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Soil nutrient stock dynamics and land-use management of annuals, perennials and pastures after slash-and-burn in the Southern Ecuadorian Andes

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ABSTRACT

Quantification of nutrient stocks and their temporal changes are considered of prime importance in farming systems of the humid tropics to answer the question of sustainable management. The research area in the Southern Ecuadorian Andes included forest, annual (0–5 years old) and different aged perennial (0–5, 6–10, 11–20, 21–30) and pasture (0–5, 6–10, 11–20, 21–30, >30) sites. Soil organic carbon (SOC), total and plant available soil nutrient stocks and nutrient balances were investigated to assess temporal soil nutrient dynamics in relation to management activities. Forest conversion by slash-and-burn caused a decrease in SOC stocks in all three land-uses amounting between 14% and 19%. This was mainly due to the absence of an organic layer and losses in the upper five cm of the mineral soil. Stocks of exchangeable bases and pH values increased in annuals which however, had the most negative nutrient balance of all land-uses amounting to −128, −25 and −226 kg ha^{-1} a^{-1} for N, P and K, respectively. The abandonment of annual sites after five years was linked to a shortage of available N and P due to low-external-input management which caused SOC stock decreases. Major soil nutrient changes in perennials and pastures did not occur directly but 6–20 years after forest conversion with increases in stocks for total N, P, S and exchangeable bases above forest level. SOC stocks of medium aged perennials and pastures increased above forest level in the mineral soil. Easily available inorganic N and P stocks remained low throughout the chronosequence in perennials and pastures, indicating a quick uptake by plant roots and microorganisms. Compared to medium aged sites, oldest perennials and pastures showed a strong decrease in SOC (−28% and −16%) and soil nutrient stocks. Stocks for total N, P, S and exchangeable bases were up to 50% below those of medium aged sites in oldest perennials and pastures.

1. Introduction

Sufficient area of productive cropland and maintenance of high crop yields are considered to be the crucial factors in food production (Ramankutty et al., 2002). Nonetheless, vast areas of the world's agricultural soils are already degraded (Lal, 1997). Therefore, it is essential to maintain soil fertility in agriculture since the majority of the world's fertile soils are under cultivation (Young, 1999). The expansion of agricultural areas continues to exist particularly in the tropics due to the quickly growing population and changing dietary preferences in developing countries (Smith, 2008). Even though land-use change is a local process, the impact on the earth system functioning is global indicated by changes in climate, biodiversity and agroecosystems (Lambin et al., 2006).

Ecuador in particular has the highest annual deforestation rate of 1.8% in South America where on average 0.5% of the forests is cleared per year (FAO, 2011). The traditional clearing method in the Amazon region is slash-and-burn (Alegre et al., 1988) provoking one of the greatest disturbances known to an ecosystem (Giardina et al., 2000b). Burning aboveground biomass during slash-and-burn causes significant soil organic carbon (SOC) and nutrient losses by volatilization as well as by erosion, runoff and leaching if the soil is unable to absorb all released nutrients (Juo and Manu, 1996). A short-term increase in soil fertility is usually induced by the incorporation of Ca, Mg and K from nutrient-rich ash into the cation exchange pool (Nye and Greenland, 1960). However, studies with diverse results exist for plant available N and P showing increases (Giardina et al., 2000a), no change (Ewel et al., 1981) or decreases (McGrath et al., 2001). Nonetheless, many slash-and-burn systems

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fail in the long-term due to ever shorter fallow periods dismantling nutrient cycling and its use efficiency (Palm et al., 1996). In contrast, the slash-and-mulch technique where the slashed vegetation remains unburned induces a longer term release of nutrients and is spreading increasingly in the Amazon of Ecuador (Mainville et al., 2006).

Slash-and-burn agriculture and subsequent land-use in the tropics often involves time periods of more than 50 years before abandonment (Hamer et al., 2013). Since soil characteristics are subject to change from forest conversion until the end of agricultural use (Bewket and Stroosnijder, 2003), a chronosequence approach can help quantifying these changes in soil nutrient dynamics over the course of time (Huggett, 1998). The quality and quantity of change in conjunction with time may help in the assessment of different agricultural management practices (Arshad and Martin, 2002) in land-use systems of the humid tropics (Schroth et al., 2001). This facilitates the modification of the current management practice as was shown in the Amazon region by the replacement of disadvantageous components of the slash-and-burn system (Denich et al., 2005). Nevertheless, it is difficult to draw common conclusions on slash-and-burn and subsequent soil nutrient dynamics for two reasons. Firstly, statements on soil nutrient dynamics should only be drawn for the investigated age and not for longer time periods in between. Yet, many studies involved only one age group after forest conversion. Secondly, studies in the tropics including several age groups after forest conversion cover a wide range of results and seem to be site specific. Increasing (Hamer et al., 2013) versus unchanged (Koutika et al., 1997) C and N stocks were reported for pasture chronosequences in Ecuador and Brazil respectively. In addition, perennial cocoa agroecosystems in Nigeria (Ekanade, 1988) and Cameroon (Yemefack et al., 2006) showed diverse SOC patterns indicating decreases versus increases in oldest sites of a chronosequence respectively.

Soil nutrient depletion is a process which may induce chemical degradation of soils (Lal, 1993). Since weathering, loss of bases, acidification and desilification quickly progresses in tropical soils (Navarrete et al., 2009), they are especially subject to soil nutrient depletion if managed in low-external-input systems (Tan et al., 2005). Hence, losses by leaching or removal of crop residues should be minimized in these land-use systems (Graves et al., 2004). The calculation of nutrient balances can help in the assessment of the quality and quantity of soil nutrient depletion for a specific land-use system as was performed with the NUTMON approach (Smaling and Fresco, 1993). Pasture management and cultivation of annual and perennial crops are the dominant land-use types in Ecuador (de Koning et al., 1999). Ecuadorian pasture systems are characterized by the application of low fertilizer amounts (de Koning et al., 1997). They are commonly abandoned after several decades due to soil nutrient depletion (Hamer et al., 2013) or secondary succession often induced by bracken fern infestation (Hartig and Beck, 2003). Nutrient depletion in perennial cropping systems is usually lower than in annuals due to better nutrient uptake and low rates of soil erosion (Hartemink, 2005; Jordan et al., 2007). Additionally, their utilization as cash crops induces more intensive fertilization compared to those annuals which are used only for subsistence (Hartemink, 2003). Moreover, it was shown that low-external-input systems generate lower yields compared to management systems with higher resource endowment (Tittonell et al., 2008). Consequently, soil fertility decline and decreasing yields after slash-and-burn in annual cropping systems often lead to abandonment after a few years (Alegre et al., 1989; Henrot and Robertson, 1994) in contrast to a longer-term cultivation potential in pastures and perennials.

Sustainable management of land-use change is dependent on the monitoring of different temporal and spatial scales since the alteration is not linear, but a complex cycle affected by human decisions (Uriarte et al., 2010). To the author's knowledge, however, comparative studies of nutrient dynamics and management of the long-term cultivation cycle in annuals, pastures and perennials after slash-and-burn in the tropics are scarce. Therefore, SOC and total and plant available major nutrient elements (N, P, K, Ca, Mg and S) were measured and stocks were calculated. The impact of management was assessed by the calculation of nutrient balances for NPK. The objectives of the study were (1) to detect the immediate impact on soil C and soil nutrient stocks after forest conversion to agricultural land-use, (2) to find out whether abandonment of annuals after a short period of cultivation is related to soil nutrient depletion and (3) to determine long-term dynamics of soil C and soil nutrient stocks in pastures and perennials using a chronosequence approach.

The following hypotheses were postulated for agricultural management systems of the Southern Ecuadorian Andes:

i. Soil nutrient depletion due to management activities leads to the abandonment of annual sites after a short period of cultivation.
ii. Pastures and perennials rather than annuals show a long-term cultivation potential in low-external-input agricultural systems.

2. Methodology

2.1. Site description and sampling

Study sites were located in the province of Zamora-Chinchipe within the canton of Yantzaza (3°47′S–3°56′S; 78°43′W–48°46′W) in south-eastern Ecuador (Fig. 1). Yantzaza lies in an altitude of 820 m a.s.l. at the eastern escarpments of the Andes in the transition zone between mountain and lowland tropical rainforest at the Rio Zamora. Mean annual air temperature and rainfall in a nearby climate station were 22.1 °C and 1944 mm, respectively (Richter, 2003). The local geology is dominated by granites, granodiorites and dacites (Litherland et al., 1995). The establishment of soil profiles served for the description and classification of the Haplic Cambisol (humic) (FAO et al., 2006) as the dominant soil type in slope positions (Fig. 1). Natural vegetation is comprised of an evergreen submontane rainforest (Homeier et al., 2008) which in present days can only be found in top slope positions. Local farmers of the investigated sites moved from the south Ecuadorian dry forests to the Yantzaza area in the 1960s and have been commonly using slash-and-burn to convert forest into agricultural land. In 2010 land-use distribution for the farms of the Yantzaza region was 53% for forest, 42% for pastures, 3% for perennials and 2% for annuals (Romero et al., 2010). Extensive grazing management (livestock density of 1.2 animals ha^{-1}) with the cultivation of annual crops for subsistence (low-external-input agriculture) and perennial cash crops is the predominant land-use.

Preliminary studies included a thorough review of geological, climate and agroecological maps. Farm interviews and field observations with local experts (from university and governmental organizations) were performed to acquire a detailed overview about site conditions. Farm surveys with local farmers were carried out using a structured questionnaire to obtain information about land-use history such as date of forest conversion or agricultural management. Required conditions for the application of a chronosequence approach in the present study were to maintain all soil-forming factors constant except for time (Huggett, 1998). Hence, in order to assure comparability of the sites, the following conditions were considered: (i) granite had to be the parent material which was verified using geological outcrops in nearby roads; (ii) sites had to be situated in slope position with approximately 20–30° since transported sediments in riverbeds are difficult to assign to a specific group; (iii) neither crop rotation or land-use