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Sediment and soil source apportionment using geochemical fingerprinting techniques in the Winam Gulf, Lake Victoria

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ABSTRACT

Accelerated soil erosion is a major cause of land degradation in East Africa's agricultural and pastoral landscapes with severe consequences for food, water and livelihood security. In this study, we aimed to provide a tool to support the sustainable management of land and water resources in a region significantly impacted by land degradation. We employed source apportionment methods to quantify the relative contribution of sediment sources within the Nyando and Sondu-Miriu River basins and their subcatchments in the Winam Gulf, Kenya. A total of 237 riverbed sediment samples and 76 composite surface soil samples were collected from the Nyando and Sondu-Miriu River basins. The total elemental concentrations of these samples, determined using ICP-MS/MS, were utilised as geochemical tracer properties. Conservativeness index, consensus ranking and consistent tracer selection methods were then used to identify the optimum unmixing tracers before applying the frequentist unmixing model FingerPro to determine sediment provenance. Sediment source analysis revealed that the Ainamutua and Nyando-Kipchorian subcatchments, areas predominantly affected by land degradation activities such as poor crop management practices and deforestation on steep slopes, contributed 39 ± 4 % and 44 ± 4 %, respectively. In contrast, the Awach Kano and Nyaidho subcatchment, with a higher proportion of tree-cover and lower soil erosion rates, only contributed 17 ± 7 %. In the Sondu-Miriu, the Yurith and Kipsonoi subcatchments contributed 68 ± 5 % and 20 ± 6 %, respectively, due to the predominance of forest encroachment and ridges in the Yurith subcatchment. Additional fingerprinting analysis within each of the Nyando and Sondu-Miriu basins reveals the significance of land use, landform and soil types on source contributions. Quantifying sediment source contributions within large river basins provides essential information for environmental managers and policymakers developing integrated catchment management plans. The results from this study can be used to implement sustainable land use policy focused on soil restoration in the Lake Victoria drainage basin.

1. Introduction

Land degradation caused by soil erosion is a major threat to ecosystem functions, such as agricultural productivity and water resource management (Amundson et al., 2015; Borrelli et al., 2017; Gemeda and Sima, 2015). Global soil erosion rates are estimated to be 36 Pg yr^{-1} with anthropogenically accelerated erosion caused by deforestation, cropland expansion, urbanisation, agricultural intensification and unsuitable agricultural practices having severe consequences for food, water and livelihood security (Alewell et al., 2020; Dai et al., 2018; Feeney et al., 2023; Humphrey et al., 2022). Over the next 50 years climate change is predicted to cause erosion rates to increase by 30–66 %, with the greatest impact anticipated in Sub-Saharan Africa where more frequent high-energy storm events will negatively impact the already poorly managed agricultural land (Borrelli et al., 2020; Watene et al., 2021). It is estimated that one third of all soils have a lifespan of < 200 years (Evans et al., 2020), which highlights the serious threat erosion poses to global soil sustainability. On land, erosion leads

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to the loss of nutrient rich topsoil and organic matter which negatively impacts soil fertility and crop yields, whilst increased sediment loads impact turbidity, siltation, light attenuation, and increase the delivery of contaminants to waterways leading to the degradation of aquatic environments (Feeney et al., 2023; Upadhayay et al., 2020; Vale et al., 2022). The composition of sediment in river ecosystems reflects erosional processes occurring within a catchment (Owens et al., 2005), understanding these complex interactions is an ongoing challenge. The implementation of erosion mitigation and sustainable management practices within a catchment requires the identification of sediment sources and deconvoluting transport and delivery mechanisms (Vale et al., 2022; Walling and Collins, 2008).

Sediment fingerprinting is a technique used to predict the relative contribution of each source by comparing conservative tracer properties in source and endpoint samples using quantitative mixing models (Collins et al., 2010; Latorre et al., 2021; Walling et al., 1999). The spatial variation of biogeochemical tracers within a catchment is influenced by geology, pedogenic processes, climate, vegetation, and management practices. As such, tracers including geochemistry (Blake et al., 2018; Crespo et al., 2023; Gaspar et al., 2019; Mohammadi et al., 2023; Nascimento et al., 2023; Vale et al., 2020), fallout radionuclides (^{137}Cs, ^{210}Pb) (Evrard et al., 2013; Navas et al., 2020), and compound specific stable isotopes (CSSIs) (Alewell et al., 2016; Lizaga et al., 2021; Mabit et al., 2018; Vale et al., 2022) have all previously been used to quantify sediment provenance. Whilst initial fingerprinting studies were performed using single tracers (Walling et al., 1979) the development of quantitative mixing models, using both Bayesian and Frequentist statistics, significantly improved the technique by incorporating a larger number of tracers with better source discrimination (Lizaga et al., 2020b). Despite the emergence of multiple unmixing models including SedIment Fingerprinting Tool (SIFT) (Pulley and Collins, 2018); MixSIR (Moore and Semmens, 2008); Deconvolutional MixSIAR (D-MixSIAR) (Blake et al., 2018); and FingerPro (Lizaga et al., 2020c), tracer selection methodologies have emerged as the prevailing challenge associated with the fingerprinting technique.

Sediment fingerprinting techniques assume that the tracer properties behave conservatively, meaning that they preserve the signature of the source material during erosion and transportation processes downstream to the receiving environments and can therefore be directly compared (Collins et al., 2017; Vale et al., 2022). The inclusion of non-conservative tracers substantially modifies the unmixing results. Common methods for removing erroneous tracers exhibiting non-conservative behaviour include a range test (RT) to assess mass conservation, coupled with a two-step statistical procedure proposed by Collins and Walling (2002) using Kruskal-Wallis (KW) and discriminant function analysis (DFA) tests. However, these classical tracer selection methods fail to exclude some non-conservative tracers and introduce uncertainty to the model, negatively affecting the results of both Frequentists and Bayesian unmixing approaches (Latorre et al., 2021; Lizaga et al., 2020b). To combat this, Lizaga et al. (2020b) developed and validated a new and robust tracer selection approach, which combines the predictions of single-tracer models to identify non-conservative and dissenting tracers through a conservativeness index (CI) and consensus ranking (CR) methods. Latorre et al. (2021) further developed this approach and introduced the consistent tracer selection (CTS) method capable of exploring the possibility of multiple discriminant solutions within a dataset, thus ensuring the most accurate application of the fingerprinting technique.

This contribution explores how the sediment tracer approaches outlined above can be used to support sedimentation-related management challenges in Lake Victoria, East Africa. Lake Victoria is the second largest freshwater lake in the world with an area of ~ 69,000 km^2 and its shoreline is shared by Kenya (6 %), Uganda (45 %) and Tanzania (49 %). Its basin is home to ~ 42 million people (Deirmendjian et al., 2020; Nyamweya et al., 2023). Within the Kenyan portion of Lake Victoria, the Winam Gulf exhibits a complex nexus of intense climatic conditions, steep slopes, poor agricultural practices, high erosion-risk soils, overpopulation and lack of appropriate management policies and overreliance on subsistence crop farming (Kogo et al., 2020). This consequently leads to soil erosion, reduced agricultural productivity, and flooding which impacts the lake's ecology and associated fisheries. In this study, we aimed to apply a sediment tracing tool to yield evidence that can support the sustainable management of land and water resources in a region significantly impacted by land degradation. To meet our aim, the objectives of the study were to (i) collect and characterise sediment and soil samples in the two dominant river basins, the Nyando and Sondu-Miriu; (ii) use conservativeness index, consensus ranking and consistent tracer selection methods to identify the optimum unmixing tracers; and (iii) quantify the relative contribution of sediment sources within the Nyando and Sondu-Miriu River basins in the Winam Gulf catchment by using source apportionment methods.

2. Materials and methods

2.1. Study area

This study was carried out on the two largest rivers flowing into the Winam Gulf (0°38′S–0°10′N, 34°8′E–35°33′E), in western Kenya within the Lake Victoria basin; the Nyando River and Sondu-Miriu River (Figs. 1 and 2). The Winam Gulf is a semi-enclosed inlet with an area of ~ 1400 km^2 and an average depth of 5 m. The gulf receives 9.2×10^9 m^3 yr^{-1} of water from inflowing rivers, of which the major influxes are from the Nyando River (5×10^8 m^3 yr^{-1}) and the Sondu-Miriu River (1.3×10^9 m^3 yr^{-1}) (Alexander and Imberger, 2013; LVEMP, 2003).

The Nyando River is ~ 150 km long and has a total drainage area of ~ 3550 km^2. The river originates from the western side of Mau Forest complex (North Tinderet Forest, Tinderet Forest, South West Mau Forest and Londiani Forest). The Nyando River basin contains several distinct physiographic features including the low-lying Kano Plains neighbouring the Winam Gulf, the Nandi escarpment in the north, the volcanic hills and plateau including the Mau Forest Complex to the west and the Kendu escarpment and Nyabondi plateau to the south bordering the Kano Plains (Owuor et al., 2012). The two largest tributaries of the Nyando River, the Ainamutua River and the Nyando-Kipchorian River, are found in the highlands to the east of the catchment, they converge before meeting with the Awach Kano and Nyaidho Rivers in the plains before entering the Winam Gulf, Lake Victoria at about 1100 m.a.s.l (Olang and Fürst, 2011). Agriculture is the dominant land use, including large-scale tea, coffee, maize, sugarcane and rice irrigation activities (Raburu et al., 2009). Radionuclide analysis of sediment cores collected from the mouth of the Nyando River in the Winam Gulf shows that sedimentation rates have quadrupled over the last 100 years, whilst the Nyando basin only occupies ~ 2 % of the overall Lake Victoria basin drainage area, it makes a substantial contribution to the sediment load of the lake (World Agroforestry Centre, 2006).

In comparison, the Sondu-Miriu River is ~ 190 km from its headwaters to the shores of Lake Victoria with a similar drainage area of ~ 3500 km^2. The Sondu-Miriu River basin is comprised of two main subcatchments, the Kipsonoi to the south and the Yurith to the east. The Kipsonoi has its headwaters in Kuresoi in Nakuru County, whilst the Yurith's subtributaries the Timbilil, Kiptiget and the Itare all originate in Kuresoi and the Mau Forest complex, converging at Kabianga tea estate to form the Yurith subcatchment (Koech et al., 2022). The Sondu-Miriu River basin has a range of diverse land use types including forestry, agriculture, urban and sub-urban settlements, agronomy-based industries and hydroelectric power generation (Masese et al., 2012). However, deforestation, encroachment and the subsequent conversion to agricultural land use have reduced the forest cover by 32 % over the last 60 years, notably since the year 2000. The Sondu-Miriu River basin can be categorised into three zones based on altitude and crop cover. The upper zone (1700 – 2800 m.a.s.l) is covered by forests, woodlands, tea plantations and small-holder farms, whilst the middle zone

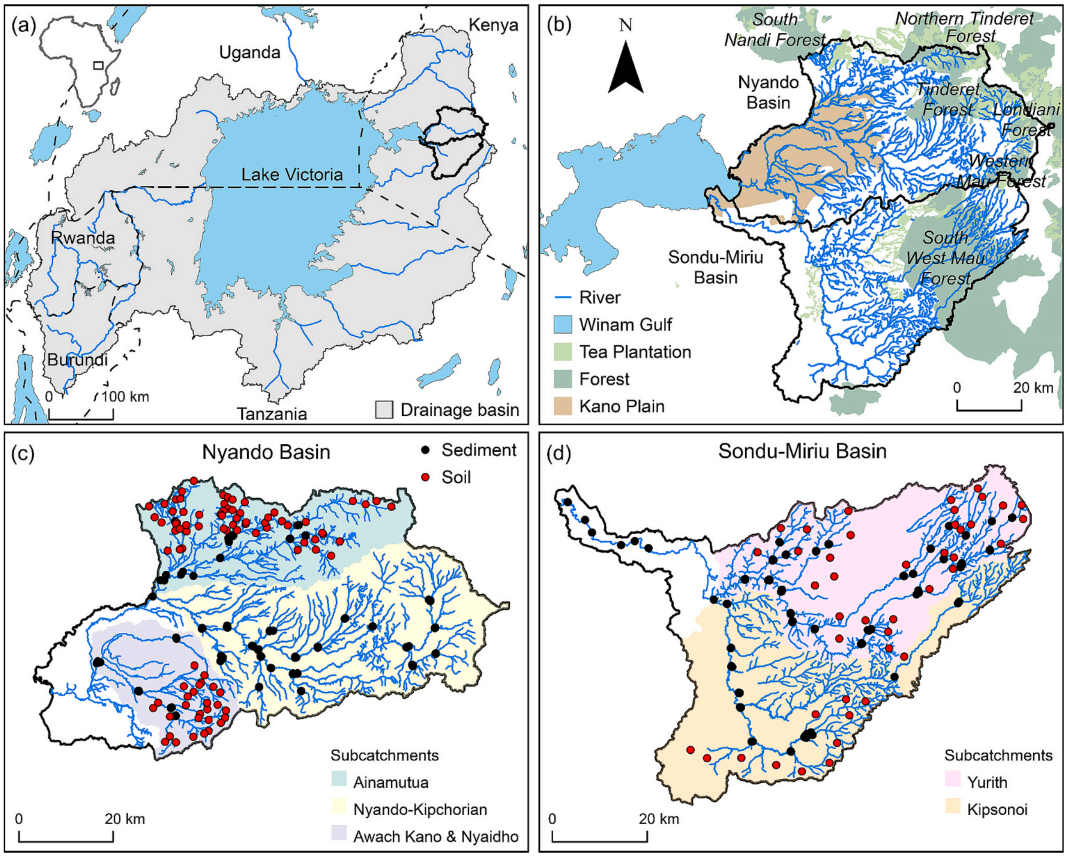

Fig. 1. Location of the study area in the Lake Victoria basin (a), the Winam Gulf (b), and the distribution of sediment and soil source sampling sites in the Nyando (c) and Sondu-Miriu (d) River basins and their subcatchments.

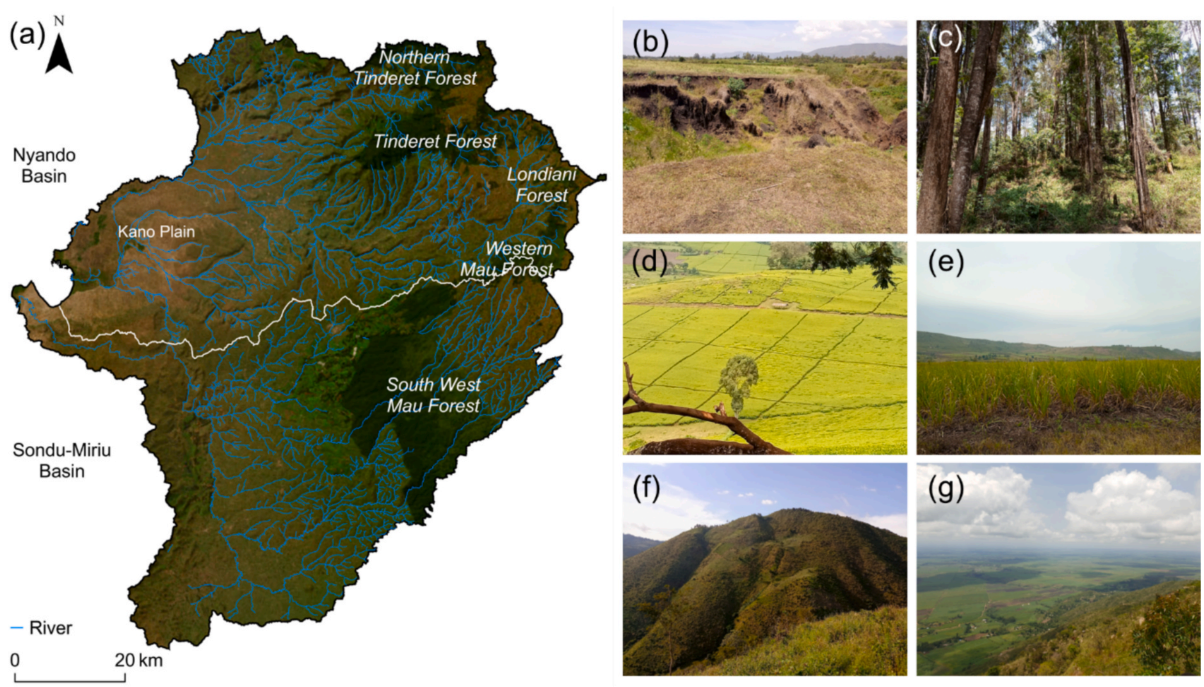

Fig. 2. Satellite image of the Nyando and Sondu-Miriu River basins (a). Pictures of the different land uses within the catchments; eroded soils (b), forested area (c), tea plantations (d), sugar cane fields (e), steep sloped highlands (f), and the Kano Plain (g).

(1400–1700 m.a.s.l) is hilly and covered by herbaceous vegetation and the lower zone (1100–1400 m.a.s.l) is covered by sparsely distributed shrubs and subsistence agriculture (Masese et al., 2012).

A diverse range of soil types exists within the study area. Soils in the Kano Plain region are predominantly derived from Holocene sedimentary deposits; fluvisols, vertisols, planosols, cambisols and solonetz soils are common (Andriesse and Van der Pouw, 1985). The upland soils in the Nyando and Sondu-Miriu basins are derived from a wide variety of parent materials including phonolites, quartzites, nephelinites, granitoid gneisses, dolorites, monzonites and granidiorites and are representative of the majority of the Kenyan portion of the Lake Victoria Basin (Binge, 1962). The dominant soils in these areas include nitisols, cambisols, phaeozems, andosols and ferralsols (Andriesse and Van der Pouw, 1985; IUSS Working Group, 2014; Mungai et al., 2011).

The climate is largely influenced by the inter-tropical convergence zone, with variations modified by local orographic effects. The annual average temperature varies between 15 and 30 °C (Calamari et al. 1995). The region experiences bimodal seasonal rainfall and equatorial climate having a long rainy season between the months of April and June, and a short rainy season between September and December. There is significant interannual variation in the volume and duration of rainfall in both catchments with the annual average precipitation between 600 and 2000 mm (Fusilli et al., 2013; Okungu et al., 2005).

2.2. Sampling strategy

Prospective sediment and soil sampling locations were identified prior to fieldwork campaigns with particular attention paid to elevation (m), land use, landform, soil classification, lithology and modelled soil erosion rates (Supplementary Fig. 1) (Humphrey et al., 2022). Due to challenging environmental and logistical constraints associated with sample collection, the samples used in this study were collected over a 12-month period between June 2021 and June 2022, incorporating both dry and wet seasons. In East-African catchments, the contribution of potential sediment sources can be significantly influenced by the highly variable spatial and temporal rainfall patterns (Ambroise, 2004; Wynants et al., 2020). Therefore, this study works under the assumption that the riverbed sediment samples collected provide a time-integrated and representative mixture from their respective sources throughout the catchments.

2.3. Sediments

A nested sampling design, as described in Blake et al. (2018), was used to collect 237 composite riverbed sediment samples (0–5 cm) within the Nyando (117) and Sondu-Miriu River (120) catchments. Each sample was composed of 8–10 subsamples spanning the width of the river channel over a length of approximately 50 m to incorporate potential random spatial variation in riverine sediment deposition; adhering to the widely accepted guidance (Collins et al., 2017; Owens et al., 2016). Riverbed sediment samples were collected at the mouth of the inflow and at the point of confluence of the two tributaries throughout the catchments.

2.4. Soils

A total of 76 composite surface soils (0–5 cm) were sampled within specific subcatchments of the Nyando and Sondu-Miriu River basins. Soil samples incorporated all the major land use types assumed to be susceptible to soil erosion based on existing and visual evidence of erosive features and location in the landscape. Each soil sample was comprised of a composite of 8–12 subsamples spaced 50–100 m apart, depending on the homogeneity, pooled into a single sample in the field to ensure the geochemical representativeness of the corresponding potential sediment source.

2.5. Sample preparation and geochemical analysis

Prior to analysis, all samples were air-dried at 40 °C, ground, homogenised and sieved to ≤ 63 μm, to minimise any particle size effects following the most widely accepted methods (Owens et al., 2016; Collins et al., 2017). Sediment and soil samples (0.25 g) were digested in a mixed acid solution (HF:2.5 ml/ HNO_3:2 ml/$HClO_4$:1 ml/ H_2O_2:2.5 ml) for the determination of the total concentrations of a broad suite of major and trace elements as described in Watts et al. (2019). Analyses of the acid digests were performed by a tandem quadrupole inductively coupled plasma mass spectrometry instrument (Agilent 8900 ICP-MS/MS, Agilent Technologies) using (i) collision cell mode (He-gas) for Li, Be, B, Na, Mg, Al, P, S, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, As, Rb, Sr, Y, Zr, Nb, Mo, Ag, Cd, Sn, Sb, Cs, Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Hf, Ta, W, Tl, Pb, Bi, Th and U; and (ii) H_2-reaction cell mode for Se; and (iii) O_2-reaction cell mode for As (mass shifted at m/z 91). Internal standards Sc, Ge, Rh, In, Te and Ir were employed to correct for signal drift. The complete dataset for each catchment, limits of detection and analytical performance for appropriate certified reference materials are presented in full in the Supplementary Data file. The average recovery for the certified reference materials was 93.0 ± 7.7 % (n = 14) for NIST2711a Montana Soil, 96.0 ± 5.5 % (n = 27) for USGS BCR-2 Basalt, 98.0 ± 8.1 % (n = 15) for BGS102 Ironstone Soil, and 95.3 ± 7.0 % (n = 8) NRC MESS-4 Marine Sediment.

2.6. Quantitative provenance analysis

2.6.1. Tracer selection method

In this study, the R package 'FingerPro' (Version 1.33) (Lizaga et al., 2020b; Lizaga et al., 2020c) was used to employ conservativeness index (CI), consensus ranking (CR) and consistent tracer selection (CTS) methods to identify the most appropriate tracers for each catchment and to test the consistency and existence of multiple solutions. This method needs at least $n - 1$ tracers to determine the sediment source apportionments (where n is the number of sources) (Crespo et al., 2023; Latorre et al., 2021; Lizaga et al., 2020b; Lizaga et al., 2020c). Critical to the success of source apportionment unmixing is the removal of non-conservative and out of range tracers prior to unmixing as the inclusion of erroneous tracers will produce inconsistent results (Crespo et al., 2023; Latorre et al., 2021). Here we evaluate the suitability of measured geochemical tracers in the end-point mixtures and compare them to the measured values in the potential sources to identify robust tracers that can accurately discriminate and unmix their relative contribution from potential sources. The conservativeness index (CI) method is a non-parametric test that uses the predictions of single-tracer models to identify non-conservative properties. The predicted source contributions from each tracer are first calculated and characterised by their centroid. Then, the CI index is calculated as the percentage of solutions with conservative apportionments ($0 \leq W_i \leq 1$) relative to the centroid position (Lizaga et al., 2020a; Lizaga et al., 2020b; Lizaga et al., 2024; Tian et al., 2023). The CR method then combines predictions from multiple single-tracer models through random debates between tracers. In each debate, a random subset of the tracers is selected. The consensus of each round is measured from 0 to 100, and a tracer's consensus ratio is calculated based on its participation and lost debates:

$$\text{consensus} = 100\left(1\text{-}\frac{\text{lost debates}}{\text{total debates}}\right) \quad (1)$$

A high consensus ratio indicates a high level of agreement with the group, while a low score suggests frequent conflicts, for more detailed information about CI and CR, see Lizaga et al. (2020b). For the tracer to be included in the model it had to have a CI score in or above the 75th percentile and > 50 while simultaneously having a CR score in or above the 50th percentile and > 70. However, the thresholds for expectance are significantly influenced by the database and more lenient or restrictive limits may be applied.

Finally, to assess whether there are multiple solutions in a dataset the consistent tracer selection (CTS) methods are used to extract the multiple discriminant and consistent solutions inside fingerprinting datasets with three sources. The CTS method is similar to the discriminant function analysis outlined in (Lizaga et al., 2020c) and identifies the most discriminant tracers, whilst also examining their mathematical properties to ensure consistency in over-determined datasets (Lizaga et al., 2022). In this study, we started with the optimal pair of tracers defined by the lowest dispersion which implies higher discrimination and high consensus ranking and progressively incorporated tracers from the dataset that maintained solution consistency (normalised error threshold $\varepsilon \leq 0.025$ and CI > 90). For more detailed information about CTS, see Latorre et al. (2021).

2.6.2. Source apportionment FingerPro unmixing model

The relative contribution of each potential sediment source is determined using a standard linear multivariate mixing model:

$$\sum_{j=1}^{m} a_{i,j} \cdot \omega_j = b_i \tag{2}$$

which satisfies:

$$\sum_{j=1}^{m} \omega_j = 1, \ 0 \leq \omega_j \leq 1 \tag{3}$$

where b_i is the tracer property i ($i = 1$ to n) of the mixture, $a_{i,j}$ signifies the tracer property i in the source type j ($j = 1$ to m), ω_j is the unknown relative contribution of the source type j, m represents the number of sediment sources and n is the number of tracer properties selected. As described in Lizaga et al. (2020c) this procedure aims to find the source proportions that conserve the mass balance for all selected tracers. All possible combinations of each source contribution (0–100 %) are examined in small increments, using Latin hypercube sampling. To evaluate the accuracy and efficiency of the discrimination result in sediment sources the goodness of fit (GOF) of the model was calculated based on the sum of the squares of the relative error.

3. Results and discussion

3.1. Optimum tracer selection for source discrimination

The results of the CI and CR methods with three sources are presented as ternary diagrams, representing all the possible predictions from each tracer for the selected mixture in a specific catchment. Individual tracer predictions are quantified by, incorporating the mixture information into the analysis, a key limitation to the widely used two-step KW and DFA tests (Lizaga et al., 2020b). The ternary diagrams show the contribution (0–100 %) from sediment sources 1, 2 and 3, presented in a clockwise orientation beginning at the bottom left corner, and provide a visual reference of the consistency of the tracers the finer lines represent higher discrimination, and their orientation indicates which sources are better discriminated. After applying the CI and CR methods, a total of 8 and 10 conservative tracers were retained from the initial 57 tracers for the Nyando and Sondu-Miriu basins, respectively. The selection methods identified that Be, K, Ni, Sr, Zr, Cd, Nd, and U (Fig. 3), and Ti, Zn, Ga, Se, Zr, Nb, La, Pr, Eu, and U (Fig. 4) were the optimum tracers for the Nyando and Sondu-Miriu catchments, respectively. The ternary diagrams suggest that Be, Ni, and Sr can discriminate sources 1, 2, and 3 in the Nyando basin and that P, Zn, and La can discriminate the sources 1, 2 and 3 in the Sondu-Miriu basin, respectively. The CR method identifies problematic tracers that remain distant from the theoretical solution and quantifies differences in the variability and discrimination (Lizaga et al., 2020b). Furthermore, the CR method shows how each tracer behaves in relation to the other tracers in the dataset. Optimum tracers with conservative behaviour, lower variability and higher discrimination are given high rankings (>90), for example, Nb, Eu and Pr in the Nyando (Fig. 3) and Ni, Se, Nb in the Sondu-Miriu (Fig. 4). In general, the ternary diagrams of the Sondu-Miriu sediments have higher dispersion compared to the Nyando sediments, particularly for Na, Mg, and Ca. This single-tracer model has many benefits over conventional tracer selection methods (RT, KW and DFA), as it is able to quantify the effect of the dispersion of the corresponding tracer in the sources; the distance of the average value of the sources, and the relative position of the tracer in the mixture (Lizaga et al., 2020b).

The consistent tracer selection (CTS) method was developed to investigate the possibility that multiple solutions may exist within a dataset. Having applied the CTS algorithm to the datasets to reveal consistent and discriminant tracer groups, the minimal compatible tracer sets ordered by their discriminant capacity (Supplementary Tables 1 and 9, respectively). The top result in both Tables corresponds to the most discriminant pair of tracers Sr-Nd and Y-Sb for the Nyando and Sondu-Miriu datasets, respectively. Whilst the top pair is also identified by the CI and CR methods in the Nyando catchment, only Sb was selected by the CI and CR methods in the Sondu-Miriu catchment. Each of the pairs identified by the CTS method was then expanded to incorporate additional conservative tracers from the database with a maximum normalised error threshold < 0.025 (Supplementary Tables 2–7 and 10–15, respectively). The optimum tracers, selected by the CTS method for the Nyando and Sondu-Miriu basins were Sr, Nd, Be, Eu, K (Supplementary Table 2) and Se, Al, Tb, Cd (Supplementary Table 15), respectively. The data driven approach used to identify catchment specific tracers had yielded distinct groups of tracers. Geochemical processes such as chemical weathering and elemental mobility within the catchment are reflected by end-point sediment compositions (Li et al., 2024; Négrel et al., 2015). Wynants et al. (2021) described autogenic tracers (K, Na, Mg, and Sr) as being produced within lakes and floodplains and allogenic tracers (Ti, Fe, Al, and Zn) being associated with hillslope soils, produced through location-specific pedological weathering processes (Schillereff et al., 2014). The tracers selected for sediment source apportionment in the Nyando and Sondu-Miriu catchments reflect the complex interactions occurring in the basin. This ensemble approach, combining CR and CTS methods showcases an innovative solution to selecting optimum tracers for sediment provenance techniques. The method develops our understanding of the implication of multiple solutions within a fingerprinting dataset and has clear advantages over older tracer selection techniques which do not consider the possibility of multiple solutions (Latorre et al., 2021). By using the CTS method, it is possible to visualise the different solutions and assess the likelihood of its occurrence using expert knowledge of catchment processes. All CI, CR and CTS results for the other subcatchments assessed in this study are available in supplementary information (sediment samples: Supplementary Figs. 4 - 11 and Supplementary Tables 17–44; soil samples: Supplementary Figs. 12–19 and Supplementary Tables 45–68).

3.2. Sediment and soil source apportionment

Having selected the appropriate conservative tracers using the CI, CR and CTS methods the relative contribution of sediment sources within the Nyando and Sondu-Miriu River catchments and their subcatchments was calculated using source apportionment methods. In the Nyando catchment, the unmixing model revealed that the Ainamutua; Nyando-Kipchorian; and the Awach Kano and Nyaidho subcatchments contributed 39 ± 4 %, 44 ± 4 % and 17 ± 7 %, respectively (Fig. 5a). The relatively low standard deviation of all sources together with a high GOF result (96 ± 2 %, Supplementary Table 8) shows that the model efficiently discriminates the end-point sample against the selected sources. However, there are limitations associated with using GOF as an assessment of model reliability, as it is possible that a model with a high GOF is

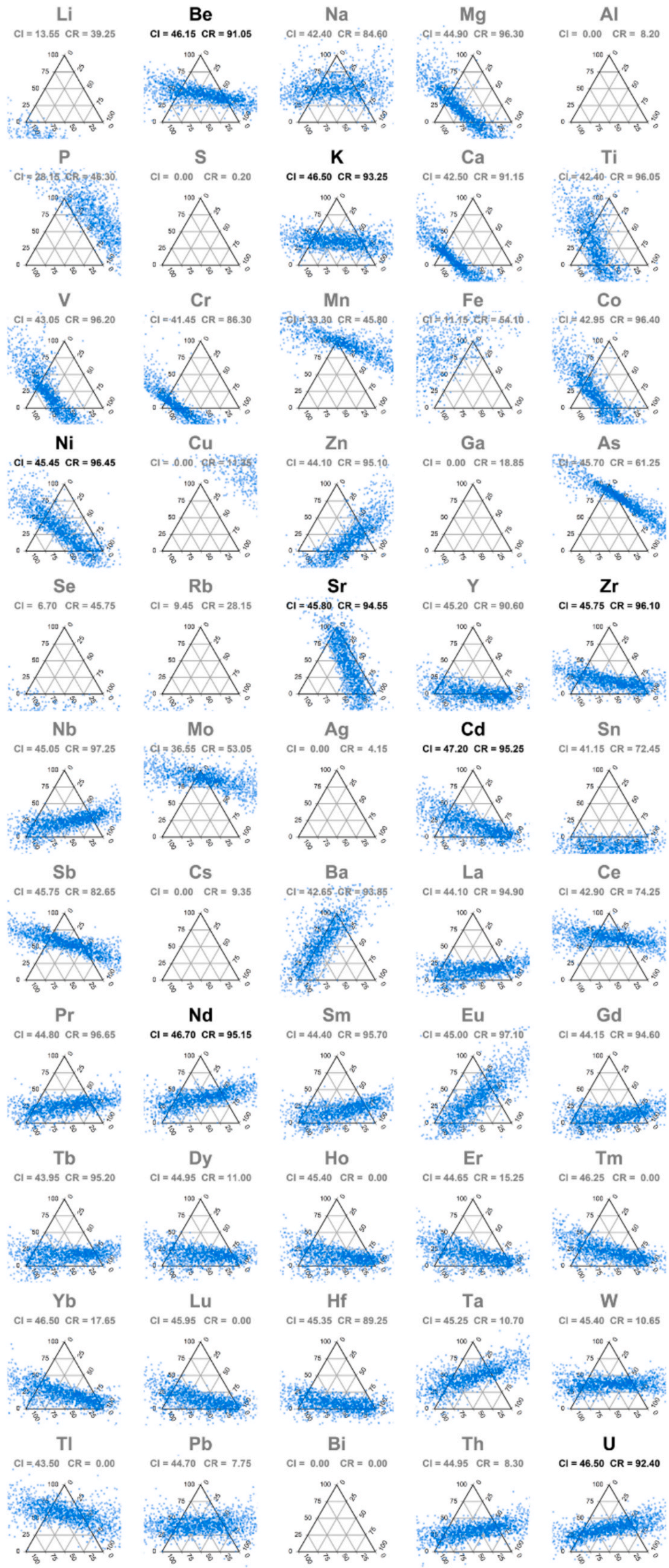

Fig. 3. Ternary diagrams showing all possible contributions of each tracer in the Nyando basin, with blue dots representing results of the simple tracer model. The ternary diagrams show the contribution (0–100%) from sediment sources 1, 2 and 3, presented in a clockwise orientation beginning at the bottom left corner. Conservativeness index (CI) and consensus ranking (CR) scores for each tracer are also represented numerically, with the tracers selected for unmixing presented in bold black text. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

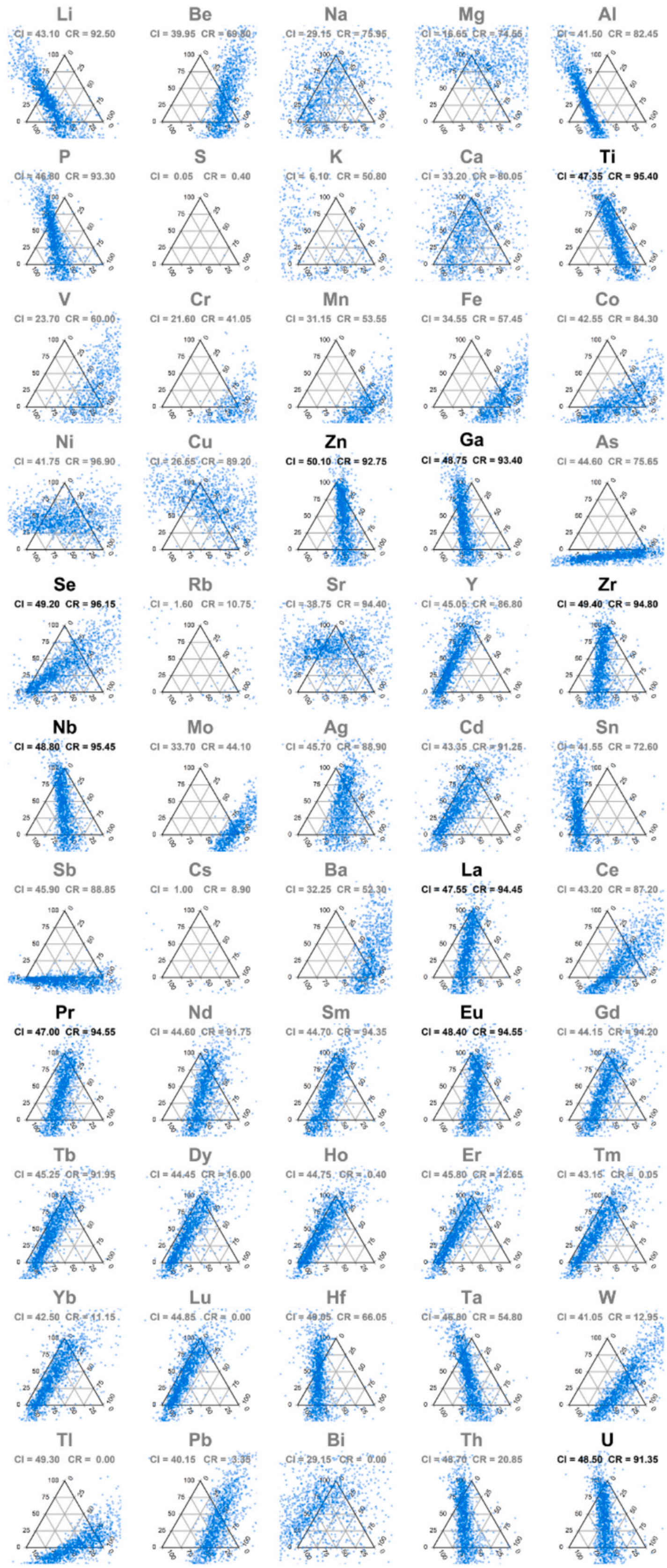

Fig. 4. Ternary diagrams showing all possible contributions of each tracer in the Sondu-Miriu basin, with blue dots representing results of the simple tracer model. The ternary diagrams show the contribution (0–100%) from sediment sources 1, 2 and 3, presented in a clockwise orientation beginning at the bottom left corner. Conservativeness index (CI) and consensus ranking (CR) scores for each tracer are also represented numerically, with the tracers selected for unmixing presented in bold black text. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

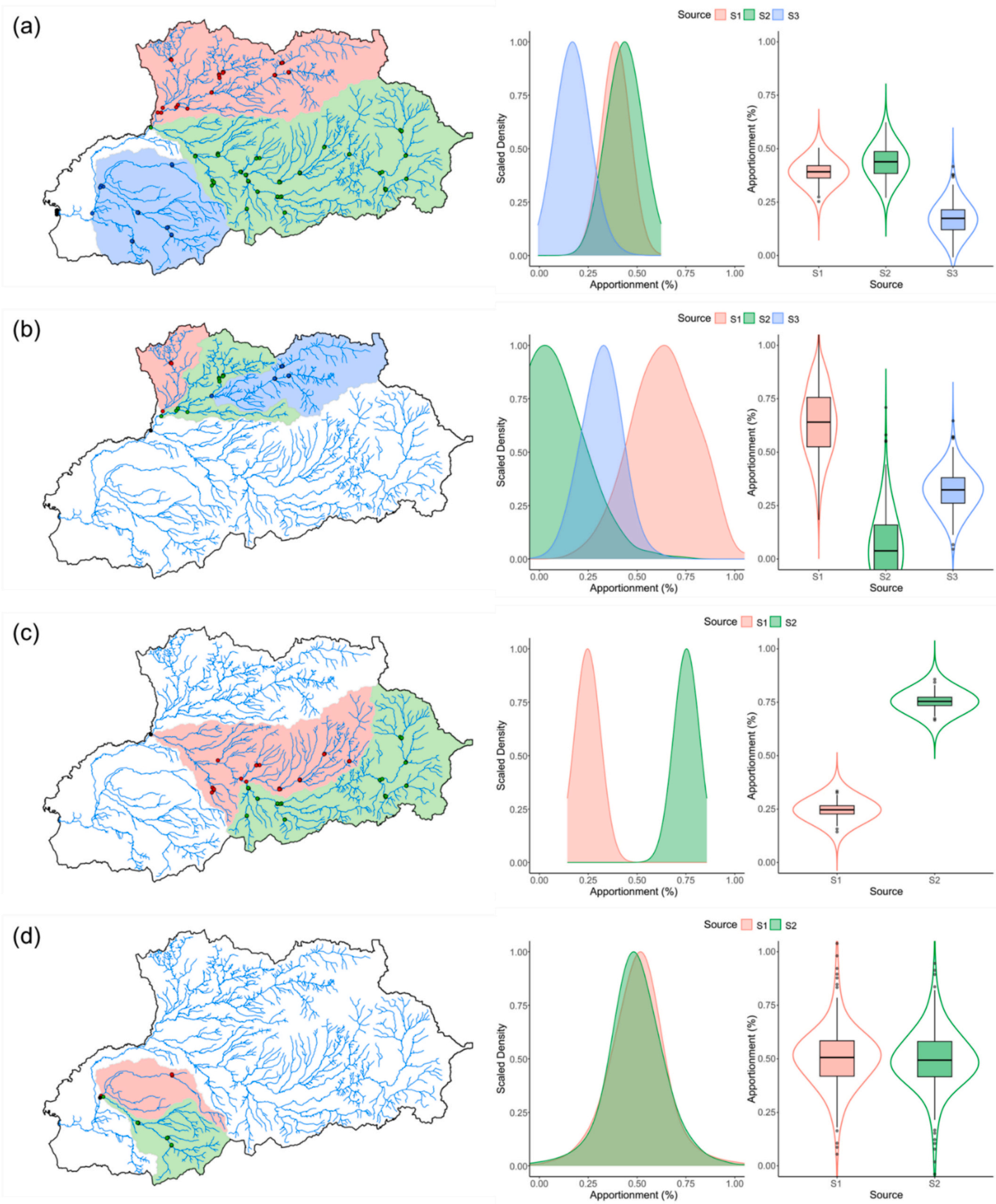

Fig. 5. Sediment source apportionment results presented as scaled density and violin plots in the Nyando basin (a) and its subcatchments, the Ainamutua (b); Nyando-Kipchorian (c); and Awach Kano and Nyaidho (d), respectively. The black dots represent the unmixing point.

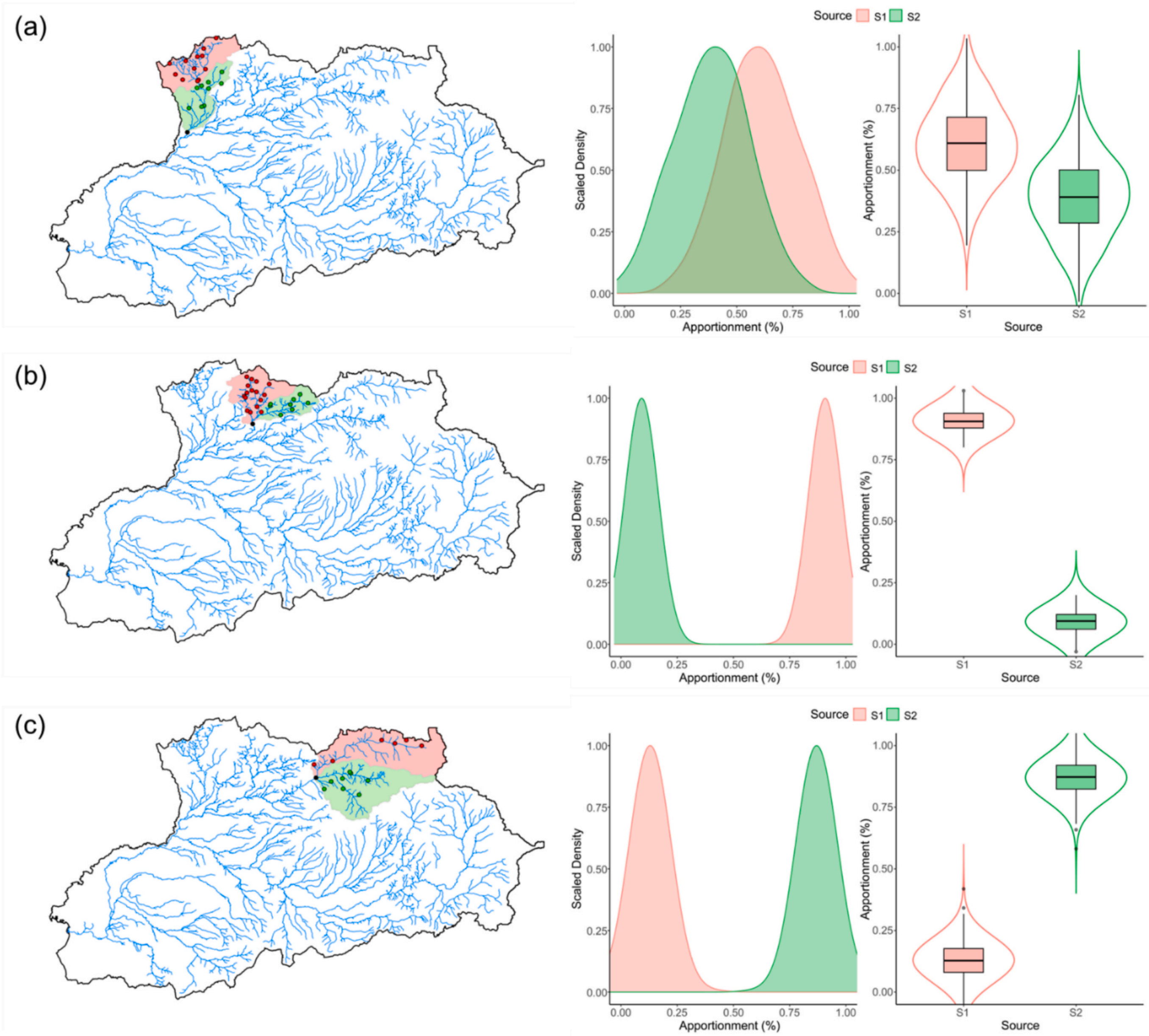

Fig. 6. Soil source apportionment results presented as scaled density and violin plots in the Ainamutua subcatchment 1 (a), Ainamutua subcatchment 2 (b), and Ainamutua subcatchment 3 (c), respectively. The black dots represent the unmixing point.

inaccurate (Gaspar et al., 2019; Lizaga et al., 2020c).

Historical sediment load assessments in the four largest Kenyan rivers (Nyando, Sondu-Miriu, Yala and Nzoia) entering Lake Victoria show that the Nyando has the highest contribution (Ong and Orego, 2002). Estimates of sediment loads in the Nyando and Sondu-Miriu rivers were predicted to be 1.46 x 10^6 Mg yr^{-1} and 5.17 x 10^5 Mg yr^{-1}, respectively (Misigo and Suzuki, 2018). There have been significant changes in land use and land cover in the Nyando River basin in the last 100 years. To meet the needs of a growing population new subsistence farming settlements have emerged on extremely steep slopes, without appropriate soil conservation measures, leading to high soil erosion and land degradation in the basin (Gathenya et al., 2011). Land degradation of this magnitude has severe negative impacts on soil fertility leading to poor crop performance, with many of the soils in the basin depleted of major soil nutrients (N, P, K) and exchangeable cations, rendering them inappropriate for conventional agricultural (Walsh et al., 2004). Soil conservation programmes in tropical African countries must focus on reducing soil erosion in degraded areas. However, the identification of these areas remains a challenge. In this study, we applied a nested sampling strategy to provide a better understanding of sediment provenance, in terms of the relative contribution of sub catchments, which can inform catchment management strategies.

In the Ainamutua subcatchment sources 1, 2 and 3 contributed 64 ± 16 %, 4 ± 19 % and 32 ± 9 % of the sediment in the streambed mixture, respectively (Fig. 5b). Source 1 has the smallest area (178 km^2) within the Ainamutua subcatchment (956 km^2); however, it contributes almost two-thirds of the total sediment output. In comparison to other sources in the catchment with more diverse land uses, source 1 is dominated by cultivated land (Supplementary Fig. 1). To further assess the sediment source provenance contributions in the Ainamutua subcatchment, soil samples were collected and unmixed against a composite streambed mixture (Fig. 6). These results can be used to pinpoint hotspots of sediment contribution arising from land degradation within the catchment. High soil erosion rates are attributed to agricultural expansion and overgrazing on sloped areas with high-intensity rainfall (James et al., 2023; Mati et al., 2008). Modelled soil erosion rates have shown

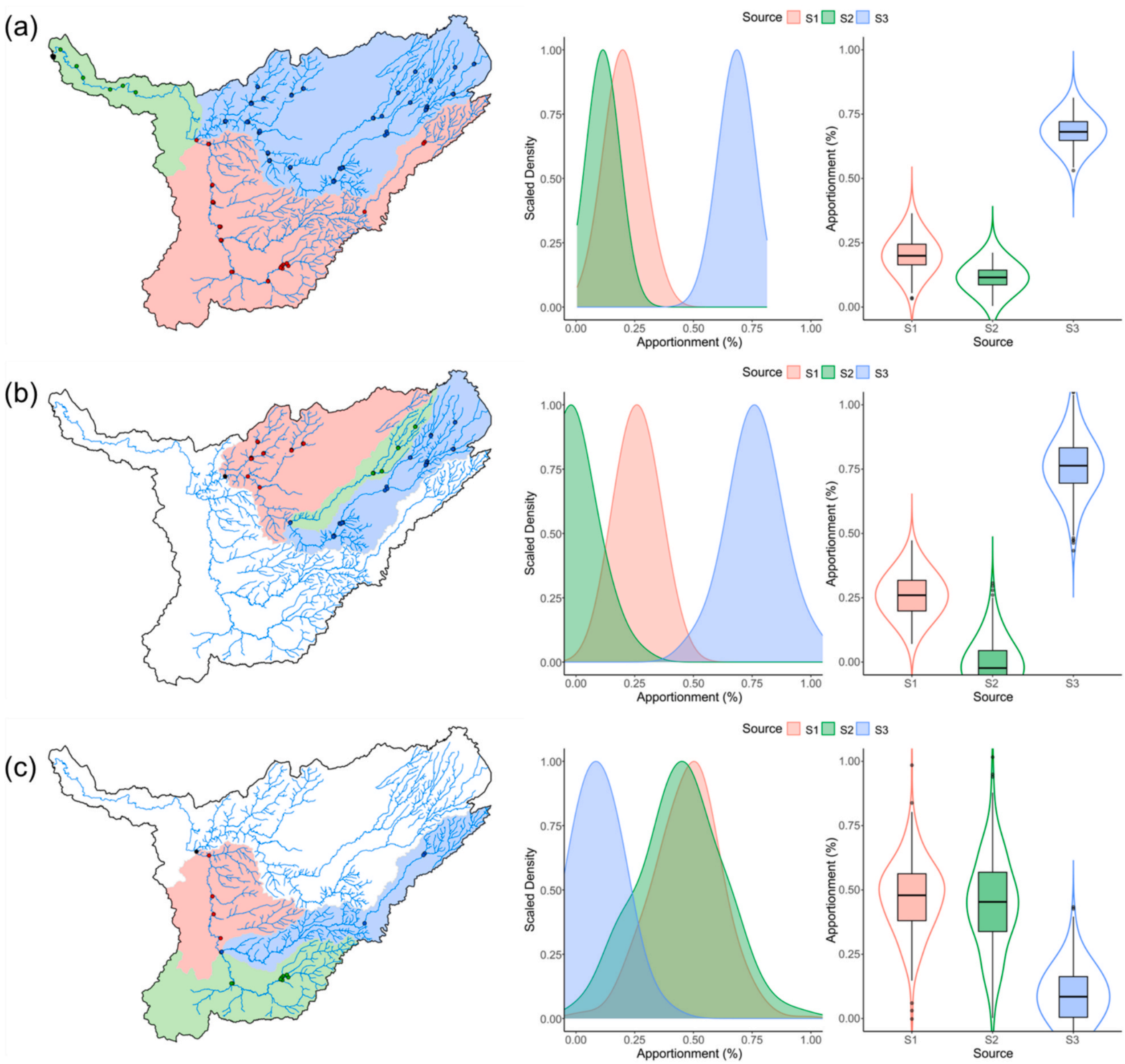

Fig. 7. Sediment source apportionment results presented as scaled density and violin plots in the Sondu-Miriu basin (a) and its subcatchments, the Yurith (b) and Kipsonoi (c), respectively. The black dots represent the unmixing point.

that this region has some of the highest potential soil loss > 20 t ha^{-1} yr^{-1} (Humphrey et al., 2022). This risk evaluation was recently validated using state-of-the-art plutonium isotopes to measure soil redistribution rates (Dowell et al., 2024), supporting the fingerprinting data. Source 2 has the lowest overall contribution to sediment within the Ainamutua subcatchment (Fig. 5b), however, by using the nested sampling design it is still possible to gain insightful information into the processes controlling soil loss in this region. This subsection of the Ainamutua subcatchment has two main landforms, ridges to the left and plains to the right (Supplementary Fig. 1). When assessing the soil source contribution (Fig. 6b) we can see that 91 $\pm$ 5 % (source 1) comes from the area with ridges, and only 9 $\pm$ 5 % (source 2) comes from the plains. In the Ainamutua subcatchment, source 3 had the second highest contribution (Fig. 5b). This area has extremely steep slopes which are increasingly being used for agriculture, in addition, this area is dominated by tea plantations in the north and the Tinderet Forest to the south (Fig. 1). Between 2000 and 2020 the Tinderet Forest lost 26.6 km^2 of tree cover, equivalent to a 10 % reduction in tree cover since 2000 (Potapov et al., 2022). The results of soil source apportionment show that 87 $\pm$ 8 % of the sediments originated from within the Tinderet Forest (Fig. 6c). Previously, Olang and Fürst (2011) investigated the impact of land cover change on flood peak discharges and runoff volumes in the Nyando basin. They determined that upstream subcatchments with higher rates of deforestation and agricultural expansion, including source 3, peak discharge increased by 30.2 % between 1973 and 2000. Given the continued deforestation we can assume that peak discharge will have increased over the past 20 years. The results presented here can be used to support policy options and catchment strategies geared towards soil erosion and flood runoff management.

In the Nyando-Kipchorian subcatchment, sources 1 and 2 contribute 25 $\pm$ 3 % and 75 $\pm$ 3 % of the sediment mixture, respectively (Fig. 5c). Despite the similar area of both sources, 771 km^2 and 876 km^2, respectively, there is a difference in their respective topography and land uses. Croplands, forests, and grassland make are 63 %, 26 % and 10 % of the land in source 1 and 70 %, 25 %, and 4 % in source 2, respectively. In the Simiyu River catchment in Tanzania grasslands have decreased from 59.3 to 7.6 %, coinciding with the dramatic expansion of cultivation (James et al., 2023; Zhang et al., 2020). Additional studies in

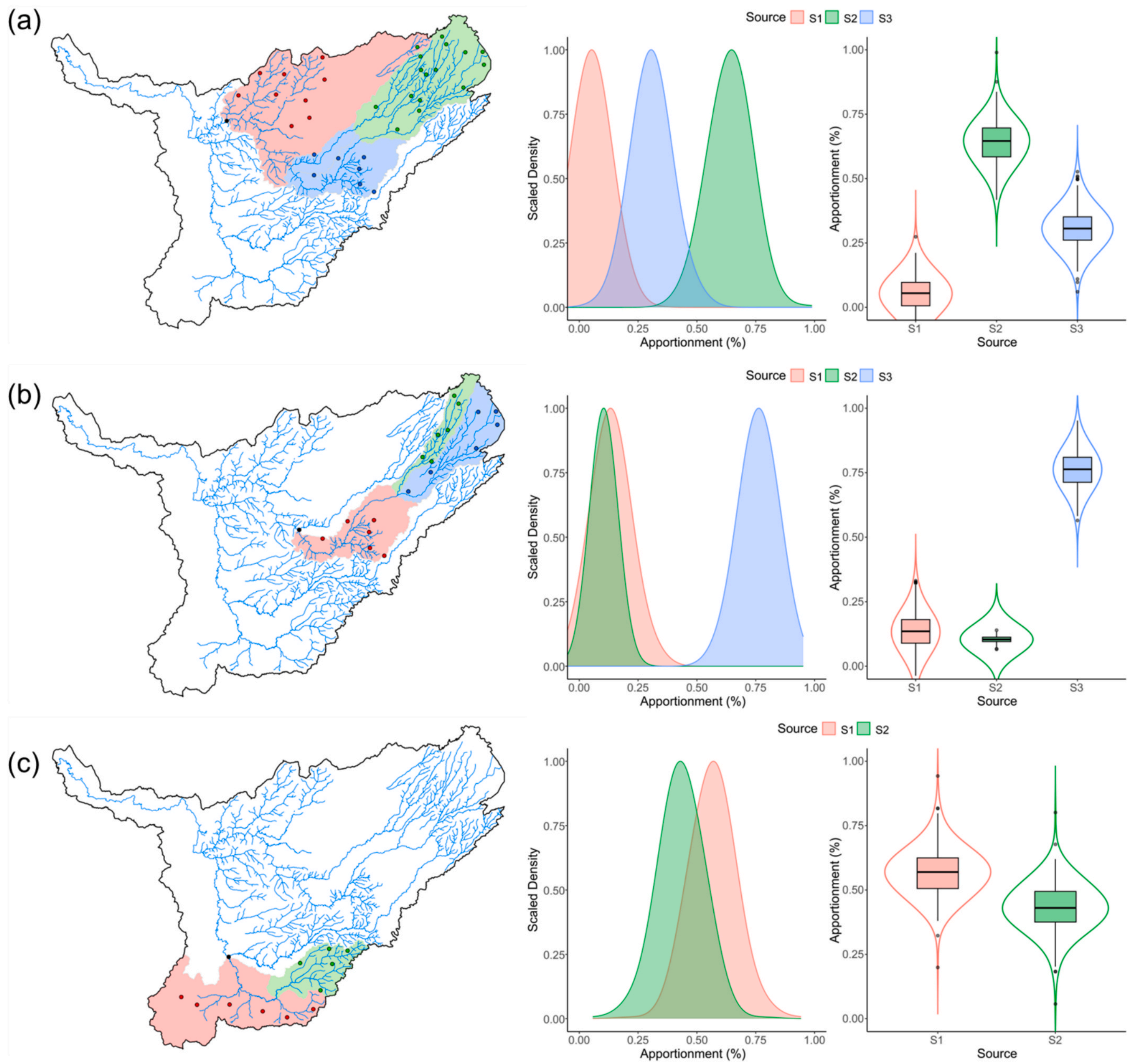

Fig. 8. Soil source apportionment results presented as scaled density and violin plots in the Yurith subcatchment (a); Yurith subcatchment 1 (b); and Kipsonoi subcatchment 1 (c), respectively. The black dots represent the unmixing point.

East Africa highlighted that land use changes have significantly impacted sediment dynamics in the river peak flow erosion rates, and suspended sediments and nutrients in the river (Dutton et al., 2018; Guzha et al., 2018). In the southernmost subcatchment, the Awach Kano and Nyaidho, both sources contribute 50 ± 15 % of the composite sediment in the streambed mixture (Fig. 5d). It is likely that the source of the sediments is the upland area to the south of the subcatchment with higher elevation and greater soil erosion risk (Supplementary Fig. 1). This area of the subcatchment is dominated by the Kano Plains, an area that has been severely impacted by flooding, which impacts > 5000 people resulting from poor catchment management (Omungu, 2014). The average damage of these floods exceeds $850,000, with additional relief and rehabilitation measures costing $600,000 (Eitel and Ochola, 2006). Deforestation in the Nyando's headwaters has previously been identified as a major contributing factor increasing runoff, erosion and the frequency of flooding in the Kano Plains. The increased runoff into the floodplains not only accelerated erosion in the basin, but also increased the vulnerability of the region to large flow events with devastating consequences for farmlands (Ocholla, 2010).

In the Sondu-Miriu catchment, the unmixing model revealed that the Yurith and the Kipsonoi subcatchment contributed 68 ± 5 % and 20 ± 6 %, respectively with the remaining 11 ± 4 % of sediment being introduced after the subcatchment had converged (Fig. 7a). Similarly to the Nyando, the low standard deviation of all sources combined with a high GOF result (96 ± 2 %, Supplementary Table 16) indicates that the model has effectively discriminated the contribution of the identified sources. The total sediment load of the Sondu-Miriu is approximately one-third of the Nyando at 5.17 x 10^5 Mg yr^{-1} (Misigo and Suzuki, 2018), with the majority originating from the upper zone (1700–2800 m.a.s.l) in the Yurith subcatchment. Additional sediment unmixing in both the Yurith

(Fig. 7b) and Kipsonoi (Fig. 7c), coupled with soil apportionment (Fig. 8) highlights the complex interactions associated with soil erosion, transport and unmixing modelling.

In the Yurith subcatchment the two largest sources are 1 and 3, which contribute 26 ± 8 %, and 76 ± 12 %, respectively (Fig. 7b). There are similar land uses within both sources, with the main difference being the addition of tea plantations in source 1. The results in the present study indicate that the upland region, with a greater proportion of subsistence agriculture, is the primary source of soil in the sediments in this subcatchment (Fig. 8a, b). Stenfert Kroese et al. (2020b) investigated seasonal sediment variation and sediment responses to hydrology in three contrasting catchments in the Yurith subcatchment in the Mau Forest Complex. They assessed suspended sediment yields over a four-year period and found significantly ($p < 0.05$) higher yields in subsistence agricultural catchment (131.5 ± 90.6 Mg km^2 yr^{-1}) compared to tea/tree plantations (42.0 ± 21.0 Mg km^2 yr^{-1}) and natural forests (21.5 ± 11.1 Mg km^2 yr^{-1}). Moreover, their research highlighted that natural forests and tea/tree plantations delivered water to streams through subsurface pathways, whereas surface runoff was dominant in agricultural catchments. This further highlights that vegetation cover is a very effective soil conservation method, as catchments with bare soil and poor soil conservation practices generated six times more suspended sediment yield (Stenfert Kroese et al., 2020b). Our results support these previous assessments of source apportionment. In the Yurith subcatchment 1 source 3, predominately covered by subsistence agriculture contributes 76 ± 7 % whilst source 1 which is in the midst of the South West Mau Forest only contributes 13 ± 7 %, yielding similar contributions to Stenfert Kroese et al. (2020b). Additional source apportionment assessments within the MixSIAR un-mixing modelling within the subsistence agricultural catchment revealed that agricultural land accounted for 75 % (95 % confidence interval 63–86 %) of the total sediment, significantly higher than channel banks at 21 % (8–32 %) unpaved tracks 3 % (0–12 %), and gullies 1 % (0–4 %) (Stenfert Kroese et al., 2020a). Interestingly, whilst rural unpaved tracks did not significantly contribute to the sediment yield, future management strategies should focus on disconnecting these unpaved paths from hillslope sources as a measure to reduce sediment yields to Lake Victoria (Stenfert Kroese et al., 2020a).

In the Kipsonoi subcatchment 1, 57 ± 9 % and 43 ± 9 % come from sources 1 and 2, respectively (Fig. 8c). Planosols are the dominant soil type in this region, making up 48 and 39 % of the area within sources 1 and 2, respectively (Supplementary Fig. 1). Planosols are found in low relief and plain landscapes prone to periodic flooding and drying cycles, typical in this region of the study area. Previous soil mapping studies in the Eastern Cape, South Africa have shown that planosols are the most susceptible to gully erosion and mitigation efforts should be implemented to limit the extent of land degradation. Conservation measures include minimising the accumulation of water within the soil, promoting vegetation growth coupled with decreased grazing to increase evapotranspiration, and establishing vegetation on existing gullies (Du Plessis et al., 2020).

Accelerated eutrophication caused by increased sediment yields stemming from nutrient-rich topsoil in poorly managed pastoral land and deforested areas is a major threat to the already enriched Lake Victoria (Chislock et al., 2013; Stenfert Kroese et al., 2020a). Following the first comprehensive sediment sampling and elemental spatial distribution of the Winam Gulf, Aura et al. (2024) observed distinguishable enrichment zones at the mouths of major rivers, including the Nyando and Sondu-Miriu, flowing into the Winam Gulf. As such, a holistic approach with targeted land management strategies for urban, industrial, transportation, and agricultural frontiers is required to reduce sediment inputs into the lake ecosystem. To reduce the sediment yield in the Nyando and Sondu-Miriu catchments targeted for soil management policies are required. Dynamic soil erosion loss rates have shown that bare soil and sparse vegetation cover at the beginning of the long rainy season leads to greater soil erosion susceptibility (Humphrey et al., 2022), with the largest proportion of the total sediment budget (~60 %) generated during this period (Stenfert Kroese et al., 2019). Stenfert Kroese et al. (2020a) recommended the installation of terraces on steep slopes and the introduction of vegetative buffer strips to moderate surface runoff which can potentially trap eroded material. However, recent assessments into soil erosion rates using fallout radionuclides on agricultural small holdings with alternative management practices (terracing, community-led bottom-up mitigation, and no mitigation) showed the highest soil erosion rates were found on the terraced plots, due to poor installation (~8.9 Mg ha^{-1} yr^{-1}) (Dowell et al., 2024). These results stress the importance of engaging with the community when implementing soil erosion mitigation practices.

4. Conclusions

Within Kenya, anthropogenically accelerated soil erosion caused by deforestation, agricultural expansion and unsuitable farming practices negatively impacts soil fertility and crop yields with the increased nutrient-rich sediment loads causing eutrophication and the degradation of aquatic environments. In this study, we aimed to quantify the relative contribution of sediment sources within the Nyando and Sondu-Miriu River basins in the Winam Gulf catchment, Kenya using source apportionment unmixing modelling to provide a tool to support the sustainable management of land and water resources in a region significantly impacted by land degradation. This data tool can be used to inform targeted mitigation activities in catchments where resources for land management are limited and no continuous monitoring of sediment fluxes exists. We employed conservativeness index (CI), consensus ranking (CR) and consistent tracer selection (CTS) methods to identify the optimum unmixing tracers within the FingerPro mixing model. Sediment source analysis revealed that the Ainamutua and Nyando-Kipchorian subcatchments, areas predominantly affected by land degradation activities such as poor crop management practices and deforestation on steep slopes, contributed 39 ± 4 % and 44 ± 4 %, respectively. In contrast, the Awach Kano and Nyaidho subcatchment, with a higher proportion of tree-cover and lower soil erosion rates, only contributed 17 ± 7 %. In the Sondu-Miriu catchment, the Yurith and Kipsonoi subcatchments contributed 68 ± 5 % and 20 ± 6 %, respectively, due to the predominance of forest encroachment and ridges in the Yurith catchment. Additional soil fingerprinting analysis pinpointed specific regions within the catchment where land use, soil type, and landform significantly influence source contribution and targeted erosion mitigation strategies are required to limit soil erosion and control annual sediment yield. Future studies could investigate the impact of seasonal variation by collecting time-integrated suspended sediment samples throughout the year to develop a greater understanding of sediment contribution fluxes arising from natural vegetation dynamics and erosional processes. Quantifying sediment source contributions within large river basins provides essential information for environmental managers and policymakers developing integrated catchment management plans. These policies require an emphasis on decreasing soil erosion, promoting ecological restoration and disconnecting sediment transport processes to Lake Victoria to ensure the sustainable use of water and soil resources.

CRediT authorship contribution statement

Olivier S. Humphrey: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Job Isaboke:** Writing – review & editing, Resources. **Odipo Osano:** Writing – review & editing, Resources, Funding acquisition, Conceptualization. **Christopher Mulanda Aura:** Writing – original draft, Funding acquisition, Conceptualization. **William H. Blake:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Michael J. Watts:** Writing – review & editing, Project administration, Funding acquisition, 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.2025.109053.

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