Soil Ecosystem Processes
in Tropical Forests, Savanna, and Croplands
of Cameroon

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Contents

CHAPTER 1 Introduction

1.1 Study background

The Congo basin in Central Africa contains the second largest contiguous block of tropical forests on Earth (FAO 2009). Agriculture remains the most significant driver of global deforestation. Small-scale subsistence agricultural processes dominate deforestation in Africa; however, large-scale commercial agriculture is likely to increase in Africa (Hosonuma et al. 2012), given that the forests most vulnerable to agricultural conversion tend to be on flat. It is therefore urgently required to establish better agricultural land use strategies in a sustainable way in tropical humid Africa.

In Africa, Oxisols are widely distributed and the leguminous family dominates the canopy (Yahara et al. 2013). Ultisols, which exhibit relatively incipient mineralogical characteristics, are also accompanied with Oxisols even in Africa. Oxisols are characterized as low nutrient availability; whereas Ultisols as strong acidity, which can affect soil ecosystem processes: nitrification is often prohibited at low pH (Jordan et al. 1979); Al toxicity inhibits plant roots growth (Delhaize and Ryan 1995). Nevertheless, previous studies treated those soils just as tropical highly weathered soils and did not differentiate ecosystem processes. It is therefore essential to understand basic ecosystem processes on respective soil conditions to establish an appropriate strategy for sustainable agricultural management.

In West and Central Africa, the interface between tropical forest and savanna, called as “forest-savanna mosaic”, is widely distributed (Mitchard et al. 2011). The local farmers conduct slash-and-burn agriculture for both vegetation in this region; nevertheless, little is known about nutrient dynamics under each vegetation. If some ecological processes between two vegetation are different, they may affect agricultural land use strategies after land reclamation, which we should take into consideration.

The objectives of the present study are (1) to evaluate the influences of soil types (Oxisols and Ultisols) on plant–soil nutrient cycles and ecosystem processes in Cameroonian forests by quantifying the nutrient fluxes through flow paths—bulk precipitation, throughfall, litterfall, and soil solutions—with special reference to the effects of soil acidity (Chapters 3 and 4), (2) to evaluate the influences of vegetation types (forests and savannas) on the effect of land reclamation on soil nutrient dynamics at forest-savanna mosaic on Oxisols of Cameroon (Chapters 5 and 6), and, (3) to establish appropriate strategies for sustainable agricultural management in tropical humid Africa (Chapter 7).

CHAPTER 2 Materials and methods

The Mvam plot (MVf) was located in South Region in forested area. The rainy season is bimodal with the minor rainy season occurring from March to July and the major rainy season occurring from September to November. The dominant vegetation consists of Fabaceae (31% of basal area). The soil is yellowish brown (10YR 5/6-8) in the subsurface horizon and is classified as Ultisols (Soil Survey Staff 2014) or Acrisols (IUSS Working Group WRB 2015).

The Andom plots (ADf, ADfc, ADs, and ADsc) were ~400 km apart from MVf and located in East Region in a forest-savanna transition area. The distribution of rainfall is also bimodal. In Andom, experiments were conducted in the forest plot (ADf), the adjacent savanna plot (ADs), and the respective adjacent cropland plots (ADfc and ADsc). The soil at AD is reddish brown (2.5YR 4/6) in the subsurface horizon and is classified as Oxisols (Soil Survey Staff 2014) or Ferralsols (IUSS Working Group WRB 2015). The dominant vegetation of forest plot consists of Fabaceae (51% of basal area). The dominant vegetation of savanna plot is *Chromolaena odorata* (Asteraceae). Maize (*Zea mays*) was cultivated in both cropland plots during each rainy season (twice a year) in 2010 and 2011 as practiced by the local farmers.

The litter chemistry and litterfall rates for forested site were monitored via five circular (72-cm diameter) litter traps, which were emptied monthly from April 2010 to May 2012. The plant samples were oven dried at 70 °C for 48 h, weighed, and milled. The C and N contents were determined using the CN analyzer as described above.

Gravitational soil solutions were collected using tension-free lysimeters in a draining surface area of 200 cm^2 at depths of 0-, 15-, and 30-cm in forested plots and 15- and 30-cm in cropland plots. Precipitation and throughfall were collected monthly. Prior to analysis, the collected solutions were individually filtered through a clean 0.45-µm cellulose acetate membrane filter and then stored at 4°C. Solution pH values were determined using the pH meter described above. The concentrations of Na^+, K^+, NH_4^+, Mg^{2+}, Ca^{2+}, Cl^-, NO_3^-, and SO_4^{2-} were determined by high performance liquid chromatography. The concentrations of total Fe and Al in solutions were determined by inductively coupled plasma atomic emission spectrometry.

The solute fluxes from each horizon were calculated as the product of the measured concentrations and the monthly water fluxes, which was the sum of the modeled half-hourly fluxes during each time period. The annual solute fluxes were calculated by summation.

CHAPTER 3 Nitrogen flux patterns through Oxisols and Ultisols in tropical forests of Cameroon

Forest conservation in Africa is a global issue. Characterization of nutrient cycles is essential from the perspective of forest management; nevertheless, we lack an understanding of nitrogen (N) cycles in these tropical forests despite the dominance of N-fixing leguminous species. Herein, we quantified N (NO_3^-, NH_4^+, and dissolved organic N) fluxes simultaneously through flowpaths including precipitation, throughfall, O-horizon solution and soil solutions as well as litterfall in two forests with soil types with contrasting soil acidity—Ultisols at MV (soil pH, 3.5–4.0) and Oxisols at AD (soil pH, 4.2–4.9)—over a 2-yr period in Cameroon. Nitrogen inputs via litterfall plus throughfall were exceedingly large relative to other tropical forests (AD: 273 kg N ha^{-1} yr^{-1}; MV: 236 kg N ha^{-1} yr^{-1}), reflecting legumes are dominant at both sites. Total dissolved N (TDN) flux from the O horizon at MV was 27 kg N ha^{-1} yr^{-1} with evenly distributed dissolved N species; in contrast at AD, 120 kg N ha^{-1} yr^{-1} was leached to the mineral soil horizon mainly as NO_3-N (~80%), indicating the AD forest has high potential for N loss. We observed a superficial root mat at MV, but not at AD (fine root biomass in O horizon: 1.5 Mg ha^{-1} at MV; 0.3 Mg ha^{-1} at AD). This is probably because exchangeable Al^{3+}, which is toxic for plant roots, in the mineral soil (0–30 cm) at MV (126 $kmol_c$ ha^{-1}) was more than twice that assayed at AD (59.8 $kmol_c$ ha^{-1}). Overall, plants at MV take up most of N at O horizon (tight N cycle) due to the intense soil acidity, which contributes to superficial root mat formation; whereas at AD, almost half of the input N leaches down to mineral soil (leaky N cycle). Taken together with the previous studies, soil type might influence the pattern of N fluxes from the O horizon with a combination of N-fixing species through effects of soil acidity, and thus determine the unique N cycles in Africa, where N-fixing species is dominant.

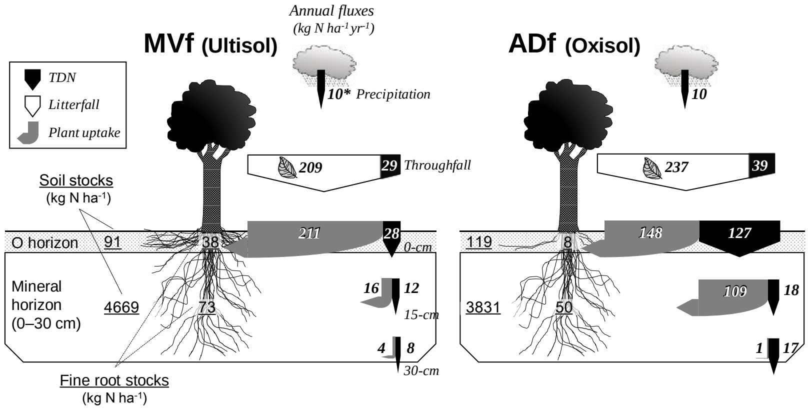

Fig. 3.1 Annual fluxes and stocks of nitrogen (N) at the study sites. Nitrogen stocks in the O horizon, in the mineral horizon (0–30 cm), and in fine roots are indicated by underlined numbers; TDN, litterfall N, and plant uptake N fluxes are indicated by numbers in italics. *The N flux in precipitation at the MVf site is assumed to be the same as that at the ADf site, because the source of rainfall at both sites is almost the same (van der Ent et al. 2010; Gimeno et al. 2012).

CHAPTER 4 Ecosystem processes of Oxisols and Ultisols in forest-soil systems of Cameroon

Tropical African forests are dominated by Oxisols and leguminous species, while Southeast Asian forests are dominated by Ultisols. Hence, their ecological processes can differ, depending on soil acidity and nitrogen (N) availability. To provide an overview of the carbon (C) and N dynamics, as well as soil acidification processes on Oxisols and Ultisols, in tropical African forests, the author quantified soil respiration and element fluxes through different flow paths (as precipitation, throughfall, litterfall, litter leachate, and soil solutions), and analyzed proton budgets in two secondary forested sites in Cameroon. The results demonstrate that at MVf, N was mostly taken up within the O horizon, which has a dense root mat, while half of the input N leached down to the mineral horizon at ADf. Nitrification was the main proton-generating process in the canopy and the O horizon of ADf, and it caused a large amount of cation leaching, which resulted in the accumulation of basic cations because of the high proton consumption rates in the A horizon. In contrast, because of the dense root mat at MVf, the excess cation uptake by plants in the O horizon made the largest contribution to proton generation, which resulted in intensive acidification of the surface soil. The results suggest that ecosystem processes differ depending on soil type (i.e., soil acidity). Thus, legumes growing on Oxisols in tropical African forests have unique plant-soil interactions via active nitrification in the O horizon.

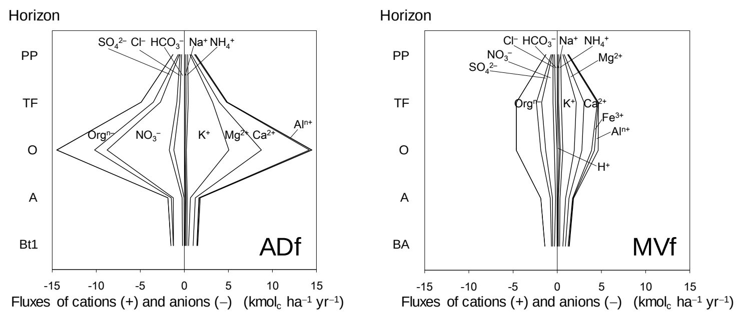

Fig. 4.2 Annual fluxes of cations and anions in each horizon. PP represents precipitation, TF represents throughfall. O, A, Bt1 and BA represent soil horizons.

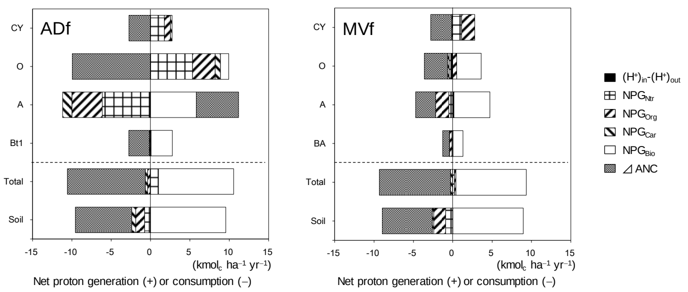

Fig. 4.1 Net proton generation and consumption in the soil profiles. CY represents the canopy; TF represents throughfall; O, A, Bt1. and BA represent soil horizons; and Soil represents total proton generation and consumption minus those of the CY.

CHAPTER 5 Effect of original vegetation on base cation loss patterns from Oxisol cropland in forests and adjacent savannas of Cameroon

Forest-savanna mosaic is widespread in tropical Africa mainly occurring on nutrient-poor Oxisols. Though sustainable agriculture is a major concern in this region, little is known about the effects of original vegetation (i.e., forest vs savanna) on nutrient losses from cropland. Hence, we evaluated basic cation losses and nutrient balance of Oxisol cropland cultivated over 2 years in the Cameroon forest-savanna mosaic. Solute fluxes at 30-cm depth in maize croplands derived from forest (ADfc) and savanna (ADsc) were compared with those in adjacent forest (ADf) and savanna (ADs) ecosystems. Nutrient inputs by rainfall, outputs from solute leaching and cropland grain removal, and soil nutrient stocks measured at depths between 0 and 30 cm were investigated. The main anion present in ADf soil solutions was NO_3^- (0.16–0.19 $mmol_c\ L^{-1}$), while it was present in negligible amounts in ADs. The 2-year NO_3^- flux in ADfc (156 kg N ha^{-1}) was double that in ADsc (78 kg N ha^{-1}), leading to greater 2-year K^+ leaching in ADfc (118 kg K ha^{-1}) than in ADsc (37 kg K ha^{-1}). The ratio of 2-year nutrient losses to total soil stocks was the greatest for Ca both in ADfc (5%) and ADsc (4%), while K loss also reached 5% in combination with lower solution pH in ADfc. In conclusion, cultivation of former forest land substantially increased NO_3^- leaching, resulting in depletion of both K and Ca; whereas, cultivation of former savanna results in mainly Ca depletion.

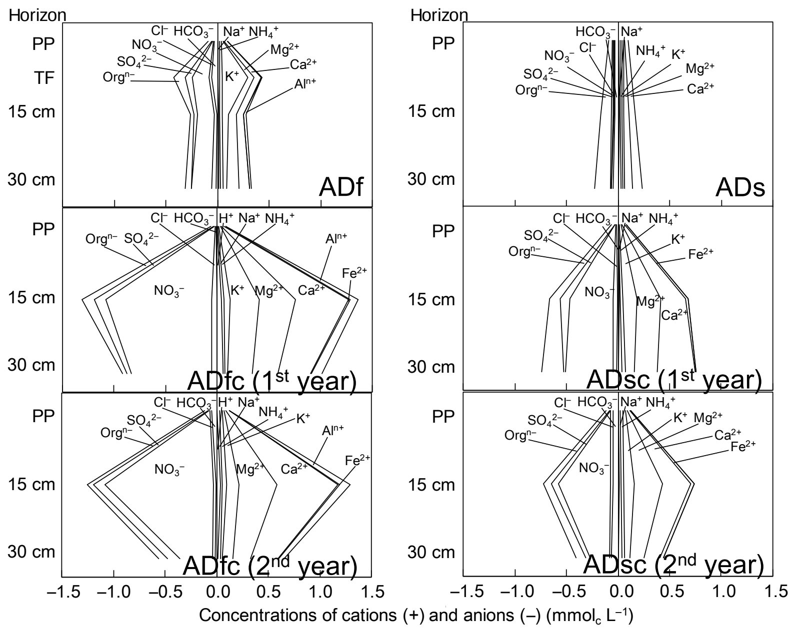

Fig. 5.1 Annual volume-weighted mean concentrations of ions leached from each stratum at each plot. PP, precipitation; TF, throughfall; 15 cm, soil solution at a depth of15 cm; 30 cm, soil solution at a depth of 30 cm.

CHAPTER 6 Changes in ecosystem processes of Oxisols after reclamation of forests and adjacent savannas of Cameroon

To understand the effects of original vegetation (forest or savanna) on changes of solute leaching and proton budgets after reclamation on Oxisols in Cameroon, the author quantified the soil nutrient fluxes in forest, adjacent savanna and each adjacent maize cropland. In forest plot, excess cation accumulation in wood has contributed to soil acidification in the entire soil profile, while soil acidification rates were much lower in savanna plot because of limited plant uptake. As a result of cultivation, NO_3^- fluxes were substantially increased and nitrification was the main process of soil acidification in both croplands. Reflecting the nutrient flux pattern of original vegetation, protons generated by nitrification in forest cropland plot (9.4–10.1 kmol$_c$ ha^{-1} yr^{-1}) was significantly higher than that in savanna cropland (3.4–4.5 kmol$_c$ ha^{-1} yr^{-1}). Despite low pH of bulk Oxisols of Cameroon, they would provide favorable habitat for nitrifiers with physically well-structured microaggregates, allowing active nitrification in the plots of Cameroon. High rate of nitrification suggests the risk of nutrient deficiency in cropland is more serious in nutrient-poor Oxisols. The effects of reclamation on soil acidification processes would depend on the original vegetation and also on soil pH and physical structure, which affect the nitrification activity. Since the ratio of K^+ concentrations to sum of Mg^{2+} and Ca^{2+} concentrations increased with decreasing soil solution pH, the lower solution pH, which could stem from cultivation, might promote K leaching from cropland.

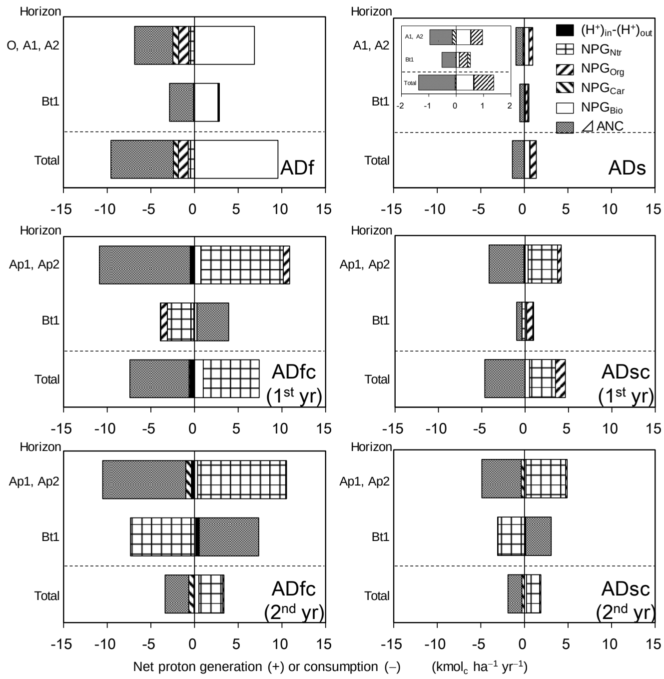

Fig. 6.1 Net proton generation and consumption and soil acidification in the soil profiles at studied plots. O, A1, A2, Ap1, Ap2 and Bt1 represent soil horizons.

CHAPTER 7 Discussion on soil ecosystem processes in tropical humid Africa on Oxisols and Ultisols for better agricultural land use

Nitrogen flow between plant and soil is large in spite of soil type due to N-fixing species. Thus, land conversion to croplands accelerates N cycling and could lead to subsoil losses of N (McGrath et al. 2001), which is accompanied by basic cations (Lucas et al. 2011). Since N contents of the soils are relatively rich as compared to other nutrients such as bases, nutrients other than N should receive more attention for external inputs. For agricultural land use management in this region, tree-based land uses, such as agro-forestry type, can be more sustainable for both soil types due to the following reasons: (1) for Ultisols with low soil pH having high exchangeable Al, the function of existing surface root mat should be utilized as the safety-net to prevent nutrient leaching (N species is mainly NH_4^+) by leaving some trees remained on reclamation; (2) for Oxisols with moderate soil pH having low exchangeable Al, the function of existing tree root in the deep soil should be utilized as the safety-net to prevent nutrient leaching (N species is mainly NO_3^-, which drives basic cations loss) by leaving some trees remained on reclamation. Since N input to the soil surface is large in forests of this region, soil C/N ratio is low and N release rates can be rapid, and then, the original safety-net systems of the forests should be utilized in the agricultural system. Besides, Ultisols in this region tend to distribute on the steep topography, so that agro-forestry type of land use can be better also to minimize soil erosion.

Since the nutrient flux of savanna cropland is smaller and soil fertility is lower, annual crop, such as cassava, can be a feasible option with Ca input from outside resources. In forest croplands, the pump-up effect of deep-soil nutrients by plant root systems of forest vegetation should be utilized with K input from outside resources since nutrient leaching flux, which is difficult to suppress, is strikingly large. Then, agro-forestry and/or mix cropping of trees with annual crops could be one of the feasible options. Shifting cultivation with forest-fallow can be another option to utilize such functions of forest vegetation for nutrient replenishment. Even though land use strategies between forest cropland and savanna cropland can be different, it is essential to notice nutrient replenishment either by the on-site recovery using tree functions or by utilizing outside resources is a must for sustainable agricultural production in the long run. Besides, the inclusion of N-fixing cover crops in the cropland should not be applied, because such practice could result in significant subsoil losses of basic cations, which is accompanied by rapidly mineralized N and not taken up by plants in the cropping system (Schroth et al. 2001) under Oxisols in this region, where active nitrification is observed.

CHAPTER 8 Summary and conclusions

The data revealed a different picture of plant-soil N dynamics in two Central African tropical forests that have Oxisols and Ultisols. Nitrogen input to the soil is exceedingly large despite soil types due to the canopy dominance of N-fixing legumes in the tropical forests of Africa. In contrast, soil acidity may control soil N transformation process and the fine root distribution through the soil profile: N species is mainly NO_3^- with deeper plant root for moderately acidic Oxisols; N species is evenly distributed with surface root mat for strongly acidic Ultisols. A forest ecosystem having combination of N-fixing trees with Oxisols may have a unique nutrient-acquiring strategy.

Higher C/N ratio of surface soil for savanna on Oxisols causes slower plant-soil nutrient cycles as compared to forest. As a result, nutrient leaching from savanna-derived cropland is less than that from forest-derived cropland for Oxisols. In forest cropland, active nitrification, accompanied by the loss of soil organic matter, causes intensive soil acidification, which brings about K release from mineral dissolution under low soil pH even for Oxisols. This is contrast with savanna cropland under moderate soil pH due to less active nitrification, where Ca loss is the primary risk from croplands

Land in this region must not be converted to the vast cropland for commercial agriculture of annual crops to prevent catastrophic soil degradation in terms of soil nutrients loss through leaching and, if hilly, through erosion. The data of this study clarified the different N (or nutrients)-acquiring strategies of forest ecosystems depending on the soil type. This safety-net should be made use of for agricultural land use. It is therefore suitable to introduce tree-based crops (such as cacao) or combination of the forest trees with some shade-tolerant annual crops (such as banana).

As base cation availability is affected by the N cycle, savanna-derived cropland on Oxisols is less susceptible to the leaching loss of nutrients than forest-derived cropland. The farmers need to grow enough food to feed themselves as subsistence agriculture by cropping as cereals and tubers. It is therefore feasible to plant such crops in the cropland derived from savanna. Note that cereals are N-demanding crop and tubers require more K and Ca, both of which are to take into consideration for land management and must not be cash crops in terms of soil nutrients. This study showed the loss of Ca from savanna cropland and K from forest cropland is serious in less than decades. For highly-weathered soil, phosphorus is mainly focused on for the crop productivity, but the loss of basic cations through leaching should also be highlighted. The function of fallow as forest/savanna for nutrient recuperation can be important in this region.