Journal of Soils and Sediments (2024) 24:3781–3788
https://doi.org/10.1007/s11368-024-03908-5

SEDIMENTS, SEC 3 • HILLSLOPE AND RIVER BASIN SEDIMENT DYNAMICS • RESEARCH ARTICLE

The sources and selectivity characteristics of organic carbon transported by debris flow events in a mountainous catchment, Southwest China

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Received: 9 January 2024 / Accepted: 15 September 2024 / Published online: 3 October 2024

Abstract

Purpose This study aims to obtain a preliminary understanding on the sources of debris flow sediments and the characteristics of organic carbon (OC) transported by debris flow events.

Methods Samples from debris flow and debris flow deposits as well as potential sources in the catchment were collected. For the collected samples, we measured grain size compositions, OC concentrations and properties such as C:N ratio, stable C isotopic composition and OC components derived from nuclear magnetic resonance (NMR) spectroscopy.

Results As inferred from OC concentrations, C:N ratios and $\delta^{13}C$ values, we found that OC in debris flow sediments and bare land soils are mainly petrogenic OC, while OC in forest, cropland and grassland soils contained a large fraction of biospheric OC. Fine particles were found to be preferentially transported in debris flow, and the particle selectivity decreased with increasing debris flow erosion intensity. However, no selectivity was observed for OC contained in debris flow, which is different from the widely observed preferential mobilization of OC in sediments by surface erosion.

Conclusions Our results show that sediments in debris flow are mainly sourced from bare lands. The fact that there are no significant differences in the petrogenic OC concentrations in various size fractions of debris flow sediment sources leads to no selectivity of OC in debris flow despite of selectivity of sediment particles.

Keywords Debris flow · Petrogenic organic carbon · Sediment transport · Southwest China · Organic carbon property

1 Introduction

Geomorphic processes have an important effect on the climate by regulating the global biogeochemical cycles. For instance, chemical weathering of silicate minerals removes atmospheric CO_2, which is referred to as the 'weathering thermostat' at the geologic timescales because of the feedbacks between tectonic activities, silicate weathering and climate change (Brantley et al. 2023). In addition, physical erosion also poses important impacts on global carbon (C) cycling through (i) burial and preservation of biospheric organic carbon (OC) in depositional environments transferred from eroding areas and (ii) exposure and oxidation of petrogenic OC contained in bedrock (e.g. Galy et al. 2007;

Responsible editor: Nikolaus Kuhn

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Torres et al. 2014; Hemingway et al. 2018; Hilton and West 2020).

Identifying sediment sources is of primary importance to quantify the effects of erosion on C cycling, because preservation of biospheric OC derived from vegetation photosynthesis results in an atmospheric C sink while oxidation of petrogenic OC releases C to the atmosphere (Hilton and West 2020). Sediment properties that are distinctly different between sediment sources as well as invariable during sediment transport by erosion can be used as tracers to locate the sediment sources. Sediment tracers such as rare earth elements (REE), soil magnetism, luminescence and fallout radionuclides (e.g. ^{137}Cs and $^{210}Pb_{ex}$) have been widely used in various environments (e.g. Parsons and Foster 2011; Mabit et al. 2014; Gray et al. 2019), which could further be employed in end-member mixing models to derive quantitative contributions from different sediment sources.

Sediment selectivity exists in various types of geomorphic processes because particles of various sizes behave differently at the moment of entrainment or deposition (e.g., Beuselinck et al. 1999; Hairsine et al. 2002). The associated OC was simultaneously sorted, because the organo-mineral interactions result in different efficiencies on OC adsorption with fine particles containing more OC in terms of per unit mass (Schiettecatte et al. 2008; Wang et al. 2010). Organic carbon components were also preferentially adsorbed by particles of particular sizes with aromatic-C found to be enriched in coarse soil particles and alkyl and O-alkyl C enriched in fine particles such as clay and silt (Lalonde et al. 2012; Han et al. 2016). As a result, sediment selectivity results in spatial variations of grain size as well as OC in both quantity and property, which further leads to spatial variations of C cycling at the landscape scale (Van Oost et al. 2005; Yoo et al. 2005; Wang et al. 2020).

Substantial efforts have been invested to explore the soil organic carbon (SOC) transported by water erosion as well as SOC cycling in both eroding and depositional regions (Harden et al. 1999; Galy et al. 2015; Wang et al. 2015). Past studies mainly focused on the effects of surface erosion on C cycling, but the effect of debris flow on OC transport has received little attention. Debris flow is a common hazard in mountainous regions, which occurs on the condition of steep slopes and sufficient loose materials. Compared to surface erosion, a debris flow is generally of higher erosion intensity, and the mobilized materials are from deeper layers. Thus, OC transport by debris flow may be different from that by surface erosion, and it would be helpful to fully understand the role of erosion in global C cycling by exploring the OC transport by debris flow.

In this study, we collected samples from debris flow and debris flow deposits as well as potential sources in the catchment. For the collected samples, we measured grain size compositions, OC concentrations and properties such as C:N ratio, stable C isotopic composition and OC components derived from nuclear magnetic resonance (NMR) spectroscopy. Our objectives are (i) to identify the sources of debris flow in the studied catchment and (ii) to characterize the sediment and OC transport by debris flow.

2 Materials and methods

2.1 Study area

This study was carried out in the Jiangjiagou Catchment, which is a part of the Yangtze River Catchment (Fig. 1). The catchment covers a total area of 48.6 km^2, and the length of the mainstream channel is 13.9 km (Guo et al. 2020). The study area has a mean annual temperature of ca. 20 °C and an average annual precipitation of 600–700 mm. Soils in the region are mainly Ferralsols according to the WRB system (WRB IUSS Working Group 2015). The bulk density of the soils in the top layer ranges from 1.67 to 2.05 g cm^{-3} (Zhang et al. 2023). The study area is mainly covered by forests (e.g. *Pinus yunnanensis*), grasses (e.g. *Heteropogon contortus*) and crops (e.g. corn and peanut). Due to active tectonics and human activities such as deforestation, debris flow events are frequent in the Jiangjiagou Catchment (Guo et al. 2020).

2.2 Soil sampling and laboratory processing

Soil samples from potential source areas (i.e., forest, cropland, grassland and bare land) and sediments of debris flow and debris flow deposits were collected to explore the sources of sediment and associated OC in debris flow and to characterize the mobilization of sediment and OC by debris flow (Fig. 1). In forest, grassland and cropland areas, three 20 m × 20 m transects were established at each site with intervals less than 20 m. In each transect, six sampling points were selected according to the method of Poeplau and Don (2013). For each site, all soil samples were collected to the depth of 10 cm and were mixed to one composite sample as a representation of the sampling site. Soil cores were excavated using a hammer drill, before the organic matter layer (O horizon) was removed. In bare land areas, samples were taken from deposits on slopes resulting from landslides. Five topsoil (0–10 cm) samples were randomly collected along the hillslope. At the Dongchuan Debris Flow Observation Station, 62 debris flow samples were collected from 2004 to 2008 at the moment when debris flow occurred. Flow velocity and discharge were also monitored at the time of sampling. Sediment concentrations were measured for the collected samples. Eight samples were collected at different positions of the debris flow fans, and were mixed to one composite sample as a representation of the debris flow deposits. All samples were air-dried and passed through a

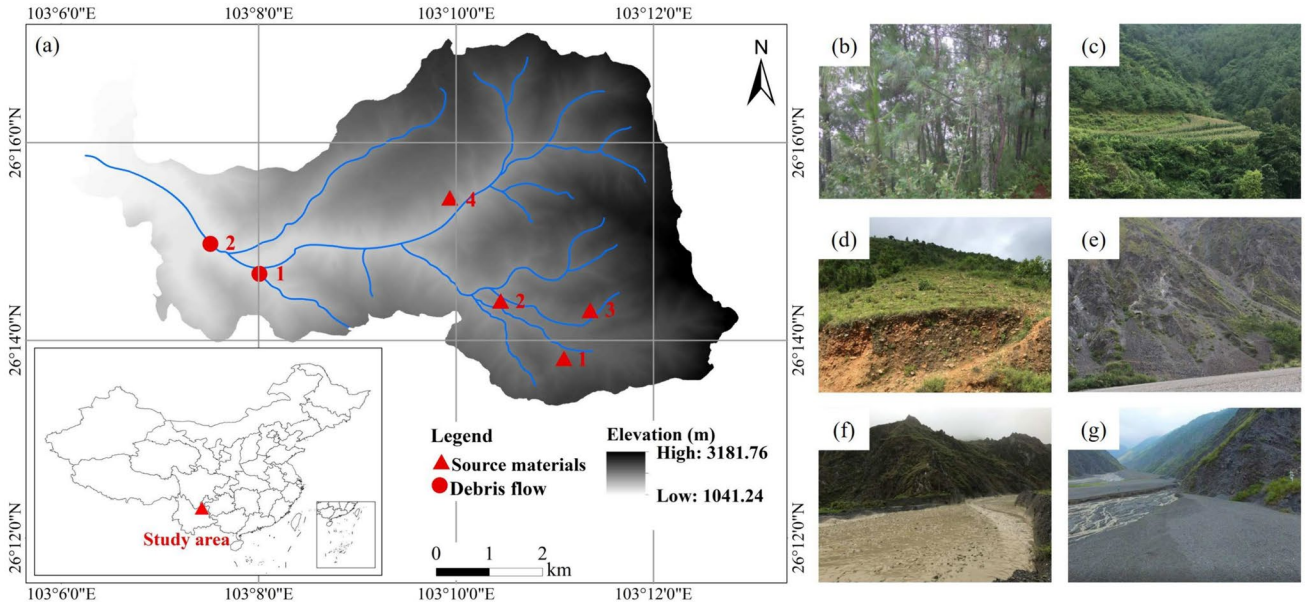

Fig. 1 The locations of study area and sampling sites (**a**) and photos of forest (**b**), cropland (**c**), grassland (**d**), bare land (**e**), and debris flow (**f**) and debris flow deposits (**g**). Source material areas 1, 2, 3 and 4 marked with triangles in (**a**) refer to forest, cropland, grassland and bare land, respectively. Debris flow sites 1 and 2 marked with circles refer to debris flow and debris flow deposits

2 mm sieve after removing plant roots and stones manually. Soil texture was measured using a Mastersizer 2000 laser grain-size analyzer after adding 50 ml solution of sodium hexametaphosphate and sodium carbonate (1%) to 20 g sediment/soil for dispersion.

2.3 Fractionation of OC pools

Fractions of OC pools were physically separated based on the particle size (Plante et al. 2006; Stewart et al. 2008). Air-dried soil samples (<2 mm) added with sodium polytungstate solution (1.85 g cm^{-3}) were ultrasonically dispersed for ca. 3 min, and centrifugated for ca. 30 min. The suspension was filtered using 0.45 µm cellulose nitrate filters and washed with deionized water to remove the free light fraction. The remaining suspension was wet-sieved using 250 µm and 53 µm sieves to obtain the three particle size fractions (i.e. 250–2000 µm, 53–250 µm and < 53 µm). The derived three fractions were dried and grounded for further analysis.

2.4 Measurements of OC, total nitrogen and stable C isotope

Soil samples were fumigated with the HCl solution (0.50 mol L^{-1}) to remove inorganic C (Harris et al. 2001). The concentrations of OC and total nitrogen (TN) of various fractions of the samples were measured using an Elemental Analyzer (Vario EL cube, Hanau, Germany) after the soil samples had been oven-dried. The natural abundance of $\delta^{13}C$ values in OC were determined with an isotope ratio mass spectrometer (Delta V Advantage, Germany). The stable C isotopic composition was expressed as the relative value to the Vienna Pee Dee Belemnite (PDB) standard:

$$\delta^{13}C\ (‰) = \left(\frac{\left({}^{13}C/{}^{12}C\right)_{\text{sample}}}{\left({}^{13}C/{}^{12}C\right)_{\text{standard}}} - 1 \right) \times 1000 \quad (1)$$

where $\left({}^{13}C/{}^{12}C\right)_{\text{sample}}$ and $\left({}^{13}C/{}^{12}C\right)_{\text{standard}}$ are the molar ratio of ^{13}C to ^{12}C of the soil sample and the international PDB reference, respectively.

2.5 NMR spectroscopy

Grounded soil samples were combined with 10% (in volume) hydrofluoric acid solution and oscillated for ca. 30 min to reduce paramagnetic substances (Schmidt et al. 1997; Rumpel et al. 2006). The suspension was centrifuged and set for at least 12 h before the supernatant liquid was removed with a plastic syringe (Schmidt et al. 1997). The remaining samples in the centrifuge tube were washed with deionized water until pH became neutral. After being freeze-dried for ca. 48 h and grounded, the chemical compositions of soil samples were determined using a solid-state ^{13}C NMR spectrometer (Bruker Avance III 400 MHz NMR spectrometer, Germany) with cross polarization and magic angle spinning (CPMAS). The ^{13}C NMR spectra were divided into four chemical shift regions, representing alkyls (0–45 ppm),

O-alkyls (45–110 ppm), aromatic (110–160 ppm), and carboxyl C (160–220 ppm), respectively (Baldock et al. 1992).

2.6 End-member mixing model

The end-member mixing model has been widely used to quantify the relative contributions of various source materials in mobilized sediments (McCorkle et al. 2016; Liu et al. 2021). The end-member mixing model was used to determine the sources of OC in debris flow and debris flow deposits based on the following mass-balance equations:

$$\delta^{13}C_D = \sum_{j=1}^{n} f_{Sj} \times \delta^{13}C_{Sj} \quad (2)$$

$$(C:N)_D = \sum_{j=1}^{n} f_{Sj} \times (C:N)_{Sj} \quad (3)$$

$$\sum_{j=1}^{n} f_{Sj} = 1 \quad (4)$$

where $\delta^{13}C_D$ and $\delta^{13}C_{Sj}$ are the $\delta^{13}C$ values of the debris flow and source materials, respectively; $(C:N)_D$ and $(C:N)_{Sj}$ are the C:N ratios of the debris flow and source materials, respectively; f_{Sj} is the relative contribution of various source materials to debris flow; n is the number of end-members.

2.7 Enrichment ratio

The enrichment ratio (ER) was used to evaluate the selectivity of different particle sizes (i.e., gravel, sand, silt and clay) and OC during the mobilization and deposition processes, which was calculated as:

$$ER_X = \frac{X_D}{X_S} \quad (5)$$

where X_D is the proportion of mineral particles (%) or OC (g kg^{-1}) in debris flow or debris flow deposits, and X_S is the proportion of mineral particles (%) or OC (g kg^{-1}) in source materials. ER_X values higher than 1 indicate enrichment of particles or OC in debris flow sediments, while ER_X values lower than 1 indicate depletion of particles or OC in debris flow sediments.

3 Results

3.1 OC concentrations and chemical compositions

Areas of grassland and bare land had high fractions of gravel (40–50%, Table 1), which is comparable to the gravel fraction in debris flow and debris flow deposits. In contrast, the gravel fractions in the forest and cropland areas were much smaller (ca. 2%). The 250–2000 μm fraction had lower OC concentration compared to <53 μm and 53–250 μm fractions in the forest, cropland and grassland areas (Fig. 2). The OC concentrations of fractions of <53 μm, 53–250 μm and 250–2000 μm were similar in bare land soils, debris flow and debris flow deposits. The OC concentrations of various fractions in debris flow and debris flow deposits were close to those of bare land soils, and were lower than those of the forest, grassland and cropland areas. As indicated by the NMR spectroscopy, the chemical compositions of OC in

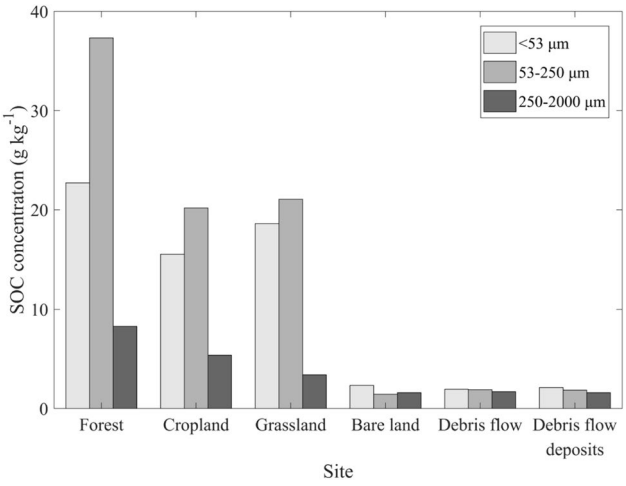

Fig. 2 SOC concentrations of various soil fractions for the sampling areas

Table 1 Grainsize composition of the sampling areas

Site	Grainsize composition			
	Clay (%) (<0.002 mm)	Silt (%) (0.002–0.05 mm)	Sand (%) (0.05–2 mm)	Gravel (%) (>2 mm)
Forest	24.10	58.03	15.40	2.47
Cropland	28.78	47.92	22.21	1.08
Grassland	9.55	27.18	19.32	43.95
Bare land	4.06	15.18	23.91	56.85
Debris flow	3.92	22.69	20.07	53.32
Debris flow deposits	6.69	30.61	13.04	49.66

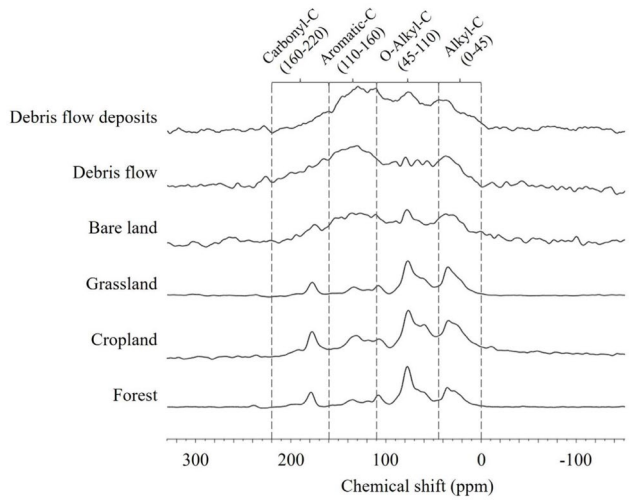

Fig. 3 The ^{13}C NMR spectra of SOC of fine particles (<2 mm) from the sampling sites

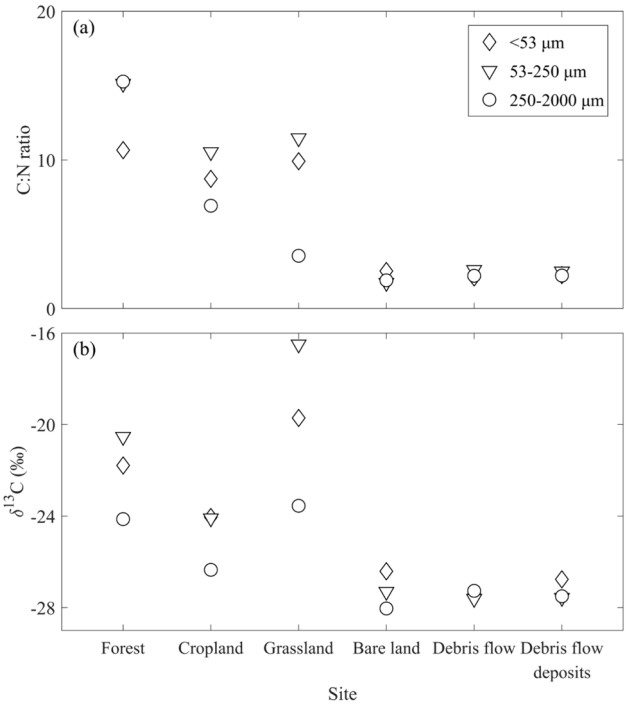

Fig. 4 C:N ratios (**a**) and $\delta^{13}C$ values (**b**) of various fractions for the sampling areas

fine particle (<2 mm) from forest, cropland and grassland had stronger signals of O-alkyls and alkyl C than aromatic C compared to bare land soils, debris flow and debris flow deposits (Fig. 3).

3.2 $\delta^{13}C$ values and C:N ratios

The C:N ratios of fine particles (fractions of <53 μm, 53–250 μm, and 250–2000 μm) in bare land soils, debris flow and debris flow deposits were similar, which were much lower than the C:N ratios of SOC from forest, cropland and grassland areas (Fig. 4a). The $\delta^{13}C$ values of various fractions in debris flow and debris flow deposits were similar to those of bare land, and were lower than those of soils from forest, cropland and grassland (Fig. 4b). In addition, OC in bare land soils, and debris flow and debris flow deposits were more assemble in the figure of the relationship between C:N ratios and $\delta^{13}C$ values (Fig. 5). Based on the end-member mixing model, the results of C:N ratio analysis indicated that more than 95% of OC in debris flow and debris flow deposits were derived from bare land and the $\delta^{13}C$ results showed that the OC in bare land soils contributed ca. 93% and 86% to the OC in debris flow and debris flow deposits, respectively (Table 2).

3.3 Sediment and OC selectivity

In debris flow, the enrichment ratios of gravel showed a positive non-linear relationship with velocity, discharge and sediment concentration (T-test, $p < 0.001$, Fig. 6). The enrichment ratios of sand, silt and clay showed a negative non-linear relationship with erosion intensity denoted by flow velocity, discharge or sediment concentration (T-test, $p < 0.001$). The OC enrichment ratio suggested no statistically significant relationship with velocity, discharge and sediment concentration.

4 Discussion

4.1 Sources of sediments and OC in debris flow

The OC concentration and properties are different between the potential sites, which warrants that they could be used as tracers to identify the sources of debris flow. Soils of forest, cropland and grassland receive C from vegetation (i.e., biospheric OC), while OC in bare land soils deposited by hillslope processes is mainly petrogenic OC derived from parent materials. This is verified by the OC properties of these potential debris flow sources. The $\delta^{13}C$ value of bare land soils was close to that in the regional rocks (ca. −27 ‰) as reported by Zhang et al. (2023). Also, the C:N ratio in petrogenic OC is lower than that in biospheric OC. Alkyl and O-alkyl Care labile fractions of OC, and they are preferentially mineralized during the thermal maturity of kerogen. As a result, petrogenic OC becomes enriched in more recalcitrant components such as aromatic and carboxyl C compared to biospheric OC (Agrawal and Sharma 2018). Similar to bare land soils, debris flow and debris flow deposits had lower OC concentration, less negative $\delta^{13}C$ values, lower

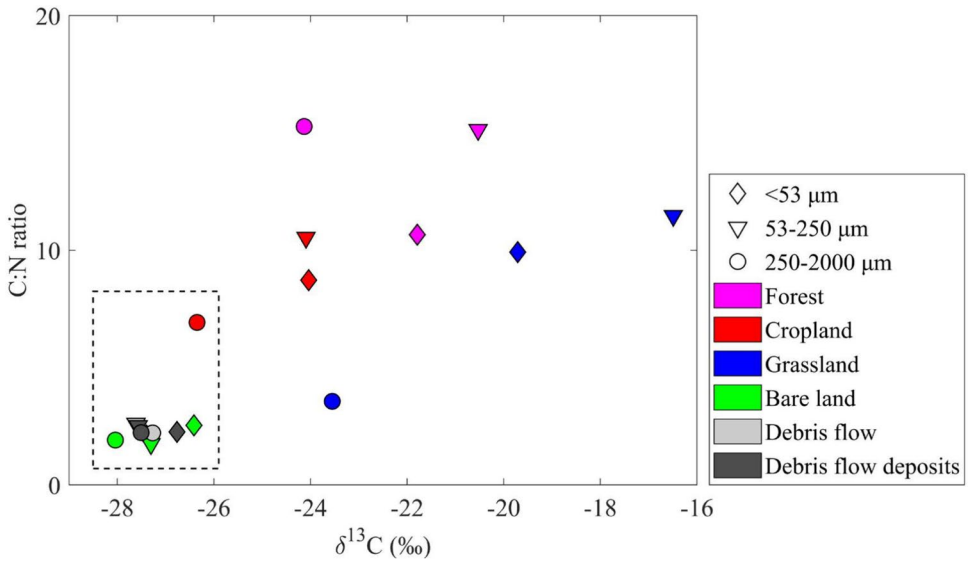

Fig. 5 The relationship between C:N ratios and $\delta^{13}C$ values of various SOC fractions for the sampling areas. The rectangle indicates the ranges of C:N ratio and $\delta^{13}C$ values of petrogenic OC

Table 2 Contributions of various sources to debris flow and debris flow deposits based on the end-member maxing model

Source	C:N		$\delta^{13}C$ (‰)	
	Debris flow	Debris flow deposits	Debris flow	Debris flow deposits
Forest	4.49	4.16	0	0
Cropland	0	0	7.00	13.82
Grassland	0.07	0	0	0
Bare land	95.44	95.84	93.00	86.18

C:N ratios and higher fractions of aromatic and carboxyl C compared to forest, cropland and grassland soils (Figs. 2, 3, and 4). This indicates that sediments in the debris flow and debris flow deposits were mainly sourced from bare land, which is consistent with the findings based on ^{137}Cs and soil magnetism in studies conducted in the catchment (Wen et al. 2003; Jia and Wei 2009). Although bare land covers less than 30% of the catchment area, it contributes ca. 90% of sediments in debris flow. This confirms the importance of vegetation in reducing debris flow erosion.

4.2 Sediment and OC selectivity

Sediments mobilized by interrill erosion and exported in the river system were found to be enriched in fine particles such as clay and silt, because fine particles (< 2 mm) were easier to be mobilized and transported (Wang et al. 2010, 2013). Debris flow was also found to be enriched in silt and clay in this study (Fig. 6). In events of high erosion intensities, both fine and coarse particles can be mobilized and transported, and thus the debris flow was found to become less selective for sediment particles with increasing erosion intensity (Fig. 6). This is consistent with the observations from Alps, where the fractions of silt and clay decrease with the increase of flow velocity (Bolliger et al. 2024). Apart from soil particles, SOC was also found to be preferentially mobilized and transported by surface erosion, because fine particles have a large surface area that helps to retain organic matter (Torn et al. 1997; Singleton et al. 2017). However, OC selectivity was not observed in debris flow (Fig. 6), which could be attributed to the difference of OC distribution in various size fractions between the source materials of surface erosion and debris flow. As observed in previous studies (Palis et al. 1997; Zinn et al. 2007), the SOC concentrations generally decrease with the increase of particle sizes for the source materials of surface erosion (i.e. soils) (Fig. 2). However, for the source materials of debris flow (e.g. bare land soils in this study), the OC concentrations in the fraction >250 μm and fractions <250 μm were similar (Zhang et al. 2023). Therefore, when sediment sorting occurs, OC selectivity is observed in surface erosion but not in debris flow. The causes of the differences in the variations of OC with particle sizes are mainly because OC in bedrocks has different sources from that in soils. OC in bedrocks is mainly petrogenic OC (enriched in aromatic and carboxyl C as inferred from NMR spectroscopy, Fig. 3), which already exists before the bedrock is broken into particles of different sizes by physical weathering. Physical weathering does not alter the mineral composition, and therefore the particle size of the source materials of debris flow is not related to mineral compositions. Therefore, there are no significant differences in the OC concentrations in various size fractions of sediments in the debris flow and debris flow deposits. For soils, the major part of OC is biospheric

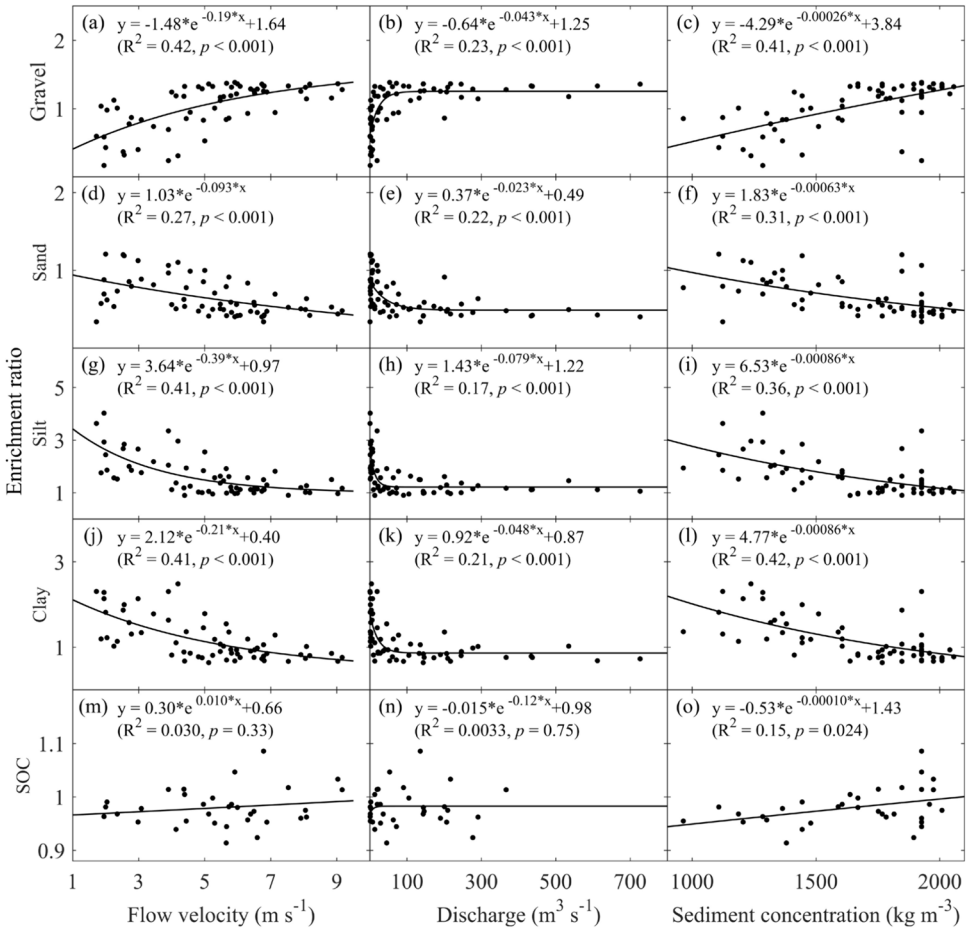

Fig. 6 The relationship between the enrichment ratios of different particle sizes and flow velocity, discharge and sediment concentration of debris flow

OC (enriched in O-alkyls and alkyl C, Fig. 3), which is added to soil particles by vegetation. Thus, fine particles are more efficient in adsorbing biospheric OC in terms of per unit soil mass because of large surface areas (Palis et al. 1997; Zinn et al. 2007).

5 Conclusions

Lateral fluxes of OC caused by erosion exert an important impact on global C cycling, but transport of OC by debris flow has received little attention. Our study showed that OC properties could be used as a tracer for sediment sources due to the distinct differences between petrogenic OC from bedrocks and biospheric OC from shallower layers of vegetated soils. OC in debris flow had lower C:N ratio, more negative $\delta^{13}C$ values and higher fractions of aromatic and carboxyl C, which indicated that OC contained in debris flow sediments was mainly petrogenic OC. Thus, the debris flow was mainly sourced from bare land with similar OC properties. Since OC concentration did not vary with particle sizes in the bare land, debris flow was not found to be selective for OC.

Acknowledgements This study is funded by the Natural Science Foundation of China (grant no. 52125902, 52388101 and 42171025).

Data availability Data are available from the corresponding author on request.

Declarations

Competing interests The authors declare no competing interests.

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