susceptible to erosion; however, compared to soils from other parts of the world, their interrill erodibilities are classified as low. The cultivation of arable crops in these lower zones may be limited by the soils' low water-storage capacity and susceptibility to nutrient leaching. Irrespective of elevation, the young soils in the southern part of the study area have inherently low potassium contents and would greatly benefit from K additions. While erosional degradation does not pose a major threat, water and nutrient management appear to be key elements of agricultural sustainability in the Cotacachi area.

INDEX WORDS: Active amorphous constituents, aggregate stability, allophane, amorphous materials, andic soil properties, Andisol, crop growth modeling, DSSAT, fertilization, halloysite, infiltration, interrill erodibility, irrigation, limiting factors, management practices, nitrogen, organic matter, paleosol, pedogenesis, phosphate sorption, phosphorus, plant nutrients, potassium, productivity, rainfall simulation, residue management, runoff, soil development, soil erosion, soil formation, soil loss, sustainability, volcano, water balance, water stress, weathering, WEPP.

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for my soul mate I-Sheng

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CHAPTER 1

Introduction

It was in the mid-nineties, when I was asked to deliver an infrared spectrometer from Vienna, Austria, to a jungle outpost of the Austrian Developing Service in the Amazon region of Ecuador. I was excited about this prospect; I had never been to South America and always wanted to get involved in a developing project. When the planned undertaking was cancelled, I was tremendously disappointed. A few years later, in the meantime living in Athens, Georgia, I was in quest of a suitable project for my PhD dissertation, when Dr. Robert Rhoades was looking for someone to conduct soil research within an interdisciplinary research and development program in the Ecuadorian Andes. Here was my second chance, and this time I did get to go.

The Andes project managed by Dr. Rhoades is part of the SANREM CRSP (Sustainable Agriculture and Natural Resources Management Collaborative Research Support Program), funded by the U.S. Agency for International Development and initiated in 1992 to promote sustainable food production in areas exposed to environmental degradation. The SANREM CRSP uses an interdisciplinary and participatory approach that involves scientists from the USA and host countries as well as local stakeholders.

When I first visited the study site on the slopes of volcano Cotacachi in northern Ecuador, I met local people who were very concerned about the declining productivity of their soils. On many occasions, I was told about the bounty of crop varieties their ancestors used to cultivate, the high crop yields they used to produce, and that much of this had changed over the past decades. The people were eager to know what could be done to reverse this downward trend.

The overall objective of this study was to contribute soil-related information to an integrated SANREM-Andes natural resource management plan for the area. The soil resource was to be characterized with respect to weathering and soil development, soil fertility status and productivity, as well as runoff potential and soil erodibility.

Soils derived from volcanic deposits can exhibit unique physical and chemical properties, which are largely associated with their colloidal composition (Shoji et al., 1993; Kimble et al., 2000) and therefore dependent on their path and stage of soil development. One objective was, therefore, to study weathering and soil development along the slopes of volcano Cotacachi in order to understand the spatial distribution of different soil types in the area.

Volcanic ash soils have the reputation of being fertile and highly productive (Shoji et al., 1993); however, in order to sustainably support a growing population, proper management practices are a prerequisite. A second objective of this study was to analyze the fertility status of the soils in the Cotacachi area, to identify limiting factors to crop growth in different zones of the area, and to evaluate the long-term effects of fertilization, residue management, and irrigation on crop yields.

The loss of plant nutrients and organic matter through soil erosion can pose a severe threat to the sustainability of agro-ecosystems. While volcanic ash soils are generally considered as stable and erosion-resistant (Warkentin and Maeda, 1980; Shoji et al., 1993), severe erosional degradation has been reported in the Ecuadorian Andes (Harden, 1988; de Noni et al., 1997; Podwojewski et al., 2002). A third objective was, therefore, to assess the soils' infiltration capacity and resistance to erosion.

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CHAPTER 2

Review of the Literature

1. Soil Genesis

1.1. Weathering and Development of Volcanic Ash Soils

Soils derived from volcanic deposits often exhibit unique physical and chemical properties, such as low bulk density, high water retention, variable charge characteristics, and strong phosphate sorption, which have been largely ascribed to active amorphous weathering products, such as allophane, imogolite, and aluminum-humus complexes (e.g., Shoji et al., 1993; Kimble et al., 2000). The extent to which these properties are expressed in a volcanic ash soil depends therefore on its stage of soil development. Various weathering sequences have been proposed to explain the formation and transformation of colloidal constituents in volcanic ash soils under different environmental conditions.

The formation of aluminum-humus complexes has been observed in recent and buried A horizons of volcanic ash soils, and has been reported to be favored by conditions unfavorable to the formation of allophane (Shoji et al., 1982; Shoji and Fujiwara, 1984). Aluminum-humus complexes are predominant at pH (H_2O) < 5, whereas the precipitation of allophane is favored above pH 5. It has been further suggested that the precipitation of allophane is impeded by competition between humic substances and orthosilicic acid for soluble aluminum (Wada, 1989; Shoji et al., 1993).

Allophane and halloysite are the dominant components in the clay fraction of many volcanic ash soils around the world. It has been suggested that halloysite forms over time upon weathering of allophane (e.g., Wada, 1989); however, many studies have revealed that volcanic ash may weather directly to halloysite as well as to allophane (e.g., Parfitt et al., 1983; Parfitt et al., 1984; Parfitt and Wilson, 1985; Singleton et al., 1989). Silicon activity in the soil solution has been suggested as the overriding factor responsible for the preferential formation of either halloysite or allophane. Parfitt and Wilson (1985) and Singleton et al. (1989) found that halloysite was predominant when $H_4SiO_4^0$ in soil solution exceeded 250 and 350 μmol L^{-1}, respectively, and allophane predominated below these concentrations.

A variety of factors can control soil solution chemistry and hence affect the mineralogy of a soil's colloidal fraction. Wada (1987) has suggested that in contrast with allophane, the formation of halloysite is favored by a thick depositional overburden that produces a silica-rich environment. Singleton et al. (1989) and Bakker et al. (1996) reported impeded drainage to favor halloysite formation, whereas the presence of allophane was associated with well-drained soil horizons. Parfitt et al. (1983) proposed a weathering scheme for rhyolitic ash, in which halloysite is the dominant clay mineral where the mean annual precipitation is less than approximately 1500 mm, and allophane predominates above 1500 mm. Along these lines, many subsequent studies on volcanic ash soils in different parts of the world have confirmed the importance of rainfall and leaching in mineral formation (e.g., Parfitt et al., 1984; Stevens and Vucetich, 1985; Takahashi et al., 1993; Nizeyimana et al., 1997; Nieuwenhuyse et al., 2000).

Toposequences of soils along the slopes of volcanoes have been studied to assess the effect of climate on weathering and mineral formation (Chartres and Pain, 1984; Nizeyimana et al., 1997). On an extinct volcano in Rwanda, Nizeyimana et al. (1997) found decreasing allophane contents and increasing halloysite contents with decreasing elevation, which they attributed to a concomitant decrease in rainfall. Chartres and Pain (1984) found a similar weathering pattern with elevation in highland Papua New Guinea, although there precipitation increased with decreasing elevation.

They suggested that lower rates of evapotranspiration with increasing altitude caused greater leaching, thus favoring the formation of allophane.

In addition to allophane and halloysite, 2:1-type phyllosilicates with and without hydroxy-Al interlayering are commonly found in volcanic ash soils. Their occurrence has been ascribed to *in situ* pedogenic transformations (Shoji et al., 1982; Yamada and Shoji, 1983), eolian addition (Mizota and Takahashi, 1982; Mizota, 1983), incorporation into volcanic ash during eruption (Dudas and Harward, 1975; Pevear et al., 1982; Ping et al., 1988), and mixing of recent volcanic ash with underlying paleosols (Dudas and Harward, 1975).

1.2. Chemical Extraction of Amorphous Materials

Active amorphous constituents formed upon weathering of volcanic deposits, such as allophane, imogolite, and aluminum-humus complexes, have traditionally been quantified with dissolution analyses using various chemical extractants (e.g., Wada, 1989). One of the most common extractants used for the dissolution of amorphous materials has been oxalate – oxalic acid buffered around pH 3 (Parfitt and Childs, 1988; Parfitt, 1989a), and the extraction of silicon by this reagent has been reported as specific to allophane and imogolite (Wada, 1989). Acid oxalate-extractable Si has therefore been used to estimate the allophane contents of volcanic ash soils when imogolite was present in minor quantities (Parfitt, 1990).

Allophane tends to form inside pumice grains where the hydrolysis of volcanic glass proceeds at high Si concentrations and high pH, whereas imogolite tends to form on the outside exposed to solutions of lower Si concentrations and lower pH (Wada, 1980, 1987). There is increasing micro-morphological evidence that amorphous coatings and infillings are a common feature in volcanic ash soils of humid and arid climates (Jongmans et al., 1994, 1995, 1996; Dubroeucq et al., 1998). Ranging in composition from pure silica to allophane and imogolite, amorphous precipitates are found to cover the surfaces of rock fragments and pumice grains and to infill voids. Thus, the porous interiors of pumice grains may be inaccessible to extraction solutions, which may lead to underestimation of total allophane contents when soil samples sieved to 2 mm are subjected to dissolution analysis.

Andisols generally show high structural stability with soil aggregates often strongly cemented by amorphous constituents and soil organic matter (Warkentin and Maeda, 1980; Shoji et al., 1993). Interaction of allophane and imogolite with humic substances may result in the formation of very stable silt- and sand-sized aggregates, particularly in buried A horizons of volcanic ash soils (Wada, 1980). Amorphous constituents in the interior of such aggregates may be shielded from external solutions in the soil environment and possibly from extraction solutions in the laboratory. Such protective effects are likely enhanced if the soil samples – as in most research studies – are air-dried prior to analysis, since irreversible flocculation and dramatic increases in aggregate stability have been reported upon drying of Andisols (Shoji et al., 1993; Poulenard et al., 2001). Yoshida (1992) reported sand-sized aggregates to play an important role in the phosphate retention of some air-dried volcanic ash soils and to be resistant to ultrasonic vibration and treatment with dithionite-citrate-bicarbonate and acid oxalate. Dry grinding of these samples resulted in decreased amounts of Bray-2 extractable P, which may be ascribed to increased availability of active sorption sites for phosphate after the disintegration of stable aggregates. Poulenard et al. (2002) showed that the solid – pore interfaces of volcanic soil aggregates were less accessible and the acid oxalate-extractability of Al decreased after shrinkage on drying.

2. Soil Fertility

2.1. Fertility of Volcanic Ash Soils

Soils derived from volcanic deposits have the reputation of being fertile and highly productive, allowing for high human-carrying capacity. They were conducive to the development of early civilizations in Central and South America (Lauer, 1993) as well as in Asia (Shoji et al., 1993). The high natural fertility of volcanic ash soils has been attributed to the abundance of nutrients in the soil parent material, the development of thick humus horizons containing large amounts of organic nitrogen, free drainage, high plant-available water-holding capacity, and a deep, unrestricted rooting zone (Shoji et al., 1993). However, not all soils derived from volcanic deposits can supply the large amounts of nutrients and water necessary for vigorous plant growth. The inherent fertility of volcanic ash soils is strongly dependent on texture and composition of their parent material, on the nature, intensity, and duration of its alteration by the processes of weathering, and on the magnitude of organic matter accumulation in the course of soil development.

According to their chemical composition, volcanic ashes are classified into the rock types rhyolite, dacite, andesite, basaltic andesite, and basalt (Shoji et al., 1975). The contents of silicon decrease in this order whereas the concentrations of calcium, magnesium, iron, and other micronutrients increase. However, total phosphorus and potassium contents are higher in rhyolitic compared to basaltic materials (Shoji et al., 1993). The nutrients contained in the soil parent material are largely unavailable for plant roots until liberated in the course of mineral weathering and stored in more available form on mineral and organic surfaces. Parent material texture is an important factor influencing the rate of weathering and nutrient release. The finer the texture, the greater the surface area exposed to the ambient solution and the higher the rate of chemical weathering (Shoji et al., 1993). With increasing intensity and duration of weathering and soil development, the clay contents of volcanic ash soils increase, which in turn enhances their ability to retain plant nutrients against leaching and to store plant-available water. For volcanic deposits in New Zealand, Lowe (1986) showed that tephra younger than 3000 years had less than 5 % clay, deposits of 3000 to 10 000 years contained 5 to 10 % clay, and 10 000 to 50 000 year-old tephra had clay contents of 15 to 30 %.

The clay mineralogy of volcanic ash soils is largely determined by the amount of rainfall and leaching. Active amorphous constituents, such as allophane and aluminum-humus complexes, dominate the clay fraction where the climate is moist and soil solution silicon is removed by leaching, whereas halloysite is found as the dominant clay mineral in drier, silicon-rich environments (e.g., Parfitt et al., 1983; Parfitt and Wilson, 1985). These differences in clay mineralogy have important bearings on nutrient cycling. Active amorphous constituents are responsible for the strong sorption of phosphate often observed in volcanic ash soils (e.g., Parfitt, 1989b; Wada, 1989; Shoji et al., 1993) that makes phosphorus sparingly available for plants and microorganisms. Active amorphous constituents further react with soil organic matter leading to its stabilization and enhanced protection against microbial decomposition (Parfitt et al., 1997; Gijsman and Sanz, 1998; Parfitt et al., 2001). This results in humus accumulation and the presence of appreciable quantities of organic nitrogen in these soils; however, due to above-mentioned protective effects, its mineralization is comparatively slow (Shoji et al., 1993; Parfitt et al., 2001).

2.2. Soil Fertility in the Ecuadorian Andes

Pollen analysis in lacustrine sediments has shown that the volcanic ash soils of northern Ecuador had been cultivated for thousands of years (Athens, 1999). In order for these soils to remain sustainably productive, proper management practices are a prerequisite.

Continuous cropping without adequate inputs leads to nutrient mining and declining productivity. In the Andean eco-region, fallow-rotation systems have traditionally been practiced to restore soil fertility and avoid outbreaks of pests and diseases (Sarmiento et al., 1993; Schad, 1998; Pestalozzi, 2000; Phiri et al., 2001). However, increasing population pressure, competing land-use demands, and the incorporation of elements from market-oriented agriculture have been changing these traditional systems (Sarmiento et al., 1993; Phiri et al., 2001). Using a modeling approach, de Koning et al. (1997) assessed the sustainability of Ecuadorian agro-ecosystems based on their soil fertility status. They calculated nutrient balances for different land use types and found net nitrogen and potassium losses, which were higher for cropland than for grassland. Nutrient depletion was more severe in the Andean than in the coastal region.

3. Soil Erodibility

3.1. Erodibility and Soil Properties

Studying the relation of soil properties to erodibility of 55 US Corn Belt soils, Wischmeier and Mannering (1969) concluded that particle size distribution and organic matter content were the most influential indicators of erodibility. Generally, soils with high silt, low clay, and low organic matter contents were the most erodible. Many subsequent studies have confirmed the influence of soil texture and organic matter on erodibility, and have further pointed out the importance of soil structural stability in this context. Depending on origin and composition of a given soil, the above properties were found to affect soil erodibility in different ways.

For Belgian soils with high silt contents, Verhaegen (1984) reported a significant positive correlation of soil erodibility with sand content, and significant negative correlations with silt content and aggregate stability. Egashira et al. (1983, 1985, 1986) found that the soil properties most indicative of their erodibility were aggregate stability (significant negative correlation) for Japanese Andisols and Ultisols, and silt content (significant positive correlation) for sandy residual soils derived from granitic rocks. For Alfisols and Ultisols from the southeastern USA, Miller and Baharuddin (1987) observed enrichment of eroded sediment in silt-sized particles, which were statistically related to water-dispersible soil silt. Soil loss was significantly positively correlated with water-dispersible clay but not with total (chemically dispersed) clay in this study. Non-dispersed particle size distribution was also suggested by Loch and Rosewell (1992) to be employed in predicting field values of soil erodibility for various Australian soils. Martz (1992) reported variations of soil erodibility with slope position for Canadian prairie Mollisols, which reflected variations in soil properties, such as sand content (significant positive correlation), silt and organic matter contents (significant negative correlations).

3.2. Erodibility of Volcanic Ash Soils

In the course of pedogenesis of volcanic ash soils, the above discussed soil properties undergo dramatic changes, thus changing the soils' resistance to water erosion. While fresh volcanic deposits with low cohesiveness may be particularly prone to erosion (Nammah et al., 1986), progressive development of volcanic ash soils leads to increased structural stability and decreased soil erodibility. Mature Andisols generally show strong resistance to water erosion, which has been ascribed to the presence of highly stable soil aggregates resulting in high permeability and rapid rainfall infiltration (Warkentin and Maeda, 1980; Shoji et al., 1993). However, erosion in Andisols has recently been reported to involve fragmentation of larger aggregates by raindrop impact and subsequent transport of smaller, stable aggregates of low bulk density by surface runoff (Rodríguez Rodríguez et al., 2002).

3.3. Soil Erosion in the Ecuadorian Andes

About half of Ecuador's land surface is threatened by erosional degradation, with inter-Andean catchments most severely affected (de Noni et al., 1997). In the Río Ambato catchment of central Ecuador, Harden (1988) estimated annual soil loss rates between 20 and 80 t ha^{-1} based on rainfall simulation experiments on bare soil. The same author suggested abandoned and fallow farmland as well as unpaved roads and trails to significantly contribute to runoff and sediment in the Río Paute catchment of southern Ecuador, while recently tilled cropland showed comparatively high infiltration and low soil erosion rates (Harden, 1993, 1996, 2001). Increased runoff and soil erosion in abandoned and fallow land and on unpaved roads and trails were attributed to lower organic matter contents and higher compaction, respectively, as compared to cultivated cropland.

In many parts of the Ecuadorian Andes, recent volcanic deposits overlie strata of cemented and indurated volcanic ash, locally known as *cangagua*. These layers have very low hydraulic conductivity and may thus cause mass movements of overlying material and high runoff when exposed at the soil surface (Nimlos and Savage, 1991; de Noni et al., 1997). At high elevations, the Andean ecosystem is dominated by natural grassland, locally named *páramo*. The soils of this zone are mostly Andisols and generally exhibit high organic matter contents and very high infiltration rates, thus generating little surface runoff and soil erosion (Harden, 1993; Perrin et al., 2001). However, disturbance of these high-elevation ecosystems through overgrazing and drying of the soil surface due to burning and bare fallowing has been found to decrease organic matter contents and increase the soils' water repellency thus leading to decreased infiltration and increased soil erosion (Poulenard et al., 2001; Podwojewski et al., 2002).

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CHAPTER 3

Pedogenesis of Volcanic Ash Soils in Andean Ecuador[1]

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[1] Zehetner, F., W.P. Miller, and L.T. West. Accepted by *Soil Science Society of America Journal*. Reprinted here with permission of publisher.

ABSTRACT

Weathering and development of volcanic ash soils show similar patterns in different regions of the world; however, the specific environmental conditions at a given location result in a unique combination of factors and processes governing soil formation. This research was conducted to study pedogenesis on volcanic slopes in the inter-Andean valley of northern Ecuador. Twelve pedons representing different pedogenic environments were sampled at elevations between 2410 and 4050 m above sea level (asl). In pedons above 3200 m asl, allophane and aluminum-humus complexes dominate the colloidal fraction, the topsoils are high in organic matter, and the soils classify as Andisols with melanic epipedons. In pedons below 2700 m asl, halloysite is the predominant colloidal constituent, the topsoils contain < 1 % organic carbon, and the soils are Inceptisols and Entisols. The pedons at intermediate elevations mark a transition zone, in which allophane and halloysite coexist and the soils generally classify as Andisols with umbric epipedons. This general altitudinal pattern was found to be altered in unstable landscape positions, where andic soil properties have been removed along with the erosion of topsoil material. Virtually the same altitudinal weathering sequence was observed in the 3000-year-old soils and in buried paleosols, which are considered to be older than 40 000 years. Thus, different time of pedogenesis has not caused marked differences in the composition of the colloidal fraction. Climate is considered the overriding factor responsible for the observed altitudinal differences in soil development by affecting leaching regime and organic matter decomposition.

INTRODUCTION

Soils derived from volcanic deposits often exhibit unique physical and chemical properties, such as low bulk density, high water retention, variable charge characteristics, and strong phosphate sorption, which have been largely ascribed to active amorphous weathering products, such as allophane, imogolite, and aluminum-humus complexes (e.g., Shoji et al., 1993; Kimble et al., 2000). The extent to which these properties are expressed in a volcanic ash soil depends therefore on its stage of soil development. Various weathering sequences have been proposed to explain the formation and transformation of colloidal constituents in volcanic ash soils under different environmental conditions.

The formation of aluminum-humus complexes has been observed in recent and buried A horizons of volcanic ash soils, and has been reported to be favored by conditions unfavorable to the formation of allophane (Shoji et al., 1982; Shoji and Fujiwara, 1984). Aluminum-humus complexes are predominant at pH (H_2O) < 5, whereas the precipitation of allophane is favored above pH 5. It has been further suggested that the precipitation of allophane is impeded by competition between humic substances and orthosilicic acid for soluble aluminum (Wada, 1989; Shoji et al., 1993).

Allophane and halloysite are the dominant components in the clay fraction of many volcanic ash soils around the world. It has been suggested that halloysite forms over time upon weathering of allophane (e.g., Wada, 1989); however, many studies have revealed that volcanic ash may weather directly to halloysite as well as to allophane (e.g., Parfitt et al., 1983; Parfitt et al., 1984; Parfitt and Wilson, 1985; Singleton et al., 1989). Silicon activity in the soil solution has been suggested as the overriding factor responsible for the preferential formation of either halloysite or allophane. Parfitt and Wilson (1985) and Singleton et al. (1989) found that halloysite was predominant when

$H_4SiO_4^0$ in soil solution exceeded 250 and 350 μmol L^{-1}, respectively, and allophane predominated below these concentrations.

A variety of factors can control soil solution chemistry and hence affect the mineralogy of a soil's colloidal fraction. Wada (1987) has suggested that in contrast with allophane, the formation of halloysite is favored by a thick depositional overburden that produces a silica-rich environment. Singleton et al. (1989) and Bakker et al. (1996) reported impeded drainage to favor halloysite formation, whereas the presence of allophane was associated with well-drained soil horizons. Parfitt et al. (1983) proposed a weathering scheme for rhyolitic ash, in which halloysite is the dominant clay mineral where the mean annual precipitation is less than approximately 1500 mm, and allophane predominates above 1500 mm. Along these lines, many subsequent studies on volcanic ash soils in different parts of the world have confirmed the importance of rainfall and leaching in mineral formation (e.g., Parfitt et al., 1984; Stevens and Vucetich, 1985; Takahashi et al., 1993; Nizeyimana et al., 1997; Nieuwenhuyse et al., 2000).

Toposequences of soils along the slopes of volcanoes have been studied to assess the effect of climate on weathering and mineral formation (Chartres and Pain, 1984; Nizeyimana et al., 1997). On an extinct volcano in Rwanda, Nizeyimana et al. (1997) found decreasing allophane contents and increasing halloysite contents with decreasing elevation, which they attributed to a concomitant decrease in rainfall. Chartres and Pain (1984) found a similar weathering pattern with elevation in highland Papua New Guinea, although there precipitation increased with decreasing elevation. They suggested that lower rates of evapotranspiration with increasing altitude caused greater leaching, thus favoring the formation of allophane.

In addition to allophane and halloysite, 2:1-type phyllosilicates with and without hydroxy-Al interlayering are commonly found in volcanic ash soils. Their occurrence has been ascribed to *in situ* pedogenic transformations (Shoji et al., 1982; Yamada and

Shoji, 1983), eolian addition (Mizota and Takahashi, 1982; Mizota, 1983), incorporation into volcanic ash during eruption (Dudas and Harward, 1975; Pevear et al., 1982; Ping et al., 1988), and mixing of recent volcanic ash with underlying paleosols (Dudas and Harward, 1975).

The above discussion suggests that similar trends in weathering and development of volcanic ash soils exist in different parts of the world. However, specific environmental conditions, such as the eruption histories of surrounding volcanoes, the composition of volcanic ejecta, present-day climate as well as paleoclimate and glaciation history, result in a unique combination of factors and processes governing soil formation at a given location. The pedogenesis of volcanic ash soils has been extensively studied in Japan and New Zealand; however, very little is known about weathering and soil formation on the slopes of volcanic peaks in the Andes. The objective of this study was, therefore, to investigate the factors and processes that affect soil development on volcanic slopes in the unique inter-Andean valley of northern Ecuador.

STUDY AREA

The study area is located on the slopes of volcano Cotacachi, about 35 km north of the equator (Fig. 3.1). The region has been largely deforested and the present landscape is dominated by agricultural land use below 3000 m above sea level (asl), and high-altitude scrubland and grassland (*matorral* and *páramo*, respectively) above 3000 m asl. The climate in the area is that of an equatorial high-altitude environment, with temperatures almost constant throughout the year, but showing pronounced diurnal oscillations. The mean annual temperature is about 15 °C in the town of Cotacachi, and drops by about 0.6 °C per 100 m of elevation increase. The mean annual precipitation is about 900 mm at 2500 m asl and increases with elevation to about 1500 mm at 4000 m asl (Nouvelot et al., 1995). The annual rainfall distribution is characterized by an expressed seasonality with a dry season from June to August, and about 90 % of the annual precipitation occurring from September to May.

The volcanic complex of Cotacachi has a long history of volcanic activity involving several different eruption centers, of which only Cuicocha has been active in the Holocene. The other centers have not erupted in the past 40 000 years (Hall and Mothes, 1994). Volcano Cuicocha has had three phases of activity which occurred over a period of a few hundred years, ending about 3000 years before present (yr BP) (Mothes and Hall, 1991; Hall and Mothes, 1994; Athens, 1999). The present caldera of Cuicocha was formed by explosive eruptions that resulted in massive pyroclastic flows, which reach from Laguna Cuicocha past the town of Cotacachi (Fig. 3.1). Tephra falls from these eruptions cover the southern slopes of volcano Cotacachi. The soils under study have formed on these deposits, which have andesitic to dacitic composition. Pedons 1-5, 10, and 11 are located on tephra deposits, and pedons 6-9 and 12 are located on pyroclastic flow deposits (Fig. 3.1). Selected site characteristics for the studied pedons are presented in Table 3.1. Small amounts (few cm) of tephra from later eruptions of surrounding volcanoes, notably Pululahua (2300 yr BP) and Quilotoa (800 yr BP), may have been deposited in the area (Hall and Mothes, 1994; Athens, 1999; Mothes and Hall, 1999) and mixed with preexisting soils.

METHODS

Soils were described and sampled according to genetic horizons, air-dried and passed through a 2-mm sieve. Particle-size distribution was determined with a combined sieve and pipette method after removal of organic matter with hydrogen peroxide and dispersion with sodium metaphosphate (Soil Survey Staff, 1996). Total carbon was determined by dry combustion (Tabatabai and Bremner, 1991). The values thus obtained were assumed to correspond to organic carbon, since the studied soils did not contain carbonate minerals. Water retention was measured after equilibration of rewet soil samples at 1.5 MPa in a pressure-plate extractor, and clay content (%) was estimated by (% H_2O retained at 1.5 MPa - % organic C) x 2.5 (Soil Survey Staff, 1998). Soil pH was measured in H_2O and 1 *M* KCl at a soil:solution ratio of 1:2.5 after 30 minutes of equilibration and in 1 *M* NaF at 1:50 after exactly 2 minutes (Soil Survey Staff, 1996). Phosphate retention was determined by measuring the percentage of P retained from 25 mL of a solution containing 1000 mg L^{-1} of P and buffered at pH 4.6 after shaking with 5 g of soil for 24 hours (Soil Survey Staff, 1996).

Dissolution analyses were conducted according to Wada (1989). Aluminum associated with soil organic matter, Al_p, was estimated by extraction with 0.1 *M* sodium pyrophosphate at pH 10 using a soil:solution ratio of 1:100 and shaking for 16 hours. Aluminum and silicon associated with active amorphous constituents, Al_o and Si_o, respectively, were estimated by extraction of ground (< 0.25 mm) samples with 0.175 *M* ammonium oxalate – oxalic acid at pH 3 using a soil:solution ratio of 1:100 and shaking for 4 hours in the dark. Aluminum and silicon were measured by inductively coupled plasma – mass spectrometry (ICP-MS). The molar Al:Si ratio of allophane was calculated from $(Al_o\text{-}Al_p)/Si_o$, and the amount of allophane in the samples was estimated by multiplying Si_o by 5, 6, 7, or 10 if the Al:Si ratio was approximately 1, 1.5, 2, or 2.5, respectively (Parfitt, 1990).

For mineralogical analyses, the clay fraction (< 2 μm) was separated from the soil samples by repeated dispersion and centrifugation after initial dispersion with ultrasonic vibration (Hunter and Busacca, 1989). The clay samples were analyzed with differential scanning calorimetry (DSC) at temperatures between 35 and 600 °C and infrared (IR) spectroscopy at wavenumbers between 400 and 4000 cm^{-1}. Oriented clay samples were prepared for x-ray diffraction (XRD) analysis using the filter-membrane technique (Drever, 1973) with the following saturation treatments: Mg-saturation, air-dried and ethylene glycol solvated; K-saturation, air-dried, and heated to 110, 300, and 550 °C. The samples were scanned from 3 to 32 °2θ with $CuK\alpha_{1,2}$ radiation and a curved crystal monochromator.

RESULTS

General Soil Properties

Selected characteristics of the studied pedons are presented in Table 3.2. In eight of the twelve pedons, the recent soil is overlying a paleosol formed on older volcanic deposits, and in three pedons (9, 10, and 11), more than one volcanic paleosol is found within a depth of 300 cm.

Formed on sandy and silty volcanic deposits, the studied soils generally exhibit low clay contents; however, in high-elevation pedons, incomplete dispersion of soil samples may have lead to an underestimation of clay contents measured with the pipette method, as indicated by considerably lower values than estimated from H_2O retention (Table 3.2). Topsoil clay contents increase with elevation, and in pedons above 2700 m asl, they are consistently higher than in underlying recent Bw and C horizons. On the other hand, clay contents of recent A horizons do not differ greatly from those of underlying recent Bw and C horizons in pedons below 2700 m asl. The clay contents of paleosols are generally higher than those of recent soils.

Organic carbon contents of both recent and buried A horizons increase with altitude. Given the same age of the recent parent materials, average carbon sequestration rates appear to be an order of magnitude higher in high-elevation pedons compared to low-elevation pedons. Soil pH (H_2O) values decrease with increasing elevation, and are generally lower in recent A horizons than in underlying soil horizons including buried A horizons. In all the studied pedons, pH (KCl) is consistently lower than pH (H_2O), indicating exchangeable acidity in these soils.

Amorphous Colloidal Constituents

The results of the dissolution analyses and properties related to amorphous material are presented in Table 3.3. In pedons at elevations above 3200 m asl, pH (NaF) values are generally above 9.4 in the entire profile, i.e. in recent soils and underlying paleosols. This indicates the dominant presence of active Al-OH groups in the exchange complex of these soils (Wada, 1980). In pedons between 3200 and 2700 m asl, pH (NaF) values are above 9.4 only in the upper horizons, and in pedons below 2700 m asl, pH (NaF) values are below 9.4 in all horizons. Phosphate retention shows similar trends as pH (NaF) with the highest values in high-elevation pedons, high values in the upper horizons of pedons at intermediate elevations, and low values in all horizons of low-elevation pedons.

Pyrophosphate-extractable aluminum (Al_p) is correlated with organic C (r = 0.91***) and generally increases with elevation. Acid oxalate-extractable aluminum and silicon (Al_o and Si_o, respectively) confirm the trends observed for pH (NaF) and PO_4 retention, and are particularly high in buried A horizons of high-elevation pedons (Table 3.3).

The molar ratios of pyrophosphate-extractable Al to organic C (Al_p/C) were calculated for recent and buried A horizons (Table 3.3). The Al_p/C ratios of recent A horizons are significantly higher in pedons above 2700 m asl than in pedons below (α = 0.05), and buried A horizons generally have higher Al_p/C ratios than recent A horizons. The 2Ab2 and 3Ab horizons of pedon 10 and the 3Ab horizon of pedon 11 exhibit particularly high Al_p/C ratios (0.16 – 0.19). Aluminum appears to be bound very strongly to organic functional groups in these horizons, exceeding the extraction power of ammonium oxalate – oxalic acid, which results in negative values of Al_o-Al_p (Table 3.3).

The clay fractions of the studied soils exhibit a single IR absorption maximum around 1000 cm^{-1} (data not shown) and show no dehydroxylation between 300 and 400 °C (Fig. 3.2), which rules out the presence of imogolite. Therefore, silicon extracted with acid oxalate (Si_o) is assumed to originate from allophane, although some of it may arise from incongruent dissolution of poorly ordered minerals, such as embryonic halloysite (Wada and Kakuto, 1985). In the studied soils, allophane contents increase with altitude and are highest in the three highest-elevation pedons (above 3200 m asl), where significant amounts are found in the entire profile. In pedons at intermediate elevations (3200 – 2700 m asl), allophane is found in smaller quantities and predominantly in the upper part of the profile, and in low-elevation pedons (below 2700 m asl), allophane contents are generally below 1 % (Table 3.3).

The molar ratios of Al_p/Al_o, calculated for soil horizons with ≥ 1 % allophane (Table 3.3), reveal that in recent A horizons of high-elevation pedons, the majority of active aluminol groups pertains to Al-humus complexes ($Al_p/Al_o > 0.5$), whereas in subsurface horizons including buried A horizons, the majority of active Al-OH groups appears to be associated with allophane ($Al_p/Al_o < 0.5$).

Crystalline Colloidal Constituents

Pedons 2, 3, and 4, representing a toposequence on the slopes of Cerro Huanansí (Table 3.1, Fig. 3.1), were selected to further study the mineralogy of the soil colloidal fraction at elevations ranging from 3000 to 3900 m asl. The clay fractions of C horizons from recent soils and paleosols were analyzed with differential scanning calorimetry (DSC; Fig. 3.2) and x-ray diffractometry (XRD; Figs. 3.3 and 3.4).

In recent C horizons of pedons 2 and 3 (3900 and 3400 m asl, respectively), a large endothermic peak between 35 and 150 °C was found, which is attributed to the removal of large amounts of adsorbed water, presumably associated with allophane, but no further DSC peaks were detected above 150 °C (Fig. 3.2). On the other hand, recent C horizons of pedon 4 (3000 m asl) show a rather small water peak between 35 and 100 °C, but exhibit a distinct endothermic peak between 400 and 500 °C, which is larger in the C1 than in the C2 horizon. In the paleosol, pedon 3 shows a small and pedon 4 a large endothermic peak between 400 and 500 °C (Fig. 3.2). This peak is considered to arise from the dehydroxylation of kaolin minerals, such as halloysite. It occurs at lower temperatures in the studied clay samples than in the reference pure halloysite sample (Fig. 3.2), which may be due to smaller crystal sizes in the studied clays.

The XRD patterns of pedons 2 and 3 reveal that the C1 horizons of both pedons are devoid of clay minerals (Fig. 3.3). However, in the C2 horizons, a prominent reflection at 1.4 nm was found with Mg saturation, part of which expanded upon ethylene glycol (EG) solvation. Saturation with K resulted in partial collapse of this reflection, which gradually shifted toward 1 nm upon heating to 110, 300, and 550 °C (Fig. 3.3). This indicates the presence of smectitic (and possibly vermiculitic) layers with partial hydroxy-Al interlayering. The peak at 0.7 nm is believed to correspond with the 002 reflections from the 1.4-nm phases, since the DSC data of these horizons did not indicate the presence of kaolin minerals (Fig. 3.2).

The C1 horizon of pedon 4 exhibits a 1.4-nm reflection with Mg saturation that expands upon EG solvation and collapses to 1 nm with K saturation, and is therefore considered to pertain to smectite (Fig. 3.3). The same horizon further shows a broad reflection between 0.72 and 1 nm, part of which expands to near 1.1 nm when solvated with EG. The reflection sharpens and collapses to near 0.72 nm when heated to 110 and 300 °C and disappears when further heated to 550 °C (Fig. 3.3). This is attributed to the presence of two populations of halloysite, i.e. the 7 Å and the hydrated 10 Å forms, respectively. The C2 horizon of pedon 4 shows a similar XRD pattern, indicating the presence of smectite and halloysite. However, the reflections are weaker and the collapsed halloysite peak (after heating to 110 and 300 °C) is broader than in the horizon above (Fig. 3.3). This suggests that the crystallinity of halloysite decreases from the C1 to the underlying C2 horizon of pedon 4.

In the paleosol, smectite was not detected; however, both 7 Å and 10 Å halloysite was found in pedon 3 (Fig. 3.4), and only hydrated (10 Å) halloysite was found in pedon 4 (Fig. 3.4). The collapsed halloysite peaks are sharper in the paleosols than in the recent soils (Figs. 3.3 and 3.4), indicating higher crystallinity in the former.

The presence of halloysite in recent soils and paleosols of pedons below 3000 m asl was further confirmed by XRD analysis (data not shown). A diffuse, broad hump above 20 °2θ observed in the XRD patterns of the studied clay samples is ascribed to the presence of pyroclastic glass.

DISCUSSION

Genesis and Classification of Recent Soils

With an age of approximately 3000 years, the soils formed on the recent volcanic deposits of the study area are considered to be in their early stages of development. This is also evident from their generally low clay contents and the abundance of primary minerals and pyroclastic glass. However, there appear to be dramatic altitudinal differences as to the path and rate at which pedogenesis proceeds in the area under study. Key soil properties of recent A horizons, such as organic carbon content, acid oxalate-extractable aluminum, and PO_4 retention, are significantly correlated with elevation (r = 0.93***, 0.83***, and 0.90***, respectively) and suggest grouping of the studied pedons into three elevation zones, i.e. a high zone above 3200 m asl, an intermediate zone between 3200 and 2700 m asl, and a low zone below 2700 m asl. The above-mentioned soil properties are significantly different ($\alpha = 0.05$) between these three zones. The observed altitudinal trends correspond with climatic differences as determined by elevation on the volcano; however, these differences are interrelated with differences in land use and vegetation. At higher elevations, higher rainfall and lower evapotranspiration (ET) caused by lower temperatures and higher humidity, result in greater leaching and less pronounced seasonal drying. As precipitation decreases and ET increases with decreasing elevation, the soils experience less leaching and a pronounced period of desiccation during the dry season.

The high-leaching environment at elevations above 3200 m asl has resulted in the formation of andic soil properties, as defined by Soil Survey Staff (1998) and manifested by the dominant presence of active aluminol groups associated with allophane and Al-humus complexes as well as by high PO_4 retention. High additions of organic matter from the *páramo* vegetation combined with slowed decomposition due to low temperatures, low pH values, and the presence of stabilizing Al-humus complexes may have caused the increased accumulation of organic C and the formation of melanic epipedons at these elevations. The soils are classified as Melanocryands and Melanudands, which due to their relatively weak development and comparatively low contents of weathering products belong to the Vitric and Pachic Vitric subgroups, respectively (Table 3.1). The colloidal fraction of these soils is dominated by amorphous constituents and characterized by the absence of halloysite. The predominance of Al-humus complexes over allophane in the uppermost horizons of the highest-elevation pedons is believed to be mainly a result of pH (H_2O) values < 5 in these horizons, which have been shown to inhibit the formation of allophane and favor that of Al-humus complexes (Shoji et al., 1982; Shoji and Fujiwara, 1984). The increased presence of organic ligands in these horizons may have further impeded the precipitation of allophane by competition with orthosilicic acid for soluble aluminum.

Evidence of 2:1-type phyllosilicates with partial hydroxy-Al interlayering was found in the C2 horizons of pedons 2 and 3, whereas the overlying C1 horizons as well as the underlying C3 horizon (pedon 2) did not contain clay minerals (Fig. 3.3). Since no A horizons were found in between the three tephra layers, they are considered to arise from consecutive eruptions of more or less the same age. Because of the isolated occurrence of 2:1-type phyllosilicates in only the C2 horizons, it is believed that incorporation during eruption, as reported by Dudas and Harward (1975), Pevear et al. (1982), and Ping et al. (1988), is the likely origin of the observed clay mineral association. The presence of expandable silicate layers may have counteracted the formation of allophane by competition with orthosilicic acid for hydroxy-Al polymers, thus resulting in lower allophane contents in the C2 horizons than in the C1 horizons above (Table 3.3).

As leaching decreases with decreasing elevation, andic soil properties become less strongly expressed and are confined to the upper horizons in pedons between 3200 and 2700 m asl, disappearing completely in pedons below 2700 m asl. Organic matter contents decrease with decreasing elevation, presumably because of less additions in cultivated land and more rapid decomposition due to higher temperatures, higher pH values, and lower amounts of stabilizing Al-humus complexes. This has resulted in the formation of umbric epipedons at intermediate elevations (3200 – 2700 m asl) and ochric epipedons containing < 1 % organic C at elevations below 2700 m asl. At intermediate elevations, the soils are classified as Humic Udivitrands with the exception of pedon 4, which has andic soil properties in the A horizon, but does not meet the depth requirement for Andisols (Soil Survey Staff, 1998) and is therefore classified in the Andic subgroup of Inceptisols (Table 3.1). At elevations below 2700 m asl, the soils are classified as Dystrudepts in the presence, and Udorthents in the absence of a Bw horizon, all belonging to the Vitrandic subgroup due to high contents of pumice fragments and pyroclastic glass (Table 3.1).

Pedon 4 is located on the lower backslope of Cerro Huanansí, with pedons 2 and 3 located close to the summit and on the middle part of the backslope, respectively, and pedon 5 just 50 m below pedon 4, on the upper part of a depositional fan with considerably lower slope gradient (Fig. 3.1). The influence of topography on pedogenesis has been shown by Chen et al. (1999), who studied a toposequence of volcanic ash soils in subtropical Taiwan and attributed thinner sola and lower topsoil organic matter contents in backslope positions to increased lateral water flow and surface runoff. The toposequence of Cerro Huanansí demonstrates the impact of topography on soil development in the area under study. While the summit pedon has two A horizons reaching to a depth of 100 cm, the topsoils are considerably shallower (40 and 30 cm) in the middle and lower backslope positions, respectively (Table 3.2). This is likely the result of translocation of topsoil material downslope, which has been deposited where the gradient shows a sharp decline, as evident from the presence of four A horizons reaching to a depth of 150 cm in pedon 5 (Table 3.2). Thus, whereas pedons 2, 3, and 5 are classified as Andisols, the removal of andic soil properties along with the erosion of topsoil material results in the classification of pedon 4 as an Inceptisol.

As a result of drier conditions, halloysite becomes increasingly dominant in the colloidal fraction of pedons below 3200 m asl, whereas allophane and Al-humus complexes only occur in the upper profile of pedons between 3200 and 2700 m asl and are absent below 2700 m asl. Larger amounts and higher crystallinity of halloysite in the C1 than in the underlying C2 horizon of pedon 4 (Figs. 3.2 and 3.3) suggest pedogenic origin with enhanced weathering closer to the soil surface. The coexistence of allophane and halloysite in recent soils at intermediate elevation marks a transition from the allophane-dominated soils at high elevation to the halloysite-dominated soils at low elevation. Leaching during the rainy season appears to lower soil solution Si activity sufficiently in the upper profile and thus trigger the formation of allophane in the upper soil horizons of this transition zone, whereas desiccation during the dry season may promote the formation of halloysite. Similar differential formation of amorphous and crystalline weathering products with fluctuating leaching and desiccation periods has been proposed by Takahashi et al. (1993) for volcanic ash soils in the xeric moisture regime of northern California.

Elevated topsoil clay contents in pedons above 2700 m asl may be the result of a more aggressive weathering environment involving greater leaching and diurnal freeze – thaw cycles; however, part of the clay fraction may arise from minor additions of fine-textured tephra from surrounding volcanoes, which may have been deposited in the higher-lying western part of the study area. The lower soil pH (H_2O) values at higher elevations are believed to arise from greater proton inputs with increased precipitation, greater leaching of basic cations, and greater activity of organic acids as a result of slowed organic matter decomposition.

Pedogenesis of Paleosols

Paleosols buried by the recent volcanic deposits are frequently encountered in the study area. Some mixing of new deposits with the old surface may have occurred upon deposition of recent tephra. This seems to be noticeable in pedons 1-4, where the upper Ab horizons have significantly lower organic C contents than the Ab horizons underneath (Table 3.2). The pedogenesis of paleosols has been taking place over a longer time and under climatic conditions that may have deviated from those of the present day.

It has been shown for volcanic ash soils that humus evolves over time from forms with low complexing ability to forms with high complexing ability for aluminum (Wada, 1980). This appears to be the case in the paleosols of pedons 10 and 11, which are highly compacted and presumably represent the oldest soils encountered in the study area. Higher clay contents and smaller amounts of primary minerals as compared to the recent soils reflect the prolonged exposure of paleosols to the processes of weathering. Nevertheless, the composition of their colloidal fraction shows virtually the same altitudinal sequence observed in the recent soils, with allophane and Al-humus complexes dominating at higher elevations and halloysite dominating at lower elevations. However, the contents of these constituents are higher in paleosols than in recent soils (Table 3.3, Fig. 3.2).

The highest allophane contents among the studied soils were found in paleosols above 3200 m asl (Table 3.3). This may reflect longer soil development as well as differences in parent material compared to the overlying recent soils. The paleosols of pedons 1 and 2 are believed to have formed after the last glaciation, which reached as low as 3400 – 3600 m asl (Schubert and Clapperton, 1990), approximately 10 000 to 12 000 years ago. The paleosols of pedons 3 and 4 have formed on tephra deposits that are believed to be associated with earlier eruptions from the volcanic complex of Cotacachi with an age of more than 40 000 years (Hall and Mothes, 1994). In a road cut near pedon 1, the buried A horizons were found to directly overlie what appear to be colluvial deposits of unweathered volcanic rocks. The abrupt boundary between this colluvium and the deepest Ab horizon and the absence of weathered rock fragments in the Ab horizon point to a paleosol parent material different from the colluvium, possibly glacial outwash deposited on top of the colluvium. In this case, the parent material could have been pre-weathered and already contained allophane at the beginning of post-glacial pedogenesis in the early Holocene, which would explain the relatively high allophane contents in the 2Ab3 horizon of pedon 1 (Table 3.3).

Wada (1980) reported interaction of soil organic matter with allophane in buried A horizions to result in the formation of stable silt- and sand-size aggregates that are resistant to dispersion. The presence of such aggregates in the Ab horizons of high-elevation pedons is suggested by pronounced differences between measured and estimated clay contents (Table 3.2). In these horizons, complexation with humic substances may have stabilized and protected allophane against dissolution and thus fostered its accumulation over time. A significant fraction of the humus complexing sites may be associated with aluminum from allophanic structures, possibly through ligand exchange of carboxyl groups to aluminol surface groups (Harsh, 2000).

Small amounts of fairly crystalline halloysite were found in the 2C3 horizon of pedon 3 (Figs. 3.2 and 3.4), which also contains significant amounts of allophane (Table 3.3). The presence of halloysite in the paleosol of this pedon may be explained by increased Si inputs due to leaching from the recent depositional overburden. In that case, the conditions favoring halloysite formation would have been established with the deposition of recent tephra about 3000 yr BP. However, the halloysite found in the paleosol of pedon 3 is clearly more crystalline than that found in the recent tephra of pedon 4 (Figs. 3.3 and 3.4). This suggests that the former has formed over a longer time, possibly under different climatic conditions. In fact, pollen analysis in lacustrine sediments near the study area reveal evidence for a drier climate in the late-glacial period (Colinvaux et al., 1988), which could have resulted in the preferential formation of halloysite in pedon 3. As the climate became moister at the beginning of the Holocene (Colinvaux et al., 1988), increased leaching may have lowered soil solution Si activities thus favoring the dissolution of halloysite and the precipitation of allophane.

SUMMARY AND CONCLUSIONS

In the area under study, three altitudinal zones can be distinguished with respect to soil formation; i.e. a high zone above 3200 m asl, an intermediate zone between 3200 and 2700 m asl, and a low zone below 2700 m asl. In the high zone, the soil colloidal fraction is dominated by amorphous material and the soils are Andisols with melanic epipedons. In the low zone, halloysite is the predominant colloidal constituent and the soils are Inceptisols and Entisols. The intermediate zone is a transition zone in which allophane and halloysite coexist. The soils of this zone are generally Andisols with umbric epipedons.

This altitudinal weathering sequence was observed in the 3000-year-old recent soils and in paleosols considered older than 40 000 years, which shows that different time of soil development has not caused marked differences in the formation and transformation of colloidal weathering products.

Climate is considered the overriding factor responsible for the observed altitudinal differences in soil development. Differences in rainfall and evapotranspiration resulting in different leaching regimes are believed to have caused the differential formation of allophane or halloysite and thus the differential development of andic soil properties. Temperature has further affected organic matter decomposition causing increased accumulation with elevation and thus resulting in the altitude-dependent formation of different epipedons.

There is some evidence that halloysite formed at higher elevations under the drier climatic conditions of the late-glacial. Thus, while the observed trends suggest altitudinal zonation with respect to soil formation, the boundaries between the zones may shift according to climatic changes over time.

Moreover, the effects of topography on soil development may be superimposed on the general altitudinal trends, as observed on the steep sloping parts of the study area, where andic soil properties have been removed from backslope positions along with the erosion of topsoil material.

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Table 3.1. Site information for the studied pedons.

Pedon	Location	Northing†	Easting†	Elevation	Land use	Soil classification‡
		m	m	m asl§		
1	Antenas	37 602	796 351	4050	*Páramo*¶	Vitric Melanocryands
2	Cerro Huanansí	37 596	798 308	3900	*Páramo*	Vitric Melanocryands
3	Cerro Huanansí	36 668	798 689	3400	*Matorral*#	Pachic Vitric Melanudands
4	Cerro Huanansí	35 731	799 010	3000	Pasture	Andic Dystrudepts
5	Iltaquí Alto	35 600	799 229	2950	Cropland	Humic Udivitrands
6	La Piyaba	33 341	795 921	3060	*Matorral*	Humic Udivitrands
7	Morochos	33 293	797 508	2900	Cropland	Humic Udivitrands
8	Morochos	32 664	799 252	2740	Cropland	Humic Udivitrands
9	Chilcapamba	32 899	801 233	2570	Cropland	Vitrandic Dystrudepts
10	Iltaquí Bajo	33 429	801 258	2560	Cropland	Vitrandic Udorthents
11	Topo Grande	34 939	801 793	2630	Cropland	Vitrandic Udorthents
12	Pilchibuela	34 146	805 607	2410	Forest	Vitrandic Udorthents

† Datum: Provisional South American 1956; Ellipsoid: International. Projection: UTM; Zone: 17N.
‡ According to Soil Survey Staff (1998).
§ asl ... above sea level.
¶ Local term for high-altitude grassland.
\# Local term for scrubland.

Table 3.2. Selected characteristics of the studied pedons.

Horizon	Depth	pH (H_2O)	pH (KCl)	Organic C	Sand	Silt	Clay	Estimated clay†	H_2O retention at 1.5 MPa
	cm			%					
Pedon 1, 4050 m asl‡									
A	0 - 60	4.8	4.3	7.5	46.4	40.2	13.3	15	13.4
AB	60 - 85	5.1	4.6	3.8	71.6	21.9	6.5	20	11.7
Bw	85 - 105	5.6	4.8	1.4	78.8	18.9	2.2	11	5.6
C1	105 - 125	5.4	4.9	0.5	60.8	35.0	4.1	8	3.6
C2	125 - 155	5.7	4.9	0.3	61.2	34.0	4.8	6	2.8
C3	155 - 165	5.7	4.9	0.3	66.5	30.1	3.4	4	2.0
C4	165 - 175	5.4	4.8	0.2	85.2	12.0	2.8	4	1.8
C5	175 - 195	5.5	4.9	0.2	63.3	31.9	4.7	6	2.8
C6	195 - 210	5.6	4.9	0.2	77.3	19.0	3.8	4	1.9
C7	210 - 225	5.5	4.8	0.0	70.8	25.3	3.9	6	2.4
C8	225 - 240	5.9	4.9	0.0	88.5	11.0	0.5	3	1.1
2Ab1	240 - 260	5.9	4.9	3.5	48.0	46.0	6.0	17	10.3
2Ab2	260 - 275	5.5	5.0	3.7	46.7	47.5	5.8	23	12.9
2Ab3	275 - 320	5.6	5.1	7.0	71.5	21.4	7.1	51	27.3
R	320+								
Pedon 2, 3900 m asl									
A1	0 - 50	4.6	4.3	10.3	31.3	41.1	27.7	31	22.6
A2	50 - 100	5.3	4.8	4.1	71.4	23.7	4.8	16	10.5
C1	100 - 115	6.0	5.2	1.9	57.2	38.6	4.2	13	7.3
C2	115 - 140	5.7	5.1	0.9	58.0	37.5	4.4	8	4.0
C3	140 - 175	5.9	4.9	0.2	90.3	7.1	2.6	2	1.0
2Ab1	175 - 200	5.5	5.0	2.4	53.6	37.7	8.7	13	7.6
2Ab2	200 - 220	5.6	5.0	2.0	50.3	39.9	9.8	16	8.4
2Ab3	220 - 270	5.6	5.0	6.4	39.7	46.2	14.1	37	21.1
R	270+								
Pedon 3, 3400 m asl									
A	0 - 40	5.4	4.5	7.7	45.2	37.3	17.5	24	17.4
AC	40 - 55	5.3	4.9	2.4	63.5	31.2	5.4	13	7.7
C1	55 - 70	5.7	4.9	1.2	64.8	30.3	4.9	8	4.5
C2	70 - 90	5.8	5.0	0.6	84.0	12.2	3.8	4	2.3
2Ab1	90 - 110	5.7	4.7	2.0	72.2	20.4	7.4	9	5.7
2Ab2	110 - 180	5.8	4.9	6.3	42.8	41.2	16.0	32	18.9
2Ab3	180 - 200	5.7	5.1	4.2	71.3	16.8	11.9	31	16.5
2C3	200 - 300+	5.7	5.1	0.6	79.9	12.4	7.7	17	7.4
Pedon 4, 3000 m asl									
A	0 - 30	5.3	4.7	3.4	49.3	42.7	8.0	13	8.7
C1	30 - 55	5.7	4.5	0.1	65.2	26.3	8.5	10	4.1
C2	55 - 75	5.9	4.5	0.0	73.2	21.1	5.7	6	2.3
C3	75 - 110	5.8	4.7	0.0	84.2	13.1	2.7	5	1.8
2Ab1	110 - 160	5.8	5.0	0.7	48.6	34.1	17.3	16	7.1
2Ab2	160 - 200	5.8	5.0	2.0	19.6	35.3	45.1	41	18.2
2ABb	200 - 230	5.9	4.9	0.5	29.2	29.5	41.3	56	22.9
2Bwb	230 - 240	6.0	4.9	0.4	38.0	32.3	29.7	49	20.1
2C4	240 - 270	6.0	4.8	0.2	46.0	30.2	23.9	38	15.4
2C5	270 - 305+	6.0	4.8	0.0	61.2	32.3	6.5	18	7.0
Pedon 5, 2950 m asl									
A1	0 - 20	5.6	4.9	3.6	54.5	34.0	11.5	14	9.0
A2	20 - 90	5.8	4.8	3.0	41.4	53.0	5.6	13	8.1
A3	90 - 110	5.8	4.9	1.8	60.5	30.0	9.6	9	5.4
A4	110 - 150	5.8	4.9	1.8	64.2	26.6	9.1	10	5.6
AC1	150 - 230	5.9	4.9	0.5	69.8	25.4	4.8	7	3.1
AC2	230 - 255	5.9	5.0	0.5	72.1	22.4	5.5	6	3.0
C	255 - 300+	5.8	5.1	0.0	88.1	9.6	2.3	3	1.1
Pedon 6, 3060 m asl									
A	0 - 40	5.4	4.9	6.4	53.1	25.9	21.0	19	14.2
Bw	40 - 45	5.8	4.9	0.8	81.6	13.7	4.8	5	2.7
BC	45 - 60	5.7	4.8	0.2	93.2	5.5	1.3	2	1.0
C	60 - 130+	5.6	4.7	0.0	89.7	8.2	2.1	3	1.1

Continued next page.

Table 3.2. Continued.

Horizon	Depth	pH (H_2O)	pH (KCl)	Organic C	Sand	Silt	Clay	Estimated clay†	H_2O retention at 1.5 MPa
	cm			%					
Pedon 7, 2900 m asl‡									
A1	0 - 30	6.2	5.4	3.1	46.5	38.8	14.7	15	9.0
A2	30 - 55	5.7	4.9	2.2	51.3	37.6	11.1	14	7.7
A3	55 - 70	6.3	5.1	0.9	74.9	17.8	7.3	9	4.6
Bw	70 - 85	6.4	5.1	0.3	84.4	12.9	2.8	5	2.2
C1	85 - 100	6.5	4.9	0.0	81.9	15.8	2.3	4	1.5
C2	100 - 110	6.3	4.9	0.0	84.7	12.2	3.0	4	1.5
C3	110 - 125	6.3	4.7	0.0	80.6	16.8	2.6	5	2.0
C4	125 - 155+	6.3	4.7	0.0	90.6	6.9	2.5	2	1.0
Pedon 8, 2740 m asl									
Ap	0 - 13	6.1	5.1	2.3	53.3	37.7	9.1	8	5.4
A1	13 - 70	5.6	4.6	2.1	53.0	37.6	9.3	8	5.5
A2	70 - 100	5.0	4.6	1.8	59.3	29.9	10.8	10	5.8
Bw	100 - 120	5.8	4.4	0.2	78.3	16.9	4.8	5	2.4
C	120 - 400+	6.0	4.5	0.0	86.1	10.1	3.9	3	1.2
Pedon 9, 2570 m asl									
Ap	0 - 13	7.0	6.2	0.9	75.9	19.9	4.2	5	2.9
A	13 - 53	7.1	6.4	0.5	74.2	20.7	5.2	4	2.3
Bw	53 - 86	7.2	6.3	0.6	49.9	42.1	8.0	8	3.8
2Ab	86 - 112	7.1	6.2	0.5	60.9	32.2	6.9	8	3.5
2C1	112 - 132	6.5	5.8	0.0	92.5	6.5	1.0	3	1.0
3ABb	132 - 150	7.0	6.2	0.5	61.7	32.0	6.3	4	2.3
4Ab1	150 - 190	7.0	6.1	0.5	62.6	30.3	7.1	10	4.6
4Ab2	190 - 220	7.0	6.1	0.5	68.3	25.9	5.8	10	4.7
4Bwb1	220 - 240	6.8	5.8	0.0	90.7	6.5	2.9	4	1.7
4Bwb2	240 - 250	6.7	5.8	0.1	89.0	8.1	3.0	3	1.4
4Bwb3	250 - 290	7.1	5.8	0.0	75.3	19.7	4.9	6	2.5
4C2	290 - 340+	6.9	5.4	0.0	77.3	17.3	5.3	5	2.2
Pedon 10, 2560 m asl									
A	0 - 75	5.9	4.7	0.3	87.4	9.7	2.9	4	2.0
C1	75 - 80	6.1	4.8	0.0	93.9	5.6	0.6	3	1.1
C2	80 - 100	6.1	4.8	0.0	74.6	21.9	3.5	2	1.0
C3	100 - 105	6.4	4.8	0.0	79.7	18.7	1.7	3	1.3
C4	105 - 120	6.3	4.7	0.0	58.8	37.1	4.1	4	1.5
C5	120 - 130	6.0	4.6	0.0	42.2	51.8	5.9	6	2.3
C6	130 - 140	6.1	4.7	0.0	57.1	36.0	7.0	7	2.8
C7	140 - 145	6.5	4.8	0.0	74.7	22.9	2.5	3	1.3
C8	145 - 165	6.7	4.8	0.0	25.4	65.6	9.0	9	3.6
C9	165 - 175	6.2	5.0	0.0	73.7	24.5	1.9	3	1.2
C10	175 - 178	6.7	5.6	0.0	75.3	22.4	2.3	2	0.9
C11	178 - 180	6.7	5.7	0.2	76.8	19.8	3.4	2	0.9
C12	180 - 200	6.3	4.9	0.0	83.4	13.2	3.4	1	0.6
2Ab1	200 - 215	6.7	5.7	0.5	72.7	22.9	4.4	4	2.1
2Ab2	215 - 245	6.2	5.3	0.6	56.4	30.4	13.2	13	5.7
2C13	245 - 263	6.6	4.7	0.0	52.0	40.0	8.0	11	4.3
3Ab	263 - 300+	6.6	5.6	1.7	18.6	52.4	29.1	31	14.3
Pedon 11, 2630 m asl									
A	0 - 70	6.5	5.4	0.6	68.3	24.4	7.3	6	3.1
C1	70 - 90	6.6	5.4	0.0	63.7	29.9	6.3	6	2.5
C2	90 - 130	6.1	4.5	0.0	69.3	25.6	5.0	6	2.5
2Ab	130 - 160	6.5	5.4	0.5	60.9	26.2	12.9	12	5.4
2C3	160 - 200	6.4	5.0	0.0	53.0	34.7	12.4	12	4.9
3Ab	200 - 250+	6.6	5.7	1.5	25.1	45.7	29.2	29	13.3
Pedon 12, 2410 m asl									
A1	0 - 65	5.8	5.1	0.4	76.1	20.1	3.8	4	2.1
A2	65 - 75	6.2	5.7	0.6	71.6	23.3	5.1	5	2.7
AC	75 - 85	6.3	5.6	0.2	75.7	20.9	3.4	4	1.7
C1	85 - 140	6.2	5.2	0.0	78.7	18.8	2.5	3	1.0
C2	140 - 150	6.2	5.4	0.0	76.8	20.2	3.0	4	1.5
C3	150 - 160	6.4	5.3	0.1	53.4	43.1	3.5	2	0.8
2Ab1	160 - 190	6.5	6.0	0.5	65.3	29.2	5.4	7	3.4
2Ab2	190 - 200	6.8	6.3	0.5	69.9	26.7	3.4	5	2.5
2C4	200 - 240+	6.6	6.0	0.0	63.1	33.4	3.5	5	1.9

† Estimated clay (%) = (% H_2O retained at 1.5 MPa - % organic C) x 2.5 (Soil Survey Staff, 1998).
‡ asl ... above sea level.

Table 3.3. Dissolution analyses and properties related to amorphous material in the studied pedons.

Horizon	Al_p†	Al_o‡	Si_o‡	Al_o-Al_p	(Al_o-Al_p)/Si_o	Al_p/Al_o	Al_p/C	Allophane	pH (NaF)	PO_4 retention
	g kg^{-1}				molar			%		%
Pedon 1, 4050 m asl§										
A	7.0	12.0	3.9	5.0	1.4	0.6	0.04	2.3	10.82	90
AB	4.4	15.6	6.6	11.2	1.8	0.3	-	4.6	10.48	89
Bw	2.4	12.9	6.1	10.5	1.8	0.2	-	4.3	10.48	67
C1	0.7	7.7	4.1	7.0	1.8	0.1	-	2.9	10.47	46
C2	0.5	7.1	4.1	6.7	1.7	0.1	-	2.5	10.22	30
C3	0.4	4.9	2.8	4.6	1.7	0.1	-	1.7	10.09	39
C4	0.2	4.2	2.4	3.9	1.7	0.1	-	1.4	9.58	23
C5	0.4	6.4	3.6	6.0	1.8	0.1	-	2.5	10.25	37
C6	0.2	4.2	2.5	4.0	1.7	0.1	-	1.5	9.79	24
C7	0.2	4.5	2.6	4.3	1.7	0.0	-	1.6	9.53	29
C8	0.1	2.6	1.6	2.5	-	-	-	< 1	9.35	14
2Ab1	2.5	10.6	5.8	8.2	1.5	0.2	0.03	3.5	9.79	59
2Ab2	3.0	18.9	11.4	15.9	1.5	0.2	0.04	6.8	9.78	78
2Ab3	4.7	48.0	28.7	43.3	1.6	0.1	0.03	17.2	10.14	98
Pedon 2, 3900 m asl										
A1	10.1	12.9	2.6	2.9	1.2	0.8	0.04	1.3	10.83	91
A2	4.9	15.5	6.5	10.6	1.7	0.3	0.05	3.9	10.96	87
C1	2.6	15.9	8.5	13.3	1.6	0.2	-	5.1	10.57	78
C2	1.5	9.4	5.5	7.9	1.5	0.2	-	3.3	10.26	52
C3	0.5	3.0	2.0	2.5	1.3	0.2	-	1.2	9.21	18
2Ab1	2.9	10.2	5.1	7.3	1.5	0.3	0.05	3.1	10.16	65
2Ab2	2.5	10.5	5.6	8.0	1.5	0.2	0.05	3.3	10.03	67
2Ab3	7.8	22.9	11.6	15.1	1.4	0.3	0.05	6.9	9.82	92
Pedon 3, 3400 m asl										
A	7.6	14.0	4.5	6.4	1.5	0.5	0.04	2.7	10.57	88
AC	4.0	15.8	7.1	11.8	1.7	0.3	-	4.3	10.82	79
C1	2.3	11.6	5.7	9.3	1.7	0.2	-	3.4	10.63	57
C2	1.1	5.8	3.1	4.7	1.6	0.2	-	1.9	9.90	30
2Ab1	2.8	6.1	2.5	3.4	1.4	0.4	0.06	1.5	9.83	50
2Ab2	7.4	13.9	5.7	6.5	1.2	0.5	0.05	2.8	9.30	81
2Ab3	6.3	28.8	14.7	22.4	1.6	0.2	0.07	8.8	10.02	92
2C3	1.3	13.6	8.2	12.3	1.6	0.1	-	4.9	9.63	54
Pedon 4, 3000 m asl										
A	3.6	10.2	3.9	6.6	1.8	0.3	0.05	2.8	10.39	61
C1	0.4	2.7	1.5	2.3	-	-	-	< 1	8.22	13
C2	0.2	1.7	1.0	1.5	-	-	-	< 1	7.93	8
C3	0.2	1.1	0.8	0.9	-	-	-	< 1	7.82	7
2Ab1	1.7	2.0	1.3	0.3	-	-	0.12	< 1	8.01	14
2Ab2	4.1	6.6	2.6	2.5	1.0	0.6	0.09	1.3	8.27	39
2ABb	2.8	7.3	2.5	4.5	1.8	0.4	-	1.8	8.07	38
2Bwb	2.0	8.1	2.7	6.1	2.3	0.2	-	2.7	8.04	28
2C4	1.7	5.2	1.9	3.5	1.9	0.3	-	1.3	8.28	20
2C5	0.4	2.6	1.4	2.2	-	-	-	< 1	8.08	6
Pedon 5, 2950 m asl										
A1	3.0	7.2	2.7	4.2	1.6	0.4	0.04	1.6	9.40	46
A2	3.4	7.2	3.1	3.8	1.3	0.5	0.05	1.9	9.72	46
A3	1.8	3.0	1.6	1.2	-	-	0.04	< 1	8.42	20
A4	1.8	2.9	1.6	1.1	-	-	0.05	< 1	8.55	18
AC1	0.8	1.9	1.2	1.1	-	-	-	< 1	7.86	11
AC2	0.4	1.3	0.9	0.9	-	-	-	< 1	7.81	6
C	0.1	0.9	0.7	0.8	-	-	-	< 1	7.70	3
Pedon 6, 3060 m asl										
A	5.6	12.1	4.5	6.5	1.5	0.5	0.04	2.7	10.54	74
Bw	1.9	6.0	3.2	4.1	1.3	0.3	-	1.9	9.87	37
BC	0.7	3.1	2.0	2.4	1.3	0.2	-	1.2	9.24	15
C	0.4	2.5	1.7	2.1	1.3	0.2	-	1.0	9.00	11

Continued next page.

Table 3.3. Continued.

Horizon	Al_p†	Al_o‡	Si_o‡	Al_o-Al_p	(Al_o-Al_p)/Si_o	Al_p/Al_o	Al_p/C	Allophane	pH (NaF)	PO_4 retention
	g kg^{-1}				molar			%		%
Pedon 7, 2900 m asl§										
A1	3.0	9.7	4.7	6.8	1.5	0.3	0.04	2.8	10.43	52
A2	2.4	9.1	4.9	6.7	1.4	0.3	0.05	2.9	10.23	48
A3	1.1	5.4	3.5	4.3	1.3	0.2	0.06	2.1	8.98	27
Bw	0.5	3.7	2.8	3.2	1.2	0.1	-	1.4	8.54	14
C1	0.3	2.3	1.7	2.0	-	-	-	< 1	8.03	8
C2	0.2	1.4	0.9	1.2	-	-	-	< 1	7.90	4
C3	0.3	1.1	0.7	0.9	-	-	-	< 1	7.78	3
C4	0.2	1.0	0.8	0.8	-	-	-	< 1	7.71	1
Pedon 8, 2740 m asl										
Ap	1.7	4.2	1.7	2.5	1.6	0.4	0.03	1.0	9.16	26
A1	2.6	5.9	2.2	3.3	1.6	0.4	0.05	1.3	9.79	38
A2	2.0	6.5	3.3	4.5	1.4	0.3	0.05	2.0	9.54	36
Bw	0.5	2.8	1.7	2.3	1.4	0.2	-	1.0	7.96	8
C	0.1	1.2	1.1	1.1	-	-	-	< 1	7.78	0
Pedon 9, 2570 m asl										
Ap	0.2	1.6	0.9	1.4	-	-	0.01	< 1	8.68	4
A	0.2	1.5	0.8	1.3	-	-	0.02	< 1	8.54	4
Bw	0.4	2.1	1.3	1.8	-	-	-	< 1	9.04	9
2Ab	0.4	2.3	1.4	1.9	-	-	0.04	< 1	8.82	7
2C1	0.1	1.2	0.8	1.0	-	-	-	< 1	8.09	1
3ABb	0.2	2.1	1.3	1.9	-	-	-	< 1	8.86	6
4Ab1	0.5	3.6	2.1	3.1	1.6	0.1	0.04	1.2	9.10	11
4Ab2	0.4	3.3	2.0	2.9	1.5	0.1	0.04	1.2	9.14	13
4Bwb1	0.3	2.6	1.6	2.3	-	-	-	< 1	8.50	7
4Bwb2	0.2	1.9	1.2	1.7	-	-	-	< 1	8.62	6
4Bwb3	0.3	2.0	1.1	1.8	-	-	-	< 1	8.81	4
4C2	0.2	1.3	0.9	1.1	-	-	-	< 1	8.51	3
Pedon 10, 2560 m asl										
A	0.2	1.9	1.0	1.7	-	-	0.03	< 1	8.17	7
C1	0.0	0.8	0.6	0.8	-	-	-	< 1	7.86	3
C2	0.0	1.3	1.1	1.3	-	-	-	< 1	7.86	1
C3	0.1	0.9	0.8	0.9	-	-	-	< 1	7.83	1
C4	0.1	0.8	0.6	0.8	-	-	-	< 1	7.89	3
C5	0.1	1.0	0.8	0.9	-	-	-	< 1	8.05	1
C6	0.2	1.2	0.9	1.0	-	-	-	< 1	8.01	3
C7	0.1	0.9	0.8	0.8	-	-	-	< 1	7.90	0
C8	0.2	1.0	0.7	0.9	-	-	-	< 1	8.09	3
C9	0.1	0.9	0.7	0.8	-	-	-	< 1	7.80	1
C10	0.1	0.7	0.7	0.6	-	-	-	< 1	7.79	1
C11	0.1	0.9	1.0	0.8	-	-	-	< 1	7.85	0
C12	0.1	1.0	1.0	1.0	-	-	-	< 1	7.78	0
2Ab1	0.3	1.0	0.7	0.7	-	-	0.02	< 1	7.89	3
2Ab2	2.0	1.8	1.1	-0.2	-	-	0.16	< 1	8.21	11
2C13	0.3	2.2	1.5	1.9	-	-	-	< 1	8.18	6
3Ab	6.7	2.3	1.1	-4.4	-	-	0.17	< 1	8.34	15
Pedon 11, 2630 m asl										
A	0.3	1.5	0.9	1.2	-	-	0.02	< 1	8.49	6
C1	0.2	1.6	1.0	1.4	-	-	-	< 1	8.51	0
C2	0.2	0.9	0.7	0.7	-	-	-	< 1	8.04	1
2Ab	1.1	1.6	1.0	0.4	-	-	0.10	< 1	8.22	7
2C3	0.9	1.7	1.0	0.8	-	-	-	< 1	8.20	7
3Ab	6.4	2.5	1.1	-4.0	-	-	0.19	< 1	8.50	17
Pedon 12, 2410 m asl										
A1	0.1	1.0	0.6	0.9	-	-	0.01	< 1	7.91	6
A2	0.1	1.3	0.9	1.2	-	-	0.01	< 1	7.89	6
AC	0.1	1.1	0.7	1.0	-	-	-	< 1	8.00	4
C1	0.0	0.9	0.7	0.8	-	-	-	< 1	8.00	3
C2	0.1	1.0	0.7	0.9	-	-	-	< 1	7.97	4
C3	0.0	0.7	0.5	0.7	-	-	-	< 1	8.13	4
2Ab1	0.1	1.4	0.8	1.3	-	-	0.01	< 1	8.40	6
2Ab2	0.1	1.2	0.7	1.1	-	-	0.01	< 1	8.49	6
2C4	0.1	1.2	0.8	1.1	-	-	-	< 1	8.54	7

† p … pyrophosphate-extractable.
‡ o … acid oxalate-extractable.
§ asl ... above sea level.

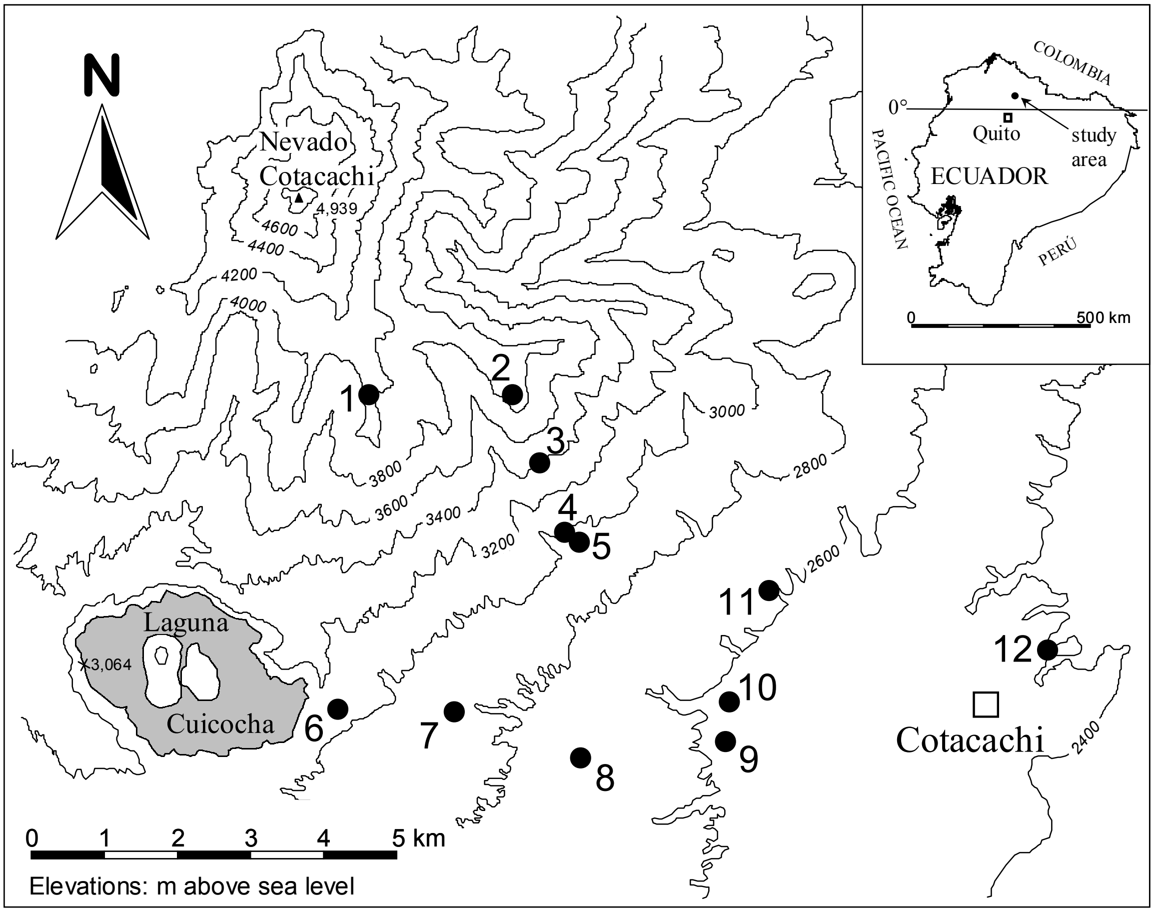

Fig. 3.1. Study area; the locations of the studied pedons are marked with solid dots, numbered 1 through 12.

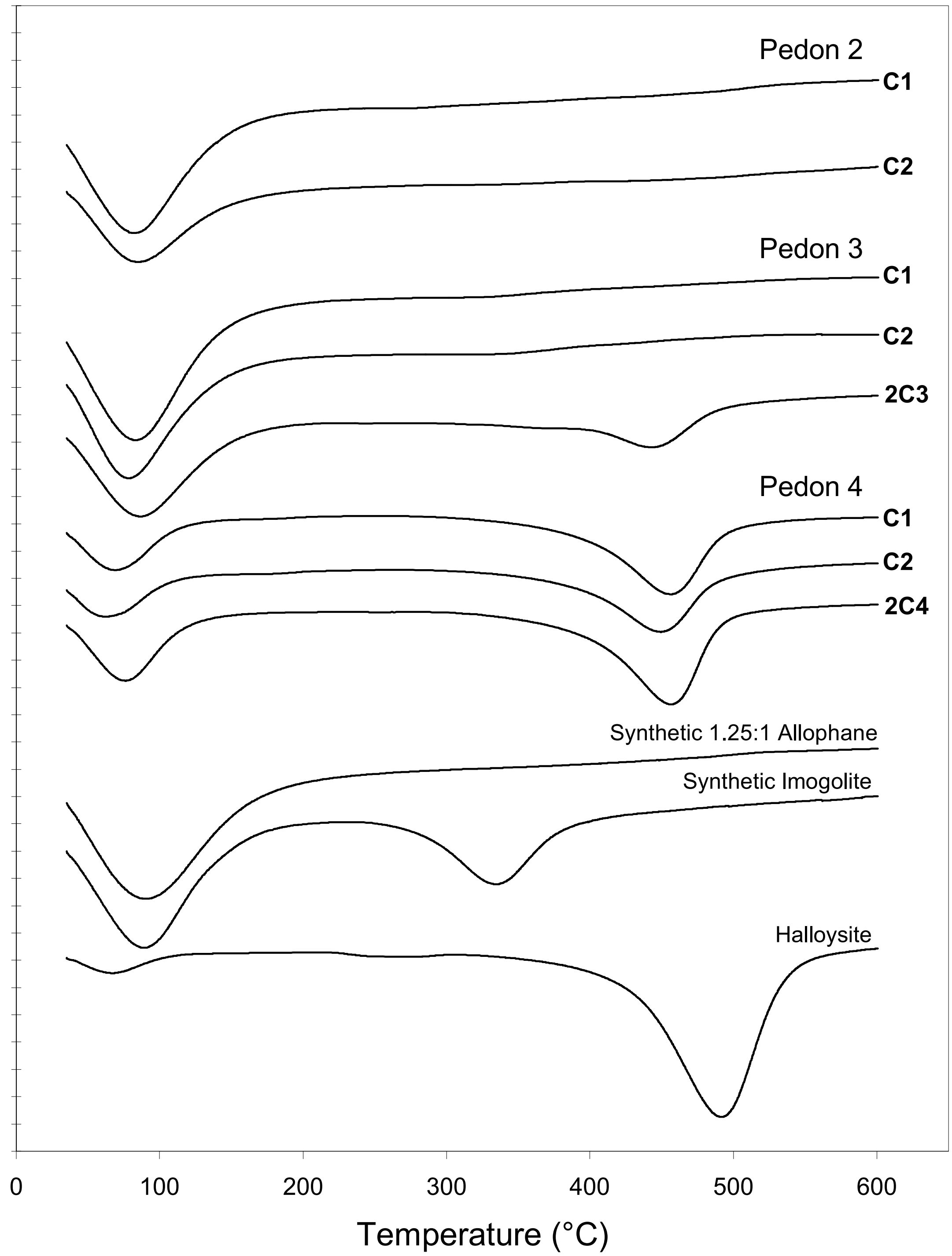

Fig. 3.2. DSC graphs of selected soil horizons and pure materials; one increment on the y-axis corresponds to a heat flow of 0.2 W g^{-1}.

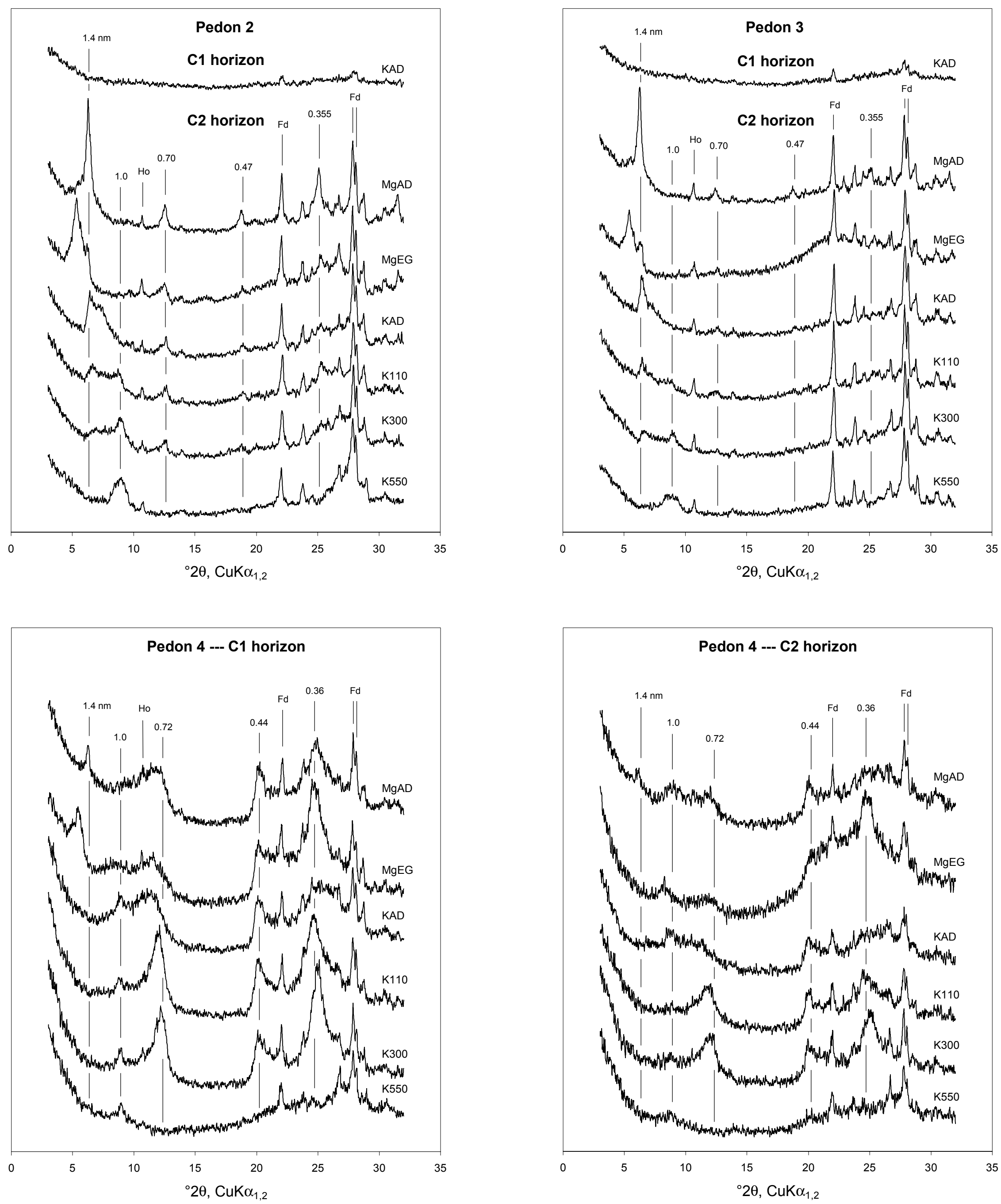

Fig. 3.3. XRD patterns of selected recent soils; MgAD and MgEG: Mg-saturation, air-dried and ethylene glycol solvated, respectively; KAD, K110, K300, and K550: K-saturation, air-dried, and heated to 110, 300, and 550 °C, respectively; Ho: hornblende; Fd: feldspar.

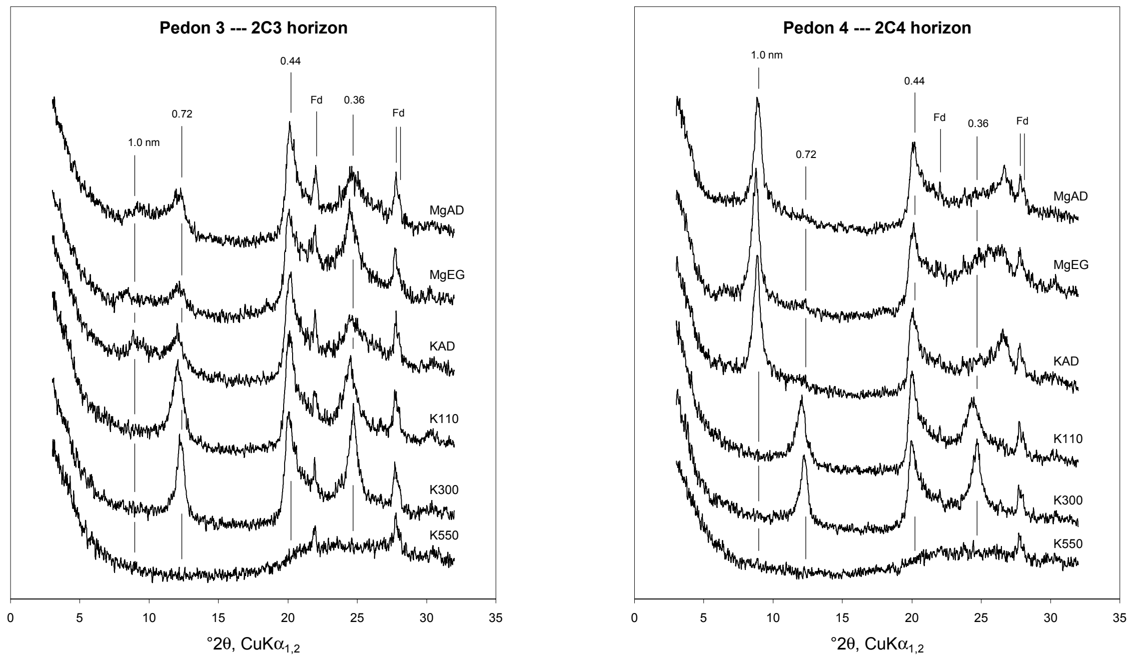

Fig. 3.4. XRD patterns of selected paleosols; MgAD and MgEG: Mg-saturation, air-dried and ethylene glycol solvated, respectively; KAD, K110, K300, and K550: K-saturation, air-dried, and heated to 110, 300, and 550 °C, respectively; Fd: feldspar.

CHAPTER 4

The Effect of Sample Grinding on the Estimation of Allophane Contents in Volcanic Ash Soils[1]

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[1] Zehetner, F., L.T. West, and W.P. Miller. Submitted to *European Journal of Soil Science*.

Summary

Allophane contents of volcanic ash soils are typically quantified using dissolution analysis. In this study, the impacts of sample grinding prior to dissolution analysis were assessed in volcanic ash soils of different colloidal composition. Sample grinding resulted in enhanced acid oxalate extraction of Si and Al. The increases were greatest in soils with a dominant presence of active amorphous constituents and were particularly pronounced in buried A horizons of such soils. Enhanced dissolution due to abrasion of soil particles during grinding was found to be small under the studied conditions, and the liberation of allophane that is protected inside stable aggregates and occluded in the interior of pumice grains is proposed as a potential mechanism leading to increased extraction after sample grinding. The mean Al:Si ratio of allophane extracted from 2-mm sieved samples was equal to 2, while that of allophane additionally dissolved after grinding was equal to 1. It is believed that the former fraction has formed in contact with relatively dilute solutions on the outside of soil particles and aggregates, and the latter has formed in contact with stagnant Si-rich solutions inside pumice grains and aggregates. If total allophane contents are to be estimated, we recommend that stable aggregates are mechanically disintegrated and pumice grains are broken up before dissolution analysis. Further research is needed to identify and describe the exact mechanisms involved and to develop a protocol for mechanical sample pre-treatment.

Introduction

Active amorphous constituents formed upon weathering of volcanic deposits, such as allophane, imogolite, and aluminium-humus complexes, have traditionally been quantified with dissolution analyses using various chemical extractants (e.g., Wada, 1989). One of the most common extractants used for the dissolution of amorphous materials has been oxalate – oxalic acid buffered around pH 3 (Parfitt & Childs, 1988; Parfitt, 1989), and the extraction of silicon by this reagent has been reported as specific to allophane and imogolite (Wada, 1989). Acid oxalate-extractable Si has therefore been used to estimate the allophane contents of volcanic ash soils when imogolite was present in minor quantities (Parfitt, 1990).

Allophane tends to form inside pumice grains where the hydrolysis of volcanic glass proceeds at high Si concentrations and high pH, whereas imogolite tends to form on the outside exposed to solutions of lower Si concentrations and lower pH (Wada, 1980, 1987). There is increasing micro-morphological evidence that amorphous coatings and infillings are a common feature in volcanic ash soils of humid and arid climates (Jongmans *et al.*, 1994, 1995, 1996; Dubroeucq *et al.*, 1998). Ranging in composition from pure silica to allophane and imogolite, amorphous precipitates are found to cover the surfaces of rock fragments and pumice grains and to infill voids. Thus, the porous interiors of pumice grains may be inaccessible to extraction solutions, which may lead to underestimation of total allophane contents when soil samples sieved to 2 mm are subjected to dissolution analysis.

Andisols generally show high structural stability with soil aggregates often strongly cemented by amorphous constituents and soil organic matter (Warkentin & Maeda, 1980; Shoji *et al.*, 1993). Interaction of allophane and imogolite with humic substances may result in the formation of very stable silt- and sand-sized aggregates, particularly in buried A horizons of volcanic ash soils (Wada, 1980). Amorphous constituents in the interior of such aggregates may be shielded from external solutions in the soil environment and possibly from extraction solutions in the laboratory. Such protective effects are likely enhanced if the soil samples – as in most research studies – are air-dried prior to analysis, since irreversible flocculation and dramatic increases in aggregate stability have been reported upon drying of Andisols (Shoji *et al.*, 1993; Poulenard *et al.*, 2001). Yoshida (1992) reported sand-sized aggregates to play an important role in the phosphate retention of some air-dried volcanic ash soils and to be resistant to ultrasonic vibration and treatment with dithionite-citrate-bicarbonate and acid oxalate. Dry grinding of these samples resulted in decreased amounts of Bray-2 extractable P, which may be ascribed to increased availability of active sorption sites for phosphate after the disintegration of stable aggregates. Poulenard *et al.* (2002) showed that the solid – pore interfaces of volcanic soil aggregates were less accessible and the acid oxalate-extractability of Al decreased after shrinkage on drying.

Many workers studying weathering and soil formation on volcanic deposits around the world have used acid oxalate with air-dried soil samples sieved to 2 mm for estimation of allophane contents from dissolved silicon (e.g., Takahashi *et al.*, 1993; Nizeyimana *et al.*, 1997; Chen *et al.*, 1999; Malucelli *et al.*, 1999; Nieuwenhuyse *et al.*, 2000). In this study, we compare the allophane contents, as estimated from acid oxalate-extractable Si, of the < 2 mm sieved fractions and the < 0.25 mm ground fractions of 45 air-dried volcanic ash soil horizons. We suggest that brief grinding breaks pumice grains apart and disintegrates stable aggregates and thus exposes the allophane otherwise occluded and protected in the interior to the extraction solution.

Materials and methods

Five volcanic ash soil profiles located at the slopes of an extinct volcano in northern Ecuador were selected for this study. The five pedons represent a rainfall-induced altitudinal Andisols – Inceptisols – Entisols sequence described in Zehetner *et al.* (2003). The soil parent materials are pumiceous, of andesitic to dacitic composition, and the most recent deposits are associated with a series of volcanic eruptions that occurred about 3000 years ago (Hall & Mothes, 1994).

The soils were sampled according to genetic horizons, air-dried and passed through a 2-mm sieve. Particle size distribution was determined with a combined sieve and pipette method after removal of organic matter with hydrogen peroxide and dispersion with sodium metaphosphate (Soil Survey Staff, 1996). Total carbon was determined by dry combustion (Tabatabai & Bremner, 1991). The values thus obtained were assumed to correspond to organic carbon, since the studied soils did not contain carbonate minerals. Water retention was measured after equilibration of rewet soil samples at 1.5 MPa in a pressure-plate extractor. Soil pH was measured in H_2O and 1 M KCl at a soil:solution ratio of 1:2.5 after 30 minutes of equilibration and in 1 M NaF at 1:50 after exactly 2 minutes. Phosphate retention was determined by measuring the percentage of P retained from 25 mL of a solution containing 1000 mg L^{-1} of P and buffered at pH 4.6 after shaking with 5 g of soil for 24 hours (Soil Survey Staff, 1996).

Dissolution analyses were conducted in accordance with Parfitt & Childs (1988), Parfitt (1989), and Wada (1989). Aluminium associated with soil organic matter, Al_p, was estimated by extraction with 0.1 M sodium pyrophosphate at pH 10 using a soil:solution ratio of 1:100 and shaking for 16 hours. Aluminium and silicon associated with active amorphous constituents, Al_o and Si_o, respectively, were estimated by extraction with 0.175 M ammonium oxalate – oxalic acid at pH 3 using a soil:solution ratio of 1:100 and shaking for 4 hours in the dark. In addition, the acid oxalate extraction was performed on samples ground in a stainless steel ball mill for two minutes to pass 0.25 mm. Aluminium and silicon were measured by inductively coupled plasma - mass spectrometry (ICP-MS). The molar Al:Si ratio of allophane was calculated from $(Al_o\text{-}Al_p)/Si_o$, and the amount of allophane in the samples was estimated by multiplying Si_o by 5, 6, 7, 10, 12, or 16 if the Al:Si ratio was approximately 1, 1.5, 2, 2.5, 3, or 3.5, respectively (Parfitt, 1990).

For further characterization of active amorphous constituents, the clay fraction (< 2 µm) was separated from the soil samples by repeated dispersion and centrifuging after initial dispersion with ultrasonic vibration (Hunter & Busacca, 1989). The clay samples were analysed with differential scanning calorimetry (DSC) at temperatures between 35 and 600 °C and infrared (IR) spectroscopy at wavenumbers between 400 and 4000 cm^{-1}.

Results and discussion

Soil properties shown in Tables 4.1 and 4.2 reflect the strong altitudinal dependence of soil development in the area under study (Zehetner *et al.*, 2003). At high elevations (pedons 1 and 2), the soils have high organic matter contents, clay mineralogy is dominated by active amorphous constituents and andic soil properties are present throughout the profiles. At low elevations (pedons 4 and 5), organic matter contents are low, clay mineralogy is dominated by halloysite and andic soil properties are absent. Pedon 3 exhibits andic soil properties only in the upper profile and represents a transition from the high allophane zone to the low halloysite zone (Zehetner *et al.*, 2003). Macro-aggregates of the high-elevation Andisols showed near 100 % stability after 5-minute wet-sieving according to Kemper & Rosenau (1986), whereas this test could not be performed on the weakly aggregated low-elevation soils, of which most aggregates got disintegrated during transport from the field to the laboratory (data not shown).

The clay fractions of the studied soils exhibit a single IR absorption maximum around 1000 cm^{-1} and show no dehydroxylation between 300 and 400 °C (data not shown), which rules out the presence of imogolite. Therefore, we assume that the silicon extracted with acid oxalate (Si_o) originates from allophane.

The results of the dissolution analyses are presented in Table 4.2. Silicon and aluminium extracted with acid oxalate from sieved samples were plotted against their respective amounts extracted from ground samples (Figures 4.1 and 4.2). All the data points lie above the dashed 1:1 line indicating increased extraction of Si and Al after grinding. It is widely accepted that excessive grinding of soil and mineral samples may result in increased extractability of structural constituents, such as silicon and aluminium (Neary & Barnes, 1993; Zhang *et al.*, 1997; Vegliò *et al.*, 1999). Zhang *et al.* (1997) showed that dry grinding of a serpentine sample resulted in structural changes from a crystalline into an amorphous state, which gave rise to enhanced acid extraction of Si and Mg. However, grinding times of more than 15 minutes were necessary for these changes to occur.

Since the five studied pedons have comparable sand contents (Table 4.1) and similar sand mineralogy (data not shown), abrasive effects due to dry grinding are believed to be of similar magnitude in all soils. Thus, enhanced extraction of Si and Al due to abrasion of soil particles during grinding should result in a distribution of data points parallel to the dashed 1:1 line in Figures 4.1 and 4.2, and the corresponding regression equation should have a slope of 1 and a y-intercept equal to the mean increase in extractable Si and Al, respectively.

In the soils we studied, the amounts of additional Si and Al extracted after grinding, that is the distances of the data points from the 1:1 line, increase with increasing amounts of Si and Al originally extracted from the 2-mm sieved samples (Figures 4.1 and 4.2). The slopes of the regression equations are 2.4 and 1.4 for Si and Al, respectively, and are significantly different from 1 ($P < 0.001$). The regression lines cross the y-axis at 0.35 and 0.53 g kg^{-1} for Si and Al, respectively, with the former value not significantly different from 0. These y-intercepts may be interpreted as the average portion of Si and Al liberated due to grinding-induced abrasion. In a number of soils, active amorphous constituents were practically absent, as indicated by low pH (NaF) values and low PO_4 retention (Table 4.2). These soils were included in this study as "blanks" to evaluate the abrasive effects of grinding on the estimation of allophane contents. Despite an average increase of acid oxalate-extractable Si and Al of 0.7 and 0.9 g kg^{-1}, respectively, in soils with < 10 % PO_4 retention, estimated allophane contents were still < 1 % after grinding in these soils (Table 4.2). Thus, while the grinding procedure that we used has enhanced extraction of Si and Al from those soils without active amorphous materials presumably due to abrasion of other soil constituents, the increases were not large enough to cause significant overestimation of allophane contents.

Figures 4.1 and 4.2 suggest that enhanced extraction of Si and Al after grinding is not only caused by abrasion but is considerably affected by other mechanisms involving active amorphous materials. These mechanisms may include the liberation of allophane occluded in the interior of pumice grains or protected inside stable aggregates. The biggest differences in acid oxalate-extractable Si and Al between ground and sieved samples were found in buried A horizons of high-elevation pedons (Figures 4.1 and 4.2, Table 4.2). In these soils, high complexing capacity of humus for Al may have fostered interactions of organic and inorganic constituents thus leading to the formation of particularly stable aggregates, as suggested by Wada (1980).

The average molar Al:Si ratios of allophane extracted from sieved and ground samples as well as that of the portion liberated through grinding were estimated by the slopes of the respective regression equations given in Figure 4.3. Whereas the mean Al:Si ratio of allophane dissolved from sieved samples is about 2 with maximum values of over 4, the fraction additionally extractable after grinding has an average Al:Si ratio of about 1. These differences may reflect differential formation in contact with solutions of different chemical composition. The fraction extracted from 2-mm sieved samples is considered to be located on the outside of mineral grains, pumice fragments, and stable aggregates, and thus likely to be in contact with relatively dilute solutions in the soil environment, which foster leaching of silicon and other mobile elements. On the other hand, the fraction liberated through sample grinding is considered to be protected inside stable aggregates and occluded in the interior of pumice grains, where the solutions are more stagnant and exhibit higher Si concentrations (Wada, 1980, 1987). Allophane extracted from ground samples constitutes a mixture of the two fractions mentioned above and thus shows a mean Al:Si ratio in between these two fractions (Figure 4.3).

Conclusions and recommendations

Grinding soil samples to pass 0.25 mm resulted in enhanced acid oxalate extraction of Si and Al relative to 2-mm sieved samples. A portion of this increase is ascribed to abrasion of soil particles during grinding; however, it was comparatively small and did not cause significant overestimation of allophane contents. The differences between ground and sieved samples were biggest in soils with a dominant presence of active amorphous constituents and were particularly pronounced in buried A horizons of such soils. We suggest that the liberation of allophane protected inside stable aggregates and occluded in the interior of pumice grains results in enhanced dissolution after sample grinding. Allophane extracted from sieved samples had a mean Al:Si ratio of 2, which may reflect formation under desilicating conditions on the outside of soil particles and aggregates. Allophane additionally dissolved after grinding had a mean Al:Si ratio of 1, which may point to formation in contact with stagnant Si-rich solutions inside pumice fragments and aggregates. If total allophane contents are to be estimated, mechanical disintegration of stable aggregates and break-up of pumice grains is therefore recommended prior to dissolution analysis.

In a complement to the present study, we will assess how much sample drying contributes to the protective effects of aggregation in the studied volcanic ash soils. Further research should focus on two aspects. First, the exact mechanisms leading to enhanced extraction of Si and Al after sample grinding need to be identified and described. Micro-morphological and ultra-structural methods may shed more light on the processes involved, and new synchrotron-based spectroscopic methods may elucidate the spatial distribution of active amorphous materials and their interactions with other constituents in volcanic ash soils. Second, the mechanical sample pre-treatment needs to be examined in more detail for soils of different parent materials. A protocol should be developed including procedures that completely liberate occluded active amorphous materials and minimize abrasion of other soil constituents.

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Table 4.1. Selected characteristics of the studied pedons.

Horizon	Depth	pH (H_2O)	pH (KCl)	Organic C	Sand	Silt	Clay	H_2O retention at 1.5 MPa
	/cm			/%				
Pedon 1; 3900 m asl;[a] Vitric Melanocryands[b]								
A1	0 - 50	4.6	4.3	10.3	31	41	28	22.6
A2	50 - 100	5.3	4.8	4.1	71	24	5	10.5
C1	100 - 115	6.0	5.2	1.9	57	39	4	7.3
C2	115 - 140	5.7	5.1	0.9	58	38	4	4.0
C3	140 - 175	5.9	4.9	0.2	90	7	3	1.0
2Ab1	175 - 200	5.5	5.0	2.4	54	38	9	7.6
2Ab2	200 - 220	5.6	5.0	2.0	50	40	10	8.4
2Ab3	220 - 270	5.6	5.0	6.4	40	46	14	21.1
R	270+							
Pedon 2; 3400 m asl; Pachic Vitric Melanudands								
A	0 - 40	5.4	4.5	7.7	45	37	17	17.4
AC	40 - 55	5.3	4.9	2.4	63	31	5	7.7
C1	55 - 70	5.7	4.9	1.2	65	30	5	4.5
C2	70 - 90	5.8	5.0	0.6	84	12	4	2.3
2Ab1	90 - 110	5.7	4.7	2.0	72	20	7	5.7
2Ab2	110 - 180	5.8	4.9	6.3	43	41	16	18.9
2Ab3	180 - 200	5.7	5.1	4.2	71	17	12	16.5
2C3	200 - 300+	5.7	5.1	0.6	80	12	8	7.4
Pedon 3; 2900 m asl; Humic Udivitrands								
A1	0 - 30	6.2	5.4	3.1	47	39	15	9.0
A2	30 - 55	5.7	4.9	2.2	51	38	11	7.7
A3	55 - 70	6.3	5.1	0.9	75	18	7	4.6
Bw	70 - 85	6.4	5.1	0.3	84	13	3	2.2
C1	85 - 100	6.5	4.9	0.0	82	16	2	1.5
C2	100 - 110	6.3	4.9	0.0	85	12	3	1.5
C3	110 - 125	6.3	4.7	0.0	81	17	3	2.0
C4	125 - 155+	6.3	4.7	0.0	91	7	3	1.0
Pedon 4; 2570 m asl; Vitrandic Dystrudepts								
Ap	0 - 13	7.0	6.2	0.9	76	20	4	2.9
A	13 - 53	7.1	6.4	0.5	74	21	5	2.3
Bw	53 - 86	7.2	6.3	0.6	50	42	8	3.8
2Ab	86 - 112	7.1	6.2	0.5	61	32	7	3.5
2C1	112 - 132	6.5	5.8	0.0	92	7	1	1.0
3ABb	132 - 150	7.0	6.2	0.5	62	32	6	2.3
4Ab1	150 - 190	7.0	6.1	0.5	63	30	7	4.6
4Ab2	190 - 220	7.0	6.1	0.5	68	26	6	4.7
4Bwb1	220 - 240	6.8	5.8	0.0	91	6	3	1.7
4Bwb2	240 - 250	6.7	5.8	0.1	89	8	3	1.4
4Bwb3	250 - 290	7.1	5.8	0.0	75	20	5	2.5
4C2	290 - 340+	6.9	5.4	0.0	77	17	5	2.2
Pedon 5; 2410 m asl; Vitrandic Udorthents								
A1	0 - 65	5.8	5.1	0.4	76	20	4	2.1
A2	65 - 75	6.2	5.7	0.6	72	23	5	2.7
AC	75 - 85	6.3	5.6	0.2	76	21	3	1.7
C1	85 - 140	6.2	5.2	0.0	79	19	3	1.0
C2	140 - 150	6.2	5.4	0.0	77	20	3	1.5
C3	150 - 160	6.4	5.3	0.1	53	43	3	0.8
2Ab1	160 - 190	6.5	6.0	0.5	65	29	5	3.4
2Ab2	190 - 200	6.8	6.3	0.5	70	27	3	2.5
2C4	200 - 240+	6.6	6.0	0.0	63	33	3	1.9

[a] asl ... above sea level.
[b] according to Soil Survey Staff (1998).

Table 4.2. Dissolution analyses and properties related to amorphous material in the studied pedons.

Horizon	Al_p[a]	Al_o[b]S[c]	Al_oG[d]	Si_oS	Si_oG	Allophane S	Allophane G	pH (NaF)	PO_4 retention
	/g kg^{-1}					/%			/%
Pedon 1									
A1	10.1	9.7	12.9	1.5	2.6	< 1	1.3	10.83	91
A2	4.9	11.1	15.5	3.1	6.5	2.2	3.9	10.96	87
C1	2.6	11.7	15.9	3.8	8.5	3.8	5.1	10.57	78
C2	1.5	6.6	9.4	2.4	5.5	1.7	3.3	10.26	52
C3	0.5	1.8	3.0	0.6	2.0	< 1	1.2	9.21	18
2Ab1	2.9	6.6	10.2	2.4	5.1	1.5	3.1	10.16	65
2Ab2	2.5	7.9	10.5	3.3	5.6	2.0	3.3	10.03	67
2Ab3	7.8	14.0	22.9	3.5	11.6	2.5	6.9	9.82	92
Pedon 2									
A	7.6	11.4	14.0	1.7	4.5	1.7	2.7	10.57	88
AC	4.0	11.6	15.8	2.0	7.1	3.1	4.3	10.82	79
C1	2.3	8.6	11.6	1.4	5.7	2.3	3.4	10.63	57
C2	1.1	3.6	5.8	0.8	3.1	< 1	1.9	9.90	30
2Ab1	2.8	4.3	6.1	0.9	2.5	< 1	1.5	9.83	50
2Ab2	7.4	8.7	13.9	2.1	5.7	1.0	2.8	9.30	81
2Ab3	6.3	18.1	28.8	3.9	14.7	4.7	8.8	10.02	92
2C3	1.3	8.9	13.6	2.5	8.2	3.0	4.9	9.63	54
Pedon 3									
A1	3.0	7.2	9.7	1.9	4.7	1.9	2.8	10.43	52
A2	2.4	6.3	9.1	2.5	4.9	1.5	2.9	10.23	48
A3	1.1	4.2	5.4	2.7	3.5	1.3	2.1	8.98	27
Bw	0.5	2.4	3.7	1.8	2.8	< 1	1.4	8.54	14
C1	0.3	1.5	2.3	1.1	1.7	< 1	< 1	8.03	8
C2	0.2	0.4	1.4	0.2	0.9	< 1	< 1	7.90	4
C3	0.3	0.3	1.1	0.2	0.7	< 1	< 1	7.78	3
C4	0.2	0.1	1.0	0.1	0.8	< 1	< 1	7.71	1
Pedon 4									
Ap	0.2	0.6	1.6	0.2	0.9	< 1	< 1	8.68	4
A	0.2	0.7	1.5	0.3	0.8	< 1	< 1	8.54	4
Bw	0.4	1.3	2.1	0.6	1.3	< 1	< 1	9.04	9
2Ab	0.4	1.1	2.3	0.4	1.4	< 1	< 1	8.82	7
2C1	0.1	0.3	1.2	0.2	0.8	< 1	< 1	8.09	1
3ABb	0.2	0.9	2.1	0.3	1.3	< 1	< 1	8.86	6
4Ab1	0.5	2.2	3.6	0.7	2.1	< 1	1.2	9.10	11
4Ab2	0.4	2.0	3.3	0.8	2.0	< 1	1.2	9.14	13
4Bwb1	0.3	1.0	2.6	0.3	1.6	< 1	< 1	8.50	7
4Bwb2	0.2	0.7	1.9	0.2	1.2	< 1	< 1	8.62	6
4Bwb3	0.3	0.5	2.0	0.1	1.1	< 1	< 1	8.81	4
4C2	0.2	0.2	1.3	0.0	0.9	< 1	< 1	8.51	3
Pedon 5									
A1	0.1	0.4	1.0	0.1	0.6	< 1	< 1	7.91	6
A2	0.1	0.4	1.3	0.1	0.9	< 1	< 1	7.89	6
AC	0.1	0.3	1.1	0.1	0.7	< 1	< 1	8.00	4
C1	0.0	0.1	0.9	0.1	0.7	< 1	< 1	8.00	3
C2	0.1	0.2	1.0	0.2	0.7	< 1	< 1	7.97	4
C3	0.0	0.3	0.7	0.1	0.5	< 1	< 1	8.13	4
2Ab1	0.1	0.5	1.4	0.1	0.8	< 1	< 1	8.40	6
2Ab2	0.1	0.4	1.2	0.1	0.7	< 1	< 1	8.49	6
2C4	0.1	0.4	1.2	0.1	0.8	< 1	< 1	8.54	7

[a] p … pyrophosphate-extractable.
[b] o … acid oxalate-extractable.
[c] S … sieved to pass 2 mm.
[d] G … ground to pass 0.25 mm.

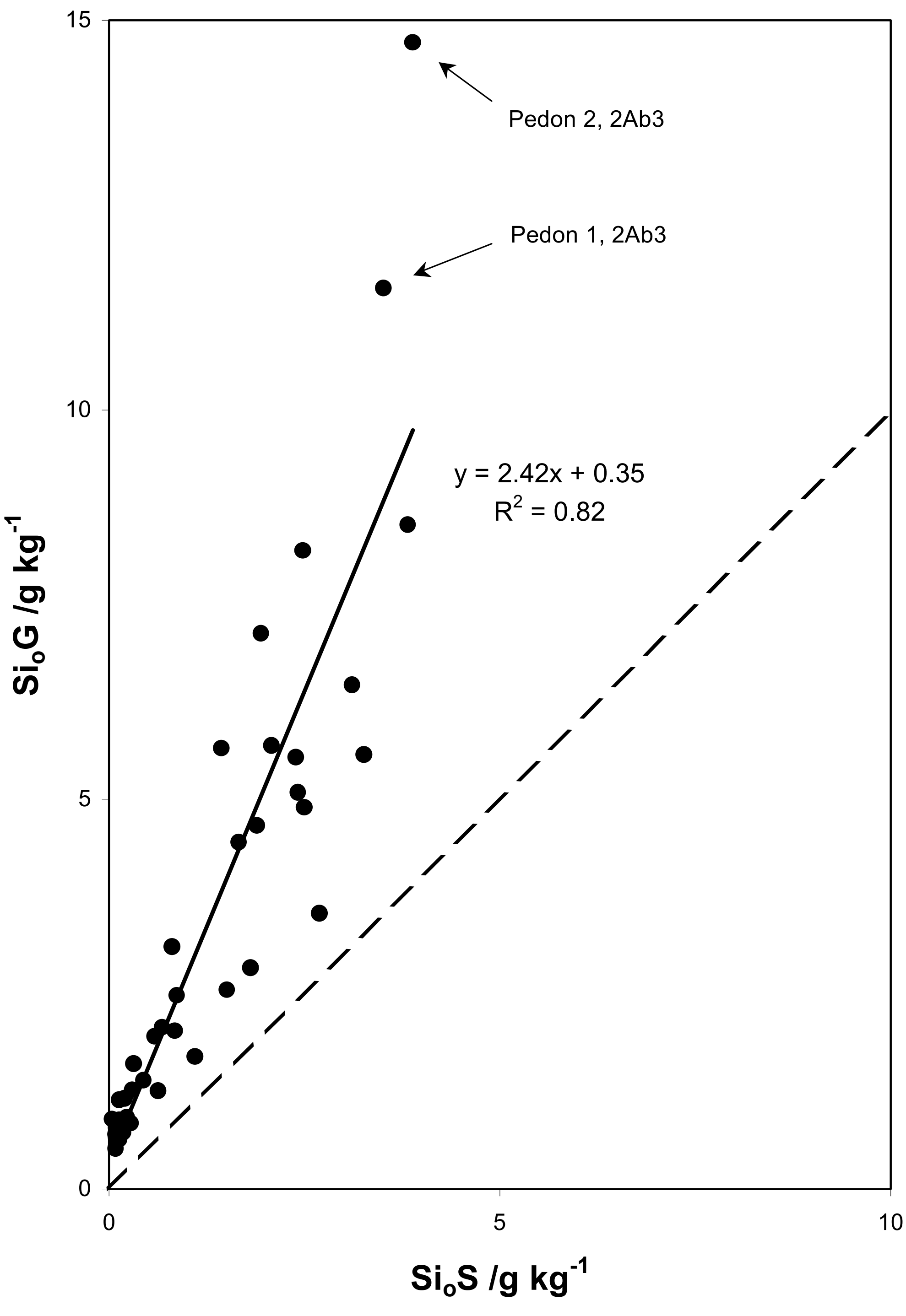

Figure 4.1. Acid oxalate-extractable silicon from sieved (Si_oS) vs. ground (Si_oG) soil samples. Dashed line represents 1:1 slope.

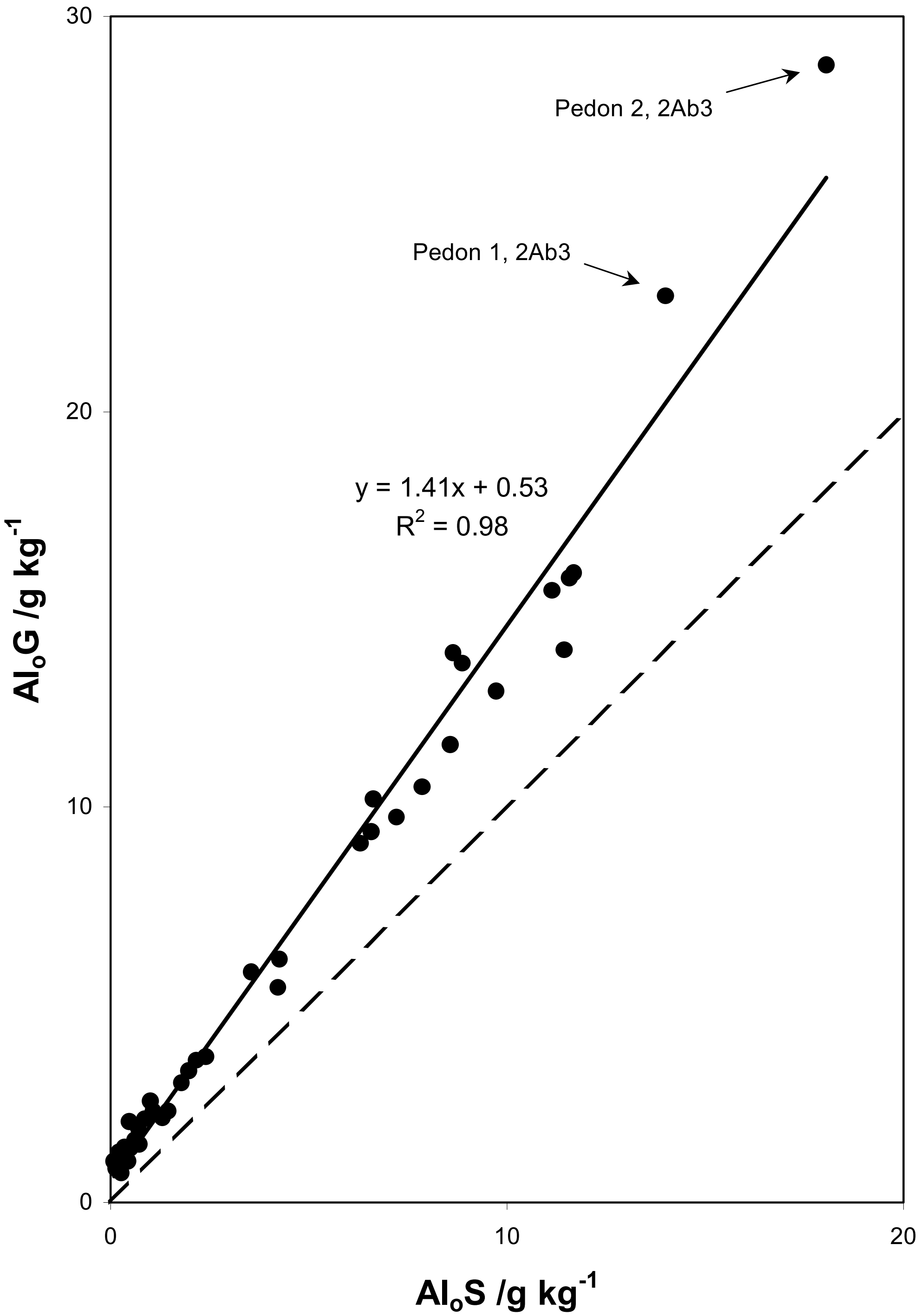

Figure 4.2. Acid oxalate-extractable aluminium from sieved (Al_oS) vs. ground (Al_oG) soil samples. Dashed line represents 1:1 slope.

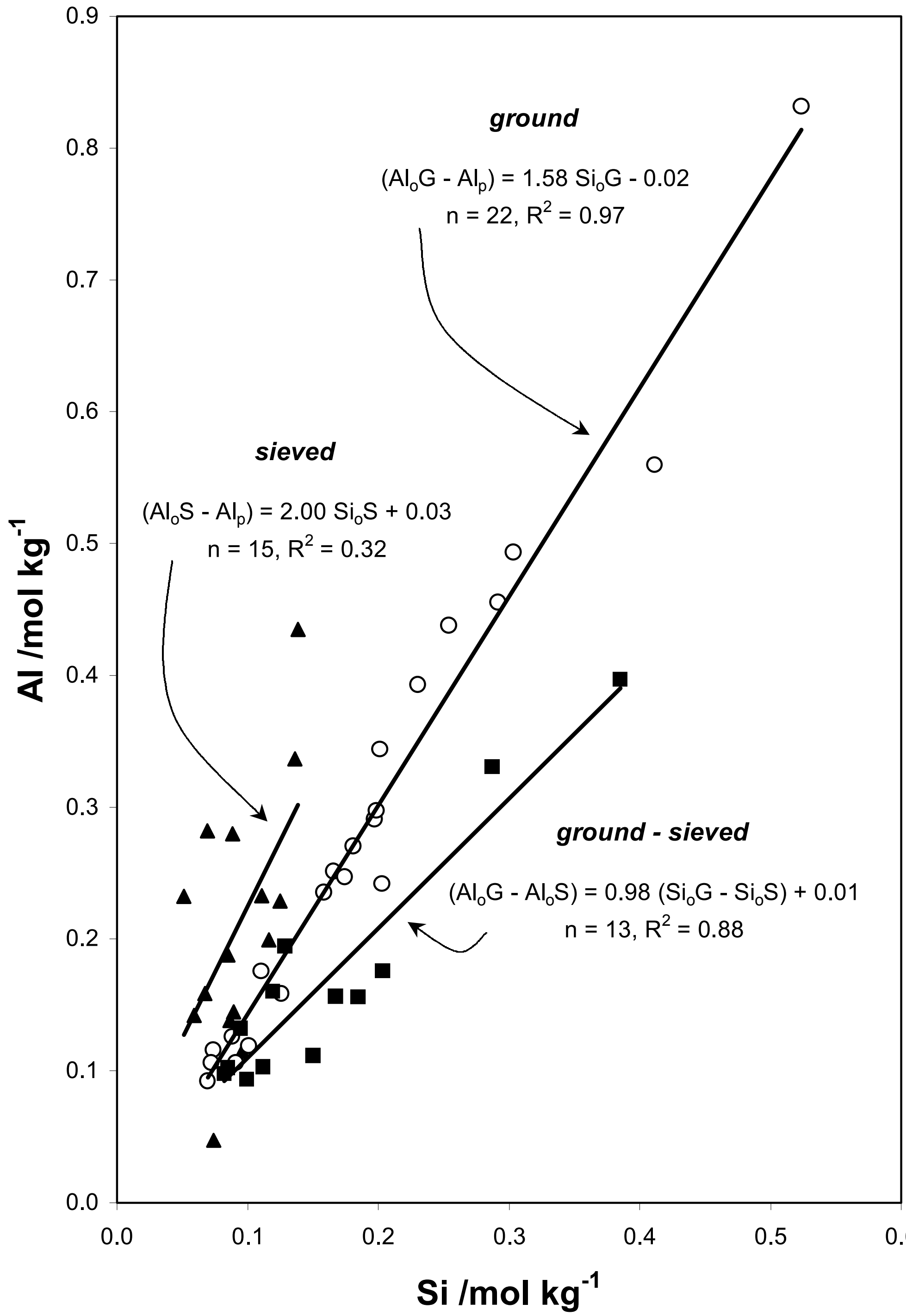

Figure 4.3. Average molar Al:Si ratios of different allophane fractions. Only samples with allophane contents ≥ 1 % were used.

CHAPTER 5

Soil Fertility and Crop Growth in Andean Communities of Northern Ecuador[1]

[1] Zehetner, F., and W.P. Miller. To be published in a book edited by R.E. Rhoades.

Abstract

The volcanic ash soils of northern Ecuador have supported agricultural activities for thousands of years; however, at the dawn of a new millennium, the sustainability of agricultural production seems to be threatened in the peasant communities of Cotacachi, where crop yields have been declining over the past decades. In this study, we analyzed the fertility status of the soils in the Cotacachi area, identified limiting factors to crop growth in different zones of the area, and discussed possible avenues for restoring and maintaining soil fertility. While rainy season water availability is generally sufficient, water stress can drastically limit crop growth during the summer dry season, especially in the drier low-elevation zones, where soils have low organic matter contents and sandy textures with little water-storage capacity. An expansion of existing irrigation systems would therefore considerably improve dry-season crop production in these low zones. Plant nutrients may become yield-limiting in certain parts of the study area. The young soils in the southern study area have inherently low potassium contents and would greatly benefit from additions of this nutrient. In high-elevation soils, strong phosphate sorption may induce phosphorus deficiencies and necessitate increased P inputs for optimum crop growth. Despite high organic matter contents, nitrogen may be mineralized too slowly to satisfy crop requirements in high-elevation soils, whereas leaching losses may impair adequate N supply in low-elevation soils. The nitrogen status of all soils would greatly benefit from returning residues to the soil after harvest, including leguminous plants in crop rotations, and managing short, improved fallows. For a number of reasons, the addition of nutrients through organic sources seems preferable over the use of inorganic fertilizers.

Introduction

Archaeological finds near Otavalo have revealed that the Andean region of northern Ecuador has been inhabited for thousands of years. Pollen analysis in Lago San Pablo sediments has confirmed that the volcanic ash soils of the area had been cultivated by early maize agriculturalists as long as 4200 years ago (Athens, 1999). Volcanic ash soils have the reputation of being fertile and highly productive, allowing for high human-carrying capacity. They were conducive to the development of early civilizations in Central and South America (Lauer, 1993) as well as in Asia (Shoji et al., 1993).

The high natural fertility of volcanic ash soils has been attributed to the abundance of nutrients in the soil parent material, the development of thick humus horizons containing large amounts of organic nitrogen, free drainage, high plant-available water-holding capacity, and a deep, unrestricted rooting zone (Shoji et al., 1993). However, not all soils derived from volcanic deposits can supply the large amounts of nutrients and water necessary for vigorous plant growth. The inherent fertility of volcanic ash soils is strongly dependent on texture and composition of their parent material, on the nature, intensity, and duration of its alteration by the processes of weathering, and on the magnitude of organic matter accumulation in the course of soil development.

According to their chemical composition, volcanic ashes are classified into the rock types rhyolite, dacite, andesite, basaltic andesite, and basalt (Shoji et al., 1975). The contents of silicon decrease in this order whereas the concentrations of calcium, magnesium, iron, and other micronutrients increase. However, total phosphorus and potassium contents are higher in rhyolitic compared to basaltic materials (Shoji et al., 1993). The nutrients contained in the soil parent material are largely unavailable for plant roots until liberated in the course of mineral weathering and stored in more available form on mineral and organic surfaces. Parent material texture is an important factor influencing the rate of weathering and nutrient release. The finer the texture, the greater the surface area exposed to the ambient solution and the higher the rate of chemical weathering (Shoji et al., 1993). With increasing intensity and duration of weathering and soil development, the clay contents of volcanic ash soils increase, which in turn enhances their ability to retain plant nutrients against leaching and to store plant-available water. For volcanic deposits in New Zealand, Lowe (1986) showed that tephra younger than 3000 years had less than 5 % clay, deposits of 3000 to 10 000 years contained 5 to 10 % clay, and 10 000 to 50 000 year-old tephra had clay contents of 15 to 30 %.

The clay mineralogy of volcanic ash soils is largely determined by the amount of rainfall and leaching. Active amorphous constituents, such as allophane and aluminum-humus complexes, dominate the clay fraction where the climate is moist and soil solution silicon is removed by leaching, whereas halloysite is found as the dominant clay mineral in drier, silicon-rich environments (e.g., Parfitt et al., 1983; Parfitt and Wilson, 1985). These differences in clay mineralogy have important bearings on nutrient cycling. Active amorphous constituents are responsible for the strong sorption of phosphate often observed in volcanic ash soils (e.g., Parfitt, 1989; Wada, 1989; Shoji et al., 1993) that makes phosphorus sparingly available for plants and microorganisms. Active amorphous constituents further react with soil organic matter leading to its stabilization and enhanced protection against microbial decomposition (Parfitt et al., 1997; Gijsman and Sanz, 1998; Parfitt et al., 2001). This results in humus accumulation and the presence of appreciable quantities of organic nitrogen in these soils. However, until mineralized (converted from organic to mineral form in the course of organic matter decomposition), this nitrogen is not available for plant uptake; and due to above-mentioned protective effects, nitrogen mineralization is comparatively slow in soils with active amorphous constituents (Shoji et al., 1993; Parfitt et al., 2001).

In order for volcanic ash soils to remain sustainably productive, proper management practices are a prerequisite. Continuous cropping without adequate inputs leads to nutrient mining and declining productivity. In the Andean eco-region, fallow-rotation systems have traditionally been practiced to restore soil fertility and avoid outbreaks of pests and diseases (Sarmiento et al., 1993; Schad, 1998; Pestalozzi, 2000; Phiri et al., 2001). However, increasing population pressure, competing land-use demands, and the incorporation of elements from market-oriented agriculture have been changing these traditional systems (Sarmiento et al., 1993; Phiri et al., 2001). Using a modeling approach, de Koning et al. (1997) assessed the sustainability of Ecuadorian agro-ecosystems based on their soil fertility status. They calculated nutrient balances for different land use types and found net nitrogen and potassium losses, which were higher for cropland than for grassland. Nutrient depletion was more severe in the Andean than in the coastal region.

Crop yield data collected by the Ecuadorian *Centro Andino de Acción Popular* (CAAP) indicate comparatively low maize yields in the Cotacachi area (Field, 1991), and members of the Cotacachi communities have identified decreasing soil fertility as a threat to their subsistence (UNORCAC, 1999). In this study, we analyze the fertility status of the soils in the Cotacachi area and identify limiting factors to crop growth in different zones of the area. We use crop growth modeling to examine the long-term effects of nitrogen fertilization, residue management, and irrigation on maize yields, and discuss possible avenues for restoring and maintaining soil fertility as the basis of sustainable agricultural production.

The Cotacachi Area

Landscape and Volcanoes

The area under study is located about 35 km north of the equator (Figure 5.1) on what the German explorer Alexander von Humboldt called *The Avenue of the Volcanoes*. In the Ecuadorian Andes, two parallel chains of stratovolcanoes stretch north-south and enclose the 50-km wide *inter-Andean valley*. The studied communities are located on the inner slopes of volcano Cotacachi oriented towards this temperate *inter-Andean valley* (Figure 5.2). The landscape of the region is dominated by high volcanic peaks, including Cotacachi (4939 m), Imbabura (4630 m), and Cayambe (5790 m), as well as by the enormous calderas of Cuicocha (3064 m) and Mojanda (3716 m). Thus, landscape development has been heavily influenced by volcanic phenomena, such as lava and pyroclastic flows, pumice and ash falls, and subsequent mudslides induced by heavy rainfall events and earthquakes. Streams have deeply carved into the land forming ravines and dissecting the landscape into plateau-like upland areas stretching parallel to streams.

The volcanic complex of Cotacachi has a long history of volcanic activity involving several different eruption centers, of which only Cuicocha has been active in the Holocene. The other centers have not erupted in the past 40 000 years (Hall and Mothes, 1994). Volcano Cuicocha has had three phases of activity that occurred over a period of a few hundred years, ending about 3000 years ago (Mothes and Hall, 1991; Hall and Mothes, 1994; Athens, 1999). The present caldera of Cuicocha was formed by explosive eruptions that resulted in massive pyroclastic flows and tephra falls. These relatively young deposits have shaped the southern part of the study area, whereas the northeastern part is covered with older deposits originating from other eruption centers.

Climate

The climate in the area is that of an equatorial high-altitude environment, with temperatures almost constant throughout the year, but showing pronounced diurnal oscillations. Variations of climatic parameters over the landscape are largely a function of elevation. The mean annual temperature is about 15 °C at 2500 m, and drops by about 0.6 °C per 100 m of elevation increase. Rainfall in the area is generally dominated by low-intensity events. The mean annual precipitation is about 900 mm at 2500 m and increases with elevation to about 1500 mm at 4000 m (Nouvelot et al., 1995). Mean annual PET (potential evapotranspiration) amounts to about 900 mm at 2500 m and decreases with increasing elevation due to lower temperatures and higher humidity. The annual distribution of rainfall and PET for the nearby town of Otavalo (2550 m) is shown in Figure 5.3. The climate is characterized by an expressed seasonality with a dry season of pronounced water deficit from June to September. With increasing elevation on the volcano, the climate becomes more humid, the dry season shorter, and the summer water deficit less pronounced.

Soil Types

The volcanic soil parent materials in the area are generally pumiceous and have andesitic to dacitic composition. The soils in the southern part of the study area have formed on the 3000-year-old Cuicocha deposits and are in their early stages of development, whereas the soils in the northeastern part have formed on deposits older than 40 000 years and are thus more advanced in their development.

Apart from differences in age and composition of parent materials, soil formation in the area is heavily influenced by climatic differences with elevation along the volcanic slopes. At high elevations, the soils have high organic matter contents and clay mineralogy is dominated by active amorphous constituents. At low elevations, organic matter contents are low and clay mineralogy is dominated by halloysite (Zehetner et al., 2003). Andic soil properties increase with elevation and according to US Soil Taxonomy (Soil Survey Staff, 1998), the high-elevation soils are classified as Andisols and the low-elevation soils as Inceptisols and Entisols (Zehetner et al., 2003).

The recent volcanic deposits overlie an older, more developed surface formed on volcanic parent materials of preceding eruption episodes. A typical soil profile is presented in Figure 5.4 and shows recent soil development on a series of Cuicocha tephra overlying a buried soil (paleosol) formed on older tephra that in turn overlies an even older paleosol. The parent material of this deepest paleosol is volcanic ash that has been cemented and indurated over time and is locally referred to as *cangagua*. In areas where the recent soils have been eroded, the older paleosol strata can reach close to the surface or crop out entirely and thus play an agronomic role once again.

Land Use and Land Management

The region has been largely deforested and native tree species have generally been replaced with fast-growing eucalyptus (*Eucalyptus globulus* Labill.). The present landscape is dominated by agricultural land use below 3000 m, and high-altitude scrubland and grassland (*matorral* and *páramo*, respectively) above 3000 m. Most of the agricultural lands lie on upland plateaus exhibiting slope gradients between 0 and 20 %. The major agricultural crops in the area are maize (*Zea mays* L.), bean (*Phaseolus vulgaris* L.), and potato (*Solanum tuberosum* L.).

Indigenous peoples have inhabited the region for thousands of years (Athens, 1999) and have employed farming practices well suited to climate and topography of the area. Ancient bench terraces, likely of pre-Colombian origin, are a proof of an early awareness of natural resource conservation. Over the past 500 years, the social and agricultural structures have undergone dramatic changes involving the centuries-long enslavement of the indigenous population within the *hacienda* system, a half-hearted land reform in the 1960s, the advent of the *Green Revolution* in the 1970s, and lately a newly awakened consciousness among the indigenous population to preserve their own heritage.

At present, agriculture shows marked differences between *hacienda*-type operations on the one hand and smallholder farms in the mostly indigenous peasant communities on the other. The large-scale *hacienda* agriculture is characterized by intensive management with high inputs and a high degree of mechanization. The situation in the peasant communities is different. Many farmers own less than 2 ha of arable land and very little livestock. Due to limited resources and the desire to produce organically, the use of chemical fertilizers and pesticides is uncommon. Manure application rates are generally low, and many farmers don’t fertilize their land at all. The limited amount of available land forces many farmers to crop continuously and avoid prolonged fallow periods. Land management operations, such as tillage and cultivation, are generally done by hand or with the use of oxen. Irrigation is only available in some low-elevation communities; however, expansion of the present irrigation systems to a larger area including higher zones is a high-priority issue for local authorities.

Methodology

Soil Sampling

A total of 145 cultivated fields in 41 Andean communities around volcano Cotacachi were randomly selected for soil analysis and geo-referenced. The locations of the sampled fields are marked by solid dots in Figure 5.2. Depending on the size of the fields, between 10 and 20 soil samples were taken from the plow layer (0-15 cm depth) and mixed to obtain one composite sample of each field. The samples were air-dried and passed through a 2-mm sieve prior to laboratory analyses.

Soil Analyses

Particle size distribution was determined with the hydrometer method according to Bouyoucos (1962). Soil organic matter was measured by wet-oxidation with the Walkley-Black method (Soil Survey Staff, 1996), and pH was measured in H_2O and 1 *M* NaF (Soil Survey Staff, 1996). Cation exchange capacity (CEC) and exchangeable Ca^{2+}, Mg^{2+}, K^+, and Na^+ were determined with 1 *M* NH_4OAc buffered at pH 7 (Soil Survey Staff, 1996). Phosphorus was extracted with 0.5 *M* $NaHCO_3$ buffered at pH 8.5 (Olsen et al., 1954). The fertilizer P availability index was determined according to Sharpley et al. (1984 and 1989) for three different soils (sites labeled A, B, C in Figure 5.2) after incubation with various amounts of P for 30 and 180 days, respectively.

Crop Growth Modeling

The *Decision Support System for Agrotechnology Transfer* (DSSAT, version 3.5) was used to simulate maize (*Zea mays* L.) growth in the area under study. DSSAT is an integrated modeling platform that comprises several crop simulation models and databases, as described in Jones et al. (1998). It operates on a field-scale with a daily time step and is capable of long-term simulations. The CERES model used within DSSAT to simulate maize growth models phenological and morphological development, biomass accumulation and partitioning, soil water balance, and soil nitrogen transformations (Jones et al., 1998).

Calibrated genetic coefficients for the local maize variety *Chaucho Mejorado* (INIAP-122) were obtained from Bowen (2000; personal communication). Using these coefficients, simulated grain yields corresponded with measured values for maize grown in the study area during the 2000-2001 rainy season. In order to analyze long-term effects of land management, 30 years of weather data were randomly generated with DSSAT's weather generator WGEN (Richardson and Wright, 1984) based on an existing 30-year weather dataset from the nearby town of Otavalo and known altitudinal variations of climatic parameters.

Parent Materials and Soil Texture

The earliest classifications of soils were based on an assessment of their ease of cultivation and management (Russell, 1988), which is largely determined by their particle size distribution or textural class. To this day, soil texture is among the most widely used farmers' criteria of local soil classification systems (Talawar and Rhoades, 1998). The distributions of topsoil sand and clay contents in the area under study are shown in Figures 5.5 and 5.6, respectively.

The studied volcanic ash soils generally exhibit high sand and low clay contents and are therefore easy to cultivate and not prone to compaction; however, there are marked textural variations within the study area. In the southern part, sand contents are considerably higher and clay contents considerably lower than in the northeastern part. This is likely due to different duration of soil development in the two areas. The soils in the southern part have formed on the 3000-year-old Cuicocha deposits, whereas the soils in the northeastern part have formed on deposits older than 40 000 years and have thus been exposed to the actions of physical and chemical weathering for a longer time. In the course of weathering, sand- and silt-sized primary minerals are fractured and dissolved, and new clay-sized secondary minerals are formed. As a result, soil texture becomes finer with progressive soil development. The soil age – clay content relation in the area under study is similar to that observed for volcanic deposits in New Zealand (Lowe, 1986).

The secondary or clay minerals formed during weathering are characterized by small particle sizes, charged surfaces, and high reactivity and thus dramatically change the soils' physical and chemical behavior. The higher clay contents on the older parent materials in the northeastern part lend the soils higher water-holding capacity and greater ability to retain nutrients against leaching as water percolates through the soil. On the other hand, the sandy soils encountered in the southern part, especially at lower elevations, cannot store much plant-available water and are prone to leaching losses of mobile nutrient ions, such as nitrate and potassium.

Soil Organic Matter and Nitrogen

Soil organic matter content is considered the most critical indicator of soil quality as it affects a variety of biological, chemical, and physical characteristics influencing a soil's productive capacity (Havlin et al., 1999). The importance of soil organic matter in the farmers' view is reflected by soil color being a central criterion in local soil classifications (Talawar and Rhoades, 1998).

Some of the functions of soil organic matter are as follows:

- It is a source of plant nutrients (N, P, S, and most micronutrients) that become available upon its decomposition.
- It increases a soil's exchange capacity and ability to retain nutrients against leaching.
- It enhances the plant-availability of micronutrients by forming soluble complexes.
- It improves a soil's water-holding capacity.

- It stabilizes soil structure thus promoting infiltration and making the soil more resistant to erosion.

Organic Matter in the Cotacachi Soils

The distribution of topsoil organic matter contents in the area under study is shown in Figure 5.7. In both the younger soils of the southern part and the older soils of the northeastern part, organic matter contents show dramatic increases with elevation on the volcano. This altitudinal accumulation is likely the result of slowed microbial decomposition due to lower temperatures and lower pH values at higher elevations. The presence of active amorphous constituents above 2700 m may have further contributed to the accumulation by protecting organic matter against microbial decomposition. The stabilizing effects of active amorphous constituents on soil organic matter have been demonstrated by Parfitt et al. (1997), who reported organic matter decreases upon conversion from pasture to cropland that were considerably higher in an Inceptisol than in an Andisol, the latter containing active amorphous constituents.

The low organic matter contents of the sandy low-elevation soils in the southern part of the study area further contribute to their low water-storage and nutrient-retention capacity. On the other hand, the ability to store plant-available water and to retain nutrients against leaching is greatly enhanced by organic matter accumulation in high-elevation soils.

Organic matter is an important source of plant nutrients, with the vast majority of soil nitrogen stored in organic compounds. The organic-rich high-elevation soils of the study area therefore have a considerable pool of nitrogen. However, in order for it to become available for plant uptake, organic nitrogen needs to be converted to mineral forms (mineralized) in the course of organic matter decomposition. Since for above-mentioned reasons, microbial decomposition of organic matter is slowed in high-elevation soils, the rate of nitrogen mineralization is slowed as well in these soils.

Nitrogen Cycling and Crop Growth Modeling

We used the DSSAT model to simulate nitrogen cycling and analyze the long-term effects of residue management and nitrogen fertilization on maize yields in two agro-ecological zones. The N transformations simulated by the model are presented in Figure 5.8. The two sites chosen for the modeling have markedly different soil properties. The Topo Grande site is located in the traditional maize zone at 2550 m. The soils of the area are Entisols with low organic matter contents and devoid of active amorphous constituents. The Morochos site lies 200 m higher towards the upper limit of the maize zone. The soils are Andisols with high organic matter contents and active amorphous constituents.

An annual maize-fallow rotation was simulated for a duration of 30 years at both sites. The simulation conditions were as follows: The maize crop was planted at the onset of the rainy season in October and harvested in the summer dry season, as traditionally practiced by the local farmers. Between harvest and the next planting, the land was fallow for several months. Four treatments were simulated:

1. The soil was never fertilized and all crop residues were removed after harvest.
2. The soil was never fertilized but all crop residues were returned to the soil.
3. The soil was fertilized with 25 kg ha^{-1} of N and all crop residues were returned to the soil.
4. The soil was fertilized with 50 kg ha^{-1} of N and all crop residues were returned to the soil.

Nitrogen fertilization was conducted with urea and chicken manure, which both resulted in the same grain yields and were therefore not presented separately. The default soil organic matter mineralization rate was used for the Entisol, and was multiplied by 0.2 for the Andisol, as suggested by Godwin and Singh (1998), to account for the slowed decomposition in this soil type. Nitrogen cycling was modeled while all other factors were assumed not limiting.

Model Outputs

Predicted grain yields over the 30-year simulation period are shown in Figures 5.9 and 5.10 for the Topo Grande and Morochos sites, respectively. When the fields were never fertilized and all crop residues were removed after harvest, maize yields declined at both sites from about 2000 kg ha^{-1} to little over 1000 kg ha^{-1} after 30 years of cultivation. By returning crop residues to the soil, maize yields were generally maintained above 2000 kg ha^{-1} over the 30-year simulation period, and yield declines were less pronounced. Maize yields were initially higher in Topo Grande but showed a steeper decline over time relative to Morochos. At both sites, maximum yields of around 3000 kg ha^{-1} were obtained by fertilizing with 25 kg ha^{-1} of N in inorganic or organic forms and returning crop residues to the soil.

The Andisol of the Morochos site has a larger nitrogen pool, which was maintained at a high level over the 30-year simulation period. Its lower mineralization rate provided a slow release of mineral nitrogen, which resulted in less leaching losses and more efficient plant uptake and nutrient cycling. The Entisol in Topo Grande has a higher mineralization rate resulting in more rapid release of mineral nitrogen. However, most of the nitrogen mineralized in this sandy soil was lost from the nutrient cycle through leaching, which led to a steady depletion of the soil's N reserves over the 30-year simulation period. Residue management and manuring did not efficiently counteract this depletion.

Implications for Management

Our data suggest that crop yields can be significantly improved by returning the residues to the soil after harvest. The peasant farmers in the area under study commonly remove crop residues and use them as stock feed, fuel, or roofing material. Some of thus exported nutrients may be returned in the form of animal manure, but most appear to be lost from the production systems. Solutions to this problem would greatly contribute towards agricultural sustainability in the area.

However, recycling crop residues alone cannot sustain high productivity of the soils in the study area. Additional N inputs are needed to compensate for slowed N mineralization in high-elevation soils and leaching losses in low-elevation soils, to supply the N necessary for maximum crop yields and to sustain the soil N reserves. There are several avenues by which N may be added to the soils. The most obvious, in the eyes of a western agronomist anyway, is the use of inorganic fertilizers. However, in Ecuador these are mostly imported and therefore relatively expensive and beyond the economic means of resource-poor peasant farmers. Besides, the use of inorganic fertilizers may not be most obvious to them. Traditionally, animal-based farming and shifting cultivation involving long fallow cycles have been practiced in the Andean eco-region to restore soil fertility (Sarmiento et al., 1993; Pestalozzi, 2000; Phiri et al., 2001). However, in the Cotacachi communities, theft of livestock has led many peasant farmers to give up animal-based farming, and limited amounts of available land preclude long fallow cycles.

Leguminous plants, which have the ability to bind atmospheric N, have been widely used all over the world to restore soil nitrogen fertility. The traditional intercropping of maize and beans in Andean agriculture (which we could not simulate due to model limitations) may improve the soils' N status to some extent, and crop rotations including legumes, sometimes practiced by the farmers in the study area, may increase the N supply for the following crop (Bossio and Cassman, 1991; Nieto-Cabrera et al., 1997). A particularly promising practice for adding N and organic matter to the soil is the management of short-term fallow systems with planted herbaceous or woody legumes, so-called improved fallows (Phiri et al., 2001).

Another source of N are organic fertilizers, such as chicken manure or worm compost. These have the advantage of adding other plant nutrients and organic matter along with N, and to buffer acidity that arises from plant uptake and nitrification of ammonium. The addition of organic matter would improve the soils' nutrient-retention and water-holding capacity, which is critically important for the sandy low-elevation soils in the southern part of the study area. Because of its slower decomposition, composted material is more suitable to serve this purpose.

Nitrogen loss by leaching is a common problem in well-drained soils of humid climates and a major contributor to soil fertility decline in many soils. Våje et al. (2000) found considerable leaching losses of N in a Tanzanian volcanic ash soil, and de Koning et al. (1997) estimated that leaching losses significantly contribute to N output from Andean cropland areas. If inorganic fertilizers are used, band placement near the plant roots and partitioning into several smaller applications may prove successful in enhancing their use efficiency and prevent excessive leaching losses. If organic amendments are used, composted material is preferable over fresh manure since it decomposes much slower thus releasing nitrogen at a slow and steady rate, which makes it less susceptible to leaching.

Amorphous Materials and Phosphorus

Active amorphous constituents, such as allophane and aluminum-humus complexes, are typical weathering products in volcanic ash soils; however, they require humid conditions for their formation (e.g., Parfitt et al., 1983; Parfitt and Wilson, 1985). The dominant presence of these constituents in the clay fraction of volcanic ash soils is indicated by pH (NaF) values above 9.4 (Wada, 1980). The distribution of topsoil pH (NaF) values in the area under study is shown in Figure 5.11. Irrespective of the soil parent material, the presence of active amorphous constituents shows a clear altitudinal pattern. Their formation is noticeably favored by the high rainfall – low evapotranspiration environment at higher elevations, and they are virtually absent below 2700 m.

Phosphate Sorption

Active amorphous constituents are known for their ability to strongly bind phosphate ions (e.g., Parfitt, 1989; Wada, 1989; Shoji et al., 1993), making phosphorus sparingly available for plants and microorganisms. In soils with active amorphous constituents (Andisols), P is often the growth-limiting nutrient for agricultural crops (Shoji et al., 1993). Apart from being directly yield-limiting, low P levels may further limit biological N fixation (Vitousek, 1999) thus impairing the soil N status.

To characterize phosphate sorption in the soils of the study area, we analyzed how much fertilizer P was still plant-available 30 and 180 days after application (Figures 5.12 and 5.13, respectively) in three different soils (labeled A, B, C in Figure 5.2) along a transect from high to low pH (NaF). The slopes of the straight lines in Figures 5.12 and 5.13 denote the fractions of fertilizer P that are plant-available after the respective amount of time. Soil A, an Andisol located at 2900 m, shows the highest phosphate sorption with 31 % of fertilizer P available after 30 days, decreasing to 19 % after 180 days. Soil B is an Inceptisol located near the pH (NaF) boundary of 9.4 that separates soils with and without dominant presence of active amorphous constituents. It shows intermediate phosphate sorption with 47 % of fertilizer P available after 30 days, which only slightly decreases to 42 % after 180 days. Soil C, an Entisol in the zone devoid of active amorphous constituents, shows the least phosphate sorption. Around three quarters of fertilizer P are plant-available 30 and 180 days after application.

Phosphate sorption in the area under study is largely controlled by active amorphous constituents, which predominate at higher elevations. The low soil pH (H_2O) values at these elevations further increase the positive charge of colloid surfaces thus enhancing phosphate sorption in high-elevation soils. This may lead to phosphorus deficiencies in the high zones of the study area that have traditionally been cultivated with potato and other Andean tubers.

Status of Phosphorus in the Cotacachi Soils

The distribution of bicarbonate-extractable phosphorus (Olsen-P; Olsen et al., 1954) in the area under study is shown in Figure 5.14. A soil's Olsen-P content is a measure of its phosphorus-supplying capacity for plant growth. According to the Ecuadorian *Instituto Nacional Autónomo de Investigaciones Agropecuarias* (INIAP), soils in the Andean region that have Olsen-P values below 10 mg kg^{-1} are considered low in phosphorus and require high amounts of added P for maximum crop yields. Between 10 and 20 mg kg^{-1} of Olsen-P is regarded as intermediate requiring less additions of fertilizer P, and soils with Olsen-P above 20 mg kg^{-1} supply sufficient amounts of phosphorus for optimum crop growth.

As expected, high-elevation soils generally show the lowest values of bicarbonate-extractable phosphorus, which is likely associated with the strong sorption of phosphate by active amorphous constituents, as discussed above. However, Olsen-P appears to be higher in the community of Ugshapungo above 3000 m than in the zone between 2800 and 3000 m (Figure 5.14). This may be a residual effect of high fertilizer applications in past decades, when potato was grown with high inputs in this area. Continuous heavy application of phosphorus fertilizers leads to the occupation of P sorption sites thus enhancing recovery of fertilizer P (Havlin et al., 1999) and increasing soil phosphorus to levels that may exceed plant requirements (Shoji et al., 1993).

Apart from altitudinal variations, if we only look at low-elevation areas, bicarbonate-extractable phosphorus appears to be higher in the younger soils of the southern part compared to the older soils in the northeastern part of the study area. This could be caused by differences in parent material P contents and time of soil development. Shoji et al. (1993) suggested that plant-availability of phosphorus decreases rapidly as weathering proceeds in volcanic ash soils due to the relatively rapid dissolution of apatite, the primary phosphorus-bearing mineral in volcanic deposits, and conversion of P into more insoluble forms.

Implications for Management

Phosphorus does not appear as yield-limiting in the area under study as commonly assumed and often reported for volcanic ash soils. The young low-elevation soils in the southern part of the study area generally supply sufficient amounts of P for optimum crop growth. Phosphorus additions seem necessary to assure maximum yields at higher elevations, especially when – as traditionally – potato is grown in the high zone, and may prove beneficial in some low-elevation zones of the northeastern study area.

Phosphorus is fairly immobile and is not easily lost from the root zone by leaching; however, as shown in Figures 5.12 and 5.13, added fertilizer P may be rendered unavailable through strong sorption by active amorphous constituents. For this reason, recovery of fertilizer P by agricultural crops is commonly less than 20 % in Andisols

(Shoji et al., 1993). Band applications near the plant roots and the use of P sources with low solubility may delay the reaction of phosphate with active amorphous constituents thus resulting in enhanced availability for plant uptake.

The use of organic P sources, such as chicken manure or organic wastes, may prove particularly beneficial in improving the soils' P status. Mazzarino et al. (1997) reported higher P utilization efficiency and plant uptake, higher residual Olsen-P and lower P sorption in the soil if organic amendments were used instead of inorganic fertilizer. Apart from supplying phosphorus that is mineralized upon decomposition, organic amendments can increase P availability by a second mechanism. Organic anions formed during the decomposition of organic inputs can compete with phosphate ions for sorption sites on active amorphous constituents and thereby increase plant-availability of phosphorus (Iyamuremye and Dick, 1996; Iyamuremye et al., 1996).

Cation Exchange Capacity and Potassium

An important soil fertility characteristic is the storage capacity of exchangeable nutrient cations (essentially Ca^{2+}, Mg^{2+}, and K^{+}) on the charged surfaces of soil particles. As plant roots take nutrients from the soil solution, they are re-supplied from these surfaces by exchange reactions. In the soils of the study area, most of the inherent charge arises from organic matter and active amorphous constituents. In both cases, the charge is variable, which means it is highly dependent on the ambient conditions, primarily soil pH and electrolyte concentration. As soil pH increases, the variable-charge surfaces become increasingly negative thus favoring the storage of nutrient cations.

Cation Exchange Capacity in the Cotacachi Soils

The distribution of topsoil cation exchange capacity (CEC; measured at pH 7) in the area under study is shown in Figure 5.15. However, the conventional method of determination at pH 7 can drastically overestimate the CEC of variable-charge soils at natural pH and electrolyte levels (Parfitt, 1980). The values in Figure 5.15 may therefore be viewed as estimates of a potential CEC that illustrate the spatial distribution of charge-bearing soil constituents in the area. These may or may not be effective in retaining nutrient or pollutant cations under field conditions depending on the natural soil pH values. At pH 7, the highest amounts of negative charge are found in high-elevation soils and likely originate from organic matter and active amorphous constituents. The older soils in the northeastern part of the study area generally exhibit higher negative charge than the younger soils in the southern part, which may arise from higher clay contents in the older, more developed soils.

Since exchangeable aluminum is very low in the soils of the study area – likely because of strong bonding with organic matter and the formation of Al-humus complexes – the sum of exchangeable bases (Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}) may serve as a good estimate of effective CEC. The spatial distribution of the sum of exchangeable bases, presented in Figure 5.16, shows a very different pattern with absolute values considerably lower than CEC at pH 7. The majority of the negative charge observed in the high-elevation soils of the southern study area at pH 7 is absent at the low natural soil pH values, resulting in low amounts of exchangeable bases (Figure 5.16). Effective CEC slightly increases with pH in the lower parts of the southern study area; however, due to the sandy textures absolute values are still very low. The finer-textured soils in the northeastern part of the study area show considerably higher effective CEC, which results in better ability to retain nutrients against leaching, to filter pollutants, and to buffer acidity.

Exchangeable Potassium

The amount of exchangeable potassium held on the charged surfaces of soil particles is a reliable indicator of K availability to plants (Shoji et al., 1993). The distribution of exchangeable K in topsoils around the study area is shown in Figure 5.17. The young, sandy soils in the southern study area have considerably lower exchangeable K than the older, finer textured soils of the northeastern part. Exchangeable K is particularly high in the zone just north of the town of Cotacachi (Figure 5.17). Differences in age and composition of parent materials are likely responsible for these variations within the area under study. With concentrations of about 1.3 % as K_2O, the Cuicocha deposits of the southern study area are on the lower end of K contents reported for volcanic parent materials (Shoji et al., 1993). Moreover, there has not yet been enough time for weathering in these 3000-year-old deposits to form significant amounts of clay and exchange surfaces for the retention and storage of potassium ions. As with nitrogen, leaching losses of potassium may be significant in these sandy soils. On the other hand, de Koning et al. (1997) attributed net K losses from Andean cropland areas mainly to removal with harvested products.

Exchangeable potassium contents below 0.3 $cmol_c\ kg^{-1}$ may be considered as low, resulting in potassium deficiencies in common upland crops (Shoji et al., 1993). However, in field trials conducted during the 2000-2001 rainy season in the southern part of the study area, maize yields showed marked responses to additions of fertilizer K on soils that had 0.6 $cmol_c\ kg^{-1}$ of exchangeable potassium.

Exchangeable Calcium and Magnesium

The spatial distributions (maps not shown) of exchangeable Ca and Mg exhibit similar patterns as observed for exchangeable K, with higher values in the northeastern compared to the southern part of the study area. The soils generally have adequate ratios of Ca^{2+}, Mg^{2+}, and K^+ on the exchange surfaces and low exchangeable acidity, which prevents nutrient imbalances and assures sufficient supply of Ca and Mg to agricultural crops.

Implications for Management

The distribution of exchangeable potassium suggests that K deficiencies may limit crop growth in the southern part of the study area. Such conclusion is supported by our field experiments that showed clear yield increases of maize upon K fertilization in that area. Additions of potassium seem therefore necessary for adequate crop growth in the young soils of the southern study area. If potassium is added through inorganic fertilizers, band placement near the plant roots and partitioning into several smaller applications is recommended to enhance recovery and avert excessive leaching losses. Organic fertilizers may prove more beneficial in the long term for reasons discussed in the context of N and P fertilization. It should be mentioned here that the low CEC values of the low-elevation soils in the southern study area could be increased by management practices that foster the build-up of soil organic matter, such as the continued application of organic amendments or the incorporation of improved fallows in crop rotations. The use of deep-rooting woody legumes in such fallows could mobilize potassium and other nutrients from the subsoil and recycle them back into the topsoil, available for the following crop.

Soil Acidity and pH

Soil acidity and associated aluminum toxicity may limit root development and thus impair normal growth of agricultural crops. The distribution of active acidity (pH in H_2O) in topsoils around the study area is shown in Figure 5.18. In both the younger soils of the southern part and the older soils of the northeastern part, pH (H_2O) values decrease substantially with increasing elevation on the volcano. This altitudinal pattern is likely the result of greater acidity inputs with increased precipitation, greater leaching of basic cations, and greater activity of organic acids as a result of slowed organic matter decomposition at higher elevations.

Most agricultural crops grow normally above pH 5.5 (Havlin et al., 1999) and become increasingly sensitive to elevated levels of aluminum as pH drops below this value. However, as mentioned in the context of cation exchange capacity (CEC), exchangeable Al is very low in the soils of the study area, even at pH 5 – presumably a result of strong bonding with organic matter and formation of Al-humus complexes. It is therefore unlikely that soil solution Al reaches levels toxic to plant roots even in high-elevation soils.

The variable charge characteristics of the soils under study make pH an important determinant of the soils' nutrient-retention properties. Management practices that affect soil pH are therefore likely to have a substantial effect on the fate of plant nutrients in the soil (Sollins et al., 1988). The application of liming materials at higher elevations would increase CEC and thus enhance the soils' storage capacity for potassium. It could further reduce phosphate sorption and make P more available for plant uptake. Moreover, most microbially mediated reactions are restricted under acidic conditions. Liming has been shown to enhance mineralization of organic N and to increase N fixation by leguminous plants (Havlin et al., 1999).

Thus, the application of liming materials would have several beneficial effects in the high-elevation soils of the study area. However, for the cultivation of potato, the soil pH values between 5 and 5.5 in the high zone are desirable since *Streptomyces scabies*, the disease organism that causes scab in potatoes, is much better adapted to a neutral than to an acid soil (Russell, 1988).

Plant – Water Relations and Irrigation

Plants use large amounts of water during growth and daily water use of an actively growing crop may be several times its own mass (Russell, 1988). Inadequate water availability especially during the development and fertilization of the reproductive organs can drastically limit crop production. Lal (2000) listed “sandy or stony soils with low available water capacity and susceptibility to drought” among major soil-related constraints to rainfed agriculture in developing countries.

The zones most likely affected by drought in the area under study are the low-elevation zones. Compared to the high zones, they receive less rainfall and show higher evapotranspiration, and their soils have lower water-holding capacity due to lower organic matter contents. Presently, only some of the communities at lower elevations have access to irrigation water, but an expansion of the irrigation systems to a wider area and higher elevations is desired by local farmers and considered high-priority by local authorities.

Water Balance and Crop Growth Modeling

We used the DSSAT model to simulate the water balance and analyze the long-term effects of irrigation on maize yields in two agro-ecological zones. The components of the water balance simulated by the model are presented in Figure 5.19. Both sites chosen for the modeling presently don’t have access to irrigation water. The Topo Grande site is located at 2550 m, has a mean annual precipitation of about 900 mm and soils with low water-holding capacity. The Morochos site lies at 2750 m, receives about 1100 mm of mean annual rainfall, and has soils with higher water-holding capacity due to higher organic matter contents.

An annual maize-fallow rotation was simulated with and without irrigation for a duration of 30 years at both sites. The simulation conditions were as follows: In a first model run, the maize crop was grown during the rainy season as traditionally practiced by the local farmers. Maize was planted at the onset of the rainy season in October and harvested in the summer dry season. In a second model run, maize was grown over the summer dry season, as sometimes practiced when irrigation is available. Maize was planted towards the end of the rainy season in April and harvested in the short winter dry period. Between harvest and the next planting, the land was fallow for several months. The water balance was modeled while all other factors were assumed not limiting.

Model Outputs

Predicted grain yields for maize grown during the rainy season are shown in Figures 5.20 and 5.21 for the Morochos and Topo Grande sites, respectively. At neither site was rainy season water availability yield-limiting during the 30-year simulation period, for which was assumed that climate shows similar patterns as observed in the past 30 years. Consequently, irrigation had little to no effect on maize yields, which fluctuated around 3000 kg ha^{-1} at both sites.

The situation was different when maize was grown over the summer dry season, as shown in Figures 5.22 and 5.23 for the Morochos and Topo Grande sites, respectively. Maximum maize yields, provided sufficient amounts of plant-available water, were higher due to increased growing energy during the sunny summer months. In Morochos, rainfed cultivation of maize resulted in near maximum yields only in wet years, and drought stress significantly lowered crop production in dry years. Irrigation resulted in an average yield increase of over 600 kg ha^{-1} (Figure 5.22). In Topo Grande, crop growth was drastically limited by water stress in each of the 30 simulated years, and maize yields could on average be doubled with irrigation (Figure 5.23).

Cumulative probability functions of potential yield increase upon irrigation of maize grown over the summer dry season are presented in Figure 5.24. Irrigation could increase maize yields by about 600 kg ha^{-1} in Morochos and by over 1500 kg ha^{-1} in Topo Grande with a 50 % probability, or statistically every other year. In Topo Grande, the chances to increase maize yields by over 1400 kg ha^{-1} are over 80 % (Figure 5.24).

Implications for Management

Our data suggest that water stress will seldom (only in exceptionally dry years) be limiting to crop growth during the rainy season – even in the drier low-elevation zones of the study area. An expansion of the irrigation systems seems therefore unnecessary if crops are grown during the rainy season and the land is fallow during the dry season. On the other hand, water stress can drastically limit crop growth during the dry season – especially in the drier low-elevation zones of the study area, where the soils are sandy and low in organic matter. Availability of irrigation water could therefore greatly benefit dry-season crop production, particularly in these low zones.

However, expansion of the present irrigation systems may come up against physical limits, such as total streamflow and location (elevation) of fields relative to water sources. Moreover, water availability for upland irrigation use may be limited by conflicts with emerging domestic, industrial, and floriculture demands in the valley. And finally, decisions not to irrigate despite sufficient water supply, as observed by Gilot et al. (1997) in nearby Urcuqui, could render the most sophisticated irrigation system – along with all associated painstaking studies (including this one) – completely worthless. Solutions to the latter problems are in the political and socioeconomic arenas rather than in the biophysical.

Conclusions

The volcanic ash soils in the Andean communities around volcano Cotacachi have the potential to sustainably support traditional subsistence agriculture as well as thriving market-oriented production of niche crops, vegetables, and fruits. In either case, the key to agricultural sustainability is the restoration and maintenance of soil fertility. Nutrient losses need to be minimized, and nutrients that leave the production systems through harvested products need to be replaced. The soils show marked variations within the study area, and depending on the specific location, different factors may become limiting to crop growth and therefore deserve special attention.

One potential limiting factor that becomes very obvious if one visits the area in the summer dry season, is plant-available water. The zones most likely affected by drought are the low-elevation zones of the study area. There, potential water stress caused by lower rainfall and higher evapotranspiration, is aggravated by soils with low organic matter contents and sandy textures exhibiting little water-storage capacity. Crop growth modeling suggests that, while rainy season water availability is generally sufficient, an expansion of existing irrigation systems would considerably improve dry-season crop production, particularly in these low zones.

Plant nutrients may become yield-limiting in certain parts of the study area. The young soils on the Cuicocha deposits of the southern study area have inherently low potassium contents and would greatly benefit from additions of this nutrient. In high-elevation soils, strong sorption of phosphorus on active amorphous constituents may become yield-limiting and necessitate increased P inputs for optimum crop growth. Nitrogen may be mineralized too slowly to satisfy crop requirements in high-elevation soils, whereas leaching losses may impair adequate N supply in low-elevation soils. The nitrogen status of all soils would greatly benefit from returning residues to the soil after harvest, including leguminous plants in crop rotations, and managing short, improved fallows.

Generally, organic nutrient sources seem preferable over inorganic for a number of reasons. First, they simultaneously add several nutrients including micronutrients to the soils and thus prevent potential nutrient imbalances. Second, they enhance the plant-availability of phosphorus and micronutrients by the formation of organic anions that compete with phosphate for sorption sites and form soluble complexes with micronutrient cations. Third, they increase the soils' organic matter contents and so have beneficial effects on nutrient storage, water retention, infiltration capacity, etc. Fourth, they can be produced in and by the communities themselves, are therefore more readily and cheaply available, and create less dependency on uncontrollable external factors. And fifth, they may be more compatible with local traditions and hence be more widely accepted.

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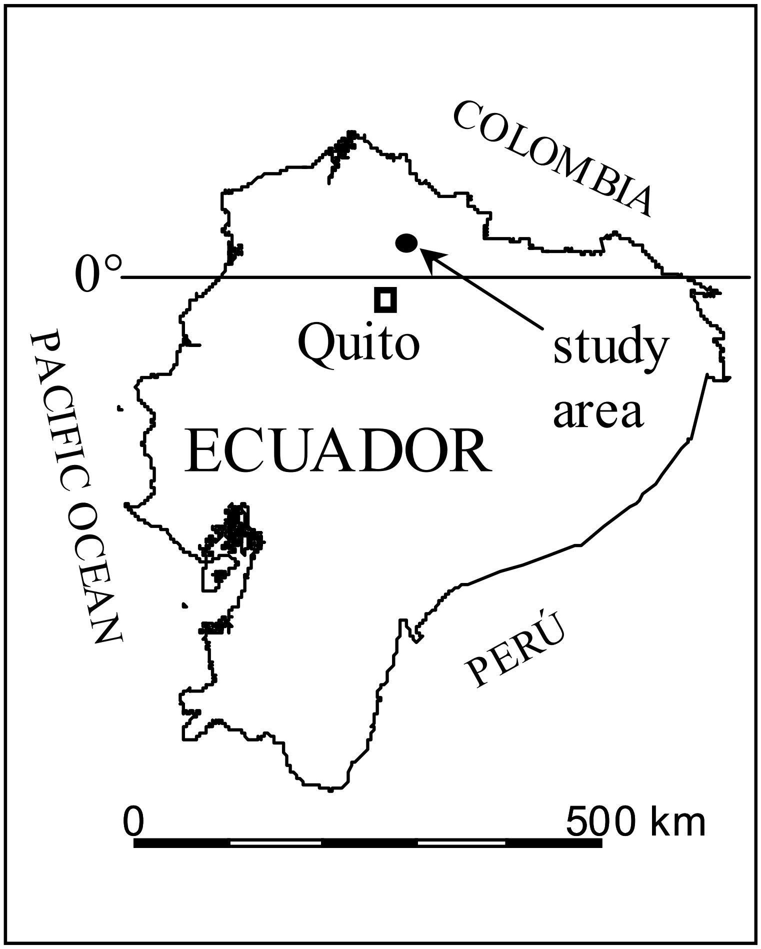

Figure 5.1. Location of the study area.

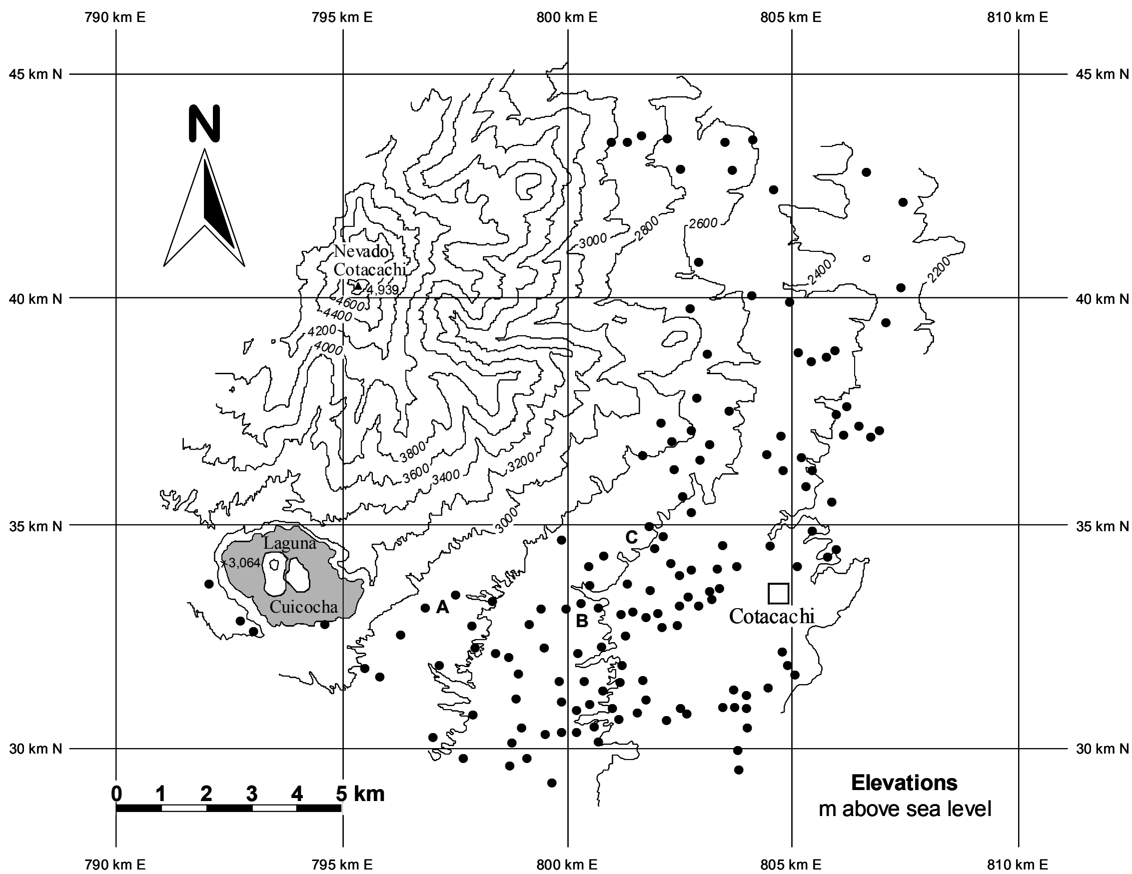

Figure 5.2. Study area; the locations of the 145 sampled fields are marked with solid dots; at sites A, B, C, the fertilizer phosphorus availability index was determined.

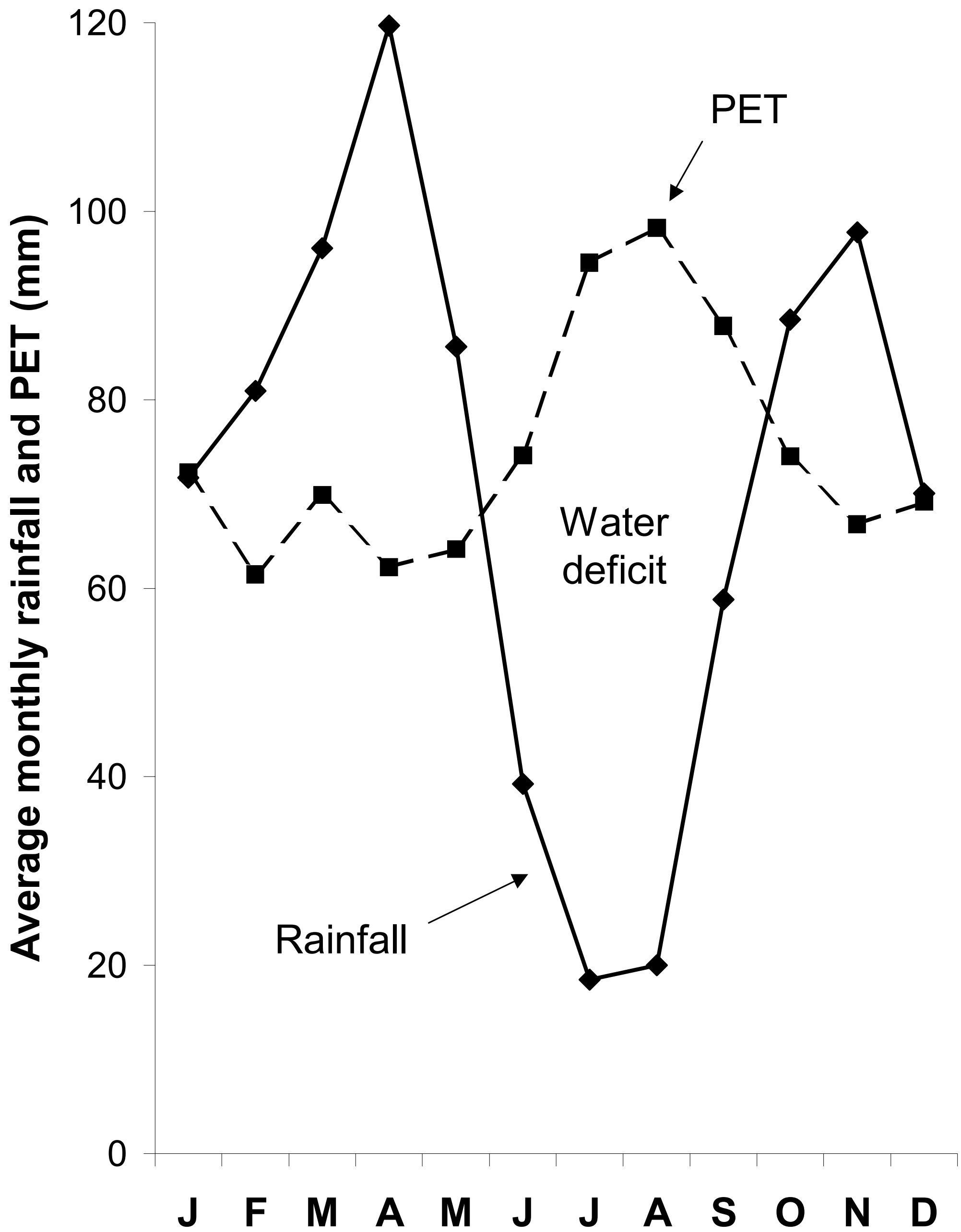

Figure 5.3. Annual distribution of rainfall and potential evapotranspiration (PET) for Otavalo.

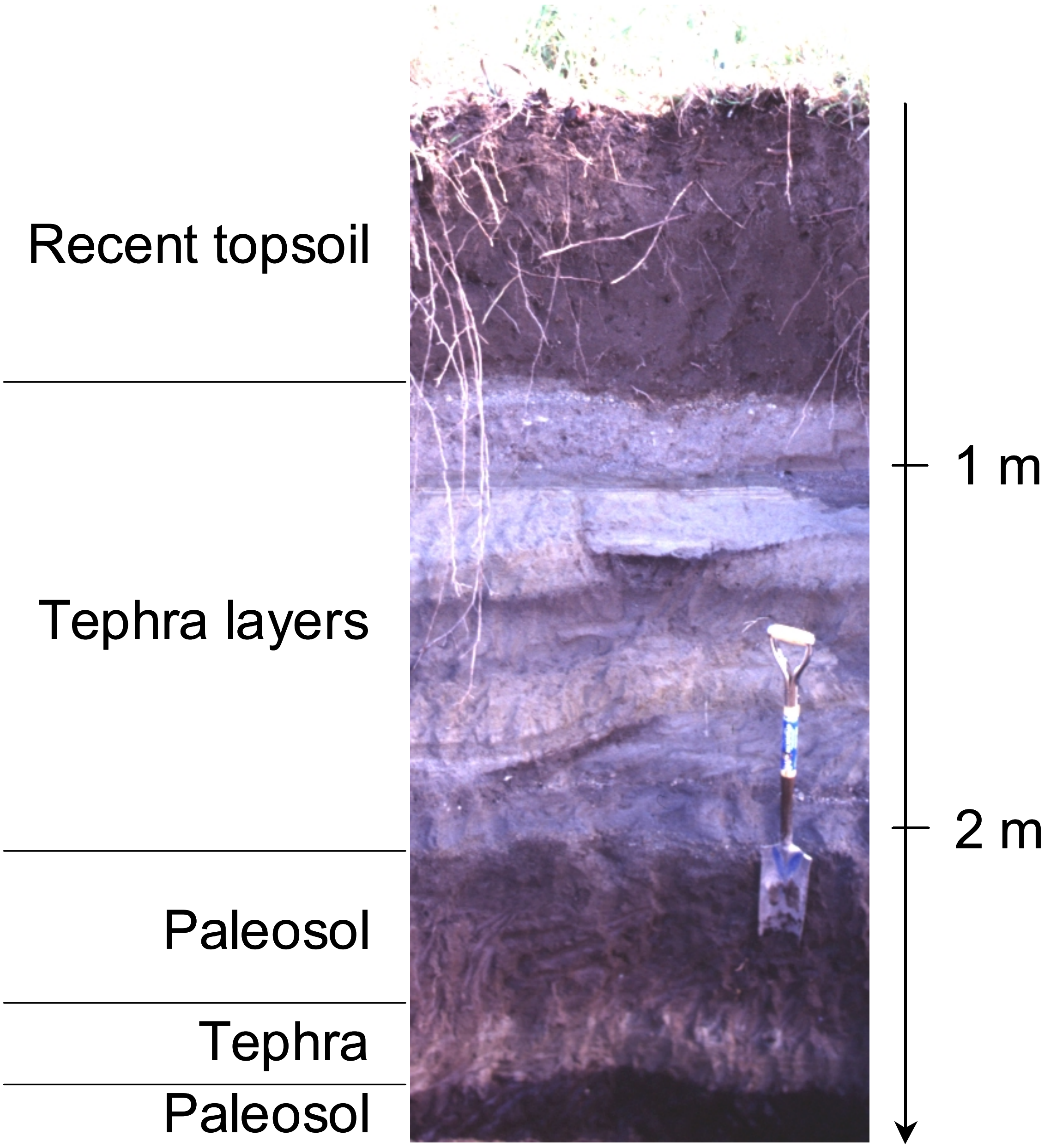

Figure 5.4. Typical profile of a volcanic ash soil in the area.

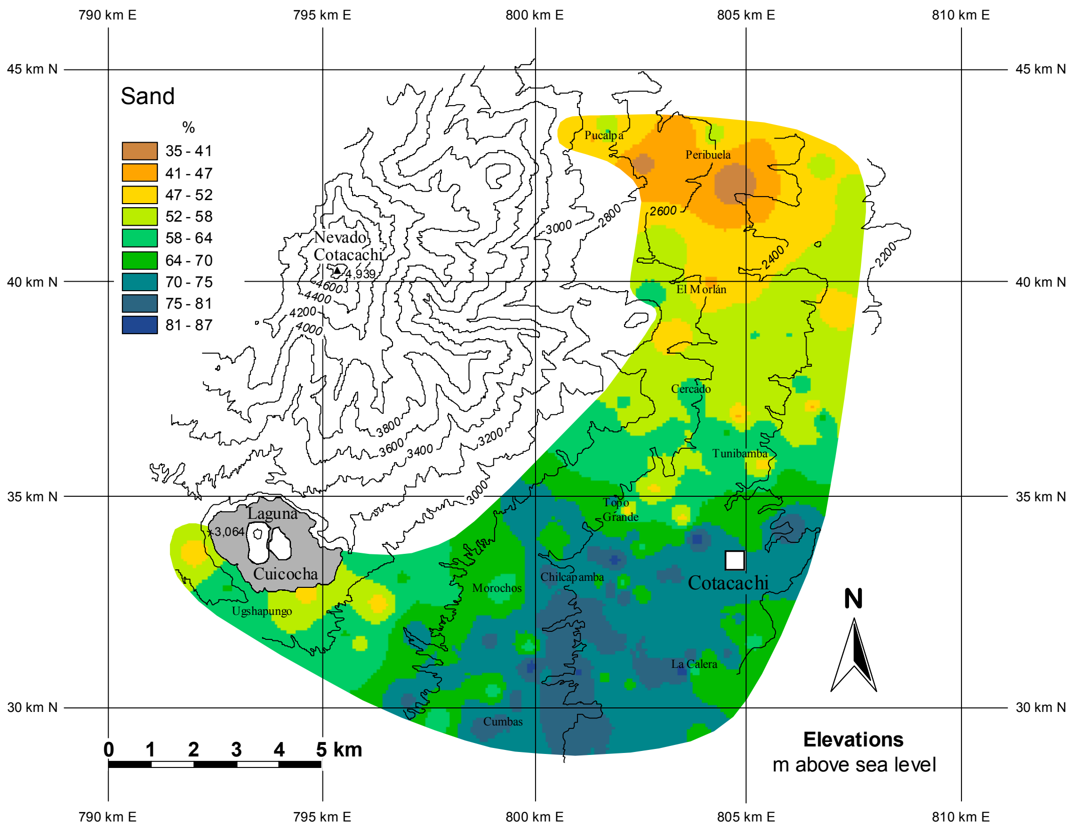

Figure 5.5. Spatial distribution of topsoil sand contents.

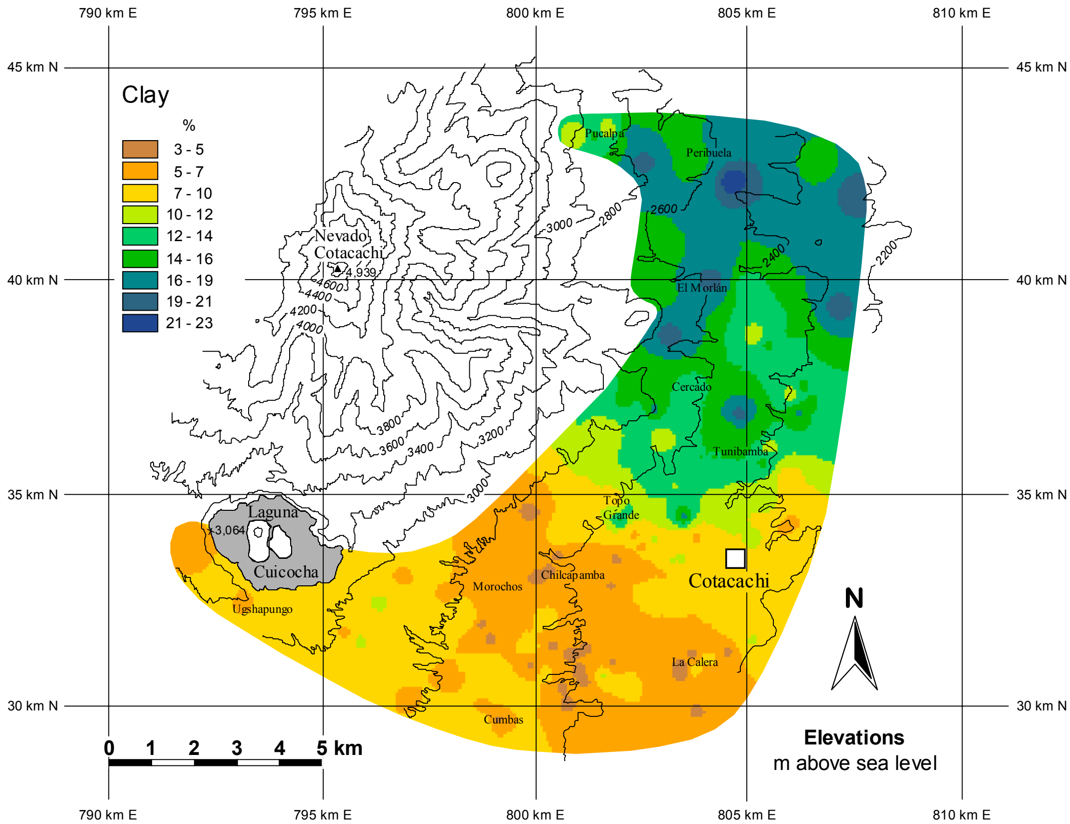

Figure 5.6. Spatial distribution of topsoil clay contents.

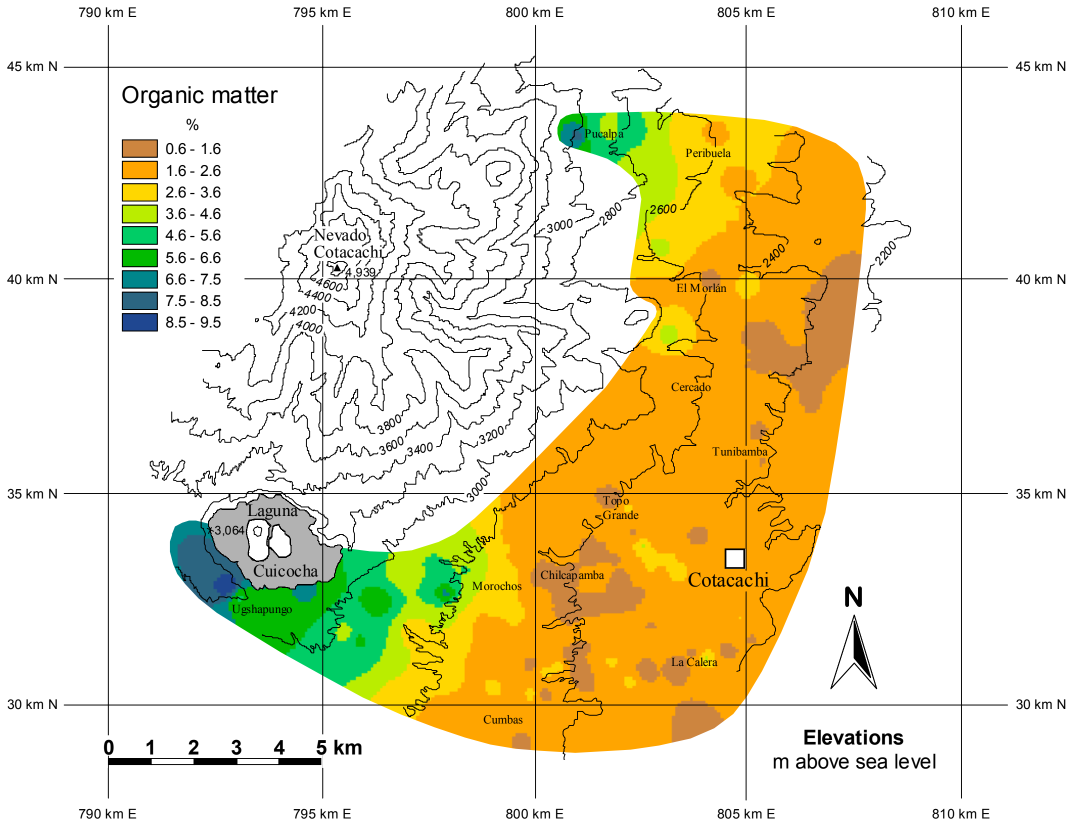

Figure 5.7. Spatial distribution of topsoil organic matter contents.

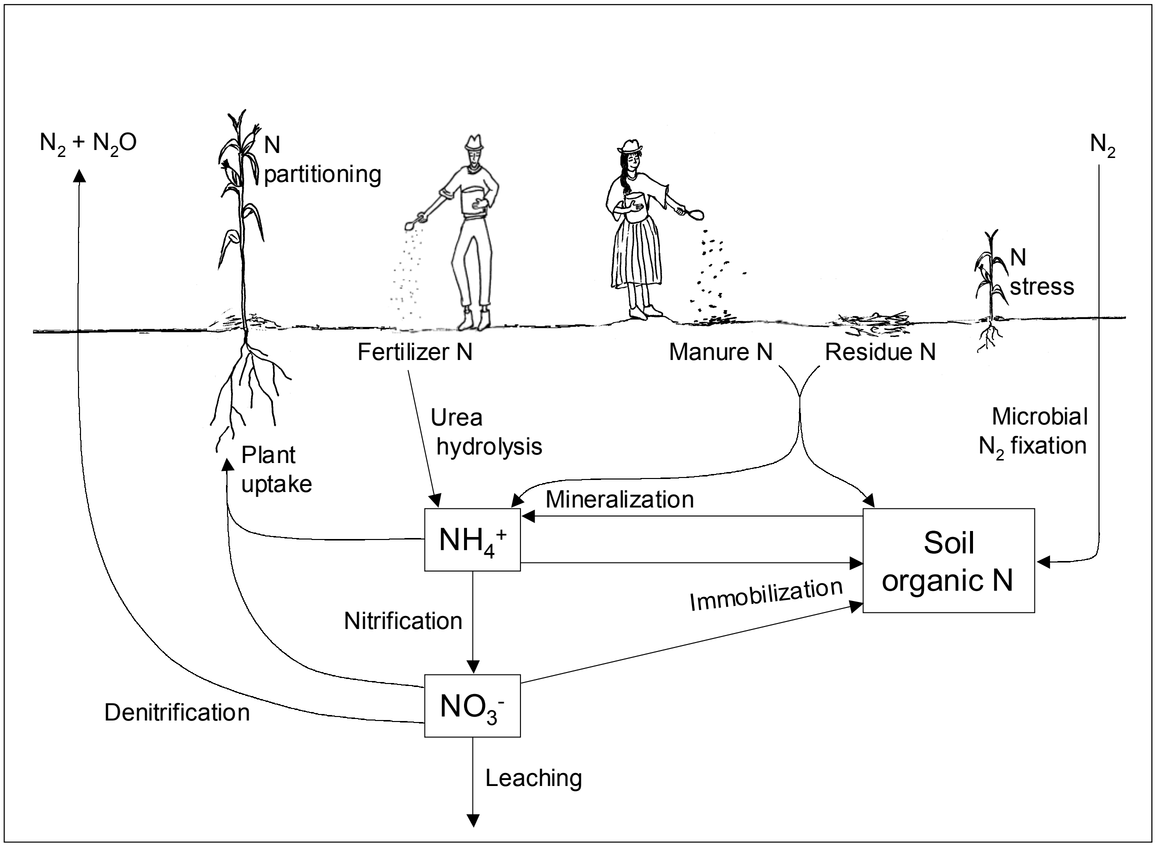

Figure 5.8. Nitrogen transformations simulated with the DSSAT model.

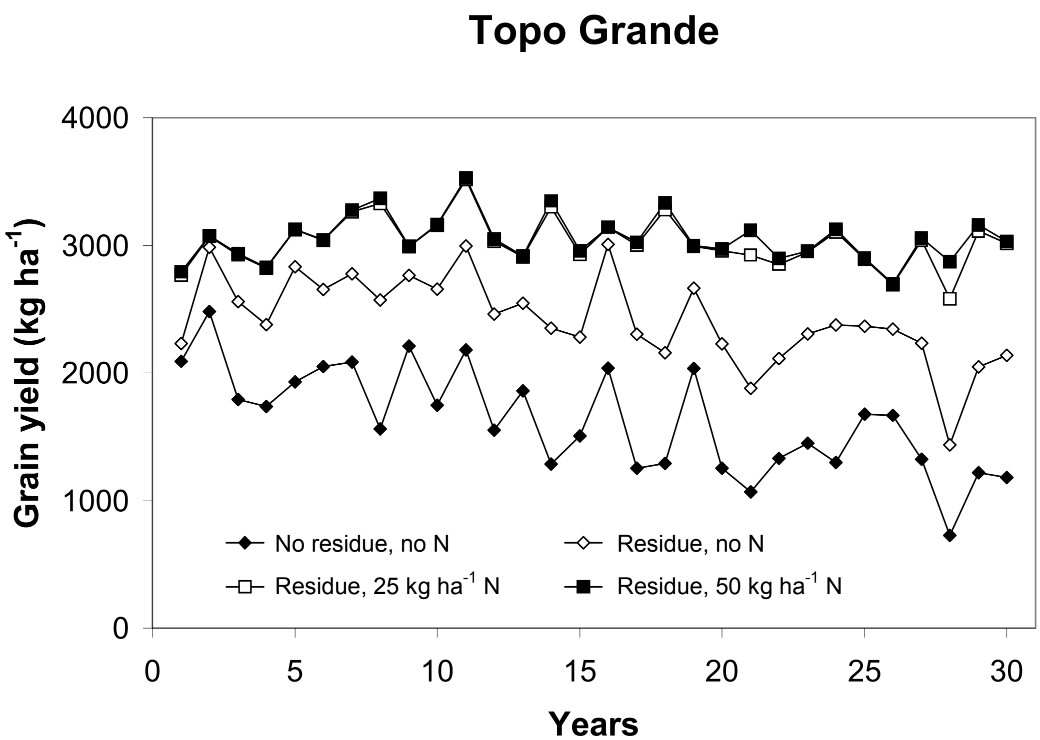

Figure 5.9. Simulated grain yields in an annual maize-fallow rotation with different nitrogen inputs from residue incorporation and fertilization for Topo Grande (soil type: Vitrandic Udorthents; elevation: 2550 m); nitrogen cycling was simulated, other factors were assumed not limiting.

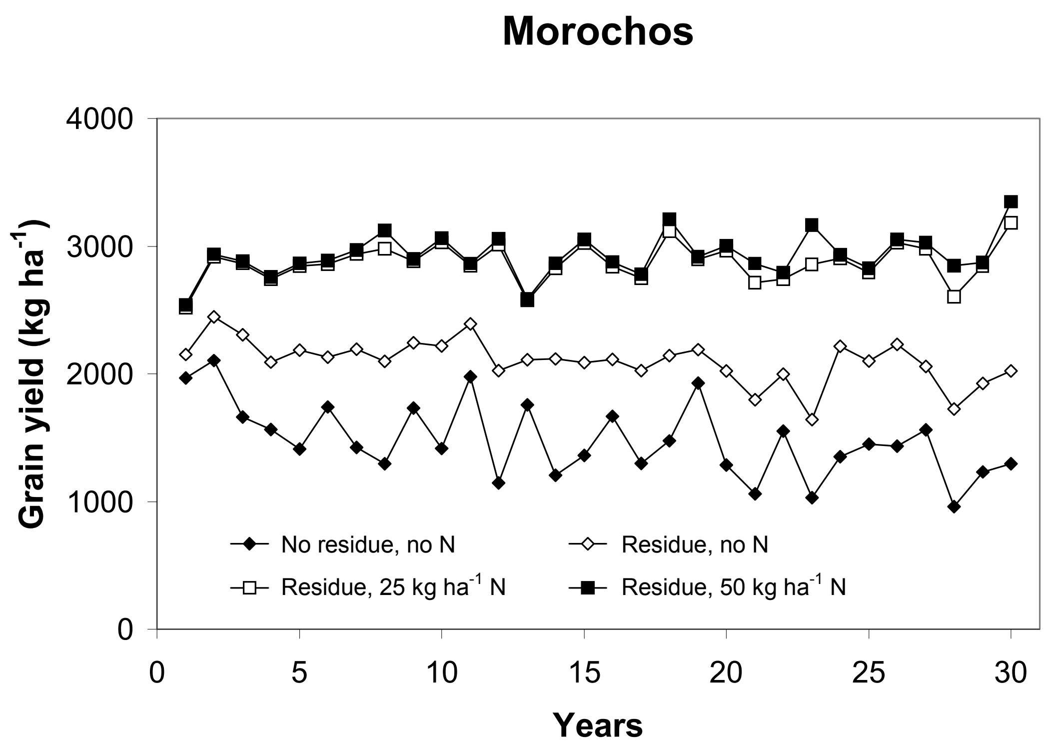

Figure 5.10. Simulated grain yields in an annual maize-fallow rotation with different nitrogen inputs from residue incorporation and fertilization for Morochos (soil type: Humic Udivitrands; elevation: 2750 m); nitrogen cycling was simulated, other factors were assumed not limiting.

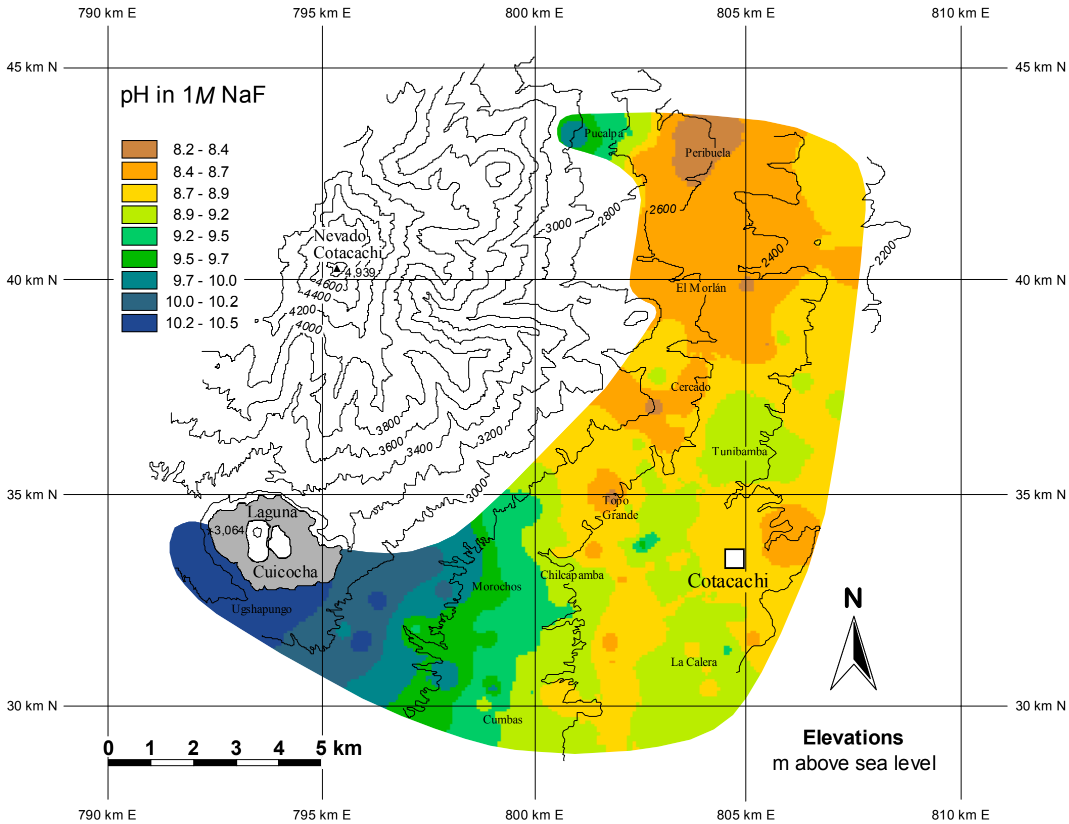

Figure 5.11. Spatial distribution of topsoil pH (NaF); values > 9.4 indicate the dominant presence of active amorphous constituents in the clay fraction (Wada, 1980).

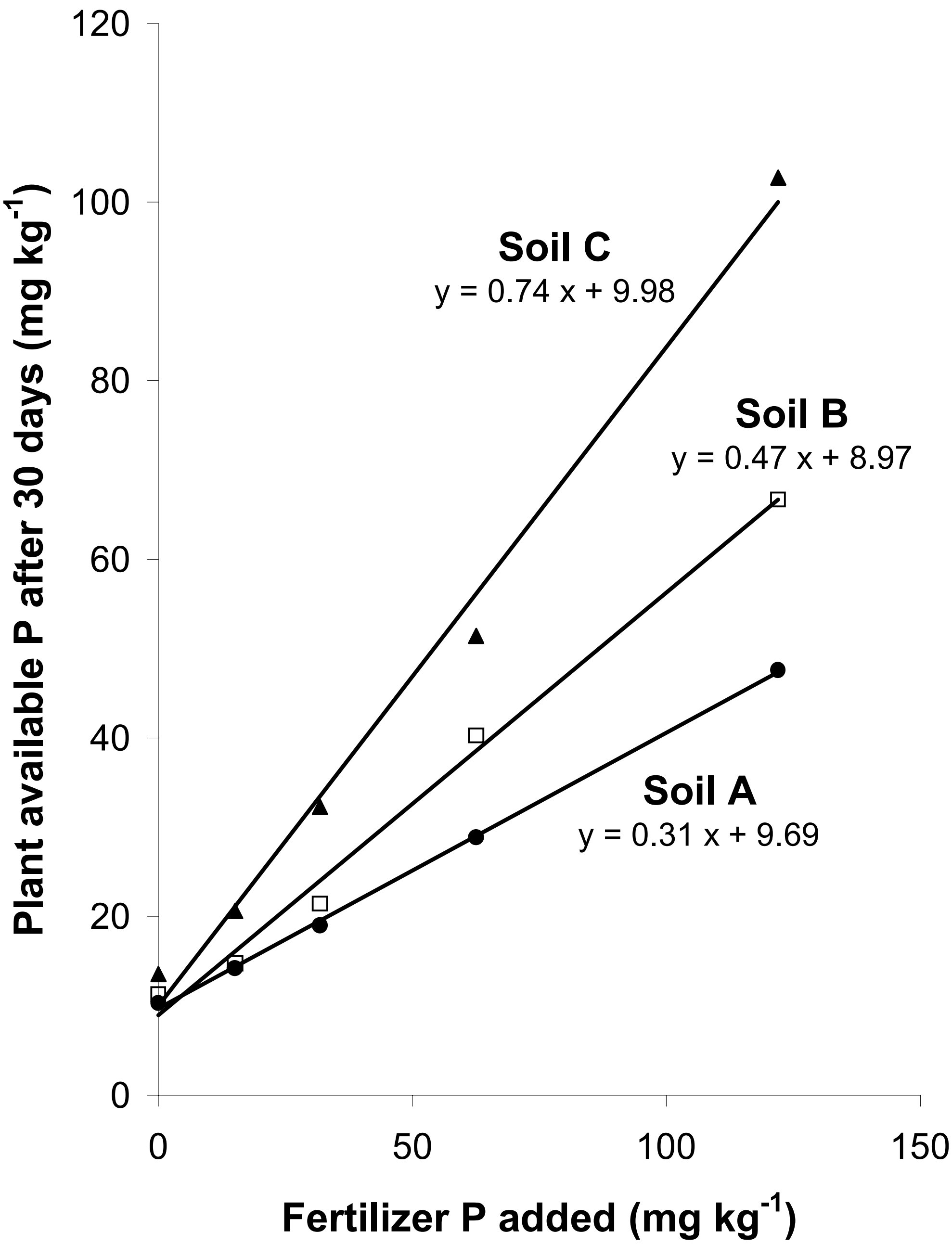

Figure 5.12. Fertilizer phosphorus availability 30 days after application in three different soils.

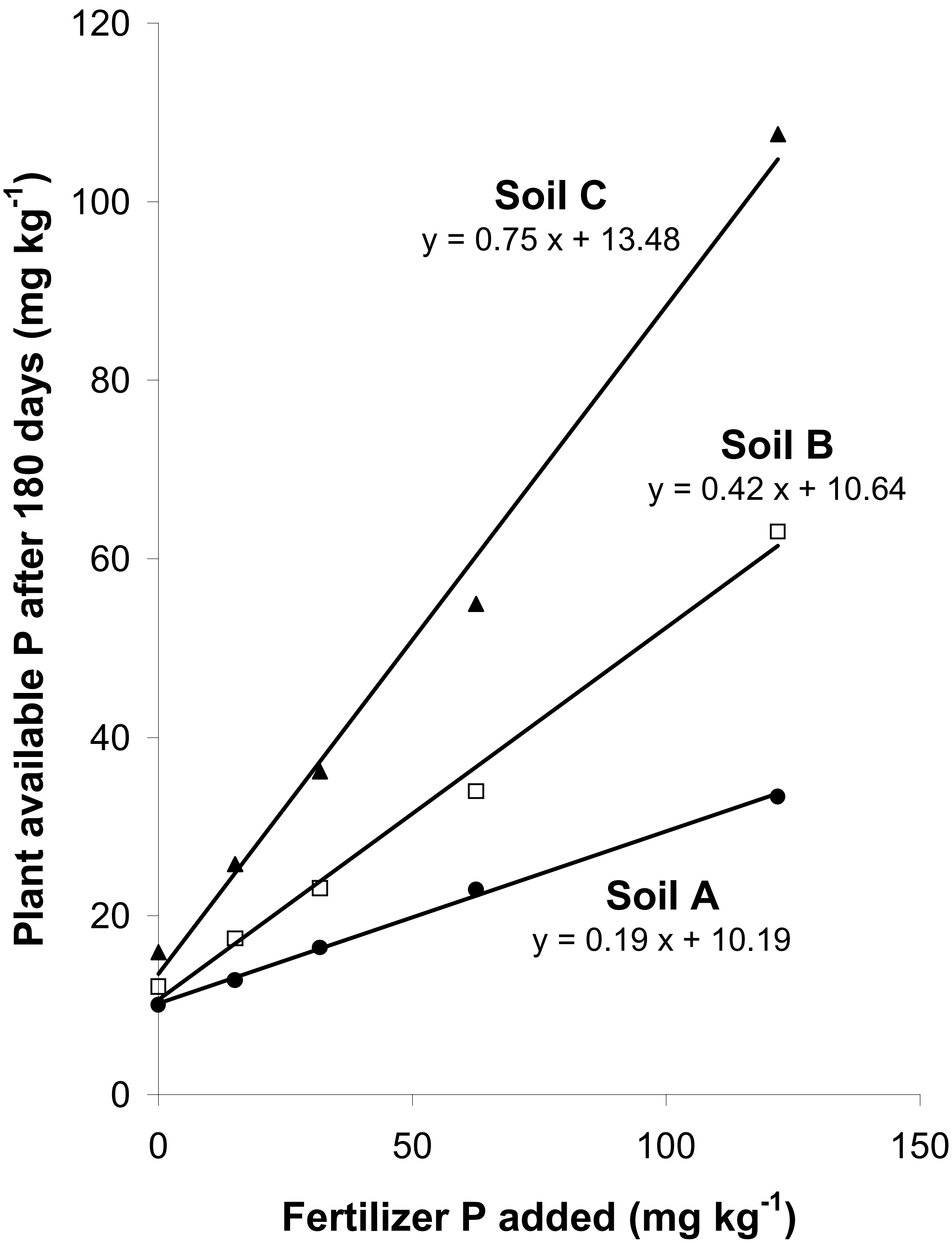

Figure 5.13. Fertilizer phosphorus availability 180 days after application in three different soils.

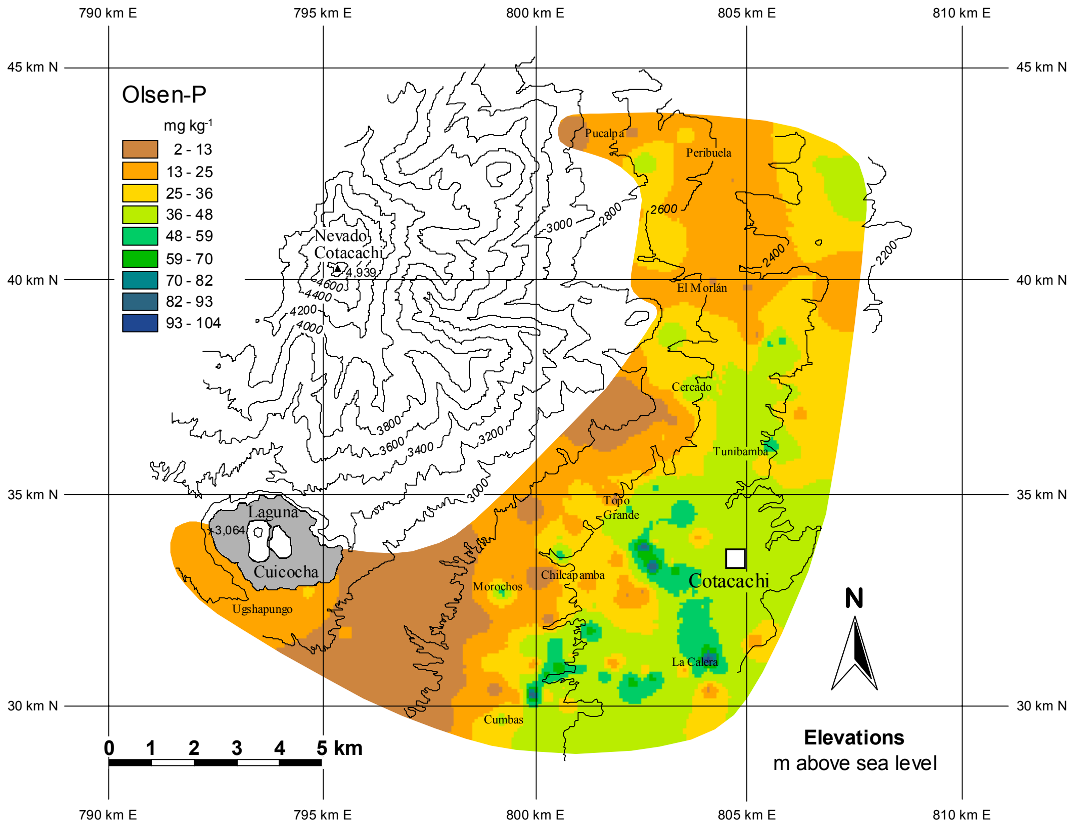

Figure 5.14. Spatial distribution of bicarbonate-extractable phosphorus (Olsen-P; Olsen et al., 1954) in topsoils.

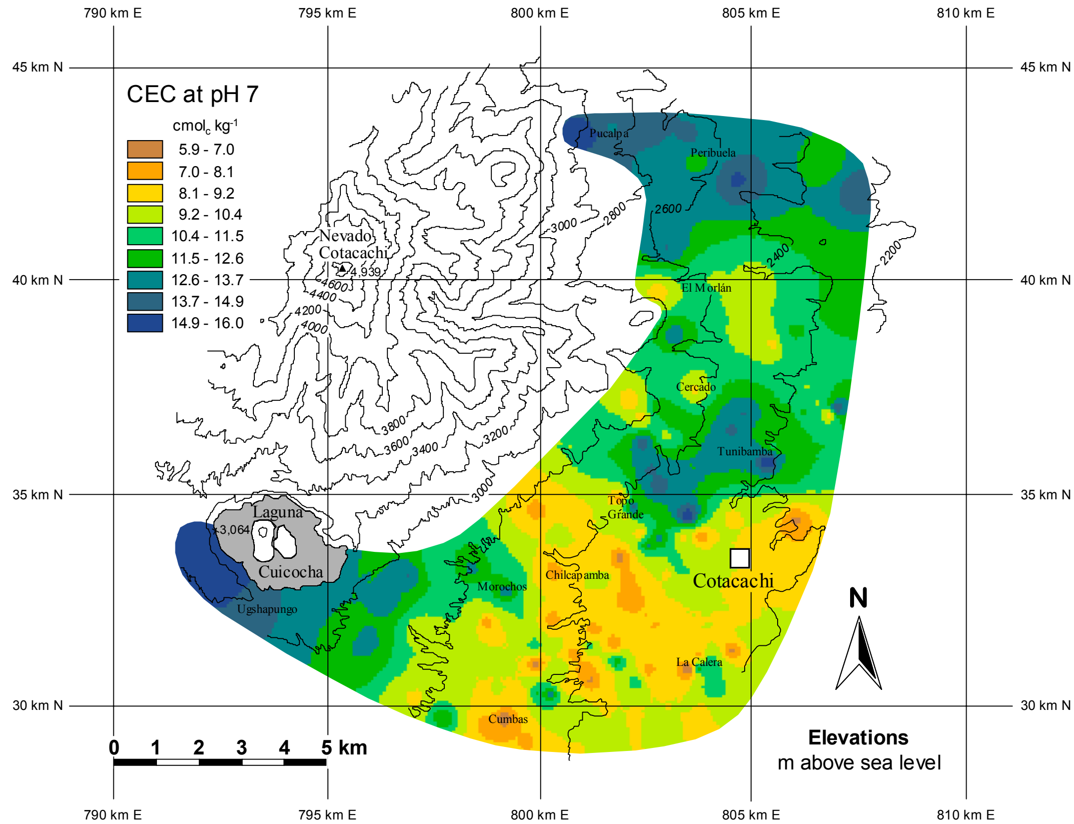

Figure 5.15. Spatial distribution of topsoil cation exchange capacity (CEC) at pH 7.

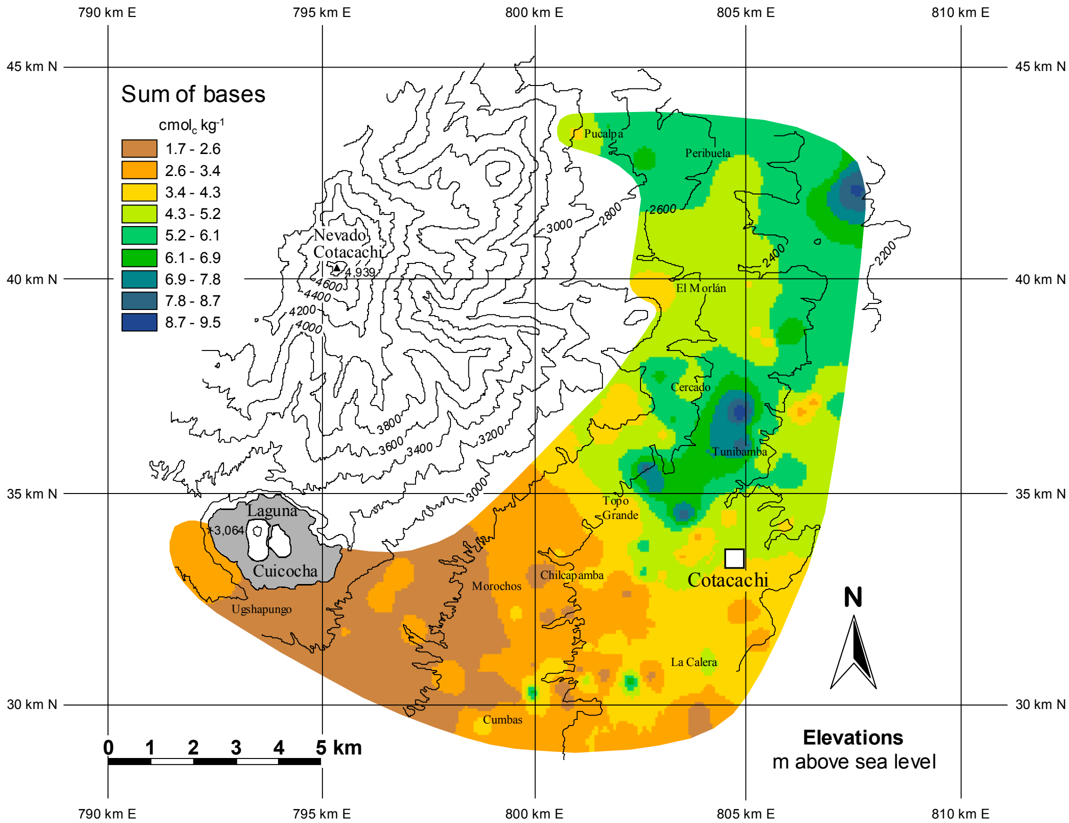

Figure 5.16. Spatial distribution of the sum of exchangeable Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+} in topsoils.

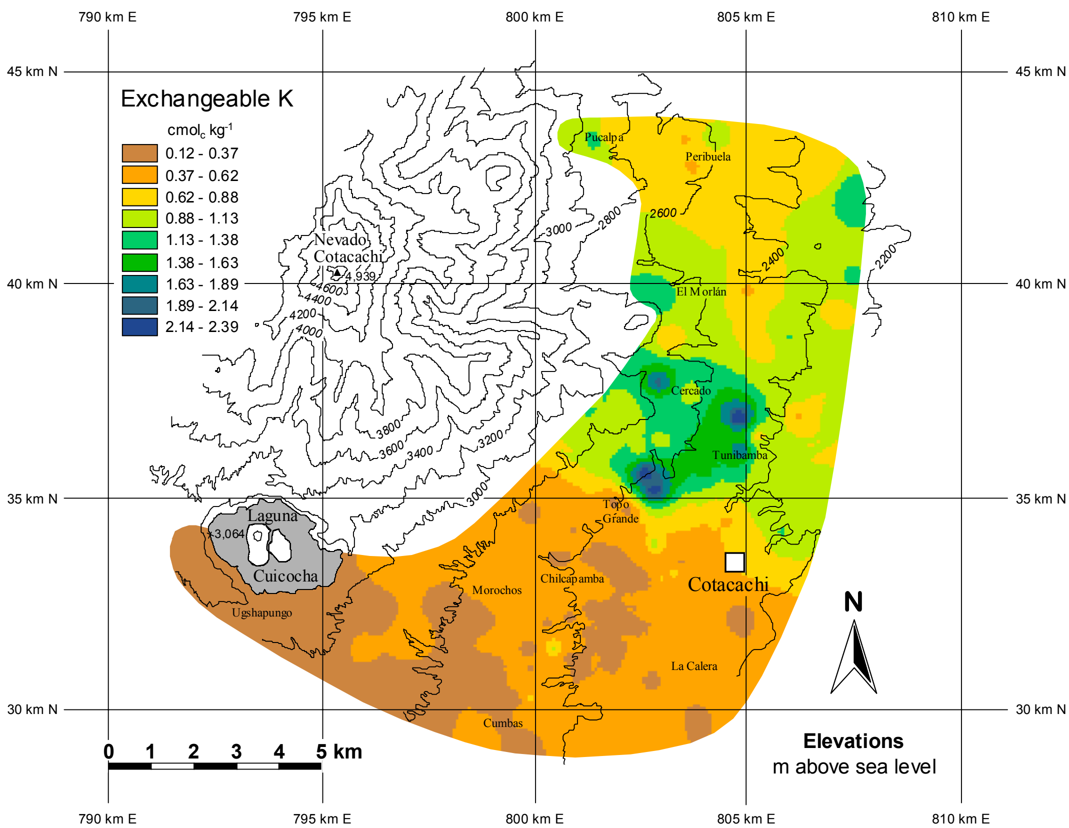

Figure 5.17. Spatial distribution of exchangeable potassium in topsoils.

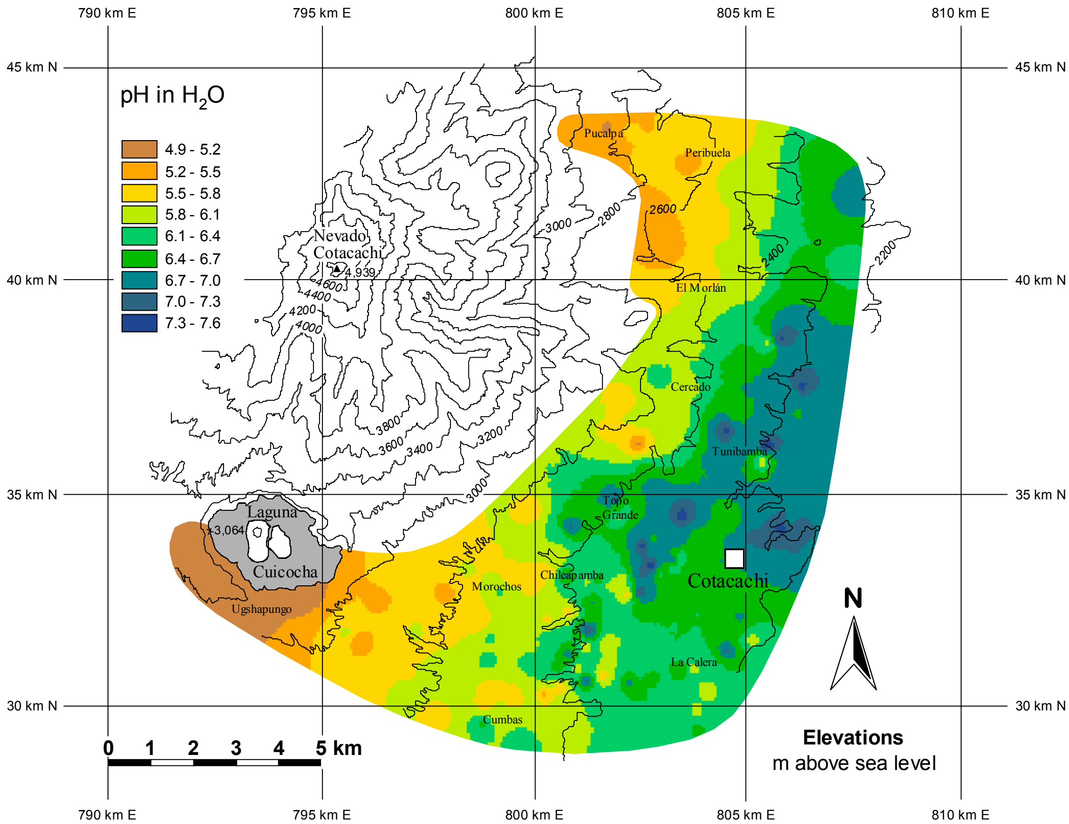

Figure 5.18. Spatial distribution of topsoil pH (H_2O).

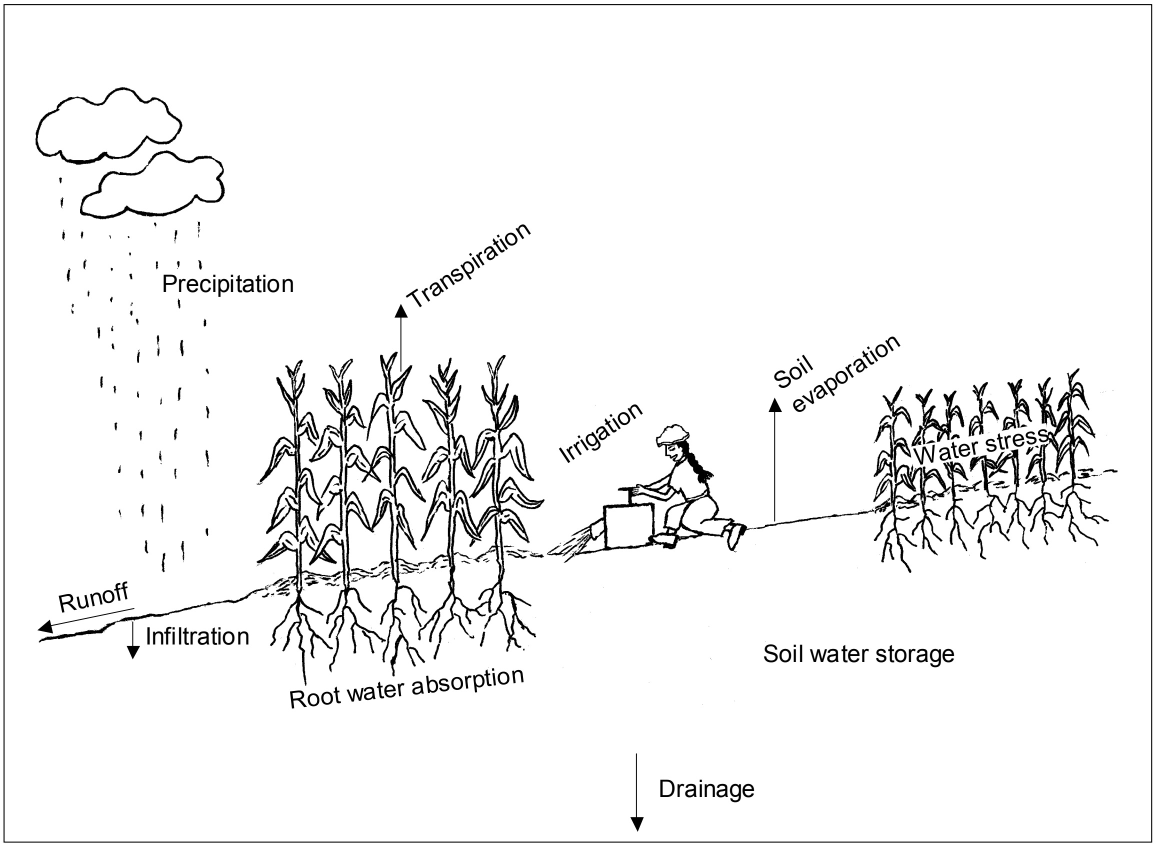

Figure 5.19. Water balance simulated with the DSSAT model.

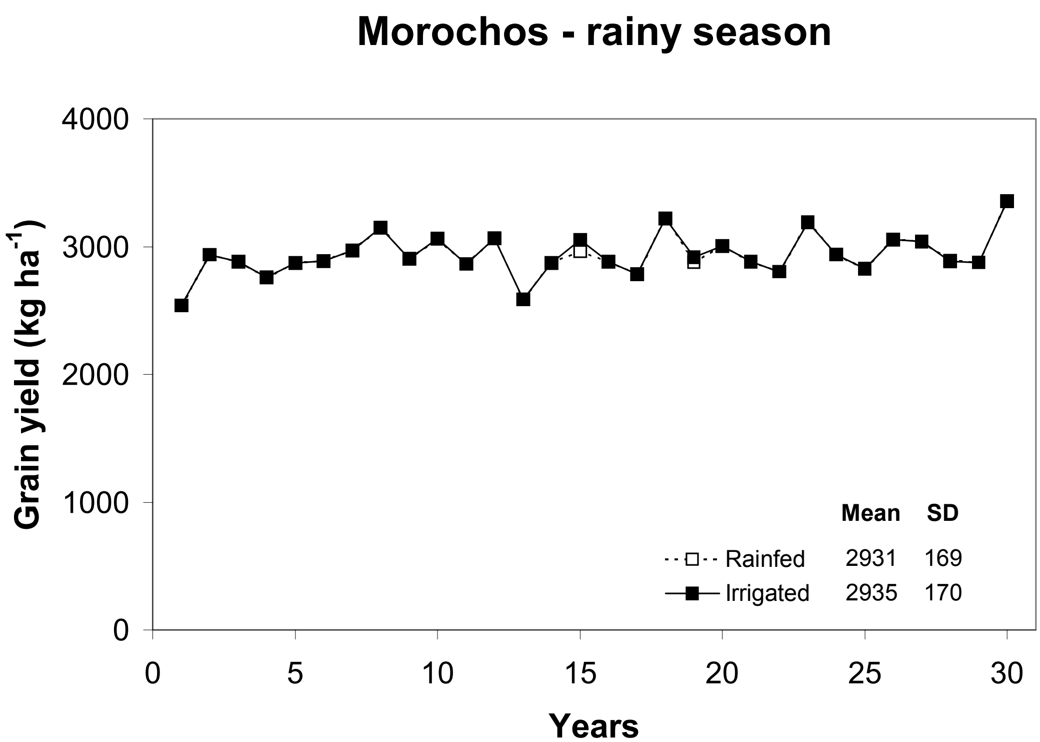

Figure 5.20. Simulated grain yields in an annual maize-fallow rotation (maize grown during the rainy season) with and without irrigation for Morochos (soil type: Humic Udivitrands; elevation: 2750 m); the water balance was simulated, other factors were assumed not limiting; SD = standard deviation.

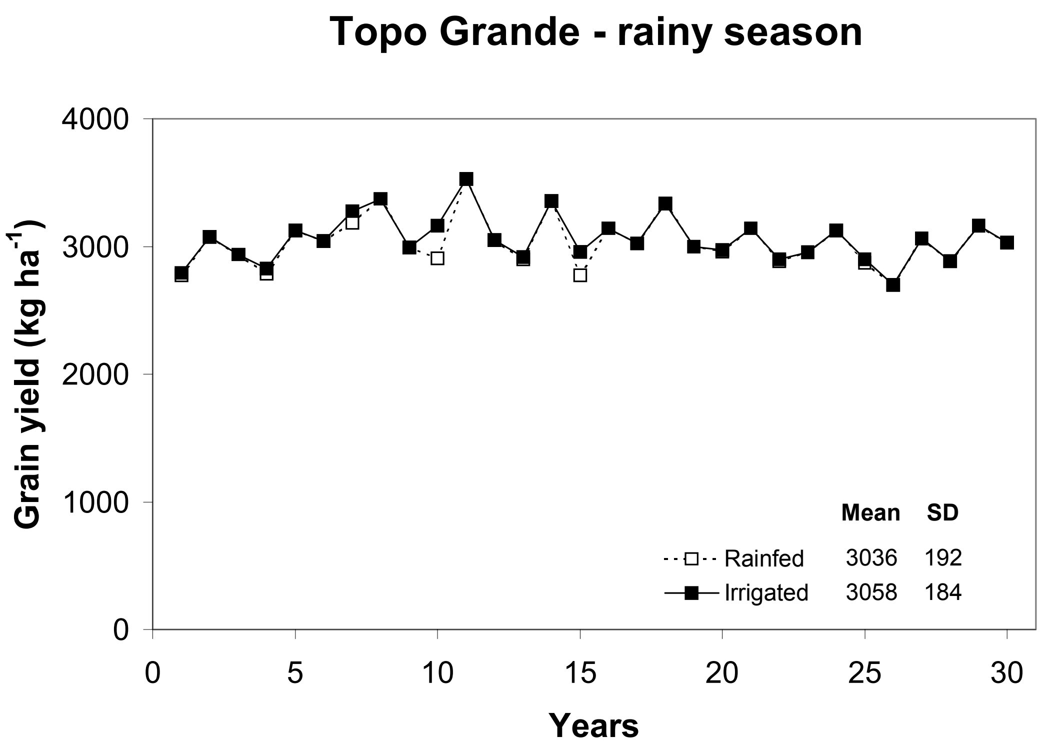

Figure 5.21. Simulated grain yields in an annual maize-fallow rotation (maize grown during the rainy season) with and without irrigation for Topo Grande (soil type: Vitrandic Udorthents; elevation: 2550 m); the water balance was simulated, other factors were assumed not limiting; SD = standard deviation.

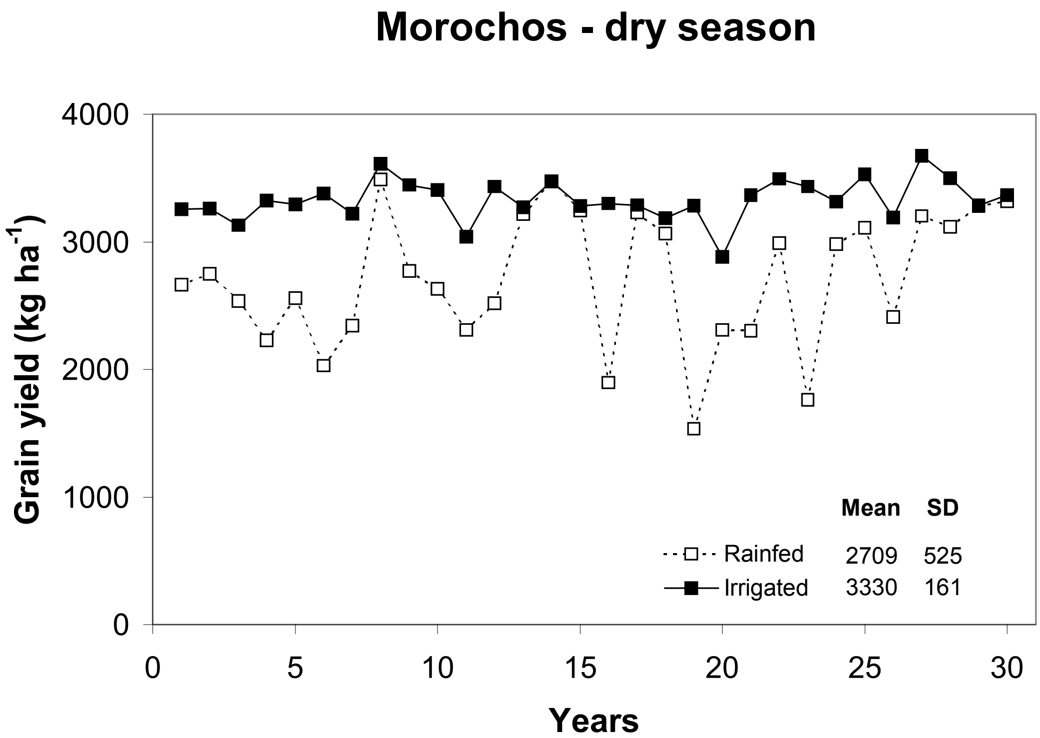

Figure 5.22. Simulated grain yields in an annual maize-fallow rotation (maize grown over the dry season) with and without irrigation for Morochos (soil type: Humic Udivitrands; elevation: 2750 m); the water balance was simulated, other factors were assumed not limiting; SD = standard deviation.

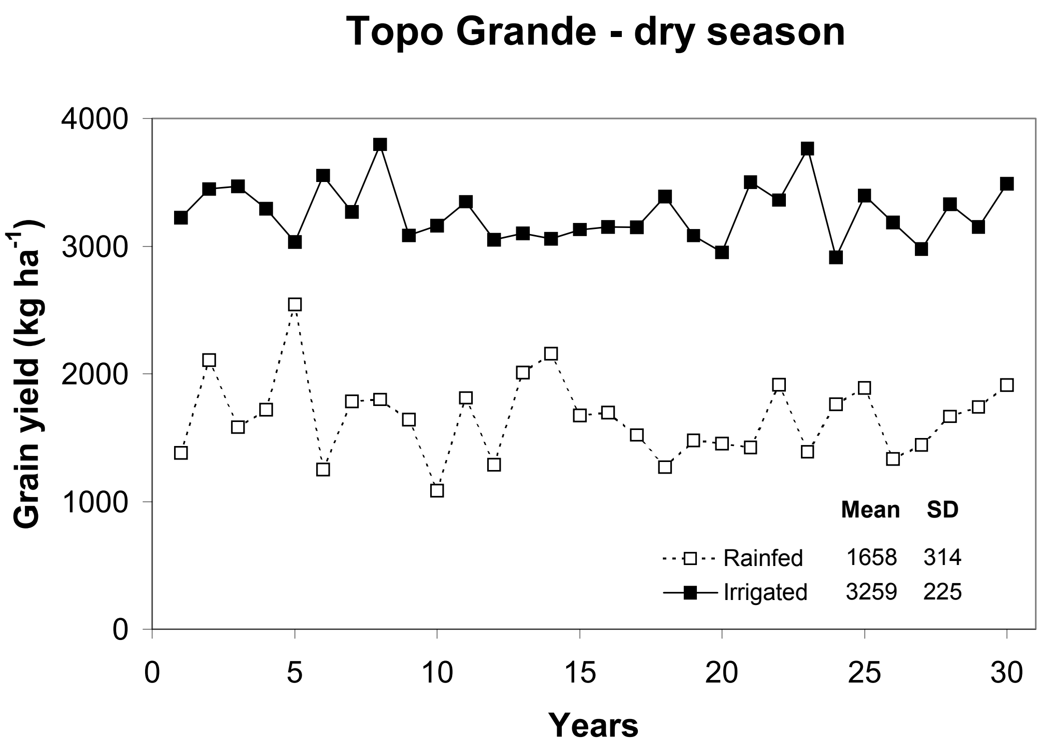

Figure 5.23. Simulated grain yields in an annual maize-fallow rotation (maize grown over the dry season) with and without irrigation for Topo Grande (soil type: Vitrandic Udorthents; elevation: 2550 m); the water balance was simulated, other factors were assumed not limiting; SD = standard deviation.

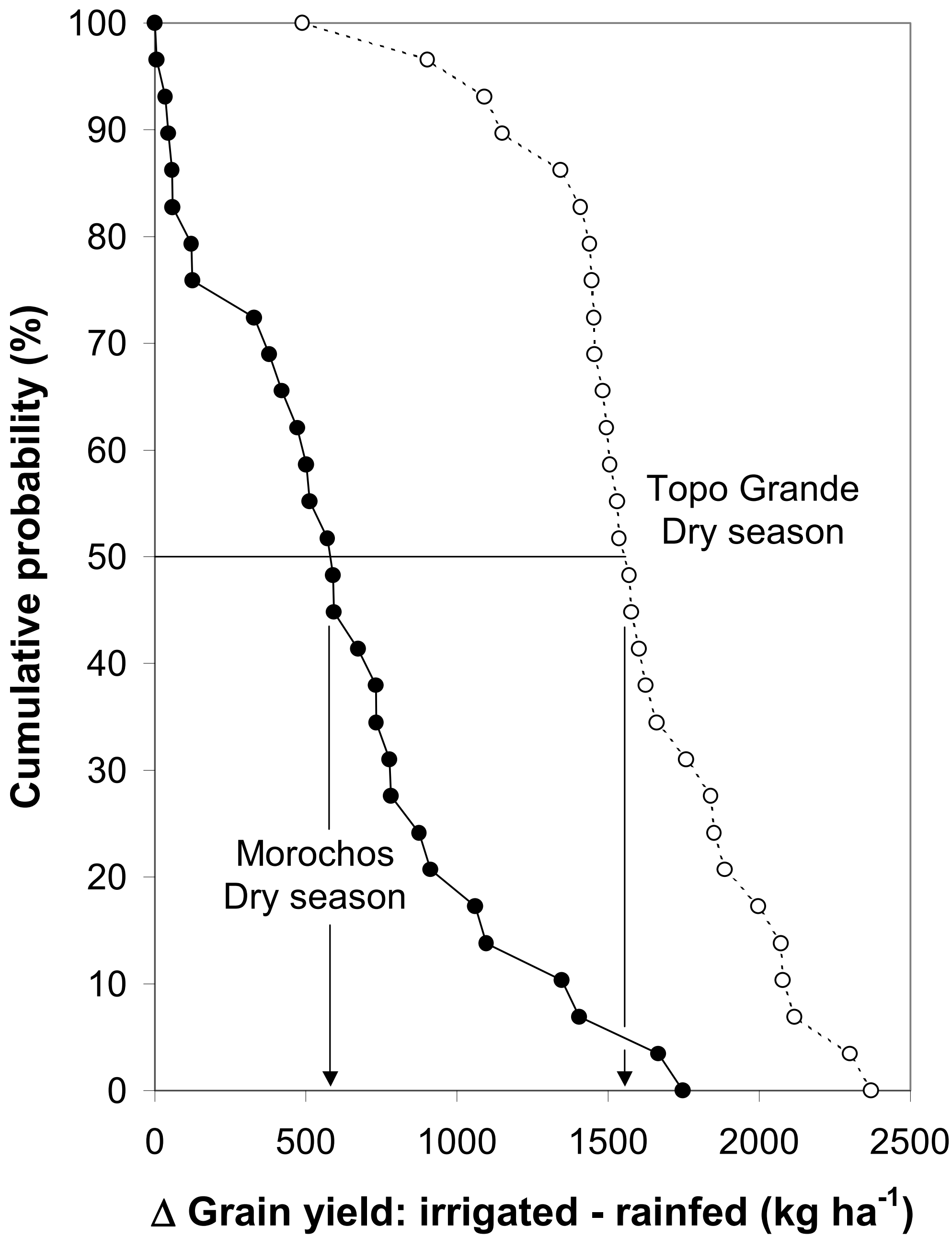

Figure 5.24. Cumulative probability functions showing expected grain yield increases upon irrigation for maize grown over the dry season in Morochos and Topo Grande.

CHAPTER 6

Erodibility and Runoff – Infiltration Characteristics of Volcanic Ash Soils in the Andes of Northern Ecuador[1]

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[1] Zehetner, F., and W.P. Miller. To be submitted to *Catena*.

Abstract

Soil erosion is a widespread phenomenon in Andean South America, where many regions are covered with soils derived from volcanic parent materials. Climate-induced differences in the genesis of these soils have been demonstrated along toposequences on volcanic slopes. This research was conducted to study the impact of such differential pedogenesis on erodibility and runoff – infiltration characteristics along an altitudinal Entisols – Inceptisols – Andisols sequence in the Andes of northern Ecuador. Surface soils were packed into small pans and placed on a 9 % slope, and a simulated rainstorm with varying intensities was applied for a duration of 30 minutes. The runoff – erosion behaviour of the studied volcanic ash soils is strongly affected by their pedological development. Accumulation of organic matter and precipitation of active amorphous materials at high elevations have led to the formation of well-developed Andisols with very stable aggregate structure. These soils remain wetable when air-dried, show very high infiltration capacity and consequently low potential for runoff generation and soil erosion. Low organic matter contents and absence of active amorphous materials at low elevation have led to the formation of weakly aggregated Entisols and Inceptisols. These soils exhibit lower infiltration capacity and are more susceptible to erosion. However, in comparison with other soils of different origin and composition, the interrill erodibilities determined for these more erodible low-elevation soils are classified as low. The findings of this study suggest that soil erosion is not a major threat to sustainability in the studied volcanic landscape, which is generally confirmed by field observations.

1. Introduction

About half of Ecuador's land surface is threatened by erosional degradation, with inter-Andean catchments most severely affected (de Noni et al., 1997). In the Río Ambato catchment of central Ecuador, Harden (1988) estimated annual soil loss rates between 20 and 80 t ha^{-1} based on rainfall simulation experiments on bare soil. The same author suggested abandoned and fallow farmland as well as unpaved roads and trails to significantly contribute to runoff and sediment in the Río Paute catchment of southern Ecuador, while recently tilled cropland showed comparatively high infiltration and low soil erosion rates (Harden, 1993, 1996, 2001). Increased runoff and soil erosion in abandoned and fallow land and on unpaved roads and trails were attributed to lower organic matter contents and higher compaction, respectively, as compared to cultivated cropland.

In many parts of the Ecuadorian Andes, recent volcanic deposits overlie strata of cemented and indurated volcanic ash, locally known as *cangagua*. These layers have very low hydraulic conductivity and may thus cause mass movements of overlying material and high runoff when exposed at the soil surface (Nimlos and Savage, 1991; de Noni et al., 1997). At high elevations, the Andean ecosystem is dominated by natural grassland, locally named *páramo*. The soils of this zone are mostly Andisols and generally exhibit high organic matter contents and very high infiltration rates, thus generating little surface runoff and soil erosion (Harden, 1993; Perrin et al., 2001). However, disturbance of these high-elevation ecosystems through overgrazing and drying of the soil surface due to burning and bare fallowing has been found to decrease organic matter contents and increase the soils' water repellency thus leading to decreased infiltration and increased soil erosion (Poulenard et al., 2001; Podwojewski et al., 2002).

To assess the sustainability of land use and land management in the region, soil erosion models are needed that are calibrated for local settings. One parameters within such models is soil erodibility, a complex property dependent on a soil's capacity to infiltrate rain and on its susceptibility to detachment and transport by rainfall and runoff.

Studying the relation of soil properties to erodibility of 55 US Corn Belt soils, Wischmeier and Mannering (1969) concluded that particle size distribution and organic matter content were the most influential indicators of erodibility. Generally, soils with high silt, low clay, and low organic matter contents were the most erodible. Many subsequent studies have confirmed the influence of soil texture and organic matter on erodibility, and have further pointed out the importance of soil structural stability in this context. Depending on origin and composition of a given soil, the above properties were found to affect soil erodibility in different ways. For Belgian soils with high silt contents, Verhaegen (1984) reported a significant positive correlation of soil erodibility with sand content, and significant negative correlations with silt content and aggregate stability. Egashira et al. (1983, 1985, 1986) found that the soil properties most indicative of their erodibility were aggregate stability (significant negative correlation) for Japanese Andisols and Ultisols, and silt content (significant positive correlation) for sandy residual soils derived from granitic rocks. For Alfisols and Ultisols from the southeastern USA, Miller and Baharuddin (1987) observed enrichment of eroded sediment in silt-sized particles, which were statistically related to water-dispersible soil silt. Soil loss was significantly positively correlated with water-dispersible clay but not with total (chemically dispersed) clay in this study. Non-dispersed particle size distribution was also suggested by Loch and Rosewell (1992) to be employed in predicting field values of soil erodibility for various Australian soils. Martz (1992) reported variations of soil erodibility with slope position for Canadian prairie Mollisols, which reflected variations in soil properties, such as sand content (significant positive correlation), silt and organic matter contents (significant negative correlations).

In the course of pedogenesis of volcanic ash soils, the above discussed soil properties undergo dramatic changes, thus changing the soils' resistance to water erosion. While fresh volcanic deposits with low cohesiveness may be particularly prone to erosion (Nammah et al., 1986), progressive development of volcanic ash soils leads to increased structural stability and decreased soil erodibility. Mature Andisols generally show strong resistance to water erosion, which has been ascribed to the presence of highly stable soil aggregates resulting in high permeability and rapid rainfall infiltration (Warkentin and Maeda, 1980; Shoji et al., 1993). However, erosion in Andisols has recently been reported to involve fragmentation of larger aggregates by raindrop impact and subsequent transport of smaller, stable aggregates of low bulk density by surface runoff (Rodríguez Rodríguez et al., 2002).

The above discussion demonstrates the complexity of soil erodibility and shows that due to their unique soil properties, volcanic ash soils deserve special attention in this context. While some research has been conducted on the erodibility of volcanic ash soils, little effort has been made to relate obtained results to erodibility values determined for other soils of different origin and composition. The impact of climate on the pedogenesis of volcanic ash soils has been recognized in various parts of the world (e.g., Parfitt et al., 1983, 1984; Stevens and Vucetich, 1985; Takahashi et al., 1993; Nieuwenhuyse et al., 2000), and has been shown along toposequences of differentially developed volcanic ash soils (e.g., Chartres and Pain, 1984; Nizeyimana et al., 1997). However, the bearing of such differential soil formation in volcanic landscapes on variations in the soils' infiltration capacity and resistance to erosion has been largely neglected to date.

The objective of the present research was therefore to study erodibility and runoff – infiltration characteristics of volcanic ash soils of a climate-induced altitudinal Entisols – Inceptisols – Andisols sequence on the slopes of a volcanic peak in the Andes of northern Ecuador, and to relate observed erodibility values to those determined for other soils in different parts of the world.

2. Study area

2.1. Geomorphology and volcanism

The area under study is located on the slopes of volcano Cotacachi in the temperate inter-Andean valley of northern Ecuador, about 35 km north of the equator (Fig. 6.1). The landscape of the region is dominated by high volcanic peaks and large calderas, and landscape development has been heavily influenced by volcanic phenomena, such as lava and pyroclastic flows, pumice and ash falls, and subsequent mudslides induced by heavy rainfall events and earthquakes. Streams have deeply carved into the land forming ravines and dissecting the landscape into plateau-like upland areas stretching parallel to streams.

The volcanic complex of Cotacachi has a long history of volcanic activity involving several different eruption centers, of which only Cuicocha has been active in the Holocene. The other centers have not erupted in the past 40 000 years (Hall and Mothes, 1994). Volcano Cuicocha has had three phases of activity which occurred over a period of a few hundred years, ending about 3000 years before present (Mothes and Hall, 1991; Hall and Mothes, 1994; Athens, 1999). The present caldera of Cuicocha was formed by explosive eruptions that resulted in massive pyroclastic flows, which reach from Laguna Cuicocha past the town of Cotacachi (Fig. 6.1). Tephra falls from these eruptions cover the southern slopes of volcano Cotacachi.

2.2. Climate

The climate in the area is that of an equatorial high-altitude environment, with temperatures almost constant throughout the year, but showing pronounced diurnal oscillations. The mean annual temperature is about 15 °C in the town of Cotacachi, and drops by about 0.6 °C per 100 m of elevation increase. The mean annual precipitation is about 900 mm at 2500 m above sea level (asl) and increases with elevation to about 1500 mm at 4000 m asl (Nouvelot et al., 1995). The annual rainfall distribution is characterized by an expressed seasonality with a dry season from June to August, and about 90 % of the annual precipitation occurring from September to May.

In the inter-Andean valley, rainfall typically exhibits low intensities; however, sporadically occurring high intensity events were found to cause considerable soil erosion (de Noni et al., 1997). For Lago San Pablo, about 15 km from the study area, Nouvelot et al. (1995) estimated maximum 5-minute intensities to be 80, 110, 131, and 138 mm h^{-1}, and maximum 30-minute intensities to be 33, 44, 53, and 56 mm h^{-1} for 2, 10, 50, and 100 year return periods, respectively.

2.3. Land use and land management

The region has been largely deforested and the present landscape is dominated by agricultural land use below 3000 m asl, and high-altitude scrubland and grassland (*matorral* and *páramo*, respectively) above 3000 m asl. The major portion of agricultural lands lies on upland plateaus exhibiting slope gradients between 0 and 20 %. The steep sides of ravines are mostly covered with shrubs and eucalyptus stands, but occasionally cultivated with agricultural crops, and the bottomland areas on the narrow floodplains inside ravines are typically used as pastures.

Indigenous peoples have inhabited the region for thousands of years (Athens, 1999) and have employed farming practices well suited to the topography of the area.

Bench terraces, earth walls, and border hedgerows are conservation practices commonly encountered in the area under study. However, increasing mechanization especially in large-scale *hacienda*-type operations has lead to a decline in these structural barriers in an attempt to increase field sizes to facilitate land management.

2.4. Spatial distribution of soils

The recent upland soils of the study area represent a climate-induced altitudinal sequence with Andisols at high elevations and Inceptisols and Entisols at lower elevations (Zehetner et al., 2003). The soil parent materials, associated with the most recent Cuicocha eruptions, are pumiceous and have andesitic to dacitic composition. Soils 1-4, 12-14, and 18 have formed on tephra deposits, and soils 5-11 and 15-17 on pyroclastic flow deposits (Fig. 6.1). Selected site characteristics for the studied soils are presented in Table 6.1.

The recent deposits overlie an older, more developed, and often indurated surface formed on volcanic parent material of preceding eruption episodes. In areas where the recent soils have been eroded, these older strata crop out and once buried paleosols become exposed at the surface. These situations can be observed in the upper parts of upland bench terraces and on the steep and unstable slopes of ravines (soils 19-22; Fig. 6.1; Table 6.1). Paleosols thus re-exposed at the surface are often mixed with remaining recent soils by agricultural activity and bioturbation. The parent material of the oldest paleosols encountered in the study area is cemented and indurated ash, locally referred to as *cangagua*. On the southern slopes of volcano Cotacachi, these indurated strata become exposed on unpaved roads and trails. Soils of the narrow floodplains (soils 23-24; Fig. 6.1; Table 6.1) have received colluvial material from the sides of ravines as well as alluvial material transported from higher watershed areas. Thus, these soils exhibit properties typically inherent to paleosols and higher-elevation soils.

3. Methods

3.1. Soil sampling

Composite topsoil samples (0-10 cm) were taken from 18 recent upland soils and from 6 other sites including floodplain soils and areas where paleosols have been re-exposed at the surface (Fig. 6.1; Table 6.1). The samples were air-dried and passed through 10-mm and 2-mm sieves for rainfall simulation and laboratory analyses, respectively.

3.2. Rainfall simulation

Rainfall simulation experiments were conducted on soils packed into small pans (0.4 m long by 0.2 m wide) similar to those described by Miller and Baharuddin (1987). The pans were filled with 3 cm of soil over 5 cm of coarse sand, and the surface was carefully smoothed to reduce micro-topographic effects. The packed pans were placed on a 9 % slope, and a rainstorm with varying intensities was applied for a duration of 30 minutes by a simulator generating rainfall with a kinetic energy of 19.5 J m^{-2} mm^{-1}. Characteristics of the simulated rainstorm are presented in Table 6.2. The maximum 5, 10, 15, 20, and 30-minute intensities of the simulated rainstorm exceeded those estimated by Nouvelot et al. (1995) for 100-year return rainstorms in the area, and corresponded roughly with 100-year return events in Quito (Nouvelot et al., 1995). During the simulated event, runoff and eroded sediment were collected in 5-minute intervals and measured by weight before and after drying. These values were used to calculate runoff and infiltration rates, sediment concentrations, and soil loss rates. The runoff coefficient was calculated as the fraction of runoff rate to rainfall intensity.

3.3. Laboratory analyses

Soil pH was measured in H_2O and 1 *M* KCl at a soil:solution ratio of 1:2.5 after 30 minutes of equilibration and in 1 *M* NaF at 1:50 after exactly 2 minutes (Soil Survey

Staff, 1996). Total carbon was determined by dry combustion (Tabatabai and Bremner, 1991). The values thus obtained were assumed to correspond to organic carbon, since the studied soils did not contain carbonate minerals. Water retention was measured after equilibration of rewet soil samples at 33 kPa and 1500 kPa in a pressure-plate extractor (Soil Survey Staff, 1996). Electrolytic conductivity was measured at a soil:water ratio of 1:2.5 after 30 minutes of equilibration. Water repellency was estimated by measuring the water drop penetration time (WDPT) according to Bisdom et al. (1993). Particle size distribution was determined with a combined sieve and pipette method after removal of organic matter with hydrogen peroxide and dispersion by reciprocal shaking with sodium metaphosphate solution for 12 hours (Soil Survey Staff, 1996). Water-dispersible particle size distribution was determined using deionized water instead of sodium metaphosphate solution in the above method.

3.4. Calculations

Interrill erodibility was calculated with the original WEPP (Water Erosion Prediction Project) interrill equation (Elliot et al., 1989):

$$Di = Ki\ I^2\ Sf$$

and with the modified equation proposed by Kinnell (1993a,b):

$$Di = Ki\ I\ Q\ Sf$$

where Di is the interrill detachment rate (kg m^{-2} s^{-1}), Ki is the interrill erodibility constant (kg s m^{-4}), I is the rainfall intensity (m s^{-1}), Q is the runoff rate (m s^{-1}), and Sf denotes a slope factor defined as:

$$Sf = 1.05 - 0.85\ e^{-4 \sin \alpha}$$

where α is the slope angle in degrees. Interrill erodibility was determined for three consecutive 5-minute intervals with varying rainfall intensities starting 10 minutes after simulation begin.

4. Results and discussion

4.1. Soil characteristics

Formed on volcanic deposits that originate from a series of eruptions about 3000 years before present, the studied recent upland soils are in their early stages of development. However, dramatic altitudinal differences in pedogenesis, corresponding largely with climatic differences, have resulted in the differential formation of Entisols and Inceptisols below 2700 m asl, and Andisols above 2700 m asl (Zehetner et al., 2003). These altitudinal trends are reflected in general soil characteristics, presented in Table 6.3.

Organic carbon contents are below 1 % at low elevations and increase with altitude to over 6 %. Water retention at 33 and 1500 kPa shows the same altitudinal trend. Active amorphous materials become more dominant with elevation, as indicated by increasing pH (NaF) values. All studied soils are classified as non-water-repellent according to Bisdom et al. (1993), and water drops show almost instantaneous surface penetration in high-elevation soils (Tables 6.1, 6.3). This represents an entirely different behaviour than observed by Poulenard et al. (2001) for organic-rich Andisols of northern Ecuador. The soils of that study developed a strong water repellency upon drying, which gave rise to increased soil erosion in the form of floating hydrophobic aggregates. However, organic carbon contents of those soils were considerably higher than in the present study, which may offer an explanation for the observed differences as soil organic matter has been shown to increase a soil's water repellency (Bisdom et al., 1993).

Chemically dispersed and water-dispersible particle size distributions are presented in Table 6.4. Formed on relatively young sandy volcanic deposits, the recent upland soils generally exhibit low clay contents; however, the finer particle sizes tend to increase with altitude (Tables 6.1, 6.4). Sand and silt fractions show no statistical differences between the two methods of dispersion; however, water-dispersible clay is significantly lower than its chemically dispersed counterpart ($\alpha = 0.05$). This suggests that primary clay particles are agglomerated into larger aggregates that are resistant to water dispersion and may thus behave like primary silt and sand particles in rainfall – runoff situations.

The soils encountered in the upper parts of upland bench terraces, on the steep sides of ravines, and in floodplains (soils 19-24) exhibit soil properties atypical of the low-elevation zone they are located in (Tables 6.1, 6.3, 6.4). In the former two landscape positions, this is due to mixing with re-exposed paleosols, which have higher organic matter contents and finer texture as compared to recent soils. Floodplain soils have received both colluvial paleosol material and alluvial material translocated from higher-elevation zones.

4.2. Infiltration, runoff, and soil loss

The impacts of the simulated rainstorm on rainfall infiltration, surface runoff, and soil erosion are shown in Table 6.5. The runoff – infiltration characteristics of the studied soils range from nearly complete infiltration to runoff coefficients of 40 %. Sediment concentrations and soil loss rates range from 0 to 23.4 g L^{-1} and from 0 to 464 g m^{-2} h^{-1}, respectively. As observed for key soil properties, the runoff – erosion behaviour of recent upland soils shows considerable variations with elevation (Tables 6.1, 6.5). The soils influenced by paleosol material and the floodplain soils (soils 19-24) exhibit relatively high infiltration and low runoff rates, low sediment concentrations and soil loss rates, thus resembling the behaviour of high-elevation soils (Tables 6.1, 6.5).

4.3. Interrill erodibility

For soils with an average soil loss rate > 50 g m^{-2} h^{-1}, i.e. recent upland soils below 2800 m asl, interrill erodibility constants were calculated according to the original WEPP (Water Erosion Prediction Project) interrill equation (Elliot et al., 1989) and according to

Kinnell (1993a,b). They range from 0.5 to 7.9 x 10^5 kg s m^{-4} for the former and from 4.3 to 25 x 10^5 kg s m^{-4} for the latter approach (Table 6.5). WEPP-Ki values are considerably lower than Kinnell-Ki values, which results from normalization of soil loss rate by rainfall intensity squared in the former and by rainfall intensity times runoff rate in the latter equation. Runoff coefficients of generally less than 50 % resulted in Kinnell-Ki constants 2 to 9 times higher than WEPP-Ki constants.

Conceptually, interrill erodibility according to the original WEPP model comprises a soil's resistance to detachment and transport as well as its infiltration capacity, whereas in the approach proposed by Kinnell (1993a,b), interrill erodibility is separated from a soil's runoff – infiltration characteristics. At given rainfall intensity and slope gradient, WEPP-Ki is therefore determined by soil loss rate and Kinnell-Ki by sediment concentration. However, neither of the erodibility constants is a fundamental soil factor (Kinnell, 1993b) and soil erodibility has been reported to vary with tillage and cropping systems, microclimate, soil consolidation, etc. (Agassi and Bradford, 1999). With these constraints in mind, an attempt will be made in the following paragraphs to compare interrill erodibilities determined for the studied soils with those reported in the literature for other soils of different origin and composition.

Interrill erodibilities of the original WEPP soil database (WEPP-Ki) range from 7.7 to 43 x 10^5 kg s m^{-4} for 36 US cropland soils and from 0.1 to 19 x 10^5 kg s m^{-4} for 20 US rangeland soils (Elliot et al., 1989; Laflen et al., 1991). In the experiments of the Water Erosion Prediction Project, cropland soils had been tilled immediately prior to rainfall simulation, whereas rangeland soils had never been tilled. Thus, the disturbed soils examined in the present study resemble cropland conditions. However, the WEPP cropland soils showed interrill erodibilities up to two orders of magnitude higher than observed for the volcanic ash soils of the present study. Exceptions are two sandy soils from south Georgia that had interrill erodibilities comparable to the most erodible soils of the present study.

For the 18 WEPP cropland soils described by Liebenow et al. (1990), Kinnell (1993a) determined interrill erodibilities according to his modified equation. For the "flat" plots (3-6 % slope) used in the Water Erosion Prediction Project, the Kinnell-Ki values for these 18 soils ranged from 18 to 64, averaging 37 x 10^5 kg s m^{-4}, whereas the WEPP-Ki values ranged from 8.8 to 53, averaging 25 x 10^5 kg s m^{-4}. Average Kinnell-Ki and WEPP-Ki constants, determined for the studied recent upland soils below 2800 m asl, are 13 and 4.1 x 10^5 kg s m^{-4}, respectively, and are about 3 and 6 times, respectively, lower than observed for the 18 WEPP cropland soils. The smaller differences in Kinnell-Ki than in WEPP-Ki between the two datasets suggest that a significant portion of the differences in WEPP-Ki may be attributed to differences in rainfall infiltration, which was considerably higher in the present study than in the WEPP experiments (Liebenow et al., 1990).

For 16 coal mine soils from Queensland, Australia, Sheridan et al. (2000) found Kinnell-Ki constants between 7.6 and 60, averaging 28 x 10^5 kg s m^{-4}. While half of these soils showed interrill erodibilities in the range of the soils under study, average interrill erodibility was more than twice as high as observed in the present study. Duiker et al. (2001) reported high infiltration and low soil loss rates for five different soils of Andalusia, southwest Spain. The interrill erodibilities (Kinnell-Ki) of these soils were similar to those observed for the most erodible soils of the present study.

The above discussion indicates that the interrill erodibilities of the volcanic ash soils under study may be classified as low compared to other soils of different origin and composition. Unfortunately, there are no interrill erodibility data available in the literature that would allow for direct comparison of the studied with other volcanic ash soils. However, the above observations appear to be in line with the findings of Ruppenthal et al. (1996), who reported low soil erodibilities (K-factors of the Universal Soil Loss Equation) for volcanic ash-derived Inceptisols in the southwest Colombian Andes.

On the other hand, Poulenard et al. (2001) reported “a very high erodibility index” for a mature Andisol of northern Ecuador after long air-drying of the bare soil surface, whereas the undisturbed and recently tilled surfaces showed comparatively low soil loss. The authors of that study applied four rainfall events within two days, with rainfall volumes of about 95 mm for each and rainfall intensities up to 120 mm h^{-1}. We used the data presented in Poulenard et al. (2001) to estimate mean interrill erodibility of the most erodible (bare, air-dried) Andisol for the portion of the fourth simulated rainfall event in which runoff occurred. Thus estimated Kinnell-Ki constant has a value of about 4.5×10^5 kg s m^{-4}, which is in the neighbourhood of the lowest interrill erodibilities determined in the present study. Thus, while the work of Poulenard et al. (2001) reveals interesting insights into the dependence of Andisol erodibility on soil surface treatments, the absolute magnitude of the observed interrill erodibilities appears to be on the very low end of the spectrum documented in the literature.

4.4. Interrelation of landscape, soil development, runoff – infiltration characteristics, and soil erodibility

For recent upland soils, correlation analysis was performed on elevation, main soil properties given in Tables 6.3 and 6.4, and runoff – erosion characteristics shown in Table 6.5. The results, presented in Table 6.6, demonstrate the strong altitudinal dependence of soil development in the area under study. The accumulation of organic matter and the increasing expression of andic soil properties with altitude, documented by Zehetner et al. (2003), are reflected in the present dataset by strong positive correlations of organic carbon content and pH (NaF) with elevation (Table 6.6).

Organic matter has been recognized as important binding and bridging agent in the soil environment, enhancing a soil's structural stability, infiltration capacity, and resistance to erosion (e.g., Wischmeier and Mannering, 1969; Amézketa, 1999; Barthès et al., 1999; Baldock and Nelson, 2000; Bryan, 2000). Accumulation of organic matter and formation of active amorphous materials may lead to particularly stable aggregate structure in soils with andic properties (Warkentin and Maeda, 1980; Shoji et al., 1993). In the present study, macro-aggregates of the high-elevation Andisols showed near 100 % stability after 5-minute wet-sieving according to Kemper and Rosenau (1986), whereas this test could not be performed on the weakly aggregated low-elevation soils, of which most aggregates got disintegrated during transport from the field to the laboratory (data not shown).

The importance of organic matter and active amorphous constituents in the runoff – erosion behaviour of the studied soils is reflected by significant negative correlations of organic carbon content and pH (NaF) with runoff rate, sediment concentration, and soil loss rate (Table 6.6). Besides its effects on structural stability, organic matter may further promote infiltration, particularly when dry soil is subjected to rainfall, by increasing a soil's water-retention capacity. Like organic carbon content, water retention at 33 and 1500 kPa is significantly negatively correlated with runoff rate, sediment concentration, and soil loss rate (Table 6.6). Recent erosion studies on volcanic ash soils have emphasized the importance of water repellency in runoff generation and soil erosion (Poulenard et al., 2001; Podwojewski et al., 2002; Rodríguez Rodríguez et al., 2002). Although the soils under study are classified as non-water-repellent (Bisdom et al., 1993), water drop penetration time shows significant positive correlations with runoff rate, sediment concentration, and soil loss rate (Table 6.6).

Electrolytic conductivity is generally low in the soils under study (Table 6.3) and does not correlate significantly with elevation or runoff – erosion characteristics (Table

6.6). The observed strong negative correlations of water-dispersible clay with runoff rate, sediment concentration, and soil loss rate seem contradictory to the findings of Miller and Baharuddin (1987); however, this may have limited meaning because of the very low range of water-dispersible clay contents in the studied soils (Table 6.4). In general, the observed significant correlations of water-dispersible and chemically dispersed particle size distributions as well as of pH (H_2O) and pH (KCl) with runoff rate, sediment concentration, and soil loss rate (Table 6.6) are believed to be mainly a result of their elevation-dependence and consequent (causal or incidental) relations to organic matter and active amorphous constituents.

The strong influence of these latter two soil properties on runoff – erosion characteristics coupled with their dramatic altitudinal variations in the volcanic landscape under study results in strong elevation-dependence of runoff rate, sediment concentration, and soil loss rate, manifested by significant negative correlations with altitude (Table 6.6). As shown in Fig. 6.2, surface runoff generated by the simulated rainstorm decreased logarithmically with increasing elevation on the volcano. The strongly aggregated Andisols above 2800 m asl showed less than 10 % runoff, whereas the weakly developed soils at lower elevations had runoff coefficients of 10 to 40 % (Fig. 6.2).

For these two altitudinal groups of recent upland soils (above and below 2800 m asl, respectively), infiltration and soil loss are presented in Figs. 6.3 and 6.4, respectively, as a function of rainfall intensity, 10 to 30 minutes into the simulated rainstorm. The high-elevation soils are characterized by uniformly high infiltration rates close to the 1:1 line of 100 % infiltration and by accordingly low soil loss rates, even at high rainfall intensity (Figs. 6.3, 6.4). Evidently, the simulated rainstorm applied to the air-dried soil surface was not enough to exceed the high infiltration capacity of these soils. However, higher initial water contents and greater rainfall volumes may generate significant runoff, as observed by Poulenard et al. (2001) for similar soils of northern Ecuador. The authors of that study attributed lower hydraulic conductivity and higher soil loss rates after long air-drying of the soil surface to increased water repellency. Erosion was dominated by floating hydrophobic and stable sand-sized aggregates; however, as we estimated above, interrill erodibilities appeared to be comparatively low in that study. Since the air-dried high-elevation Andisols of the present study show almost instantaneous water drop penetration (Tables 6.1, 6.3), very high aggregate stability, and comparatively high bulk density (data not shown), increased runoff rates are not believed to give rise to considerable interrill erosion in these soils.

Despite marked variability within the low-elevation soils, their infiltration rates were significantly lower ($\alpha = 0.05$) and their soil loss rates significantly higher ($\alpha = 0.05$) than those of high-elevation soils (Figs. 6.3, 6.4). These differences correspond with significant differences ($\alpha = 0.05$) in key soil properties, such as organic carbon content and pH (NaF), between the soils of the two elevation zones. In low-elevation soils, average soil loss rate shows a sharp increase from below 200 g m^{-2} h^{-1} at rainfall intensities between 36 and 60 mm h^{-1} to over 700 g m^{-2} h^{-1} at 96 mm h^{-1} (Fig. 6.4). This non-linear increase of interrill erosion rates with rainfall intensity is likely the result of a concomitant non-linear increase of runoff rates (the distances between the datapoints and the 1:1 line in Fig. 6.3) as the soils' infiltration rates approach a maximum.

Interrill erodibility constants of low-elevation soils, calculated according to Kinnell (1993a,b), show significant positive correlations with water drop penetration time, chemically dispersed clay, and water-dispersible silt contents, and a significant negative correlation with water-dispersible sand content (Table 6.6). This indicates that despite the non-water-repellent character of the studied soils (Bisdom et al., 1993), small differences in water drop penetration time, as observed in the present study (Table 6.3), may significantly affect the soils' susceptibility to erosion. In the more erodible soils, the time raindrops remain on the soil surface before penetration may be just enough for subsequent raindrops to hit the same spot and initiate downward movement of water and pre-detached particles. The importance of water-dispersible silt is in agreement with the findings of Miller and Baharuddin (1987), and is further substantiated by significant positive correlation of Kinnell-Ki with chemically dispersed clay, the majority of which appears to be agglomerated into larger aggregates resistant to water dispersion (Table 6.4) thus acting like silt or fine sand particles in the simulated rainstorm. Kinnell-Ki constants are not correlated with elevation, which ranges from 2600 to 2760 m asl for the soils of this low-elevation zone.

The soils influenced by paleosol material and the floodplain soils encountered at lower elevations (soils 19-24) showed significantly higher infiltration and lower soil loss rates ($\alpha = 0.05$) than the surrounding recent upland soils (soils 1-11). These differences correspond with significantly higher organic carbon contents and lower water drop penetration time ($\alpha = 0.05$) in these atypical soils. Paleosols re-exposed at the soil surface after erosion of overlying recent soils generally exhibit a high degree of cementation and induration, and low hydraulic conductivities. However, the formation of new macropores through agricultural and biological activity, combined with near 100 % aggregate stability, may lend these surfaces very high infiltration capacity, as observed in the present study.

5. Conclusions

The runoff – erosion characteristics of the studied volcanic ash soils are strongly affected by their pedological development, which in turn is governed by climate varying with elevation on the volcano. Accumulation of organic matter and precipitation of active amorphous materials have led to the formation of well-developed Andisols with very stable aggregate structure above 2800 m asl. These soils remain wetable when air-dried, show very high infiltration capacity and consequently low potential for runoff generation and soil erosion. Low organic matter contents and absence of active amorphous materials have led to the formation of weakly aggregated Entisols and Inceptisols below 2700 m asl. These soils exhibit lower infiltration capacity and are more susceptible to erosion. However, the observed altitudinal variations do not strictly correspond with differences in soil classification. The weakly developed Andisols between 2700 and 2800 m asl show runoff – erosion characteristics similar to the Inceptisols and Entisols at low elevations.

The general altitudinal trends do not strictly apply in certain landscape positions. In the upper parts of upland bench terraces and on the steep sides of ravines, re-exposed paleosols can significantly alter the soils' runoff – erosion behaviour. In the undisturbed state, these strata show very low hydraulic conductivity, which may lead to considerable surface runoff and soil erosion. However, where new macropores are formed through agricultural and biological activity, these soils become very permeable and resistant to erosion due to their high structural stability. The soils of low-elevation floodplains have received colluvial paleosol material and alluvial material from higher elevations and show runoff – erosion characteristics resembling those of high-elevation soils.

In comparison with other soils of different origin and composition, the interrill erodibilities determined for the more erodible soils of the present study are classified as low. Although soil erosion involves a number of complex processes dependent on a variety of factors, of which only a few were examined in this study, the findings obtained suggest that erosional degradation is not a major threat to sustainability in the volcanic landscape under study. Field observations generally corroborate such conclusion.

In the steeply sloping high-elevation zones, the soils are very permeable and stable, and the soil surface is well protected from raindrop impact by dense scrub and grassland vegetation. However, burning of this protective vegetation cover may result in the formation of a water-repellent surface layer that promotes runoff and soil erosion. In the lower zones, where the soils are more susceptible to runoff and erosion, lower slope gradients and the presence of structural barriers such as bench terraces, earth walls, and border hedgerows effectively decrease soil loss and sediment export. However, the removal of such barriers in large-scale agricultural operations may lead to increased sediment export and related adverse effects on water quality. Presently, most of the sediment in streams is likely from unpaved roads and trails, which in some places are deeply sunken below the surrounding fields thus exposing old, indurated ash strata, and from the sides of ravines, which despite high topsoil stability are prone to mass-wasting due to very steep slopes and in some places underlying indurated ash strata.

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Table 6.1

Site information for the studied soils

Soil	Location	Northing[a]	Easting[a]	Elevation	Land use	Soil classification[b]
		m	m	m asl[c]		
Recent upland soils						
1	Topo Grande	34 939	801 793	2630	Cropland	Vitrandic Udorthents
2	Iltaquí Bajo	33 946	800 619	2650	Cropland	Vitrandic Udorthents
3	Iltaquí Bajo	33 641	800 826	2620	Cropland	Vitrandic Udorthents
4	Iltaquí Bajo	33 994	800 535	2660	Cropland	Vitrandic Udorthents
5	Chilcapamba	32 940	800 732	2610	Cropland	Vitrandic Dystrudepts
6	Chilcapamba	33 009	800 890	2600	Cropland	Vitrandic Dystrudepts
7	Chilcapamba	32 866	800 710	2610	Pasture	Vitrandic Dystrudepts
8	Chilcapamba	33 073	799 880	2700	Forest	Vitrandic Dystrudepts
9	Morochos	32 671	799 152	2740	Cropland	Humic Udivitrands
10	Morochos	32 990	798 757	2760	Cropland	Humic Udivitrands
11	Morochos	32 694	799 215	2740	Cropland	Humic Udivitrands
12	Iltaquí Alto	35 474	799 352	2920	Cropland	Humic Udivitrands
13	Iltaquí Alto	35 604	799 221	2950	Pasture	Humic Udivitrands
14	Iltaquí Alto	35 352	799 442	2900	Fallow	Humic Udivitrands
15	Ugshapungo	32 530	792 687	3200	Cropland	Humic Udivitrands
16	Ugshapungo	32 531	792 747	3200	Pasture	Humic Udivitrands
17	La Piyaba	33 203	796 055	3010	*Matorral* [d]	Humic Udivitrands
18	Chumavi	36 400	794 671	3580	*Páramo* [e]	Humic Udivitrands
Other soils						Site description
19	Topo Grande	34 917	801 782	2630	Cropland	Upper part of terrace[f]
20	Topo Grande	34 944	801 757	2630	Cropland	Upper part of terrace
21	Iltaquí Bajo	33 537	800 551	2610	Cropland	Steep side of ravine[f]
22	Iltaquí Bajo	33 502	800 581	2610	*Matorral*	Steep side of ravine
23	Iltaquí Bajo	33 525	800 473	2590	Cropland	Floodplain
24	Iltaquí Bajo	33 420	800 567	2580	Pasture	Floodplain

[a] Datum: Provisional South American 1956; Ellipsoid: International.
Projection: UTM; Zone: 17N.

[b] According to Soil Survey Staff (1998).

[c] asl = above sea level.

[d] Local term for scrubland.

[e] Local term for high-altitude grassland.

[f] Paleosols, generally buried, can be re-exposed at the surface and mixed with overlying recent soils as these are eroded in the upper parts of upland bench terraces and on the steep sides of ravines.

Table 6.2

Characteristics of the simulated rainstorm

Time period	Rainfall	Intensity	Kinetic energy	
min	mm	mm h^{-1}	MJ ha^{-1}	
0 - 5	3	36	0.58	I_5[a] = 144 mm h^{-1}
5 - 10	12	144	2.34	I_{10} = 120 mm h^{-1}
10 - 15	8	96	1.56	I_{15} = 100 mm h^{-1}
15 - 20	5	60	0.97	I_{20} = 87 mm h^{-1}
20 - 25	4	48	0.78	I_{30} = 70 mm h^{-1}
25 - 30	3	36	0.58	
Total storm	35	70	6.82	EI_{30}[b] = 478 MJ mm ha^{-1} h^{-1}

[a] I_x = maximum x-minute intensity.
[b] EI_{30} = (total kinetic energy) x (maximum 30-minute intensity).

Table 6.3

General soil characteristics

Soil	pH (H_2O)	pH (KCl)	pH (NaF)	Organic carbon	H_2O retention at 33 kPa	H_2O retention at 1500 kPa	Electrolytic conductivity	WDPT[a]
				%	%	%	µS cm^{-1}	s
Recent upland soils								
1	6.3	5.2	8.90	0.4	8.0	4.9	48	1.4
2	5.7	5.0	8.70	0.5	11.0	3.1	41	0.3
3	6.3	5.5	8.78	0.5	11.1	5.6	48	0.5
4	6.3	5.7	8.89	0.5	14.4	4.1	43	1.6
5	6.4	5.2	8.88	0.5	10.4	5.4	36	0.7
6	7.5	6.6	8.79	0.5	10.6	2.8	45	0.5
7	6.6	5.3	9.37	0.5	10.6	5.4	36	1.8
8	5.7	4.5	9.43	1.0	8.8	5.3	39	1.2
9	6.2	5.3	9.60	2.7	18.1	10.0	46	2.5
10	6.3	5.4	9.12	1.9	12.8	6.9	41	0.5
11	6.1	4.9	9.57	2.4	22.0	9.0	38	1.5
12	5.8	5.0	9.54	2.8	22.0	10.0	49	0.6
13	5.9	4.7	9.68	3.3	20.4	11.5	50	0.2
14	6.0	4.9	9.63	2.8	22.6	12.3	61	0.4
15	5.9	4.9	10.76	4.6	27.4	13.8	39	0.4
16	5.8	4.8	10.71	3.3	23.2	7.2	47	0.4
17	6.1	5.2	10.33	6.4	27.6	17.1	46	0.2
18	6.0	5.0	10.73	3.8	18.8	11.2	34	0.0
Other soils								
19	6.5	5.4	8.98	1.6	16.9	10.9	41	0.2
20	6.4	5.7	9.06	2.4	30.8	25.9	30	0.0
21	6.6	5.8	8.93	1.7	14.9	10.1	52	0.2
22	6.7	5.9	9.13	2.5	15.4	9.4	56	0.3
23	6.4	5.5	8.86	2.7	14.2	8.8	77	0.2
24	6.7	5.9	9.40	3.1	12.5	8.7	59	0.4

[a] WDPT = water drop penetration time (Bisdom et al., 1993).

Table 6.4

Chemically dispersed and water-dispersible particle size distribution

Soil	CD[a] sand	CD silt	CD clay	WD[b] sand	WD silt	WD clay
	%					
Recent upland soils						
1	73	20	7	72	26	2
2	58	34	7	72	25	2
3	71	23	7	75	22	3
4	65	26	9	68	30	2
5	70	24	6	74	25	1
6	67	25	8	77	22	1
7	67	25	7	71	27	1
8	68	25	7	79	19	3
9	51	37	13	52	46	2
10	61	30	8	71	23	6
11	44	44	12	52	46	2
12	49	32	20	54	40	6
13	54	30	16	58	38	4
14	51	30	19	53	40	7
15	43	42	16	46	50	4
16	51	37	13	58	39	3
17	47	38	15	46	47	7
18	61	30	9	61	36	3
Other soils						
19	46	36	18	49	36	15
20	20	40	40	25	49	25
21	61	28	10	60	29	10
22	61	26	13	61	29	10
23	67	22	11	67	24	9
24	71	19	9	72	26	2

[a] CD = chemically dispersed, using sodium metaphosphate.

[b] WD = water-dispersible.

Table 6.5

Results of the 30-minute rainfall simulations

Soil	Runoff rate[a]	Infiltration rate[a]	Runoff coefficient[a,b]	Sediment concentration[a]	Soil loss rate[a]	WEPP Ki[c,e]	Kinnell Ki[d,e]
	mm h^{-1}		%	g L^{-1}	g m^{-2} h^{-1}	x 10^5 kg s m^{-4}	
Recent upland soils							
1	17.5	52.5	25	13.1	230	3.7	12.4
2	13.8	56.2	20	10.9	150	1.6	6.6
3	7.2	62.8	10	13.9	100	1.0	8.6
4	20.8	49.2	30	20.6	430	7.9	19.7
5	21.3	48.7	30	19.1	405	6.4	16.1
6	28.3	41.7	40	16.4	464	5.2	9.9
7	17.0	53.0	24	19.8	336	4.8	13.6
8	10.4	59.6	15	12.1	126	1.0	6.1
9	15.0	55.0	21	23.4	351	7.7	25.2
10	7.3	62.7	10	8.5	62	0.5	4.3
11	14.9	55.1	21	18.9	281	5.1	15.9
12	2.9	67.1	4	2.9	9	nd[f]	nd
13	1.8	68.2	3	0.0	0	nd	nd
14	6.3	63.7	9	4.9	30	nd	nd
15	1.0	69.0	1	3.6	4	nd	nd
16	5.5	64.5	8	5.7	32	nd	nd
17	1.8	68.2	3	0.0	0	nd	nd
18	1.7	68.3	2	0.0	0	nd	nd
Other soils							
19	6.3	63.7	9	4.8	31	nd	nd
20	8.9	61.1	13	2.2	20	nd	nd
21	2.1	67.9	3	4.7	10	nd	nd
22	1.6	68.4	2	3.8	6	nd	nd
23	1.3	68.7	2	3.7	5	nd	nd
24	1.3	68.7	2	0.0	0	nd	nd

[a] Average values over the 30-minute event.
[b] Runoff coefficient (%) = (runoff rate ÷ rainfall intensity) x 100.
[c] WEPP-Ki = interrill erodibility constant used in the original WEPP (Water Erosion Prediction Project) soil erosion model (Elliot et al., 1989).
[d] Kinnell-Ki = interrill erodibility constant according to Kinnell (1993a,b).
[e] Average of three measurements (5-minute intervals) at varying rainfall intensities, starting 10 minutes after simulation begin.
[f] nd = not determined.

Table 6.6

Simple correlation coefficients for main soil properties, elevation, average runoff rate, sediment concentration, soil loss rate, and interrill erodibility in recent upland soils (n = 18, unless noted otherwise)

	Elevation	Runoff rate	Sediment concentration	Soil loss rate	Kinnell Ki[a]
pH (H_2O)	-0.437	0.710 ***[b]	0.486 *	0.688 **	0.097
pH (KCl)	-0.409	0.652 **	0.439	0.628 **	0.090
pH (NaF)	0.906 ***	-0.703 **	-0.621 **	-0.609 **	0.377
Organic carbon	0.762 ***	-0.753 ***	-0.708 ***	-0.661 **	0.346
H_2O retention (33 kPa)	0.685 **	-0.670 **	-0.585 *	-0.561 *	0.558
H_2O retention (1500 kPa)	0.653 **	-0.751 ***	-0.647 **	-0.634 **	0.483
Electrolytic conductivity	-0.063	-0.210	-0.276	-0.285	0.063
WDPT[c]	-0.509 *	0.533 *	0.806 ***	0.656 **	0.787 **
CD[d] sand	-0.517 *	0.564 *	0.433	0.471 *	-0.371
CD silt	0.447	-0.429	-0.261	-0.334	0.278
CD clay	0.478 *	-0.614 **	-0.581 *	-0.551 *	0.644 *
WD[e] sand	-0.595 **	0.599 **	0.454	0.466	-0.693 *
WD silt	0.569 *	-0.517 *	-0.355	-0.367	0.761 **
WD clay	0.405	-0.706 **	-0.736 ***	-0.738 ***	-0.563
Runoff rate	-0.731 ***				
Sediment concentration	-0.746 ***	0.846 ***			
Soil loss rate	-0.677 **	0.959 ***	0.908 ***		
Kinnell-Ki[a]	0.092	0.401	0.931 ***	0.695 *	

[a] Kinnell-Ki = interrill erodibility constant according to Kinnell (1993a,b); determined only for recent upland soils below 2800 m asl (n = 11).

[b] *, **, *** = significant at the 0.05, 0.01, and 0.001 levels, respectively.

[c] WDPT = water drop penetration time (Bisdom et al., 1993).

[d] CD = chemically dispersed, using sodium metaphosphate.

[e] WD = water-dispersible.

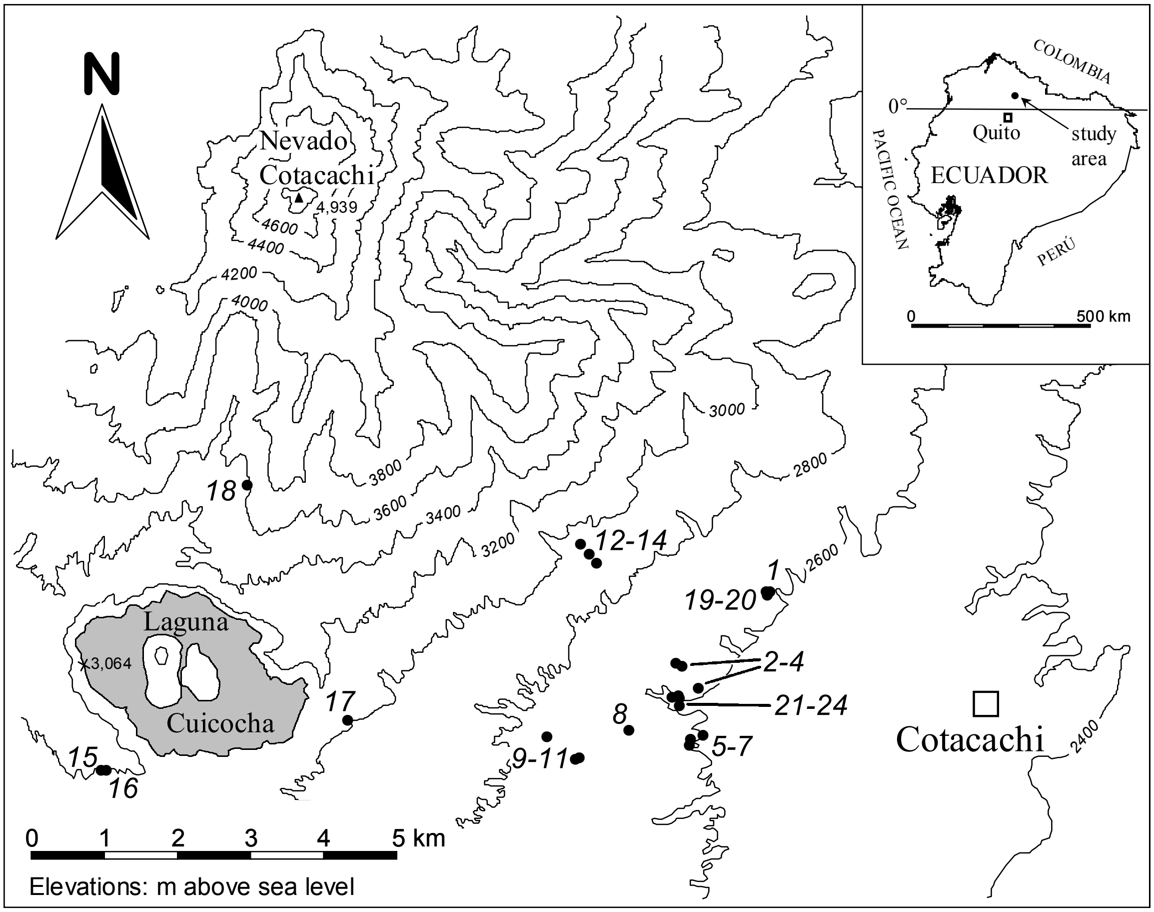

Fig. 6.1. Study area; the locations of the studied soils are marked with solid dots, numbered 1 through 24.

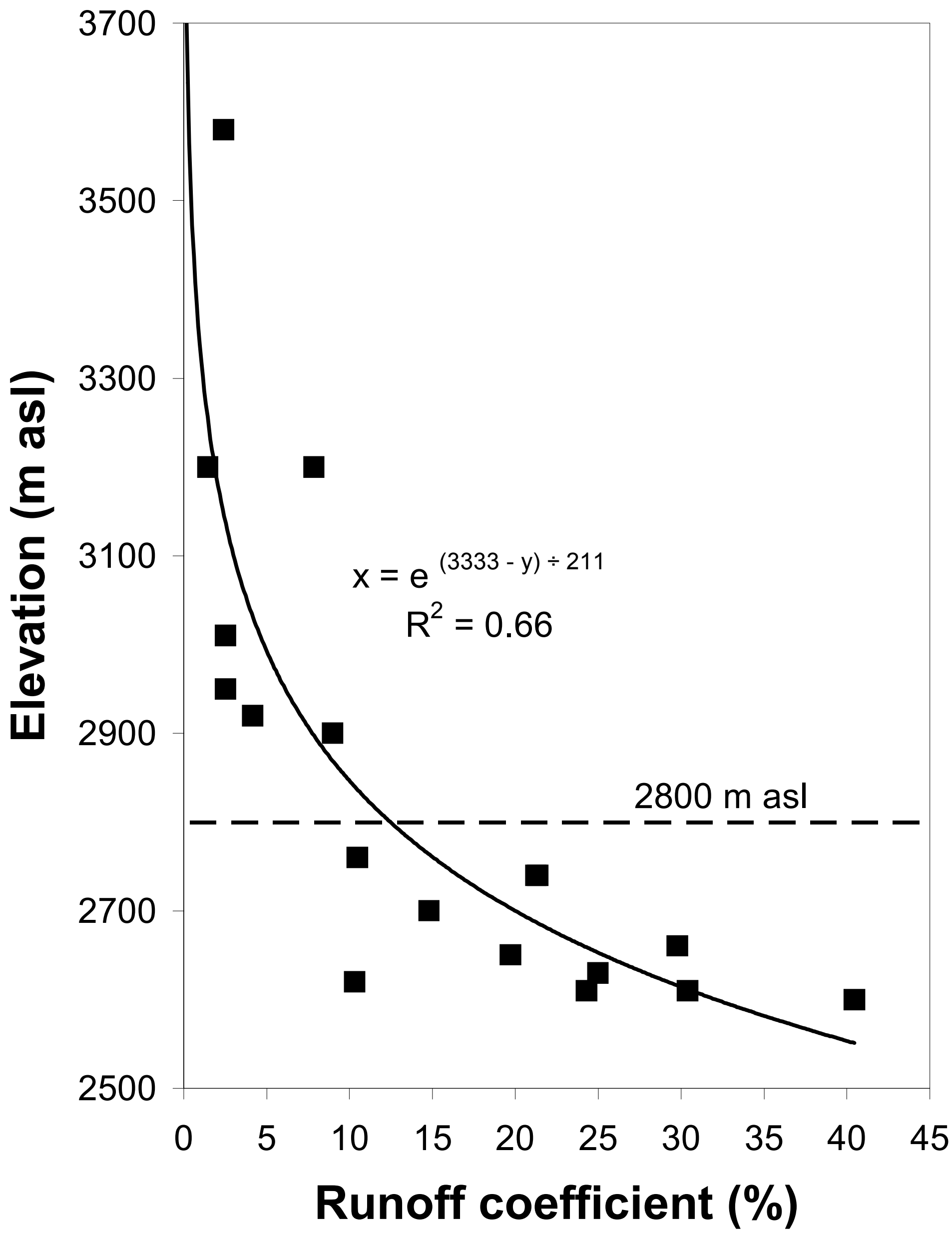

Fig. 6.2. Altitudinal dependence of surface runoff under rainfall simulation on recent upland soils; runoff coefficients are average values over a 30-minute event.

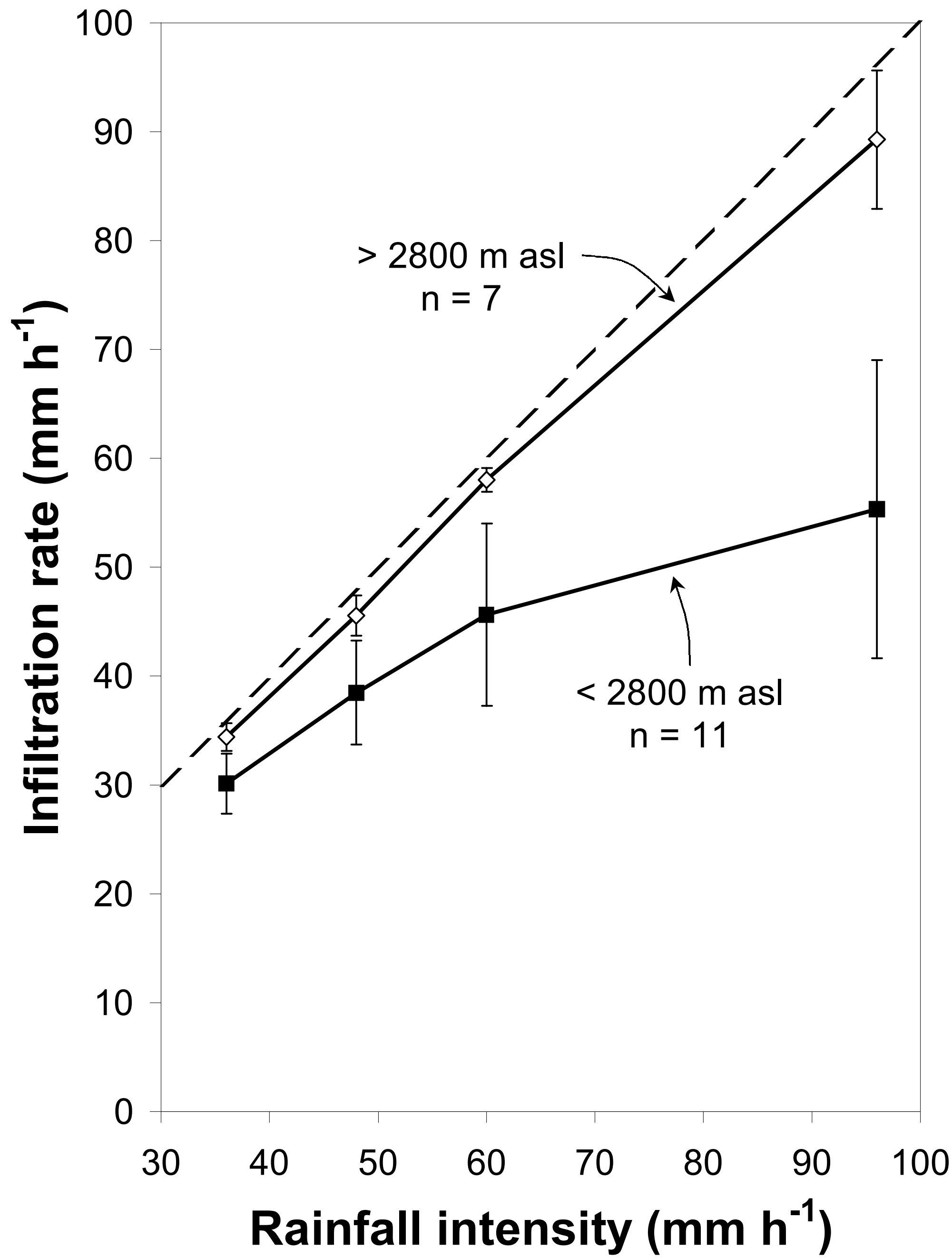

Fig. 6.3. Infiltration as a function of rainfall intensity for recent upland soils (grouped into soils below and above 2800 m asl, respectively); data points are arithmetic means with error bars showing ± one standard deviation; dashed line represents 1:1 slope.

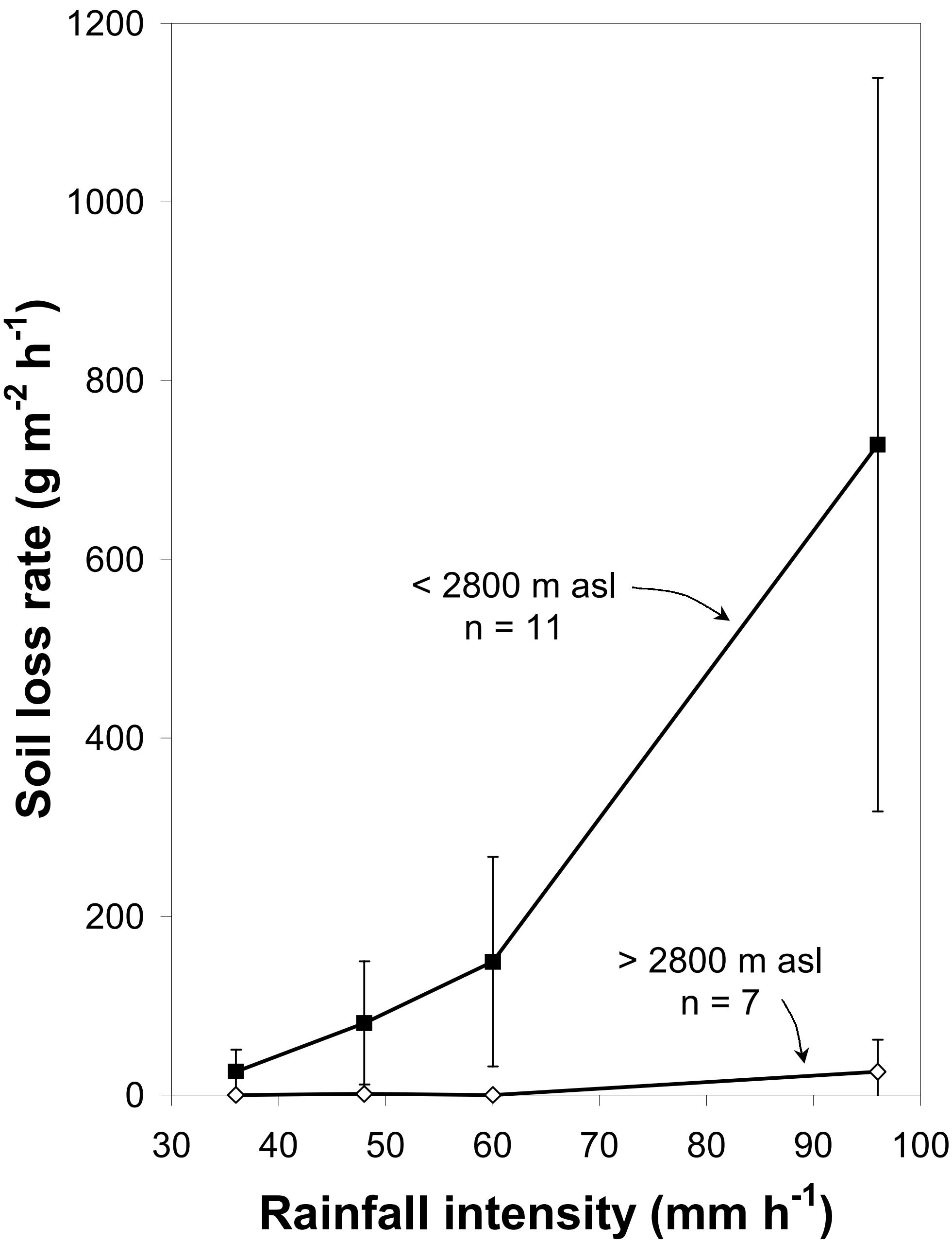

Fig. 6.4. Soil loss as a function of rainfall intensity for recent upland soils (grouped into soils below and above 2800 m asl, respectively); data points are arithmetic means with error bars showing ± one standard deviation.

CHAPTER 7

Conclusions

This study was undertaken within the SANREM CRSP (Sustainable Agriculture and Natural Resources Management Collaborative Research Support Program), as part of an interdisciplinary effort to devise a natural resource management plan for the Cotacachi area in the Andes of northern Ecuador. The objective of this study was to characterize the soil resource with respect to weathering and soil development, soil fertility status and productivity, as well as runoff potential and soil erodibility.

Located on the slopes of volcano Cotacachi, the study area spans over 2000 vertical meters from the temperate bottom of the inter-Andean valley to the natural *páramo* grassland above the tree line. Verticality is what dominates landscape and lifescape in this Andean mountain environment, and the soils are no exception to that. Altitude may be understood as the master variable that governs soil development, determines the soils' susceptibility to runoff and erosion, and affects many aspects of soil fertility.

At low elevations, organic matter contents are low, halloysite predominates clay mineralogy, and the soils are Inceptisols and Entisols. With increasing elevation, organic matter accumulates, amorphous constituents form, and the soils are Andisols above 2700 m asl. Climate is considered the overriding factor responsible for these altitudinal variations in pedogenesis. Lower temperatures slow organic matter decomposition and foster its accumulation at higher elevations. Differences in rainfall and evapotranspiration resulting in different leaching regimes have likely caused the differential formation of halloysite or allophane and thus the differential development of andic soil properties. The observed altitudinal differences in soil development and the resulting distribution of different soil types along the volcanic slopes have important bearings on the spatial distribution of soil erodibility and fertility characteristics within the area under study.

The accumulation of organic matter and the precipitation of active amorphous materials have led to the formation of a very stable aggregate structure in the high-elevation Andisols. These soils remain wetable when air-dried, show very high infiltration capacity and consequently low potential for runoff generation and soil erosion. Low organic matter contents and absence of active amorphous materials result in weak aggregation of the low-elevation Entisols and Inceptisols. These soils exhibit lower infiltration capacity and are more susceptible to erosion. However, in comparison with other soils of different origin and composition, their interrill erodibilities are classified as low. These findings suggest that erosional degradation is not a major threat to sustainability in the studied volcanic landscape, which is generally corroborated by field observations.

Conversely, water and nutrient management appear to be key elements of agricultural sustainability in the area under study. The soils in the drier low-elevation zones exhibit little water-storage capacity due to low organic matter contents and sandy textures, and thus aggravate dry-season water stress for agricultural crops. The presence of amorphous constituents in high-elevation soils results in strong phosphate sorption, which may induce P deficiencies. Despite large amounts of organic nitrogen in high-elevation soils, low temperatures and the presence of protecting amorphous materials may slow mineralization to levels that cannot satisfy crop N requirements. In contrast, excessive leaching losses may impair adequate nitrogen supply for agricultural crops in low-elevation soils. The young soils in the southern part of the study area have inherently low potassium contents irrespective of elevation.

Several strategies can be identified for improved, sustainable land management in the Cotacachi area. The maintenance of existing structural barriers such as bench terraces, earth walls, and border hedgerows would sustainably avert soil erosion, whereas the removal of such barriers in the course of large-scale agricultural operations may lead to increased sediment export and related adverse effects on water quality. While rainy season water availability is generally sufficient, an expansion of existing irrigation systems would greatly benefit dry-season crop production, particularly in the lower zones of the study area. Additions of potassium and phosphorus are necessary for optimum crop growth in certain areas, and the nitrogen status of all soils could be greatly improved by returning residues to the soil after harvest, including leguminous plants in crop rotations, and managing short, improved fallows.

In general, the volcanic ash soils in the Cotacachi area have the potential to sustainably support traditional subsistence agriculture as well as thriving market-oriented production of niche crops, vegetables, and fruits. In either case, the key to agricultural sustainability is the restoration and maintenance of soil fertility. Nutrient losses need to be minimized, and nutrients that leave the production systems through harvested products need to be replaced – in ways that are environmentally sound, economically viable, and socially acceptable.

This leads back to the idea of an integrated natural resource management plan, to which this study contributed. Such an approach, which links biophysical studies with socioeconomic and sociocultural information, will increase the potential of science to “make a difference” outside of the academic world, which should be what a perceptive and conscientious scientist desires.