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Fingerprinting sediment sources using fallout radionuclides demonstrates that subsoil provides the major source of sediment in sub-humid Ethiopia

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Abstract

Purpose To mitigate erosion, soil and water conservation measures have been introduced widely, with the ambition to reduce on-site erosion rates and catchment sediment yield. However, the success of such measures has been questioned, and often lacks a scientific basis. This is especially true in Ethiopia where gullying has been reported to worsen because of the implementation of soil and water conservation programmes targeting sheet and rill erosion from cropland only. The current research therefore focuses on identifying the sources of sediment based on the dominant erosion processes at play.

Methods This study was conducted in the Fota-Gumara catchment (211 km²), situated in the Lake Tana Basin. The investigation was based on the analysis of fallout radionuclides (^{137}Cs and ^{210}Pb-ex) tracers, which are able to discriminate between topsoil and subsoil. Target material consisted of sediment deposits collected during eight rainfall-runoff events, which occurred in the early and late rainy season of 2023. The activity of ^{137}Cs and ^{210}Pb was measured using gamma spectrometry, while the source apportionment was based on the implementation of Bayesian Models BMM and MixSIAR.

Results Our findings confirmed that subsoil was the major source of sediment. Both models showed consistent results, indicating that approximately three-quarters of the sediment originates from subsoils, contributing a median average of 73% and 81% according to MixSIAR and BMM, respectively. Both the inter-event and seasonal variability of sediment source contributions were relatively low.

Conclusions We conclude that gullies should be a land management priority. Additionally, we demonstrated the validity of using fallout radionuclides for tracing sediment sources in this region of tropical Africa.

Keywords Soil erosion · Gully · Sediment tracing · Fallout Radionuclides · Lake Tana Basin

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1 Introduction

Soil erosion is a major concern affecting soil health globally (Pimentel and Burgess 2013; Borrelli et al. 2021). In order to mitigate erosion, soil and water conservation measures have been introduced, with the aim to reduce on-site erosion rates and catchment sediment yield (Evrard et al. 2016; Rode et al. 2018; Jiang et al. 2020; Huang et al. 2022). Therefore, identifying the location and magnitude of erosion processes is crucial to design effective mitigation strategies (Collins et al. 2001, 2017; Gellis et al. 2019; Evrard et al. 2022; Frankl et al. 2022). In Ethiopia, studying erosion and sediment yield has predominantly focused on sheet and rill erosion, relying on erosion plot data (Ebabu et al. 2023) and soil erosion models (Aga et al. 2018; Lemma et al. 2019a, b; Belay et al. 2020). However, land degradation processes such as gullying, landslides or streambank erosion are often overlooked (Yibeltal et al. 2023). This is in sharp contrast to the observation by numerous studies that such processes play an important role in the loss of soil resources and in the contribution to sediment yield in Ethiopia (Laceby et al. 2015; Huang et al. 2022). For instance, Zegeye et al. (2018) reported that gullies contributed approximately 90% of the sediment in the small Debre Mewi catchment in the sub-humid Ethiopian highlands. Similarly, Yibeltal et al. (2023) reported that gullies were responsible for nearly 85% of the sediment contribution in Aba Gerima catchment in the upper Blue Nile Basin. Elevated sediment yield, which hampers the rural economy and raises environmental concerns (Donohue and Garcia Molinos 2009), has led to the rapid sedimentation of Lake Tana at a rate of 9800 Mg km^{-2} yr^{-1}, shortening its life expectancy (Lemma et al. 2020). The latter is a major concern for most lakes and reservoirs in Africa (Vanmaercke et al. 2014; Annys and Frankl 2024).

Sediment source fingerprinting is a methodology utilized to identify the provenance of sediment within a given catchment (Walling 2013; Collins et al. 2020; Evrard et al. 2022). Its specificity lies in the ability to quantify the relative contributions of different sediment source types (Evrard et al. 2022; Vale et al. 2022; Xu et al. 2022). Various tracers have been employed to differentiate between diverse sediment source types (Collins et al. 2020; Evrard et al. 2022). For example, geochemical tracers are commonly used to define which lithological units contribute to sediment mixtures (Akayezu et al. 2020), while fallout radionuclides are used to discern between sediment originating from topsoil erosion (sheet and rill erosion) and subsoil erosion (gullying and streambank) (Haddadchi et al. 2013; Evrard et al. 2016, 2020). Land cover types can also be targeted, using organic matter properties, compound-specific stable isotopes, or environmental DNA (Aliyanta and Sidauruk 2019; Evrard et al. 2019; Frankl et al. 2022). In order to enable the quantification of relative sediment source contributions, a tracer should satisfy two criteria: (1) it should be capable of uniquely identifying and discriminating between potential sediment source types, and (2) it must remain stable (i.e., conservative) during erosion transportation and deposition from source to sink (Collins et al. 2020).

Fallout radionuclides has been widely used as valuable tracers for identifying the origin of sediment in relation to erosion processes (Ben Slimane et al. 2013; Evrard et al. 2020; Foucher et al. 2021). This is because fallout radionuclide activity tends to be elevated in topsoil while being depleted in subsoil (Haddadchi et al. 2013). The most widely used fallout radionuclides for sediment source tracing are excess Lead-210 (^{210}Pb-ex), Caesium-137 (^{137}Cs) and Beryllium-7 (^{7}Be) radioisotopes (Evrard et al. 2020; Foucher et al. 2021). They have been widely employed in sediment fingerprinting research targeting catchments in the Northern hemisphere (Evrard et al. 2020). However, there have been very few studies in the tropics and the Southern hemisphere, specifically in Africa (Evrard et al. 2020). This is due to the concern that the concentration of ^{137}Cs would be too low in these areas as a result of its limited fallout (Evrard et al. 2020) and to the difficult access and the relatively high cost of laboratory analyses (Collins et al. 2017). Despite these concerns research has demonstrated that topsoil and subsoil may successfully be differentiated based on their ^{137}Cs concentrations in the Southern hemisphere (Rode et al. 2018).

Accordingly, the central question of the current research is to investigate whether the erosion of subsoils provides the major source of sediment in the Lake Tana Basin in Ethiopia, the latter representing an erosion hotspot in Africa. We conducted our investigation in a catchment, which in terms of physiography, land use and land degradation is representative for the wider environment, and explicitly considered seasonal variations when designing the study. In addition to its focus on addressing source contributions to sediment mixtures, we note that sediment source fingerprinting is still a relatively new approach in Ethiopia (e.g., Verheyen et al. 2014; Awoke et al. 2022a, b). To the best of our knowledge, fallout radionuclides have never been employed as tracers in this region. Therefore, we used tracers (^{137}Cs and ^{210}Pb-ex), which have been widely tested and which are capable of discerning topsoil from subsoil, to quantify the respective contribution of erosion processes to sediment. Indeed, sheet and rill erosion, as they only affect the soil surface, contribute topsoil to sediment mixtures. On the contrary, gullying and streambank causes deep incision into the soil, and will predominantly supply subsoil (Fig. 1).

2 Materials and methods

2.1 Study area

The study considers the Fota-Gumara catchment (211 km²; 11°36' – 11°39' N, 37°42' – 38°00' E; Fig. 2), located in the Lake Tana Basin, Ethiopia. Its elevation ranges from 2100 to 2700 m above sea level, encompassing two agro-ecological zones: midland and highland. The study area experiences a tropical monsoon climate characterized by distinct wet and dry seasons, with the main rainy season occurring from June to September. The annual average rainfall ranges from 1141 to 1515 mm, and the daily average air temperature ranges from 9.5 °C to 21.8 °C (Ayele et al. 2016). According to the Köppen-Geiger climate classification (Peel et al. 2007), the climate of the area is temperate (Cwb type), with dry winters and warm summers. Basalt is the predominant lithology, with some areas covered by volcanic ash (Poppe

Fig. 1 Photograph showing the expansion of gullying on grazing land (photo taken on 27 June 2023)

et al. 2013). The primary soil groups in the study area are Leptosols (36.5%), Luvisols (31%), Nitosols (15%) and Vertisols (5.8%) (ADSWE 2015). Due to high erosion rates, the Fota-Gumara catchment contributes a substantial amount of sediment to Lake Tana, raising significant concerns for land managers (Lemma et al. 2019a, b; Assaye et al. 2021). Of

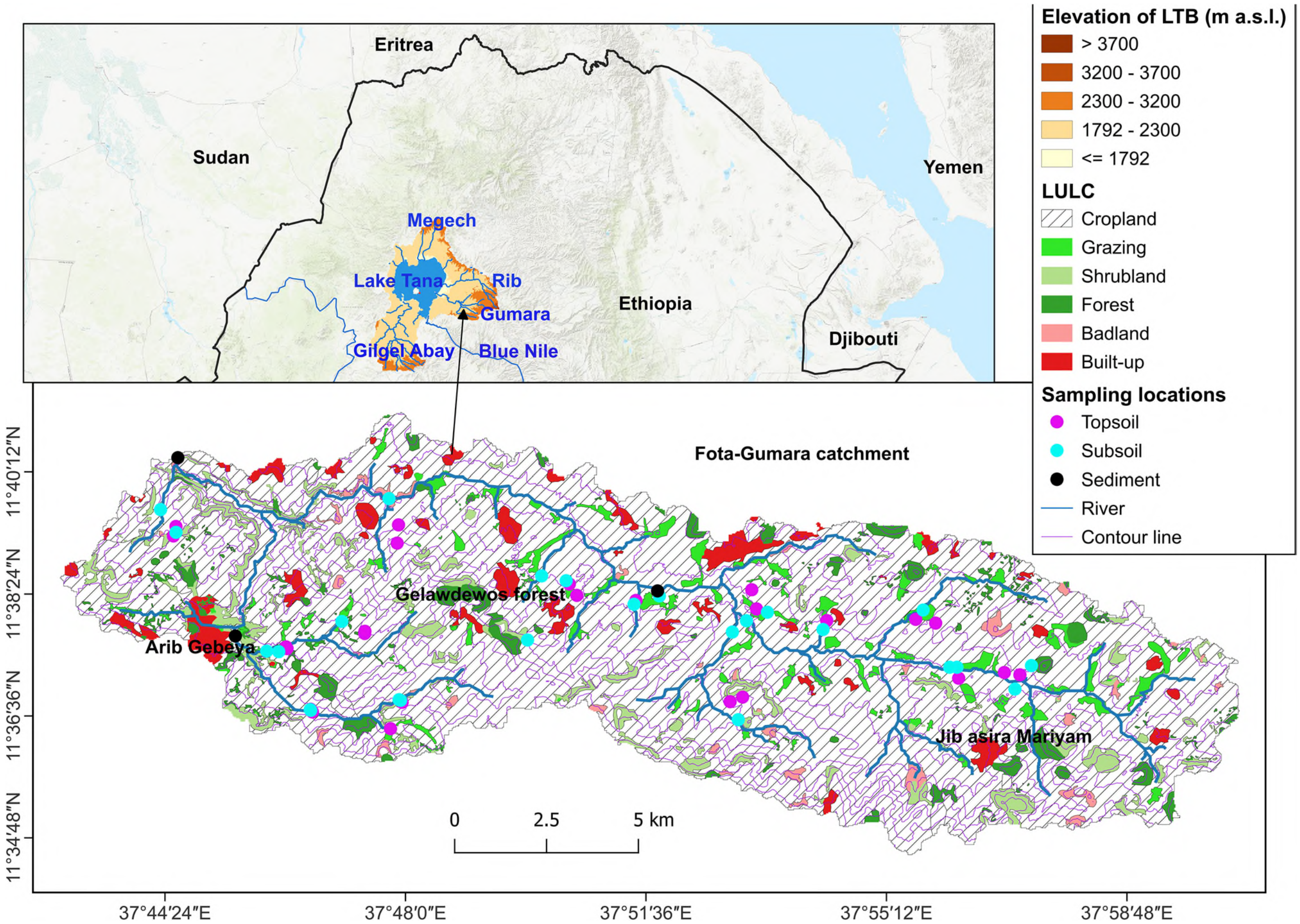


Fig. 2 Location of Fota-Gumara Catchment, its main land use types and the sampling locations (topsoil, subsoil and sediment)

particular concern is the loss of woody vegetation in valley floor areas, which has led to a sharp increase in gullying over recent decades (Frankl et al. 2019).

As shown in Fig. 2 and 80% of the study area is occupied by cropland, with the main crops being teff (*Eragrostis tef*), maize (*Zea mays*), barley (*Hordeum vulgare*), wheat (*Triticum aestivum*), finger millet (*Eleusine coracana L.)* and potato (*Solanum tuberosum*) (Assaye et al. 2021). The remaining land consists of shrubland or forest (13%), and comprising built-up areas and severely degraded zones known as "Badlands" (7%).

2.2 Soil and sediment sampling

Prior to this study, areas subjected to severe soil erosion were identified through field observations, participatory mapping and modelling (Abere et al. 2024). This approach allowed for targeting areas experiencing high erosion rates and showing efficient connectivity to drainage channels for sampling. A total of 30 topsoil samples (14 from cropland, eight from grazing land, five from forest and three from shrubland) and 25 subsoil samples (13 from gully walls and 12 from streambanks) were collected. Topsoil was obtained by taking the upper 2 cm of soil from non-cultivated fields and the upper 10 cm from cultivated fields, the latter taking account of soil homogenization due to tillage. Subsoil was collected from actively eroding gully walls and streambanks and represent the soil below the A-horizon. The soil samples were collected in June and July 2023.

Sediment samples were collected along river at the outlet of the catchment and at two major tributaries. These consider lag deposits, which were collected soon (i.e., within 1 day) after rainfall-runoff events (Laceby et al. 2015). To detect potential seasonal variations in sediment source contributions, samples were obtained both at the beginning and end of the rainy season, capturing shifts in crop phenology and hydro-sedimentological conditions (Lemma et al. 2020). A total of eight sediment samples were collected: five samples at the beginning of the rainy season (26, and 30 June 2023, 04, 06, and 18 July 2023) and three samples at the end (10, 20, and 26 September 2023). All samples correspond to composites, which are a mixture of five to ten sub-samples collected at nearby locations. This improves the representativeness of their properties while minimizing potential effects of local heterogeneity. The samples were collected using a trowel and were sealed in plastic bags. The centroid of the sampling locations serves for their localisation, recorded using a hand-held Global Navigation Satellite System (GNSS).

2.3 Radionuclide analyses

The samples were prepared for radionuclide analyses at the soil laboratory of Bahir Dar University in Ethiopia. They were air-dried and gently disaggregated using a mortar and pestle. Following the recommendations of Evrard et al. (2022), the samples were sieved to 63 µm to keep the fraction to which radionuclides are sorbed to (i.e., silt and clay). The results of this study are therefore directly relevant to understand the sources of suspended sediment. Samples of 20 g (of dry and sieved material) were prepared for radionuclide analysis and placed in airtight polyethylene containers. The activity of the radionuclides ^{137}Cs and ^{210}Pb were measured using gamma spectrometry with low-background N and P type GeHP detectors (Canberra/Ortec) at the Laboratoire des Sciences du Climat et de l'Environnement (Gif-sur-Yvette, France). Excess ^{210}Pb was calculated by subtracting the supported activity (determined using two ^{226}Ra daughters, ^{214}Pb (average count number at 295.2 and 351.9 keV) and ^{214}Bi (at 609.3 keV) from the total activity of ^{210}Pb. The results were expressed in Bq kg^{-1}. The measured activities were decay-corrected to the sampling date.

To determine whether fine-grained sources are the major contributors to sediment at the sampled locations, duplicate sediment samples of 25 g were collected and sieved using the wet sieving method. Fractions of sand, silt and clay could be determined using sieves of 63 µm and 2000 µm (Ma et al. 2024).

2.4 Tracer selection and sediment source apportionment

In order to improve the performance of the sediment fingerprinting modelling (Cox et al. 2023), a tracer selection method was applied, which is based on a two-step statistical technique to select conservative and discriminant tracers (Chalaux-Clergue et al. 2024). Initially, a standard range test was applied using the mean plus/minus the standard deviation ("mean ± SD") range test criteria to filter out non-conservative tracers. Then, the two-sample Kolmogorov-Smirnov test was used to select discriminant tracers that can differentiate between sediment derived from topsoil and from subsoil. An α-value of 0.05 was employed to determine the level of significance. We did not apply a discriminant function analysis, as we used a small number of tracers and its application remains a matter of discussion in scientific debates (Du et al. 2019). Smith et al. (2018) also stated that selecting tracers using the Kruskal-Wallis H-test and a discriminant function analysis approach is less accurate and uncertain. Furthermore, Sherriff et al. (2015) emphasize that uncertainty in source predictions can be mitigated by increasing the number of tracers.

The relative contribution of topsoil and subsoil to sediment mixtures were estimated using the following Bayesian mixing models: (1) MixSIAR (Stock et al. 2020; ver. 3.1.12) with JAGS (Stock et al. 2022; ver. 4.3.1), and (2) BMM (Batista et al. 2019) along with the fingR R-Package (Chalaux-Clergue and Bizeul 2024; ver. 2.1.0). The MixSIAR model is among the most widely used model for sediment source unmixing due to its flexibility (Davies et al. 2018; Du et al. 2019). The MixSIAR model is fitted with a Markov Chain Monte Carlo routine, allowing for a robust estimation of source contributions. The MixSIAR model was run with a very long run type (chain length = 1,000,000, burn-in = 500,000, thin = 500 and chain = 3) and process error structure (Stock and Semmens 2013, 2016). Similarly, the BMM model was run with 2500 iterations (Batista et al. 2022). The median values of the distribution predicted by both MixSIAR and BMM models were used as the source contributions to the target sediment (Chalaux-Clergue et al. 2024). All statistical analyses were conducted using R-software (R Core Team 2023).

The accuracy of the MixSIAR and BMM models was evaluated using virtual mixtures (Batista et al. 2022; Fathabadi and Jansen 2022; Chalaux-Clergue et al. 2024). For the two source types (topsoil and subsoil), 21 virtual mixtures were generated containing variable source proportions ranging from 0 to 100%, with 5% increments. All mixtures were generated using the fingR version 2.1.0 virtual mixture building function (Chalaux-Clergue and Bizeul 2024). The accuracy of the model predictions was evaluated using following metrics: (1) Continuous Ranked Probability Score (CRPS) for assessing both the accuracy and precision of mixing model predictions (Batista et al. 2022), (2) prediction interval width (W50) to measure model prediction uncertainty (Batista et al. 2022; Chalaux-Clergue et al. 2024), (3) Mean Error (ME) to understand over / under estimation, Root-Mean-Square Error (RMSE) to calculate prediction errors (Chai and Draxler 2014), (4) Pearson correlation coefficient (r^2), and (5) Nash–Sutcliffe Efficiency coefficient (NSE) to understand the performance of the models (Nash and Sutcliffe 1970; Barber et al. 2020; Duc and Sawada 2023).

3 Results

3.1 Grain size and fallout radionuclide properties

Fine texture classes (< 63 µm) dominated grain sizes for all sample types (Fig. 3), with little variability between groups.

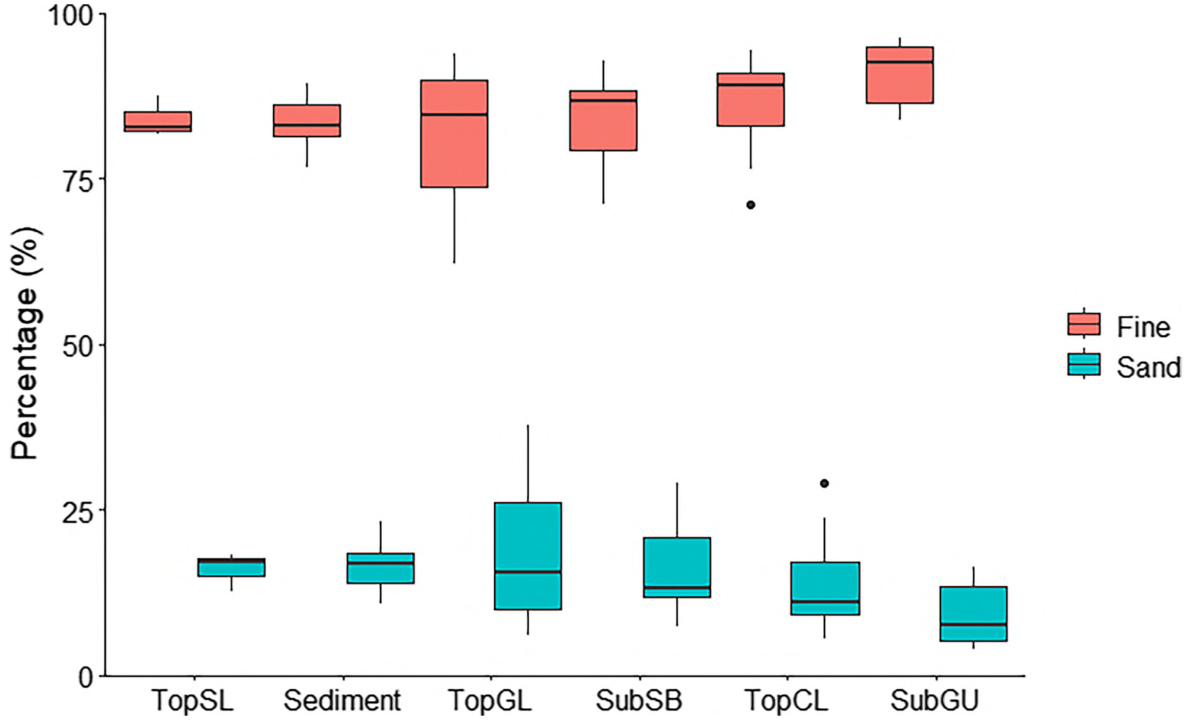


Fig. 3 Grain size proportions of the source soil and sediment samples; Fine textures refer to grain sizes below 63 µm, while sand refers to grain sizes between 63 µm and 2,000 µm. TopSL is topsoil from shrubland; TopGL is topsoil from grazing land; SubSB is subsoil from streambank, TopCL is topsoil from cropland, and SubGU is subsoil from gully

The sediment samples had an average clay and silt content of 83.6%, which falls within the full range of values represented in the boxplot of the source soil samples. The sand content of all the samples was below 35%, with an average of 15%.

The highest specific activity of ^{210}Pb-ex and ^{137}Cs was observed in topsoil from undisturbed forests, followed by topsoil from shrubland, grazing land and cropland. This may be attributed to an elevated organic carbon content and very low soil erosion rates in forest land (Cerdan et al. 2010; Gaspar et al. 2021). Accordingly, soil erosion from forest land was not considered as a potential sediment source in the current research. This is supported by a study conducted by Assaye et al. (2021), who found that the sediment yield from forests was 0.8 Mg ha^{-1} yr^{-1} in the Enkulal catchment, as small sub-catchment of our study area. In contrast, the lowest specific activity of ^{210}Pb-ex and ^{137}Cs was recorded from gullies and streambanks (Fig. 4).

3.2 Tracer selection

Based on the mean ± SD range test criterion, both ^{210}Pb-ex and ^{137}Cs could be considered as conservative tracers (Table 1). Additionally, the non-parametric two-sample Kolmogorov-Smirnov test verified that both ^{210}Pb-ex and ^{137}Cs could differentiate between top- and subsoil sources with a respective p-value of <0.001 and 0.014. Furthermore, the biplot of ^{137}Cs and ^{210}Pb-ex specific activities in Fig. 5 supports the conservative behaviour of these tracers, as the specific activity of the sediment samples was within the range found in the identified source types (i.e. sampled topsoil and subsoil types). Additionally, the violin plots in Fig. 6 also confirmed that there was indeed a difference between the activities of ^{137}Cs and ^{210}Pb-ex in the top- and subsoil sources and that values found in the target sediment samples were somewhere in-between. This demonstrated that the two tracers could differentiate between the top-and subsoil sources (Derakhshan-Babaei et al. 2024).

3.3 Mixing models accuracy

The accuracy of both MixSIAR and BMM models was evaluated using several accuracy metrics calculated using virtual mixtures (Table 2). The residual error/bias (ME) was only 2% for MixSIAR and even 0% for BMM, and the root mean square error (RMSE) amounted to 16% for MixSIAR and 5% for BMM. The Pearson's correlation coefficient (r^2) and the Nash-Sutcliffe efficiency (NSE) were high for BMM model and slightly lower for MixSIAR. Although there is no defined threshold for W50* values, the results suggested a somewhat elevated uncertainty for both models, with 21.6% for MixSIAR and 37.5% for BMM. The CRPS values were low for both models, as they remained below 9%.

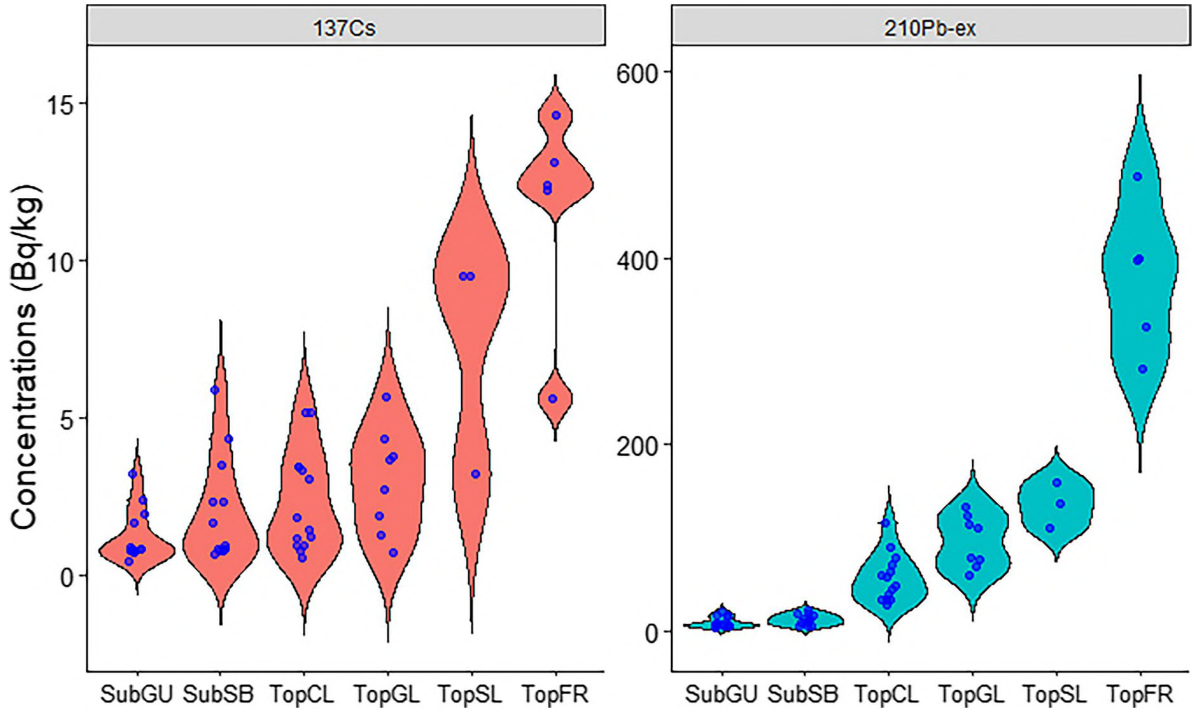


Fig. 4 The specific activity of ^{137}Cs and ^{210}Pb-ex for the identified sediment sources and undisturbed forest topsoil. SubGU is subsoil from gully, Sub SB is subsoil from streambank, TopCL is topsoil from cropland, TopGL is topsoil from grazing land, TopSL is topsoil from shrubland and TopFR is topsoil from forestland (*the blue dots are individual data points)*

Table 1 Results of the tracer selection methods

Conservativeness test		^{210}Pb-ex	^{137}Cs
Criterion	Mean ± SD	PASS	PASS
Discriminant power		^{210}Pb-ex	^{137}Cs
Two-sample Kolmogorov Smirnov test		< 0.001***	0.014*

3.4 Contribution of top- and subsoil to sediment yield

The dominance of subsoil contribution to sediment mixtures indicates that gullying and streambank erosion are the major processes contributing to sediment yield in the study area for the considered events. Both MixSIAR and BMM models showed consistent results, indicating that about three-quarters of the sediment originates from erosion processes exposing subsoils. The median contribution of subsoil to sediment mixtures ranged from 67% (95% credible interval: 22–86%) to 77% (95% credible interval: 28–93%) according to MixSIAR, and from 76% (95% credible interval: 0.1–99.9%) to 92% (95% credible interval: 0.1–99.9%) according to BMM. The central values (or average of the medians) of the subsoil contribution to sediment mixtures were 73% (95% credible interval: 20–80%) for MixSIAR and 81% (95% credible interval: 0.1–99.9%) for BMM (Fig. 7, Supplementary Material Table 1and 2).

For all investigated rainfall-runoff events, subsoil remained the major contributor to sediment mixtures, albeit minor variability between events (Fig. 8). Consequently, sampling sediment that deposited both during the early and late rainy seasons did not support the hypothesis that evidence of the occurrence of changes in the sediment contributions between the two source types.

4 Discussion

4.1 Validity of using fallout radionuclides as tracers

The proportion of clay and silt in the sediment matched that of the soils (Fig. 3), indicating that fine sediment sources dominate sediment yield in the catchment. As fallout radionuclides mainly bind to fine fractions (Evrard et al. 2020), these results support the validity of the approach (applied to < 63 µm fractions of material). In the nearby river, the bedload contribution to total sediment yield was quantified to 0.1 to 5.4% (Lemma et al. 2019a, b), which is consistent with our findings. This is also supported by Kebedew et al. (2020), who found 88% of fine fractions in the sediment of Lake Tana.

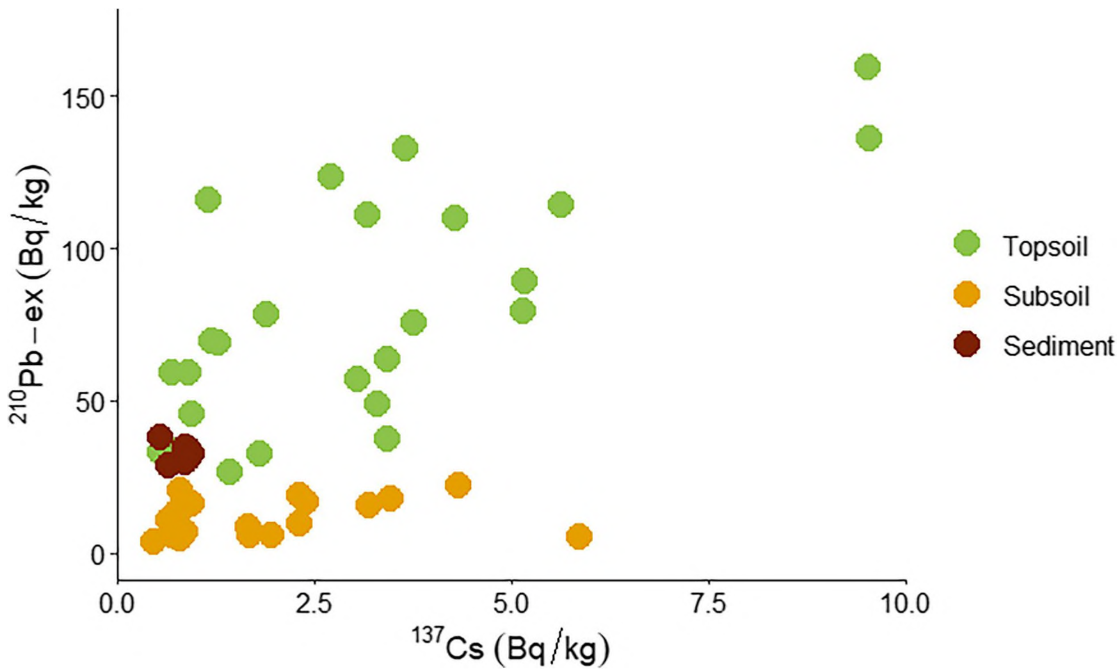


Fig. 5 Biplot of radionuclide activities (^{210}Pb-ex & ^{137}Cs) for the different source groups and the lag deposit sediment samples

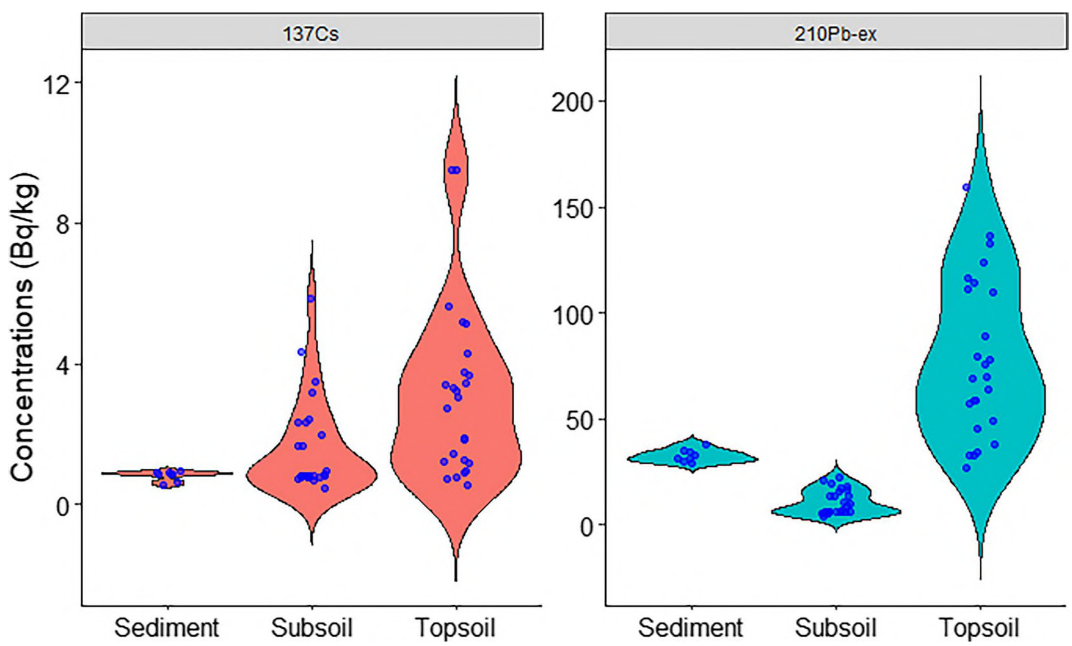


Fig. 6 The specific activity of ^{137}Cs and ^{210}Pb-ex for the source soil samples and the target sediment samples (*the blue dots are individual data points*)

Both ^{210}Pb-ex and ^{137}Cs were conservative and discriminant tracers, able to distinguish topsoil from subsoil (Table 1). This finding opens new avenues for future research in the wider region, as it demonstrates that, even though the activity of ^{137}Cs is rather low in the tropics, it remains sufficiently elevated and thus valid for implementing sediment fingerprinting. Rode et al. (2018) also reported that fallout radionuclide tracers (^{210}Pb-ex and ^{137}Cs) were applicable to differentiate topsoil and subsoil as sediment sources in Burkina Faso.

Table 2 Summary of the MixSIAR and BMM model performance metrics based on virtual mixtures ($n=21$), * indicates mean value

Sources	ME (%)	RMSE (%)	r^2 (%)	NSE (%)	CRPS* (%)	W50* (%)	Model
Subsoil	5	16	86	73	8.85	21.6	MixSIAR
Topsoil	−5	16	86	73	8.85	21.6	MixSIAR
Subsoil	0	5	99	97	6.68	37.5	BMM
Topsoil	0	5	99	97	6.68	37.5	BMM

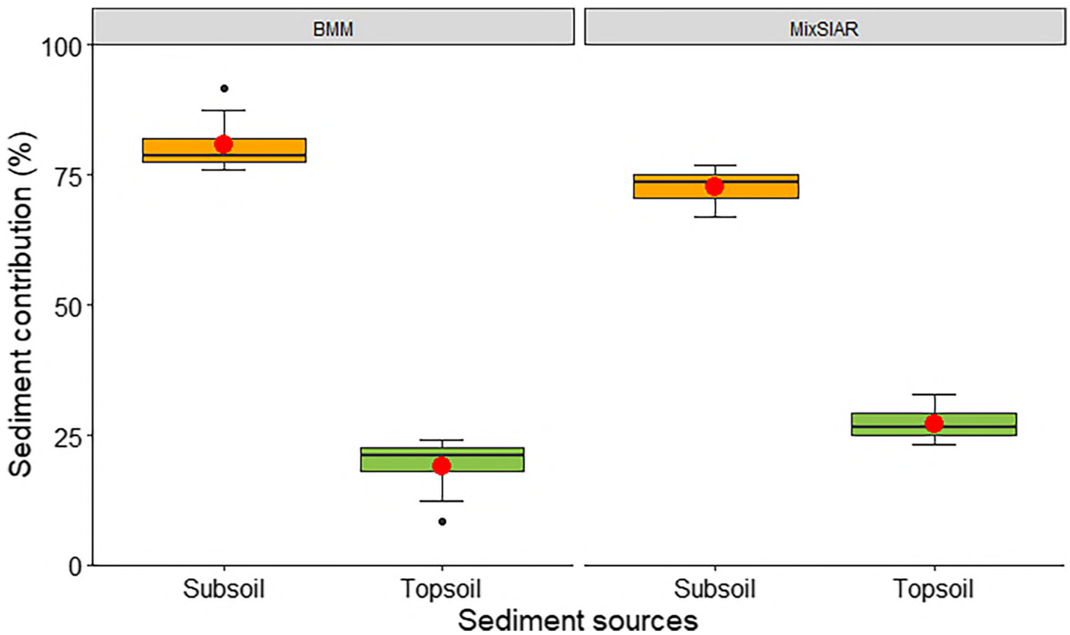
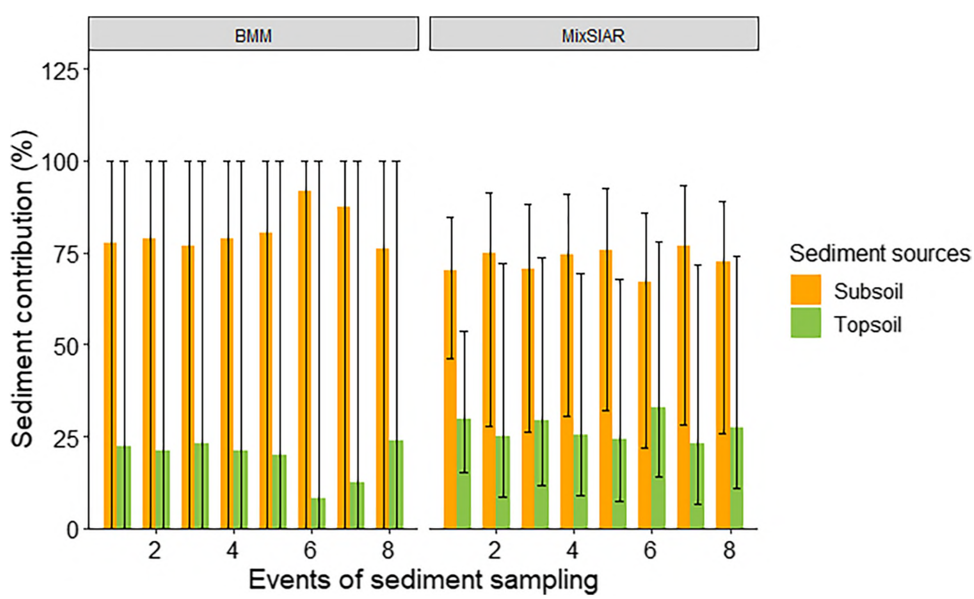


Fig. 7 The median contribution of topsoil and subsoil to the target sediment in BMM and MixSIAR models. "Red dots" indicate mean values

Fig. 8 The median contributions of subsoil and topsoil to sediment mixtures for each event using the BMM and MixSIAR models. Events 1–5 took place at the beginning of the rainy season and events 6–8 occurred at the end of the rainy season. The error bar indicates the 95% credible interval



Evaluating the MixSIAR and BMM models using virtual mixtures indicated a good performance for apportioning sediment sources (Table 2). For both models, the ME and CRPS values align with those reported by Batista et al. (2022), who found a ME value of less than 4% and a CRPS value of 9%. The RMSE values for MixSIAR were nearly similar with the findings of Chalaux-Clergue et al. (2024), who reported an average RMSE value of 14%, while these values were lower for BMM. However, the W50* values for both models were a slightly higher than those reported by Chalaux-Clergue et al. (2024), who found an average W50* value of 11%. Although the prediction uncertainty was higher for BMM, it was comparable to that reported by Batista et al. (2022). Additionally, the performance (NSE) of BMM exceeded that of MixSIAR, also aligning with the findings of Batista et al. (2022).

The specific activity of ^{137}Cs was generally low in both the top- and subsoil samples and below the detection limit in the sediment samples. However, there is a notable difference in its activity between the top- and subsoil sources at a p-value of 0.014. The specific activity of ^{210}Pb-ex was high in the topsoil, low in the subsoil, and intermediate in the sediment samples (Fig. 6). The specific activities of both tracers were nearly similar to the findings reported by Ben Slimane et al. (2013) in Tunisia (South Africa), Rode et al. (2018) in Burkina Faso (West Africa), Evrard et al. (2010, 2016) in central Mexico and Northern Laos, respectively. For long-term tracing in this region, it is likely better to rely on natural radionuclides such as ^{210}Pb-ex, as ^{137}Cs will inexorably continue to decay without being replenished (FAO 2014; Evrard et al. 2020). This is because natural radionuclides are continuously supplied through rainfall, in contrast to artificial ^{137}Cs, which was exclusively emitted during nuclear activities (Prăvălie 2014).

4.2 Subsoil as the major source of sediment

The central question of this work was to investigate whether the erosion of subsoils provides the major source of sediment in the Lake Tana Basin in Ethiopia, allowing to support our hypothesis that gullying is a major land degradation issue. Through investigating a medium-sized catchment (211 km²) and taking the variability between individual events and seasonal trends into account, this paper confirms that subsoils supplied the vast majority of sediment to rivers in the catchment. Similarly, Cheng et al. (2020) reported that subsoils contributed to 62% of the sediment in Southwestern China. Rode et al. (2018) and Evrard et al. (2016) also noted that subsoils were a primary contributor to sediment mixtures in respectively Burkina Faso and Laos. Based on extensive field surveys and previous research, gullying had been identified as a major erosion problem in the study area (Abere et al. 2024), which also efficiently conveys sediment from hillslopes to channels (Astuti et al. 2024). Gully erosion is widely recognized as a major driver of land degradation in the region (Frankl et al. 2013; De Geeter et al. 2023). For example, case studies such as that of Tebebu et al. (2010) report that gully erosion rates were nearly 20 times higher than the sheet and rill erosion rates in Debre Mewi catchment in Ethiopia. This calls for interdisciplinary approaches to improve the effectiveness of land management considering gully erosion (Frankl et al. 2016, 2019; Blake et al. 2018). Streambank erosion is less important in the investigated catchment, with the majority of the river network have low to medium energy floodplains where sedimentation rates can be high (Awoke et al. 2022a, b). Similar findings have been highlighted for other areas in the world, stressing that gullying is a major, but often overlooked concerns. This aligns with the synthesis of Poesen et al. (2003), which pointed to gullying as a major contributor to catchment sediment yield, particularly in the tropics (see relevant reference for Ethiopia in the introduction). In contrast, the sediment provenance from sheet and rill erosion was rather limited (Fig. 7). Recent land management efforts have indeed focussed on limiting soil erosion from cropland, through the implementation of soil and water conservation measures on steep slopes (Abere et al. 2024; Fenta et al. 2024), which limits sediment mobilization processes (Berihun et al. 2020).

Considering the seasonality in sediment source contributions, it is typically assumed that topsoil input to sediment mixtures is elevated at the beginning of the rainy season. This increase is due to soil exposure during the early cropping phase and the initial flush of loose sediment after the long dry season. Conversely, topsoil erosion is expected to decrease in the late rainy season, as dense crop cover protects the soil from sheet and rill erosion. This study found no evidence of seasonality in sediment sources, challenging the previously held assumption. In the Enkulal sub-catchment, Assaye et al. (2021) reported that runoff and sediment yield from zero-order catchments are largely determined by rainfall characteristics at the event scale. These rainfall-runoff event characteristics significantly influence erosion processes and sediment mobilization (Poleto et al. 2009). Multiple factors may contribute to the lack of seasonality, such as sediment dynamics being transport-limited in the early rainy season (Tilahun 2012), or the high infiltration rates which occur on steep slopes, and where infiltration-excess Hortonian flow has been reported in only 3 to 9% of rainfall events (Bayabil et al. 2010; Tilahun et al. 2016). Such findings, which do not necessarily fit the conceptualizations of hydrogeomorphic responses, have been obtained in other regions of the world too, for example in Ireland by Sherriff et al. (2018) and in the Northern Loess Plateau, China by Tian et al. (2023).

5 Conclusions

This paper highlights that subsoils provides the major source of sediment in the Lake Tana Basin in Ethiopia, allowing to support our hypothesis that gullying is a major land degradation issue. This finding is based on the first application of sediment fingerprinting using fallout radionuclides in sub-humid Ethiopia. Models provided consistent results, indicating that about three-quarters of the sediment originates from subsoils (median average of 73% for MixSIAR and 81% for BMM). We conclude that ^{137}Cs and ^{210}Pb-ex proved to be effective tracers for distinguishing between topsoil and subsoil contributions to sediment mixtures in Ethiopia. Among the two, ^{210}Pb-ex performed better, offering a more sustainable, long-term solution given the continuous decay of ^{137}Cs. The accuracy of MixSIAR and BMM models for apportioning topsoil and subsoil sediment source contributions were high. While the performance of BMM was higher than MixSIAR, the latter provided greater certainty. Both inter-event and seasonal variability in sediment contribution remained limited. Accordingly, land managers should prioritize gullies when aiming to control excessive sediment yield in the Lake Tana Basin, instead of primarily focussing on sheet and rill erosion on cropland.

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Declarations

Conflict of interest The authors declared that there is no competing interests.

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