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Low but highly variable soil organic carbon stocks across deeply weathered eroding and depositional tropical landforms

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ABSTRACT

Soil organic carbon (SOC) dynamics in temperate regions are highly affected by lateral soil fluxes induced by soil erosion. SOC dynamics in eroding tropical cropland systems characterized by deeply weathered soils and heterogeneous small-scale subsistence farming structures, however, are not well understood yet. Along topographic gradients in the East African Albertine rift region, we investigated the differences in SOC stocks and persistence for the upper meter of tropical soils developed from geochemically distinct parent materials and cultivated by subsistence farmers. We show that SOC stocks and persistence do not follow topography-driven patterns expected from research on less weathered, more fertile soils of temperate climate zones and more large-scale farming systems. At all investigated topographic positions, the SOC stocks were low compared to temperate regions while variability of stocks was high in both top- and subsoil. Full profile (0 – 100 cm) SOC stocks ranged from 256.1 t C ha^{-1} to 297.3 t C ha^{-1} at plateaus, from 224.4 t C ha^{-1} to 276.1 t C ha^{-1} at slopes and from 305.1 t C ha^{-1} to 366.0 t C ha^{-1} at footslopes. Independent of soil parent material and unless situated on very steep slopes (>15 % slope steepness), SOC stocks in eroding positions are, therefore, similar to those in non-eroding landscape positions and stable at a low level despite heavy erosion. Our results further suggest that deposition of eroded topsoil material at footslopes only slightly increases SOC stocks. Therefore, SOC stocks in this rapidly eroding tropical systems seem not to be heavily altered by soil redistribution while other soil parameters indicate heavy signs of soil disturbance. Tropical soil features and the distinctiveness of small scale subsistence farming practices create an extremely patchy and variable distribution of SOC, which requires us to rethink the way these landscapes can be modelled to represent C dynamics.

1. Introduction

Soil erosion, especially on arable land, represents a disturbance to the soil system that can have a substantial impact on biogeochemical cycles (Doetterl et al., 2016; Quinton et al., 2010; Van Oost et al., 2007; Wang et al., 2017). Specifically, lateral soil fluxes result in the horizontal and vertical redistribution of SOC in different quantities and qualities across the landscape (Berhe et al., 2007; Gregorich et al., 1998; Van Oost et al., 2005). In arable land, at eroding landscape positions, topsoil is removed, and SOC-depleted subsoil is incorporated into topsoil via tillage operations. This leads to overall SOC-depleted new topsoils where reactive minerals are getting into contact with fresh plant carbon (C) inputs through litter and roots. In consequence a process is initiated which is generally described as dynamic C replacement of C lost due to prior soil erosion and C decomposition (Dialynas et al., 2016a, 2016b; Harden et al., 1999; Stallard, 1998). At the same time, fresh C input can provide a readily available energy source for microbes that can speed up decomposition of older and formerly stabilized SOC, a process generally understood as C priming (Blagodatskaya and Kuzyakov, 2008; Chen et al., 2019; Fontaine et al., 2004, 2003), which will change the SOC compositions in these soils. Whether soil erosion creates local C sinks or sources depends on the interactions between processes of SOC priming (Blagodatskaya and Kuzyakov, 2008; Chen et al., 2019), dynamic replacement (Doetterl et al., 2016; Harden et al., 1999; Nadeu et al.,

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2012) and C conservation through soil burial. These processes have been described in detail but with a strong bias towards temperate systems (Van Oost et al., 2012; Van Oost and Six, 2023). However, process interactions and rates at which they operate are likely different in tropical soils due to their pronounced differences in chemico-physical soil features (Bukombe et al., 2022, 2021; Doetterl et al., 2025; Kidinda et al., 2023, 2022; Reichenbach et al., 2023, 2021).

In most mineral soils, the dominant long-term C stabilization mechanism is the sorption of functional C groups to mineral surfaces (Hemingway et al., 2019; Kleber et al., 2021; Possinger et al., 2020) reducing C turnover, respective enhancing C persistence in soil (Heckman et al., 2022; Schrumpf et al., 2021). Together with environmental factors that control microbial C decomposition (Basile-Doelsch et al., 2020), the mineralogical properties of the soil parent material and its weathering stage are the main factors for governing long-term C stabilization (Roering et al., 2023; Slessarev et al., 2022). Many tropical regions have undergone long lasting chemical weathering for millions of years resulting in decameter thick and deeply weathered saprolite layers (Porder et al., 2005) reducing the capacity of C sequestration by reactive minerals. Relatively thin (8 – 25 cm) fertile topsoil layers often overlay extremely thick (up to > 50 m meters) (Zauyah et al., 2010) nutrient-depleted and deeply weathered subsoil or saprolite layers. Thus, in how far dynamic replacement of C on hillslopes and accumulation in valleys can actually occur in tropical soil landscapes remains unclear as fertile topsoils are easily eroded and excavated subsoils show limited mineral reactivity. However, this is a question of the local biogeochemical and hydrological conditions.

Soil redistribution by water erosion in the Tropics differs greatly from temperate cropland systems for several reasons: (i) regular heavy tropical rainfall events result in a high frequency and severity of erosive events (Panagos et al., 2017), (ii) due to increasing pressure on land resources (Hansen et al., 2013; Karamage et al., 2016a), even very steep slopes are clear cut (Karamage et al., 2016a; Kroese et al., 2020; Tyukavina et al., 2018) for arable cultivation by smallholder farmers, (iii) subsistence farming without or minimal mineral fertilizer application is often not leaving substantial amounts of plant residues after harvest (Castellanos-Navarrete et al., 2015; Kim et al., 2021; Valbuena et al., 2015). Apart from the high water erosion potential, tillage erosion also plays a crucial role, especially on very steep slopes, which is surprising as farmers are ploughing commonly using hand held tools only (Fatumah et al., 2020; Nyakudya and Stroosnijder, 2015). This results in similar tillage erosion potential as compared to mechanized agriculture in temperate zones (Öttl et al., 2024; Zhao et al., 2024), where tillage erosion rates are often found to be similar or even higher than water erosion rates (Van Oost et al., 2006; Wilken et al., 2020).

Beside limited knowledge regarding water and tillage erosion rates in tropical subsistence farming systems, our biogeochemical understanding of accelerated agricultural soil erosion and deposition processes is strongly biased towards large-scale mechanized cropping systems in fertile soil settings that have been successfully cultivated for centuries (Borrelli et al., 2021; Öttl et al., 2024; Schimel et al., 2015; Van Oost and Six, 2023). Despite the fact that large-scale mechanized farming exists also in tropical settings (Giller et al., 2021), smallholder farming still dominates many tropical regions in which farming is conducted on deeply weathered soils. This is in particular the case for tropical sub-Saharan Africa (Lowder et al., 2016), where large parts of the population (52 %) (Lowder et al., 2016) conduct subsistence agriculture on smallholder farms and produce about 30 % (farm size < 2 ha) to 77 % (farm size ≤ 50 ha) of local food commodities (Giller et al., 2021). Such smallholder farming structures often result in small field sizes and a high degree of land use patchiness. These features can potentially impact lateral soil fluxes by creating a complex hydro-sedimentological connectivity between fields (Baartman et al., 2020; Nunes et al., 2018) and breaking the flow of water from hillslopes into valleys, substantially affecting the resulting transport mechanisms and patterns of soil redistribution after erosive rainfall events (Wilken et al., 2021).

Additionally, a large amount of eroded soil material is deposited in alluvial and colluvial settings in footslope and valley positions (Wang et al., 2015). Eventually, long-term gains from additional C sequestered through replacement of eroded C may be created by conservation of this deposited SOC in valley sediments resulting in a net C sink on decadal timescales (Van Oost et al., 2007). The effectiveness of this depositional valley soil C sink can be assessed by analysing patterns of SOC stock (more effective C sink results in higher SOC stocks) and SOC persistence using radiocarbon analyses (a more effective C sink should results in more depleted soil $\Delta^{14}C$ – and thus decreasing the average C age – due to mineral C stabilization and unfavourable environmental conditions for C decomposition) (Grant et al., 2023, 2022; Shi et al., 2020; von Fromm et al., 2024). The replacement of eroded C and conversion of deposited C depend on (i) the type of deposited soil material (e.g. C rich or C depleted soil from hillslopes or the stability of organo-mineral complexes) (de Nijs and Cammeraat, 2020), (ii) the speed of soil burial (faster burial contributing to more conservation) (Fiener et al. 2015, Zhao et al., 2022) and (iii) the environmental conditions (water-saturation and oxygen limitations) that may reduce or promote microbial decomposition to conserve labile SOC (Davidson and Janssens, 2006; Feng et al., 2017; Li et al., 2017; Moyano et al., 2012). Since many tropical regions experience rapid land use change in upland regions, leading to uneven promotion of erosion across catchments (Wilken et al., 2021), depositional settings may therefore accumulate both C-enriched and practically unaltered former topsoil, as well as C-depleted subsoil. This has implications for assessing the future size and stability of buried SOC stocks.

In summary, to date, the impact of erosion-induced lateral soil fluxes on SOC stocks across tropical landscapes, characterized by smallholder farming structures on deeply weathered and rapidly eroding soil systems, has not been sufficiently studied, and the consequences for C cycling in sloping tropical land are unclear.

The main aim of our study is, therefore, to shed light on the importance of erosion-induced lateral fluxes on SOC stocks in smallholder farming systems of tropical Eastern Africa. In our study, we will account for the variability in topography-driven soil redistribution as well as differences in geochemical soil properties derived from parent material geology. Two hypotheses will be tested, which, if verified, would suggest that the effect of soil redistribution on the landscape scale C balance in tropical soil-agricultural systems is substantially less than in temperate soil-agricultural systems.

Specifically, we hypothesize that: (i) A loss of topsoil at eroding sites on steep slopes will only slightly affect the profile (0–1 m) SOC stocks at these sites compared to (non or less eroding) plateau sites. We rationalize this with the fact that deeply weathered tropical soils are generally low in SOC contents in both top- and subsoil due to a lack of efficient mineral-related C stabilization mechanisms and low mineral reactivity, and, at the same time, rapid mineralization of most C input from plant assimilates by microorganisms. Consequently, (ii) at depositional sites, the input of former (hillslope) topsoil via erosion generally does not lead to a strong accumulation of C-rich soil and limits the C sink function caused by soil burial. Moreover, the C content of buried former topsoil (now below the plough layer) drops quickly to a typical subsoil level of sites not affected by soil redistribution as low mineral C stabilization potential and the fast microbial C decomposition still apply while C inputs through plants are missing as soil gets buried further.

While the above hypotheses will be tested and evaluated predominantly by using and comparing bulk SOC data along slope gradients, ^{14}C and CN data will be used to corroborate the persistence and likely origin of C found at varying topographic positions and soil depths.

2. Materials and methods

2.1. Study sites

Location, climate and topography.

The study region is located along the Albertine Rift, a part of the East African Rift System in the border region between the Democratic Republic of the Congo (DRC), Rwanda and Uganda (Fig. 1; Table 1). Within this region, the study sites were chosen to represent soils developed from geochemically contrasting parent materials. At the same time, climate, topography, time since conversion from forest to arable land, as well as agricultural land management are as similar as possible for comparable starting conditions regarding lateral soil fluxes.

The study region is characterized by tropical humid climate (Köppen Af-Am) with monsoonal dynamics and is subdivided into four seasons (weak dry in December – February; strong rain in March – May; strong dry in June – August; and weak rain in September – November) each covering three months (Bukombe et al., 2022). There are only minor differences in mean annual temperature (MAT), precipitation (MAP), and evapotranspiration at the different study sites in DRC, Rwanda and Uganda with somewhat higher MAP values in DRC (Tabel 1).

The active tectonism within the study region produced a steep terrain with smaller plateaus and ridges, steep slopes (up to 60 %) and various valley shapes. Cropland can be found across all hillslope positions. To represent this variable topographic situation, the study sites were sorted into stable plateaus (low / non eroding positions with slopes < 5 %), slopes up to 50 % slope steepness (highly eroding at slope steepness > 15 %), and footslope positions (low-eroding / accumulating positions), representing a transition zone between slope and valley bottom with a drop in transport capacity (Fig. 2).

Agricultural history and management.

All study sites were converted from forest to cropland before 1985 (Reichenbach et al., 2023). Thus, potential differences in time since conversion were unlikely to impact our results, as all cropland sites should have had sufficient time for SOC stocks to equilibrate to the new land cover (Don et al., 2011; Guillaume et al., 2015) and soil redistribution dynamics. The investigated fields are situated on farms that are generally small (< 5 ha), representative of the majority of farmland in the region (> 90 % of total cropland area) (Lowder et al., 2016) where soil loss via erosion can reach values of up to 80 Mg ha^{-1} yr^{-1} (Wilken et al., 2021). The average field parcel size at the study sites is about 500 m^2 with crop rotations of cassava and maize as well as various legumes and vegetables with little to no fertilizer input (Mangaza et al., 2021; Ordway et al., 2017; Tyukavina et al., 2018). Fertilizer use is mostly restricted to manure and fallow application. Pest management is done by manual weeding and soil management by hand ploughs (Doetterl et al., 2021a). Multi cropping is generally dominating over monocultures (Munyakazi et al., 2022). The individual field parcels are highly dynamic in terms of sowing and harvest time, which can result in alternating areas of bare soil and full crop cover within the same field parcel (Wilken et al., 2021). This leads to a high intra-slope variability with many different field conditions and connectivity properties.

Table 1
Location and climate conditions within the test regions. Mean annual temperature (MAT), precipitation (MAP) and potential evapotranspiration (PET) taken from Fick & Hijmans (2017).

	Central Coordinates		Climate		
Study site	Latitude (°)	Longitude (°)	Mean MAT (°C)	Mean MAP (mm yr^{-1})	Mean PET (mm yr^{-1})
DRC	−2.49222	28.76861	18.2 ± 0.7	1606 ± 88	1303 ± 80
Uganda	0.65500	30.24833	18.9 ± 0.3	1465 ± 13	1371 ± 20
Rwanda	−2.37583	29.19972	18.2 ± 0.2	1499 ± 46	1296 ± 25

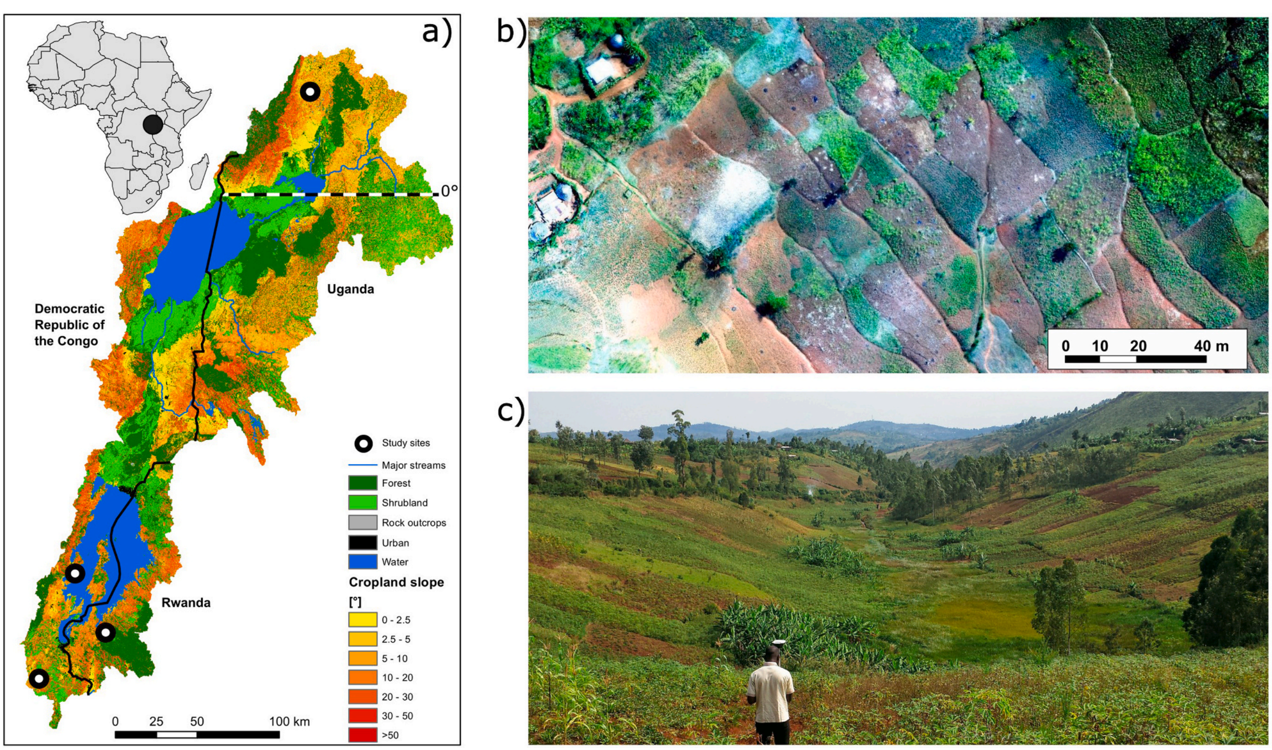

Fig. 1. (A) Overview regarding land use and slopes and the location of the test sites along the headwater catchments of the Nile and Congo (Kivu and Edward catchments), a part of the East African Rift System in the border region between the Democratic Republic of the Congo (DRC), Rwanda and Uganda. (B) and (C) showcasing the high degree of land use patchiness (roads, buildings, hedges, drainage channels, pathways, varying crop cover) on the example of two slopes in the Democratic Republic of the Congo.

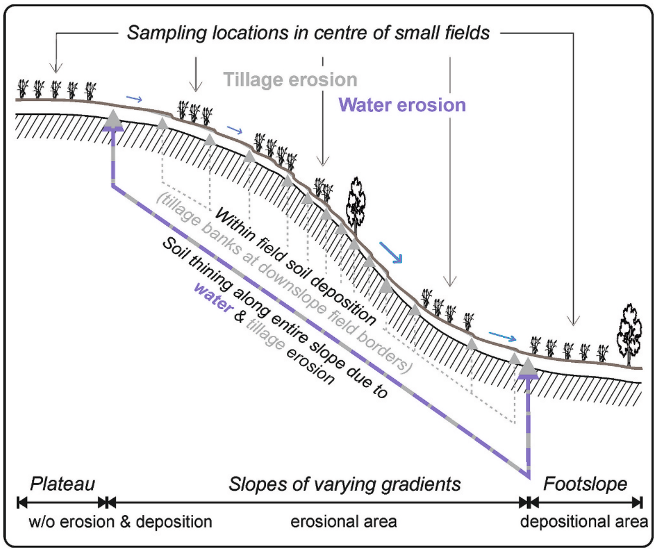

Fig. 2. Schematic figure of land use patchiness, slopes of different gradients and landscape positions, and soil sampling locations at the different study sites all under smallholder farming (field sizes < 5 ha).

During sampling, the study sites were characterized by cassava monoculture and cassava intercropped with beans and crop rotations of (soy-) bean, maize, onion, pea, and (sweet-) potato. Farmers generally aim for one or two seasons of cassava followed by one or two seasons with alternative crops or fallow, if soil fertility is limited. Some study sites in the DRC also show cassava-only rotations which can be a sign of extremely poor soil quality in terms of nutrient availability and Al-toxicity (Doetterl et al., 2021a). While on steep slopes predominantly cassava is planted, cassava intercropped with legumes is more often found at footslope positions (oral communication International Institute of Tropical Agriculture, IITA, 2018).

Soil types.

Soils at the study sites in DRC, Rwanda and Uganda were developed on mafic magmatic, mixed sedimentary, and felsic magmatic and metamorphic rocks, respectively. The soils at the study sites in DRC are classified as alic Nitisols (ochric), alic Nitisols (vetic), and mollic Nitisols (ochric), the soils in Uganda are classified as sederalic Nitisols (ochric), haplic Lixisols (nitic), and luvic Nitisols (endogleyic), while the soils in Rwanda are classified as haplic Acrisols (nitic), acric Ferralsols (vetic), and acric Ferralsols (gleyic) (Doetterl et al., 2021a). In Uganda re-fertilization of soils with rock-derived nutrients by pyroclastica occurs to various degrees at a local scale (Bailey et al., 2005; Barker and Nixon, 1989; Eby et al., 2009). Furthermore, a specific feature of soils at the study sites in Rwanda is the presence of fossil, geogenic organic carbon free of radiocarbon in the parent material (dark clay-silt schists) (Bukombe et al., 2021; Reichenbach et al., 2021).

Physicochemical soil properties.

Soils on plateaus (without erosion) across all study sites exhibit similar depth trends of all soil properties, and in all cases, the differences between topsoil and subsoil are minimal (Fig. 3). However, there is one exception, which is the subsoil C/N ratio in Rwanda. The C/N ratio increases with depth (ranging from 12.5 to 24.5) and exhibits higher variance due to the geogenic carbon influence of soil parent material there (Fig. 3B). This trend is the opposite for other study sites (ranging from 13.6 to 6.8) where C/N ratios decrease with depth. Similarly, SOC contents decrease with depth in all test regions (ranging from 44.8 t C ha^{-1} in the upper 10 cm to 12.9 t C ha^{-1} in 90–100 cm depths). Soils in Uganda have a higher content of pedogenic oxides (ranging from 2.4 wt % to 3.0 wt%) compared to soils from the DRC and Rwanda (ranging from 0.7 wt% to 1.9 wt%) (Fig. 3C). The clay content generally increases with depth in all test regions. Soils from the DRC exhibit the highest clay

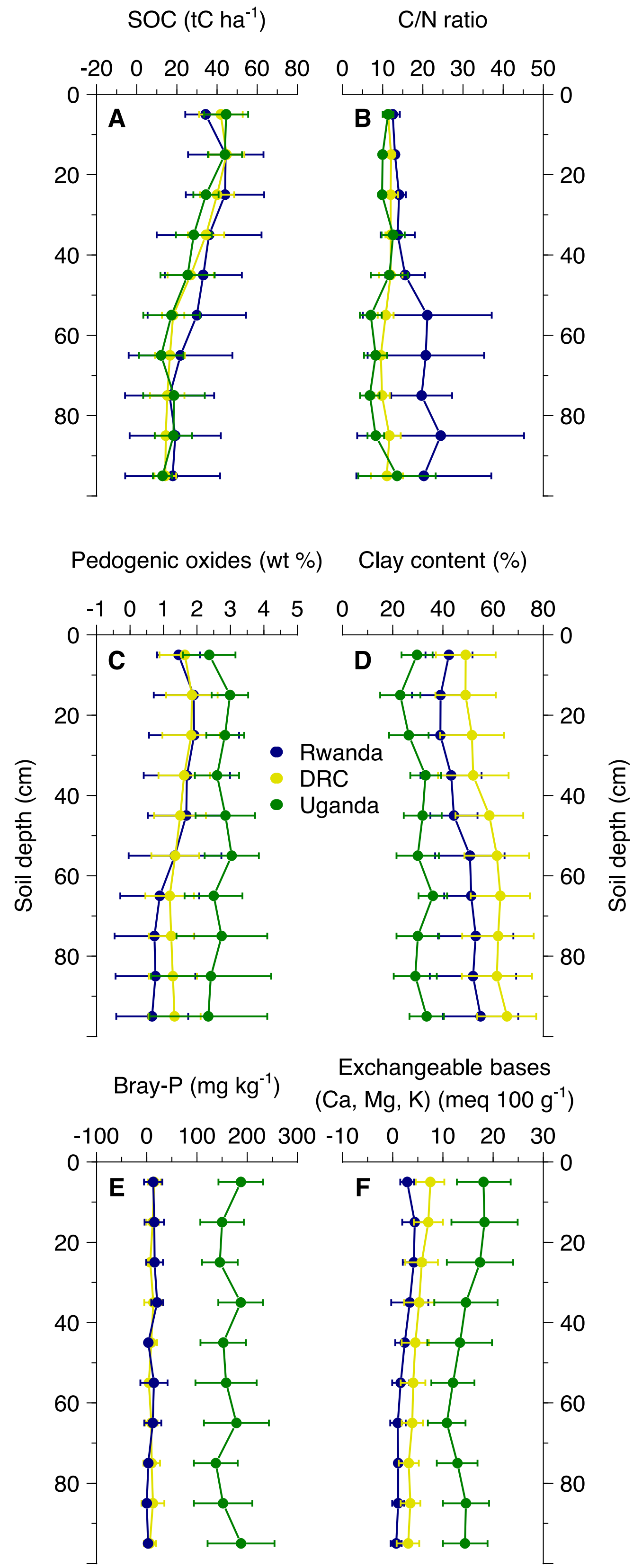

Fig. 3. Mean soil organic carbon stocks as well as important other properties at plateaus positions without erosion in the different test regions in Rwanda (n = 6), Uganda (n = 5) and DRC (n = 8). Error bars give 95 %-confidence intervals of the mean (data taken from S. Doetterl et al., 2021; Reichenbach et al., 2023).

content, ranging from 49.0 % to 65.5 %, followed by soils from Rwanda, ranging from 39.0 % to 53.1 %, and Uganda, ranging from 23.0 % to 36.0 % (Fig. 3D). There is no pronounced depth trend for bioavailable phosphorus (Bray-P) and exchangeable bases (Ca, Mg, K) (Fig. 3E & F). However, soils from Uganda show higher contents (Bray-P ranging from 187.6 mg kg^{-1} to 137.7 mg kg^{-1}, exchangeable bases (Ca, Mg, K) ranging from 10.8 meq 100 g^{-1} to 18.3 meq 100 g^{-1}) and variability in fertility proxies compared to soils from DRC (Bray-P ranging from 4.2 mg kg^{-1} to 15.1 mg kg^{-1}, exchangeable bases (Ca, Mg, K) ranging from 3.1 meq 100 g^{-1} to 7.5 meq 100 g^{-1}) and Rwanda (Bray-P ranging from 0.0 mg kg^{-1} to 20.8 mg kg^{-1}, exchangeable bases (Ca, Mg, K) ranging from 0.7 meq 100 g^{-1} to 4.4 meq 100 g^{-1}).

2.2. Soil sampling

Overall, 99 plots were analysed with a dimension of 3 m x 3 m within each study site representing individual fields cultivated with cassava at the time of sampling, (40, 25, and 34 sites in DRC, Uganda, and Rwanda, respectively). Plots were always located in the centre of the fields to avoid strong edge effects of tillage erosion, most pronounced at upslope and downslope field borders (Fig. 2). Within each plot, two soil cores were taken and combined into one depth-explicit composite sample. Cores were taken using percussion drilling and soil column sampling equipment, allowing for undisturbed sampling of 1 m deep soil cores at 9 cm diameter. Soil bulk density samples were taken with Kopecky cylinders of known volume (98.13 cm^3) or derived from the known volume and weight of the soils sampled by percussion drilling. Thus, we produced 99 composite soil cores (to 1 m soil depth) subdivided in 10 cm depth increments. As some drillings could not reach 1 m soil depth due to underlying rocks or bedrock, this resulted in 914 samples for analysis. Please refer to Doetterl et al. (2021a) for a more detailed description of the study and sampling design.

2.3. Soil analysis

The various methods of soil analysis are described in detail in the metadata of a published project-specific database of the project TropSOC (Doetterl et al., 2021b). Here we will summarize the most important information. Soil bulk density samples were oven-dried at 105 °C for 24 h and weighted subsequently. Note that rock content (> 2 mm) of all samples was negligible. Soil texture (clay, silt, sand) was analysed using the Bouyoucos hydrometer method (Bouyoucos, 1962) modified following Beretta et al. (2014). Soil fertility was assessed by analysing exchangeable base cations of calcium (Ca), magnesium (Mg) and potassium (K) on 2 mm sieved bulk soil by percolation with $BaCl_2$ at pH 8.1. The percolate was then analysed via flame photometry and atomic absorption spectrophotometry (Pauwels et al., 1992). Additionally, bioavailable phosphorus (bray-P) was analysed on 2 mm sieved bulk soil using the Bray 2 method following Okalebo et al. (2002).

Concentrations of pedogenic aluminium (Al), iron (Fe) and manganese (Mn) bearing mineral phases were assessed by a sequential extraction scheme of pedogenic oxy-hydroxides (Stucki et al., 1988) in the following order: First, extraction with sodium pyrophosphate at pH 10 following Bascomb (1968). Next, extraction with ammonium oxalate-oxalic acid at pH 3 following Dahlgren (1994). This way pyrophosphate extractable organo-metallic complexes (∑Al, Fe, Mn) and oxalate extractable oxides (∑Al, Fe, Mn) were extracted. Those two fractions were then summed up to represent pedogenic oxides relevant for mineral C stabilization (Kögel-Knabner et al., 2008; Wagai et al., 2013).

Total carbon (TC) and total nitrogen (TN) were analysed using dry combustion (Vario EL Cube CNS Elementar Analyzer, Germany) and C/N ratio used as a measure of soil organic matter (SOM) quality in terms of plant-derived and less decomposed organic matter (high C/N ratio) vs. microbio-derived and more decomposed organic matter (low C/N ratio) (Cleveland and Liptzin, 2007; Whalen et al., 2022). All C and N sources were considered of organic nature as inorganic C is absent in the investigated soils. Thus, SOC stocks of the bulk soil were calculated by multiplying the SOC concentration by soil bulk density and the thickness of the depth increment (10 cm). Bulk soil $\Delta^{14}C$ and fraction modern C (FmC) were analysed for selected depth increments on graphite prepared from purified CO_2 released on combustion (Steinhof et al., 2017) using AMS (accelerator mass spectrometry) at the Max Planck Institute for Biogeochemistry (Jena, Germany) and conventional radiocarbon age following the conventions of Stuiver and Polach (1977).

All values (n = 914) for the presented variables (except bulk density) have been analysed using a Bruker Vertex 70, (Hanau, Germany) near and mid-infrared (NIR-MIR) Fourier Transform FT-IR spectrometer. As part of the spectrometer calibration, 20 % of all samples (n = 183) were analysed with traditional wet-chemistry methods described above before predicting all samples following the workflow of Summerauer et al. (2021). NIR-MIR predictions resulted in high to very high performance in explaining the observed variability (R^2 = 0.69 to 0.93) for all assessed values.

2.4. Slope gradient and slope position as erosion and deposition proxies

To capture the effect of soil redistribution through erosion on slopes and soil accumulation through deposition at footslopes, we used a random sampling scheme for the plots along slopes (potential erosional areas) to account for differences in slope steepness. In contrast, plot locations at plateaus and footslopes (both with slopes < 5 %) were determined due to their landscape positions (Fig. 2), representing areas without erosion and deposition as well as areas representing deposition, respectively. Slopes were determined in the centre of each plot using a clinometer. We assume that slope gradient and slope position can act as a proxy for lateral soil fluxes since soil under low vegetation cover, on steep slopes and under high precipitation intensity and downslope tillage are most prone to erosion. We also conducted a series of pre-tests attempting to derive better predictors (e.g. topography indices like flow accumulation, topographic wetness index, elevation etc.) than slopes to explain the observed variability in soil properties at different landscape positions, but this resulted only in more complex statistics but limited informative value (see Appendix Table A1).

2.5. Data analysis

All data were visualized relative to the mean of the respective plateau positions to highlight the potential effects of slope gradient and topographic landscape position on SOC stock and geochemical soil properties. Therefore, we aggregated the data on the plot-level for topsoil (0 – 20 cm) and subsoil (20 – 100 cm). The SOC stock represents the total SOC content of the profile down to 1 m depth, while the mean was calculated for all other variables for the respective depth increments. To calculate the plateau references for all variables, we averaged all plateau plots for each test region and depth increment. The relative differences to the respective plateau depth increments were calculated by dividing each observation with the respective plateau reference mean and then further called “relative SOC stock” in varying contexts below. The same approach was taken for other physicochemical soil parameters such as clay content, exchangeable bases, etc. Before running parametric tests, data was tested for normality. Ordinary Least Square (OLS) regression and Pearson correlation analysis tested for relationships between SOC stock, soil fertility (Bray-P, exchangeable bases (Ca, Mg, K)) and stabilization mechanisms (clay content, pedogenic oxides). All statistical analyses were conducted at a significant level of $p < 0.05$ and realized using R 3.6.1 (R Core Team, 2020).

3. Results

3.1. Cumulative top-, subsoil and full-profile SOC stocks

At plateaus, cumulative SOC ranged from 88.5 to 78.7 tC ha^{-1} in topsoil (0 – 20 cm) and 218.6 to 167.6 tC ha^{-1} in subsoil (20 – 100 cm). At slopes, cumulative SOC ranged from 72.9 to 71.6 tC ha^{-1} in topsoil and 204.5 to 151.5 tC ha^{-1} in subsoil. At footslopes, cumulative SOC stocks ranged from 104.6 to 77.4 tC ha^{-1} in topsoil and from 288.1 to 216.3 tC ha^{-1} in subsoil. Full profile (0 – 100 cm) SOC stocks ranged from 256.1 to 297.3 tC ha^{-1} at plateaus, from 224.4 to 276.1 t C ha^{-1} at slopes and from 305.1 to 366.0 t C ha^{-1} at footslopes. Relative SOC stocks exhibited high variability across slope positions and study sites compared to undisturbed plateau positions at all aggregation levels (topsoil, subsoil, and full profile, Fig. 4). Due to this high variability, no significant differences ($p > 0.05$) were found in relative cumulative SOC stocks between study sites, slope gradients, footslopes, or plateau positions despite the trends described above. This pattern also applied to relative topsoil (0 20 cm) and subsoil (20 – 100 cm) SOC stocks, despite lower variability in topsoil compared to subsoil. Relative full-profile SOC stocks ranged from 0.3 to 2.0, with the highest values observed along slope gradients in Ugandan study sites and the lowest along slope gradients in the DRC. Variation was greater along slopes than at plateaus or footslopes, though footslopes generally exhibited higher values, albeit inconsistently. Relative to plateaus, topsoil SOC stocks ranged from 0.4 to 1.6, peaking at Ugandan footslopes and reaching their lowest values along slope gradients in Rwanda. Relative subsoil SOC stocks ranged from 0.3 to 2.4, with the highest values recorded along Ugandan slope gradients. Although slope gradient accounted for 7 % of the variance in relative full-profile SOC stocks, no significant relationships were identified between slope positions and SOC stock levels. Overall, slope gradients and footslopes displayed higher variability in relative SOC stocks compared to plateaus.

3.2. (Bio)geochemical topsoil properties

Key physicochemical properties in topsoil (as the layer most affected by soil redistribution along slopes) showed high variance with no clearly identifiable pattern that relates to topographic positions. Topsoil (0 – 20 cm) clay content ranged from 63.6 % to 26.3 % across slope positions. Pedogenic oxides ranged from 2.7 to 1.5 wt%, exchangeable bases (Ca, Mg, K) ranged from 18.2 to 3.7 meq 100 g^{-1}, bray-P ranged from 168.8 to 10.1 mg kg^{-1}, and C/N ratios ranged from 13.2 to 10.3, respectively.

Topsoil clay content along the slopes relative to the plateaus showed some variability, but only in the case of DRC exhibited a significant increase with slope gradient. At footslope, clay content in topsoil did not differ from plateaus (Fig. 5B). Only in the case of the Ugandan topsoils along the slopes, we found a significant decrease of pedogenic oxides relative to the plateaus (Fig. 5C). Analogously, the relative to plateau Bray-P content decreased with slope gradient for study sites in Uganda (Fig. 5D). Overall, the Bray-P and the exchangeable bases (Ca, Mg, K) contents exhibit the greatest variability relative to the means of the plateau positions (Fig. 5D, E) among all tested soil parameters. Relative C/N ratios showed little variability across all slope positions. In summary, driven by stronger correlations in some study sites (DRC for clay, Uganda for pedogenic oxides and bray-P), slope gradient explained overall 24 % of the variance in relative clay content, with increasing gradient correlating to higher relative clay in DRC sites. Relative pedogenic oxides and Bray-P content decreased with increasing slope gradient, explaining 45 % and 34 % of the variance, respectively.

3.3. Depth distribution of SOC content and soil $\Delta^{14}C$ across slope positions

Apart from Rwanda, where SOC content in the upper 10 cm do not show the highest values along the profile, there was a clear decrease of SOC content along all soil layers at the plateaus and along the different slope positions (Fig. 6A, C). The decrease of SOC with depths was also notable at footslopes in DRC and Uganda, with some higher values in Uganda in the soil layers between 70 and 90 cm (Fig. 6E). Interestingly, such a decrease in SOC stocks with deeper soil layers was not found in

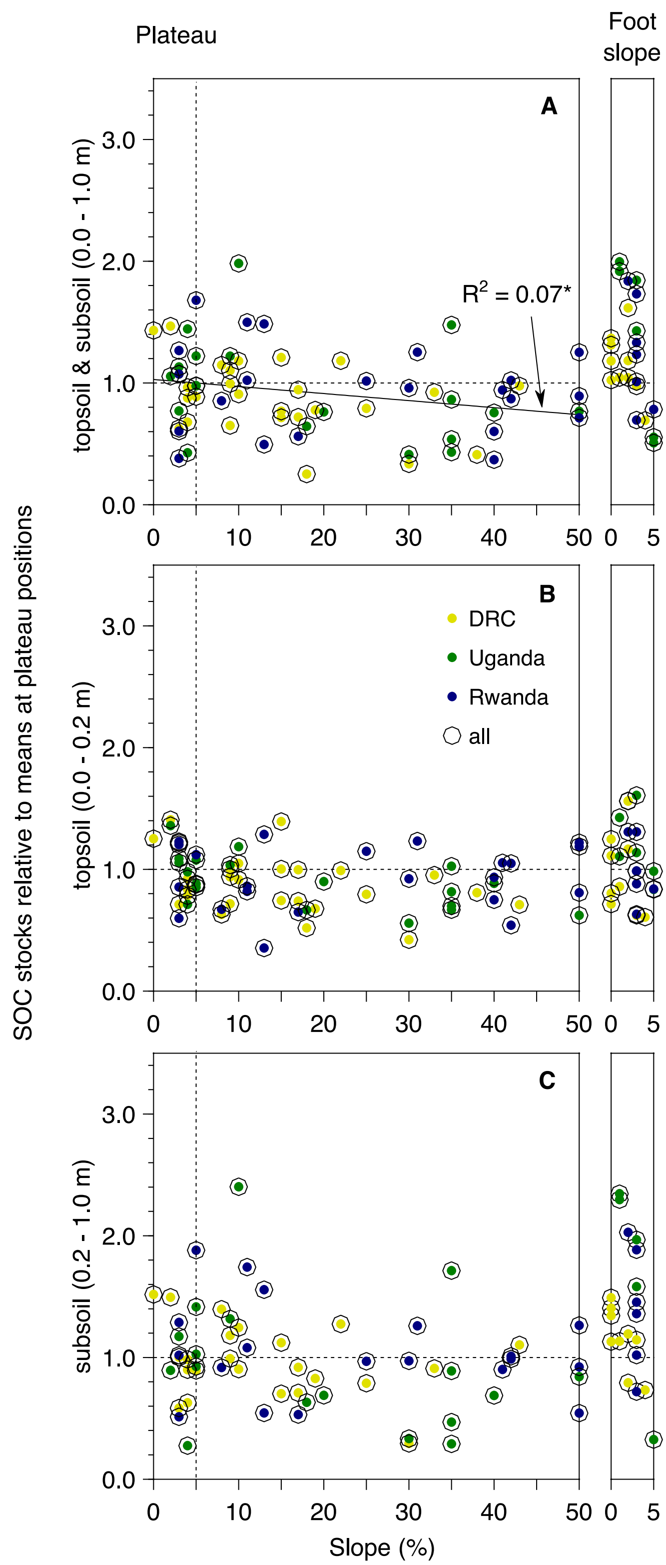

Fig. 4. SOC stocks relative to mean SOC stocks at undisturbed plateau positions are given for the entire profile (A), topsoil (B), and subsoil (C) at different landscape and slope positions. Note that the regression line given in (A) is based on all test sites (black circle symbols), excluding the footslopes affected via deposition (assuming that erosion is a continuous process from plateaus to slopes up to 50 %).

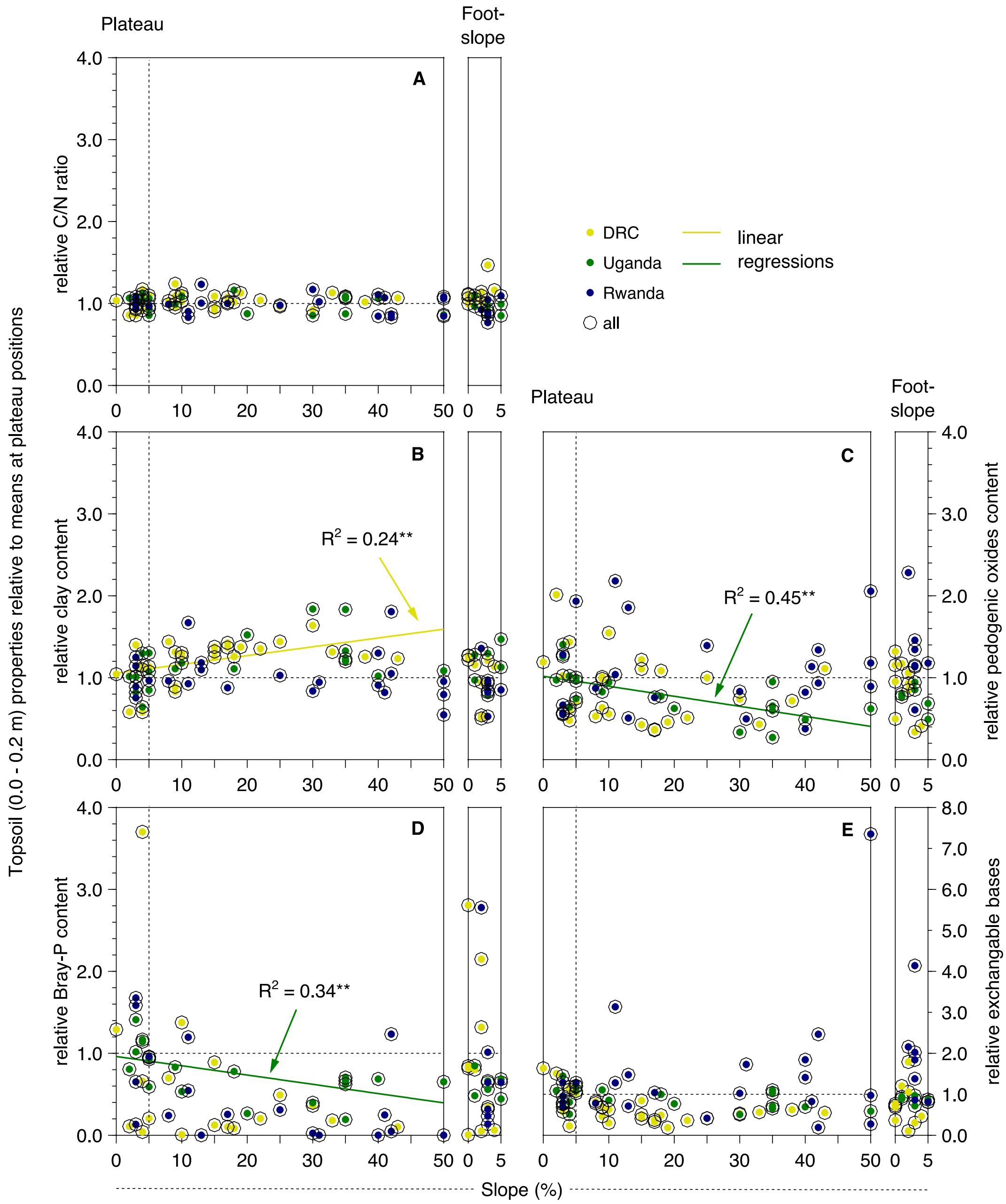

Fig. 5. Topsoil (0 – 0.2 m) properties at different slope positions and slope gradients. Regression lines are only given if Person R was significant ($p < 0.05$; whereas ** means $p < 0.01$); Note, in the case of the relative exchangeable bases, two outliers from Rwanda were above a ratio of four and hence are not displayed, so that all remaining data can be shown for an easier comparison of the rations with the same y-axis scaling.

Rwanda, which might be related to the stable fossil geogenic carbon (Fig. 6E). Overall, there were no significant differences between regions, but variability was higher at plateaus and footslopes.

For Rwandan study sites, soil $\Delta^{14}C$ data are limited to 40 cm depth due to fossil geogenic carbon in deeper layers (Fig. 6). In general, soil $\Delta^{14}C$ followed a strong depth trend at all topographic positions, with depleted $\Delta^{14}C$ signatures and less fraction modern C (FmC) at greater depth. At plateaus, $\Delta^{14}C$ ranged from 23.8 ‰ (103 % FmC) in topsoil (0 20 cm) to −399.0 ‰ (61 % FmC) in subsoil (20 – 100 cm); at slopes, from −81.5 ‰ (93 % FmC) to −339.0 ‰ (67 % FmC), and at footslopes, from to 42.4 ‰ (105 % FmC) to −244.8 ‰ (76 % FmC). Variability was greatest at plateaus and footslopes, with topsoil $\Delta^{14}C$ being less depleted in Uganda compared to DRC and Rwanda. Subsoil $\Delta^{14}C$ was less depleted in DRC than in Uganda, though this was inconsistent across slope positions.

4. Discussion

4.1. Topsoil loss and SOC stocks at eroding sites

We could verify our first hypothesis that under the tested site conditions only weak effects of soil erosion on SOC stocks (0.0 - 1.0 m) can be recognized (Fig. 4). We explain this observation with the fact that, in contrast to cropped soils derived from younger (peri) glacial parent material (~10 000 years old) (Finke and Hutson, 2008), the investigated soils have undergone intense chemical weathering (Porder et al., 2005) also depleting several meters deep subsoils from all primary minerals, leaving behind secondary end-member minerals of low reactivity (Bruun et al., 2010). Consequently, even on heavily eroded slopes, the excavation and surfacing of former deep soil layers do not lead to overcoming limitations in mineral C stabilization since degraded soils on

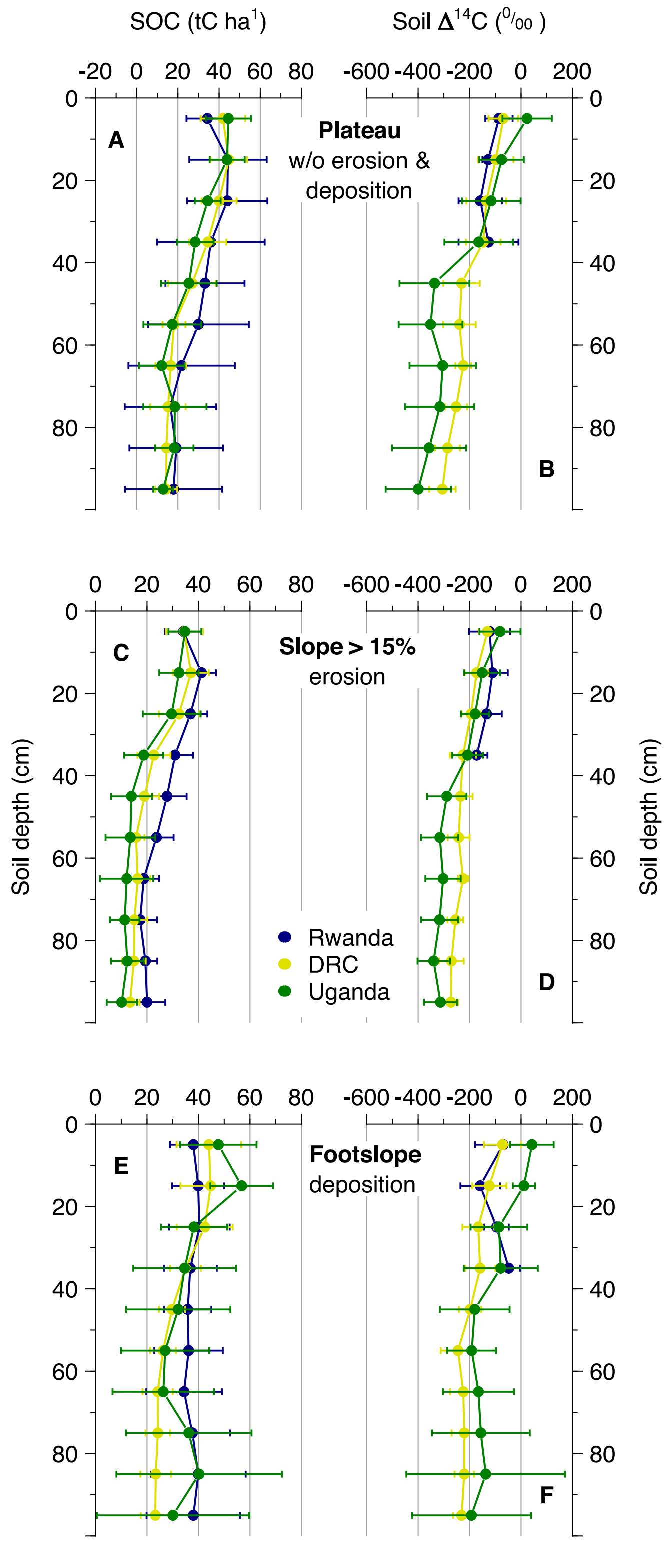

Fig. 6. Mean $\Delta^{14}C$ data for the three different sites in Rwanda, DRC, and Uganda calculated from the sites at the plateaus (no erosion or deposition), sites with slopes > 15 %, and the footslopes. Number of samples per site and depths between 5 and 13); Soil $\Delta^{14}C$ data for Rwanda are only given to a depth of 0.4 m as fossil geogenic carbon in deeper layers of some plateaus in Rwanda give misleading values. Error bars give 95 %-confidence intervals of the mean.

slopes get "stuck" in deeply weathered subsoils and less weathered layers close to the bedrock remain distant to the surface (Tanzito et al., 2020; Thomaz, 2013). This is illustrated by a subsidiary regression analysis where depth-specific correlations between SOC stocks and the assessed physicochemical soil properties do not change significantly (Fig. A1). The lack of change in controls for SOC content shows that mineral C stabilization mechanisms are not changing with soil depth or slope position. At erosional sites where there is a loss of topsoil, neither the soil properties governing C stabilization nor those governing soil fertility are changing significantly (Fig. 5). Therefore, truncation of the soil profile does not lead to a significantly different (bio)geochemical environment for SOC stabilization.

In consequence, if topsoils at eroding sites have only slightly reduced fertility, while C stabilization proxies and stocks do not show substantial differences, any input of photosynthetic products to these soils appears to be immediately processed by microorganisms with limited stabilization as SOC. Such an interpretation is supported by the generally low SOC content along the slope gradients (and relatively high fraction modern C in topsoil (Fig. 6). It is also supported by the slightly higher $\Delta^{14}C$ values (indicating "younger" SOC with faster turnover) at footslope positions than at plateau or slope positions as eroded material would get moved towards the valleys (Fig. 6). This, in combination with the relatively narrow C/N ratios in topsoils of the study region (DRC: 11.7 ± 1.4, Uganda: 10.7 ± 0.9, Rwanda: 12.8 ± 0.8, Fig. 5) suggests that, while SOC losses do occur at erosional sites, the generally rapid SOC turnover and low capacity to stabilize larger amounts of C inputs in deeply weathered soils limits the potential discrepancies that can occur for SOC stocks at eroding slopes in comparison to non or less eroding plateau (Fig. 4). This interpretation is consistent with larger-scale studies that report high SOC turnover rates combined with low SOC stocks in highly weathered tropical soils (von Fromm et al., 2024, 2021), as well as similar topsoil SOC content found at plateau sites in nearby forests (Reichenbach et al., 2023), which demonstrate that topsoil SOC stocks are hardly affected by significantly larger plant C inputs under forest compared to arable land. Thus, as long as the potential of soils to stabilize C remain unchanged due to erosion, only a small amount of C input to the topsoil at eroding sites is enough to keep topsoil SOC stocks similar to those found on non-eroding (plateau) positions. This also means that the dynamic replacement potential is small at these slope positions.

4.2. Accumulation of SOC stocks at depositional sites

We verify also our second hypothesis that depositing topsoil material at footslopes only marginally increases profile SOC stocks as material that is already relatively poor in SOC and shows low capacity to stabilize and protect C against microbial decomposition gets deposited. Although the highest SOC stocks in our study are often found at foot slopes, there appears to be no consistent pattern (Figs. 4, 6). It is likely that deposition in the vicinity of small fields is often influenced by human interventions, such as creating ditches to drain surface runoff (Labrière et al., 2015; Wilken et al., 2021). Therefore, it is highly variable and eroded soil material can be either translocated only for a few meters and deposited within the same field parcel or transported over longer distances across the entire slope eventually accumulating in more distal depositional sites (Fig. 2). Consequently, depositional footslopes can receive varying amounts of eroded soil material depending on the hydro-sedimentological connectivity across the agricultural landscape. Additionally, the difference between topsoil and subsoil SOC contents is not pronounced, so the deposited topsoil only slightly alters the SOC content along the soil profile. Finally, it could be argued that the SOC buried below the plough layer is not very stable under the soil and climate conditions in the humid Tropics (Hall et al., 2015; von Fromm et al., 2024) and that SOC turnover rates are also high in subsoils and quickly mineralize added SOC from deposition (Fig. 6). This finding is important and somewhat surprising with respect to soil burial in the temperate zone or in general for soil landscapes that are less weathered. There, at depositional sites such as footslopes, soil profiles with higher SOC stocks are frequently found with high SOC stocks also in deeper layers due to the deposition of SOC-rich topsoil (Fiener et al., 2015; Van Oost et al., 2007; Wang et al., 2015). For deeply weathered tropical soils, however, the same patterns seem not to occur due to the profound differences in C storage capacity and microbial C turnover (Figs. 4 and 6) with important consequences for assessing the overall C storage in these rapidly changing land use systems.

4.3. Assessing soil redistribution effects for the SOC balance of tropical landscapes

A large body of literature suggests (i) a significant effect of lateral soil fluxes in agricultural landscapes resulting in a topography-driven SOC stock pattern with eroding slopes (SOC losses) and depositional footslopes (SOC gains) (Dalzell et al., 2022; Dlugoß et al., 2010; Doetterl et al., 2016; Van Oost and Six, 2023; Xiao et al., 2018); and (ii) an interaction between lateral soil fluxes with geochemical soil properties leading to diverse mineral C stabilization processes across erosional and depositional sites (Chadwick and Asner, 2016; de Nijs and Cammeraat, 2020; Dialynas et al., 2016a, 2016b; Doetterl et al., 2016; Vitousek et al., 2003; Xiao et al., 2018; Zhao et al., 2019). In our study across a strongly undulating tropical landscape with steep slopes and deeply weathered soils, observed spatial and vertical distribution of cropland SOC stocks and C persistence (soil $\Delta^{14}C$) do not follow classical topography-driven patterns resulting from soil redistribution (Figs. 3 & 6) nor are they driven by diverse mineral-related C stabilization processes as widely observed in slowly eroding arable landscapes in temperate climate zones dominated by large-scale industrial farming systems (Fig. 5). Our results suggest these factors alone cannot reliably predict erosion and deposition patterns in subsistence farming systems on deeply weathered soils. Instead, our study highlights the complex interplay between topography, land use, and soil redistribution in steep, deeply weathered smallholder landscapes.

The high variability in SOC stock and soil redistribution indicators (such as $\Delta^{14}C$) underscores the need to incorporate fine-scale land use practices into erosion models, particularly in patchy, smallholder farming systems. This is particularly important since the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) and similar slope-based models often fail to capture the variability in soil redistribution driven by the mosaic of small-scale fields and dynamic land use (Kalyebi et al., 2021; Sisheber et al., 2023) but are at the same time often used as the basis for large-scale management advice to combat soil erosion. Given these complexities, future research should explore the following directions: (i) Incorporate factors such as tillage direction, crop rotation, and field size to improve model accuracy. For example, selective harvesting and down-slope tillage practices create spatial heterogeneity that influences soil movement (Turkelboom et al., 1999). (ii) Refine topographic proxies and introduce measures for infrastructure impacts (e.g., roads, terraces, hedgerows) on sediment pathways. For example, HAND values (height above nearest drainage channel) have been successfully used in agroforestry systems – which are often also characterized by intricate land use patterns – in the Amazon for modelling dynamics SOC and biodiversity (Chen et al., 2024; Schietti et al., 2014). (iii) Focus on interactions between micro-scale practices (Mangaza et al., 2021; Ordway et al., 2017; Tyukavina et al., 2018) and rainfall intensity to understand episodic soil redistribution events (Karamage et al., 2016a, 2016b; Panagos et al., 2017; Xiong et al., 2019).

5. Conclusion

This study challenges conventional assumptions about soil organic carbon (SOC) dynamics in cropland systems affected by soil redistribution. We identified profound differences between the soil carbon distribution of eroding, deeply weathered tropical landscapes compared to our established understanding of the effects of soil erosion on soil carbon stocks across eroding and depositional landforms. We found that erosion on steep slopes had a minimal impact on SOC stocks across the upper meter of soil, confirming that limited mineral reactivity in these soils can explain the absence of significant differences in SOC stabilization between eroding and stable sites and generally low SOC stocks. Similarly, we found that deposition at footslopes resulted in only modest SOC accumulation, reflecting the low stabilization potential of deposited material and rapid SOC turnover even in buried layers.

The broader takeaway from these findings is the unique behaviour of SOC dynamics in tropical smallholder landscapes. Unlike temperate regions with topography-driven SOC patterns, the highly variable and patchy nature of tropical subsistence farming complicates predictions of SOC redistribution. Dynamic C replacement may be fast, but it is not as efficient in tropical regions as in the temperate zone due to the limited potential of soil to stabilize SOC. Effective carbon management in these regions requires nuanced models incorporating fine-scale land use and biogeochemical variability. Ultimately, the observed persistence of low but variable SOC stocks highlights the urgent need for tailored conservation strategies to address the challenges of tropical soil erosion and carbon cycling.

6. Sample availability

All physically remaining soil samples are logged and barcoded at the Department of Environmental Science at ETH Zurich, Switzerland.

Author contributions

Sebastian Doetterl (SD) and Peter Fiener (PF) designed the research. Mario Reichenbach (MR) conducted the sampling campaign and collected the data. Daniel Muhindo (DH), Fernando Bamba (FB), and Florian Wilken (FW) were technical contributors and participated in data collection. SD, PF and MR analysed and interpreted the data and framed the writing process. Kristof Van Oost (KVO), FW, SD, PF, and MR all contributed to the writing of the paper.

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CRediT authorship contribution statement

Mario Reichenbach: Writing – original draft, Investigation, Formal analysis, Data curation. **Sebastian Doetterl:** Writing – review & editing, Supervision, Funding acquisition, Formal analysis, Conceptualization. **Kristof Van Oost:** Writing – review & editing. **Florian Wilken:** Writing – review & editing. **Daniel Muhindo:** Investigation. **Fernando Bamba:** Investigation. **Peter Fiener:** Writing – review & editing, Supervision, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2025.108971.

Data availability

The data that support the findings of this study are available in an open access project-specific database (Doetterl et al., 2021b) at doi:10.5880/fidgeo.2021.009.

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