doi:10.5194/soil-special_issue1134-preface

SOIL Open Access

Preface: Tropical biogeochemistry of soils in the Congo Basin and the African Great Lakes region

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Published: 29 October 2021

Abstract. Tropical forests are hotspots of modern day land-use change and are, at the same time, among the largest terrestrial carbon reservoirs. In particular, the African continent will be facing huge environmental and societal challenges with projected changes in climate and population growth of 300 % by the end of this century. Despite their importance, tropical soils and ecosystems, particularly in Africa, are among the least studied in the world. Our lack of knowledge on the consequences of land-use change in the region on plant-soil interactions also limits our ability to predict future trajectories of tropical ecosystem services to mitigate climate change. Established observatories in the Congo Basin focus on questions related to biodiversity preservation and C storage in the biosphere, largely ignoring soils. In this *SOIL* Special Issue, we highlight research done in tropical Africa on plant-soil interactions, biogeochemistry and soil ecology across various natural and managed ecosystems, with an emphasis on the work conducted within the new research network "Congo Biogeochemistry Observatory" (CBO).

1 Introduction – the African Tropics in the 21st century

1.1 Global Change in the Tropics

Human activity on the African continent will potentially cause irreversible changes to soil properties and the services they provide to the global biosphere on the scale of centuries and millennia. Rising food demand in Sub-Saharan Africa is expected to triple by 2050 (van Ittersum et al., 2016), resulting in greater forest clearance (Hansen et al., 2013; Govers et al., 2017; Seymour and Harris, 2019; Molinario et al., 2020) and soil degradation (Montanarella et al., 2016) unless land management can be improved. In the Congo Basin alone, between 2000 and 2010, forest loss was estimated to be $\sim 0.23\,\%\,\mathrm{yr}^{-1}$ (Potapov et al., 2012; Ernst et al., 2013). In neighboring Uganda, 26 % of intact forest cover has been lost between 1980–2010, roughly the size of Rwanda (Obua et al., 2010). Globally, tropical landscapes, while accounting for only 20 % of total agricultural land, hold $> 50\,\%$ of water and tillage erosion on cropland (approximately $10.3\,\mathrm{Pg\,soil\,yr}^{-1}$) (Doetterl et al., 2012), with numbers increasing with less suitable land being cultivated and soils continuing to lose fertile topsoil. The degradation and potential collapse of (agro)ecosystems across vast regions of the continent could thus lead to migration at a scale never seen before. In the context of human and ecosystem health, anthropogenic climate change in tropical Africa is increasingly becoming a threat, exacerbating the food and nutritional insecurity for over 800-million people globally. To face those challenges and to secure the future of food production and ecosystem functioning in tropical Africa, scientists need to deliver a comprehensive understanding of the consequences of human activity from local to large scales (Berhe, 2020; Berhe and Ghezzehei, 2020).

1.2 Consequences of disturbance to tropical soils

Land use planning and decisions are still based on the assumption that the negative developments of soil degradation could potentially be reversed or tackled at some time in the future. This is a potentially fatal assumption since disturbances of tropical soils are prone to fast responses in the biosphere. Tropical land use change from forest to crop- and grassland leads to a rapid decline in soil productivity, largely related to erosional soil loss. Losing a thin, fertile layer of topsoil reduces the capacity of most tropical soils for food production drastically (Olsson et al., 2019; Don et al., 2010; Veldkamp et al., 2020). Steep terrain, for example, is particularly prone to erosion once converted to cropland (Fig. 1). There, the rate of soil loss becomes the dominant control on soil fertility and soil organic C (SOC) stocks in agricultural systems with low fertilizer inputs as they are common in Tropical Africa (Heffer et al., 2014). In contrast, on stable landforms soil fertility and SOC stocks are more controlled by land management and soil geochemistry. Finally, valley landforms can become filled with sediment stemming from hillslopes which can lead to increases in soil depth and carbon storage but buried nutrient rich layers under continuous sedimentation will gradually become unavailable for plants while newly deposited soil is increasingly nutrient depleted (Doetterl et al., 2012; Wang et al., 2017). It has also been suggested that some soil substrates rich in rock-derived nutrients might stimulate higher plant productivity and yields during soil recovery (Harden et al., 2008). Furthermore, due to the change in limiting factors (less rock-derived nutrient limitation), biodiversity as well as root : shoot C allocation patterns might change drastically. While all of the above responses to soil disturbance have been demonstrated for temperate soil systems, it is still largely unknown under which conditions these processes may occur in tropical systems with very different soil development history, climatic conditions and pace of land conversion (Berhe et al., 2018).

1.3 Current knowledge on tropical soil biogeochemistry

Despite their great significance for the global climate system (Jobbágy and Jackson, 2000; Amundson et al., 2015) and the drastic changes and challenges that Africa is facing in the 21st century, little is known about biogeochemical cycling and dynamics in soils of its tropical ecosystems (Schimel et al., 2014). Established observatories, e.g. in the Congo Basin, focus mostly on biodiversity preservation and C storage in the phytosphere, while soils have received much less attention (Estrada, 2011; UN-REDD, 2018). The associated lack in knowledge is also mirrored in the representation of these regions in global earth system models. Processes and parameters in these models that address nutrient cycling between plants, soils and the atmosphere are mostly derived from temperate regions (Bastos et al., 2020; Thatrammal et al., 2019; Ciais et al., 2014). Data from tropical regions are much rarer and originate mostly from the Amazon basin (Schimel et al., 2014). However, other tropical and temperate ecosystems fundamentally differ in nutrient cycling as well as plant species composition and their ecological strategies and the dominating or limiting factors for plant growth compared to the African Tropics (Foster and Bhatti, 2006). For example, atmospheric nitrogen deposition is much higher in sub-saharan Africa than in other tropical regions due to large amounts of recurring biomass burning originating from savanna and dry forests north and south of the Wet Tropics (Bauters et al., 2018, 2021). Furthermore, in contrast to comparably young soils of the temperate zone, long lasting chemical weathering has led to the depletion of mineral nutrients from soils in tropical systems. Thus, to avoid leaching and loss of nutrients, natural tropical ecosystems evolved to be much more effective in recycling crucial nutrients between vegetation and litter (Vitousek and Sanford, 1986). It is yet to be explored whether parent material geochemistry also leaves a lasting mark on the mineralogy of old, deeply weathered tropical soils where the weathering front is often situated much deeper underground and largely decoupled from processes in the near surface biosphere.

2 Sections

2.1 This Special Issue: The human impact on tropical biogeochemical cycles in soils of tropical Africa

In order to holistically represent the consequences of human disturbance on biogeochemical cycles and the flux of nutrients between plant, soil and atmosphere in Africa's changing Tropics, it is necessary to consider the effects of climate, geology, soil formation, microbial biochemistry, vegetation and human activity combined across a variety of plant-soil systems at the landscape scale. The central objective of this special issue is therefore to give an overview of research currently conducted on biogeochemical cycles and soil dynamics in Tropical Africa with special emphasis on the crucial but yet understudied landscapes of the Congo Basin and neighboring regions which are facing rapid environmental changes. Much of the research presented here is conducted within the framework of the new research network Congo Biogeochemistry Observatory (CBO) (https://www.congo-biogeochem.com, last access: 26 October 2021). CBO is a consortium of researchers who study biogeochemical cycles and atmosphere-plant-soil interactions in tropical Africa with a focus on the Congo Basin and the African Great Lakes region. Within CBO's framework, a multinational group of

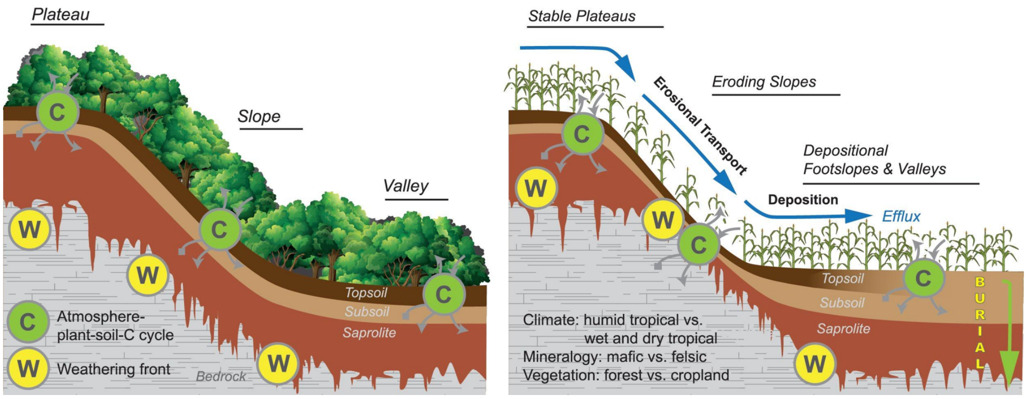

Figure 1. Conceptual depiction of the expected changes to biogeochemical cycles and weathering when vegetation on sloping land is transformed from forest into cropland, soil becomes mobilized and transported downhills and buried in colluvial and alluvial environments.

scientists from Africa, Europe and the United States conducts cross-disciplinary environmental research in one of the least studied regions of the globe. Founded in 2018 by scientists of several African and European institutions, CBO has since been creating synergies between local key institutions and international researchers, for studying biogeochemistry in soils and sediments in remote and difficult to access environments.

2.2 Scientific advances presented in the Special Issue

The special issue is structured in 4 foci points of research, covered by 11 papers:

Focus (i). Improve our mechanistic understanding of carbon stabilization and microbial responses to changing soil properties and its effect on biogeochemical cycles in the African Tropics (Bukombe et al., 2021; Kirsten et al., 2021; Reichenbach et al., 2021).

Working with forest and cropland topsoils sampled across East Usambara Mountains of Tanzania, Kirsten et al. (2021) show that aggregation in the Wet Tropics is modulated by soil mineralogical regime, causing moderate but significant differences in aggregate size distribution. However, the study also shows that aggregation has little effect on the overall persistence of organic carbon in soil, which is more regulated by direct mineral-organic interactions. Similarly, studies conducted within the framework of project TropSOC (Tropical Soil Organic Carbon dynamics, 2017–2021; Doetterl et al., 2021) provide insights into the importance of geochemistry and erosion for soil functioning in the intensely used highlands of the Albertine Rift. Specifically, the studies of Reichenbach et al. (2021) and Bukombe et al. (2021) shed light on the role of geochemistry and geomorphology for soil organic matter stabilization mechanism and patterns of SOC stocks in tropical rainforests (Reichenbach et al., 2021), and its role on heterotrophic soil respiration (Bukombe et al., 2021). Reichenbach et al. (2021) show that, despite long-lasting weathering, geochemical properties of soil parent material leave a footprint in tropical soils that affects SOC stocks and mineral related C stabilization mechanisms. Bukombe et al. (2021) show that heterotrophic soil respiration showed distinct patterns with soil depth and parent material geochemistry, depending on soil fertility conditions and the presence or absence of mineral related C stabilization mechanisms.

Focus (ii). Investigate how nutrient and greenhouse gas fluxes between tropical soils, plants and the atmosphere evolve and differ in relation to the controlling factors geochemistry, topography and land use (Baumgartner et al., 2021; Tamale et al., 2021).

The study of Baumgartner et al. (2021) focuses on differences in N-cycling as a function of forest type (tropical lowland forest, tropical montane forest, and subtropical Miombo woodland) and of local topography (slope). Soil $\delta^{15}N$ profiles indicated relatively closed cycles dominated by organic N turnover in montane forest, while other forest types showed a more open N cycle dominated by inorganic N. The effect of slope on soil $\delta^{15}N$ was limited to the more erosion-prone Miombo woodland.

In a nutrient manipulation study (N and P fertilization) carried out in a pristine tropical forest in Uganda, Tamale et al. (2021) highlight the complexities of tropical ecosystems' greenhouse gas fluxes and their responses to fertilizer application and nutrient availability. They observed an immediate but transitory increase in N_2O fluxes following N and N+P application, associated with excess soil N to allow nitrification and/or denitrification. Application of N+P also caused immediate increases in CO_2 fluxes. However, in both scenarios, there were no effects on background N_2O and CO_2 fluxes. Interestingly, P application did not influence transitory or background N_2O and CO_2 fluxes, but likely enhanced methanotrophic activity leading to the consumption of CH_4.

Focus (iii). Investigate how the geochemistry of soils and topography interact with or mediate the severity of erosional disturbance on C cycling in tropical soils (Stenfert Kroese et al., 2021; Wilken et al., 2021).

The study of Stenfert Kroese et al. (2021) assesses the effect of land use in Kenya on concentrations of particulate nutrients (CNP) in suspended sediments at the outlets from catchments covered with natural forest as well as under agricultural use. Their data clearly shows that sediment loads as well as nutrient and organic matter export were significantly higher in agricultural catchments, implying that soil fertility is progressively lost under the current low fertilization rates and soil management strategies in the region.

The study of Wilken et al. (2021) contributed to our understanding of soil degradation patterns in the region, using radioisotope $^{239+240}$Pu inventories for studying soil erosion processes in tropical forests and cropland. Results revealed that pristine forests show no indication for soil redistribution along topographic gradients. In contrast, soil erosion and sedimentation in the region's cropland reached up to 40 cm soil loss within the last 55 years, showing high intra-slope variability with locations showing severe soil erosion located in direct proximity to sites of sedimentation.

Focus (iv). Improve our spatial representation and coverage of soil data and its controls at larger scales across the Congo basin (Baumann et al., 2021; Summerauer et al., 2021; Winowiecki et al., 2020; von Fromm et al., 2021).

To enable timely and cost-efficient assessments of soil properties in yam (*Dioscorea* spp.) fields, Baumann et al. (2021) use soil samples from fields cropped to yam in West Africa to develop and test a mid-infrared (mid-IR) soil spectral library. Yam fields have been chosen since the monetary value of the West African yam production exceeds that of the value of cassava, maize, sorghum and a few other crops together in the region, yet soil research targeting improved recommendations for yam production has been scarce. Thus developing libraries allowing rapid and low-cost assessments of soil properties would (1) enable farmers to select best suited sites and (2) researchers to develop fertilizer and crop management decision support tools to improve yam cropping and livelihood systems.

In the study of Winowiecki et al. (2020) the Land Degradation Surveillance Framework (LDSF), developed by CGIAR as a response to a lack of methods for systematic landscape-level assessment of soil and ecosystem health (Vågen et al., 2015), was implemented to assess key soil and land health indicators across two districts of eastern Rwanda with variable land use and highly variable environmental preconditions. The results of the study demonstrate the importance of systematically monitoring multiple indicators at variable spatial scales to accurately assess drivers of degradation and their impact on soil organic carbon dynamics.

The study of von Fromm et al. (2021) uses a unique and comprehensive soil dataset from across sub-Saharan Africa to identify the main factors that constrain variability in soil organic carbon (SOC) content. The dataset envelopes large gradients in both climatic, land-use and soil variables. The authors conclude that geochemical properties – mainly oxalate-extractable pedogenic (Al and Fe) oxides and exchangeable calcium are as important as climatic variables to predict patterns of SOC storage across larger scales.

Finally, the study of Summerauer et al. (2021) reports the creation of a newly developed soil spectral library for central Africa (CSSL). The new library is the first of its kind to provide spectral reference data on soil organic carbon and nitrogen across large areas of the Congo basin's tropical forests at low costs and high sample throughput efficiency. CSSL is now one of the largest and most comprehensive soil depth and spatial explicit datasets for tropical central Africa with the potential to be extended spatially and to represent other crucial elements and indicators of soil fertility in the future.

3 Conclusion

The studies presented in this special issue highlight that considering feedbacks between geochemistry, land use and topography can significantly improve our insights into the role of tropical soils for reaching several key sustainable development goals such as climate mitigation and zero hunger as well as understanding and predicting C transport, stabilization and turnover in tropical forest soils and sediments.

Presented results show that even in deeply weathered tropical soils, parent material has a long-lasting effect on soil chemistry that can influence and control microbial activity, the size of subsoil C stocks, and the turnover of C in soil. At the same time, tropical soils and the cycling of nutrients between plants, soil and the atmosphere show a wide range of reaction to degradation or amelioration efforts, often distinctly different from temperate zones. Discrepancies in C cycling trajectories between controls on C stabilization and release can also not be inferred from other geochemical regions within the same climate zones and must be considered carefully when generalizing or modeling organic matter turnover in the Tropics.

Given the investigated rates of land use change in tropical landscapes and degradation of African cropland, presented work confirms the threat of a sharp decline in soil fertility with little potential of soils to recover from nutrient losses naturally on decadal or even centennial timescales. Raising awareness for the need to protect Africa's soil resources, reducing the losses of soil organic matter and the peculiarities of tropical soils will be key to sustain fertile soils in tropical Africa in the 21st century.

Acknowledgements. Special thanks goes to all researchers contributing to the special issue for their valuable additions to the knowledge base on soil biogeochemistry of tropical Africa.

Financial support. Financial support was given by Augsburg University, ETH Zurich and Ghent University. Additional financial support was given be the German Research Foundation (DFG) through project "TropSOC" (no. 387472333).

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