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Improving the design and implementation of sediment fingerprinting studies: summary and outcomes of the TRACING 2021 Scientific School

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Abstract

Purpose Identifying best practices for sediment fingerprinting or tracing is important to allow the quantification of sediment contributions from catchment sources. Although sediment fingerprinting has been applied with reasonable success, the deployment of this method remains associated with many issues and limitations.

Methods Seminars and debates were organised during a 4-day Thematic School in October 2021 to come up with concrete suggestions to improve the design and implementation of tracing methods.

Results First, we suggest a better use of geomorphological information to improve study design. Researchers are invited to scrutinise all the knowledge available on the catchment of interest, and to obtain multiple lines of evidence regarding sediment source contributions. Second, we think that scientific knowledge could be improved with local knowledge and we propose a scale of participation describing different levels of involvement of locals in research. Third, we recommend the use of state-of-the-art sediment tracing protocols to conduct sampling, deal with particle size, and examine data before modelling and accounting for the hydro-meteorological context under investigation. Fourth, we promote best practices in modelling, including the importance of running multiple models, selecting appropriate tracers, and reporting on model errors and uncertainty. Fifth, we suggest best practices to share tracing data and samples, which will increase the visibility of the fingerprinting technique in geoscience. Sixth, we suggest that a better formulation of hypotheses could improve our knowledge about erosion and sediment transport processes in a more unified way.

Conclusion With the suggested improvements, sediment fingerprinting, which is interdisciplinary in nature, could play a major role to meet the current and future challenges associated with global change.

Keywords Sediment tracing · Catchment · Basin · Watershed · Source-to-sink · Critical zone · Local knowledge · Sediment fingerprinting

1 Introduction

Sediment fingerprinting or tracing (both terms will be used interchangeably throughout the article) is a relatively recent technique developed in the 1970s and 1980s that allows quantification of sediment contributions from catchment sources by relying on the conservativeness of soil and sediment properties (Loughran et al. 1982; Peart and Walling 1986). After a first descriptive phase, the implementation of un-mixing modelling opened the way to quantitative approaches calculating sediment source contributions in target material (Walling and Woodward 1992; Collins et al. 1997). The technique has received increased attention during the last three decades, which is demonstrated by the sharp increase in research articles and several review papers describing its potential, the associated drawbacks, and discussing potential implications for catchment management (Haddadchi et al. 2013; Koiter et al. 2013; Walling 2013; Owens et al. 2016; Collins et al. 2017, 2020; Laceby et al. 2017). So far, sediment fingerprinting research has mainly focussed on methodological issues or on the use of fingerprinting results to support soil conservation and catchment restoration (Smith et al. 2015; Laceby et al. 2019).

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Although sediment fingerprinting has been applied with reasonable success, the deployment of sediment fingerprinting methods remains associated with many issues (e.g., spatial and temporal representativity of source and sediment sampling, conservative behaviour of tracers, particle size correction, number of tracers incorporated into un-mixing models, and validation of model outputs). To move forward and improve the design and the implementation of sediment fingerprinting procedures, discussions have been initiated in the framework of international conferences (e.g., Fall Meeting of the American Geophysical Union (AGU) in December 2017). Following up on these, an International Scientific School entitled "*Emerging strategies of sediment and contaminant tracing in catchments and river systems*" (initial suggested acronym "TRACING2020") was scheduled to be organised at the University Paris-Saclay, France, in May 2020. Participants from across the globe, involving both early-career and experienced researchers, were expected to gather and discuss sediment fingerprinting issues (see the full School programme in the Supplementary Information, Fig. 1). Unfortunately, the outbreak of the COVID-19 pandemic disrupted those plans and, after several postponements, the School could finally take place in October 2021 in Saint-Lambert-des-Bois, France (and was eventually referred to as "TRACING2021"). Only those participants working in European countries and possessing a valid European Union-compatible COVID vaccination certificate were able and allowed to attend the event. Although the group of attendants was restricted to a geographical region, the meeting was fruitful and led to several outputs, including the current feedback article. The main objective of the School was to update the participants' knowledge on state-of-the-art techniques and methodological issues associated with sediment fingerprinting. Most of the experienced researchers participating to the Thematic School were invited to share their knowledge in their primary field of expertise. We are

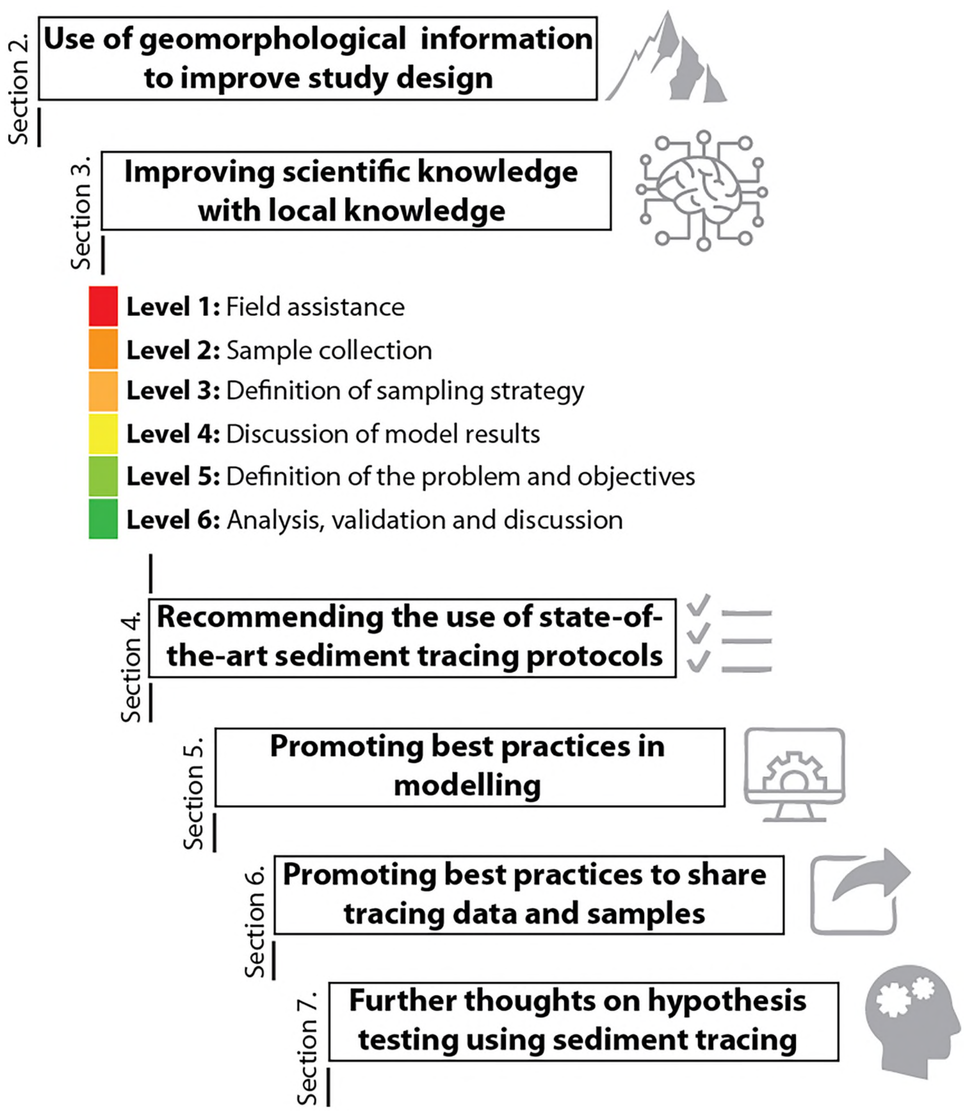

Fig. 1 Organisation of the main recommendations proposed and discussed during the TRACING 2021 School to improve the design and implementation of sediment fingerprinting studies

sharing here the main issues discussed and the most important take-home messages. Of note, the idea is not to duplicate previous recommendations nor to take away the merit of recent review articles on the technique, but instead to share ideas and suggestions that may go beyond those described in the publications mentioned above. In addition, we aim to stimulate discussions and encourage the use of what was identified as good practices by the participants. Our suggestions are described in the next sections, and they are organised around the following topics (Fig. 1): ("Sect. 2") a better use of geomorphological information to improve study design; ("Sect. 3") improving scientific knowledge with local knowledge; ("Sect. 4") recommending the use of state-of-the-art sediment tracing protocols; ("Sect. 5") promoting best practices in modelling; ("Sect. 6") promoting best practices to share tracing data and samples; and ("Sect. 7") further thoughts on hypothesis testing using sediment tracing methods.

2 Using geomorphological information to improve study design

With the aim of understanding the provenance of sediment and that of mapping hotspots of soil erosion, sediment fingerprinting studies strongly benefit from an in-depth understanding of the catchment geomorphology and, more specifically, soil erosion and sediment connectivity. Seasonal changes in hydro-meteorological conditions (e.g., glacial, nival, or pluvial) or land use and cover may translate into distinct soil erosion patterns and processes, and consequently, a seasonality in sediment provenance and yield. Such relationships are often well understood (Lemma et al. 2019, 2020) and are very important for the interpretation of sediment fingerprinting results and the associated uncertainties (Stutenbecker et al. 2019). Furthermore, sediment provenance can also be variable over short time scales. For example, soil erosion and sediment connectivity may vary with rainfall type and pattern. As shown by Navratil et al. (2012a), widespread rainfall events tend to produce more homogeneous sediment signatures than localised rainfall events such as heavy storms. Sediment provenance between flood events can, therefore, vary significantly (Navratil et al. 2012a, b). The timing of sediment sampling along the flood hydrograph may also have an impact on sediment fingerprinting results, as sediment sources transiting at catchment outlets were shown to vary considerably during runoff events (Duvert et al. 2010; Legout et al. 2013). Capturing this variability, therefore, requires frequent temporal measurements (Poulenard et al. 2012). This is also supported by the careful examination of flood hysteretic patterns and their relationship with erosion processes (Navratil et al. 2012b). A targeted fingerprinting approach is thus important, focussed on the environmental issues of interest (Battista et al. 2020).

Geomorphological information can also provide guidance for tracer selection or potential sediment source classification. For instance, in catchments with homogeneous lithologies, it will sometimes be complex to use elemental geochemistry to discriminate between different land uses (Tiecher et al. 2017), and other – more straightforward – tools such as the bulk analysis of organic matter composition (Fox 2009) or compound-specific stable isotope (CSSI) signatures may be used instead (Reiffarth et al. 2016, 2019; Lizaga et al. 2021). In contrast, in catchments with heterogeneous lithologies, an approach relying on geochemical concentrations will likely be meaningful to discriminate between contrasted sources that align with distinct terrains (e.g., steep headwaters on resistant lithology vs. erodible hills on weaker rocks) (Sellier et al. 2021). However, such an approach may be complicated when addressing specific environments where mixed sediment deposits occur, such as high mountain areas where glacial till covers a large part of the catchment.

Besides supporting the design of fingerprinting studies, complementary information can also be collected using other geomorphological methods. This includes topographic surveys, the analysis of aerial photographs or satellite images (Foucher et al. 2021b), sediment facies surveys (Minella et al. 2008; Navratil et al. 2010; Vandromme et al. 2017), hydro-sedimentary monitoring (Navratil et al. 2012b; Gateuille et al. 2019), the calculation of connectivity indices (Borselli et al. 2008; Chartin et al. 2017), hydro-sedimentary modelling (Launay et al. 2019; Dabrin et al. 2021), and soil erosion modelling (Palazón et al. 2016). Recent methodological developments relying on cutting-edge devices may enable a more flexible approach in collecting complementary information, such as the deployment of uncrewed aerial vehicles to map sediment connectivity patterns with a high spatial and/or temporal resolution (Heckmann et al. 2018) across hillslopes and catchments (Estrany et al. 2019; Hooke et al. 2021). The analysis of contrasted types of sediment matrices (e.g., lag deposits, suspended matter, sediment cores, and riverbed sediment) or that of multiple particle size fractions can also provide information on various aspects of the environmental problem under consideration (Navratil et al. 2012a; Laceby et al. 2017). The deployment of tracing strategies relying on multiple lines of evidence (i.e., those obtained with different methods) may be facilitated in catchments where long-term monitoring is being conducted, which is more frequent for water gauging than for sediment observations. These long-term monitoring units are increasingly connected in the framework of regional (Rhone Sediment Observatory; www.graie.org/osr/spip.php?rubrique62), national, or international networks (e.g., critical zone observatories; https://czo-archive.criticalzone.org/national/; https://www.lter-europe.net/) (Brantley et al. 2017).

3 Improving scientific knowledge with local knowledge

An important, but often overlooked, way of obtaining detailed geomorphological information on the catchment is to exchange with local communities, who often have profound knowledge on topics such as (i) the chronology and magnitude of flooding events, (ii) the distribution of rainfall across the catchment, (iii) the areas eroded during the major floods that affected the region (main landslide zones, areas exposed to sheet erosion or gullying, extent of channel bank erosion), (iv) the level of connectivity of the sediment sources to the stream network, (v) information on seasonal variations in vegetation or crop rotations, and (vi) the success of implemented erosion control techniques or the conservation methods. During field campaigns, we often meet, discuss, and work with locals, such as inhabitants, municipality workers, and NGO employees. Scientists can (and should) cross-check scientific knowledge with information obtained from local communities, who often know their living environment better than anyone else in terms of land use development and relevance of geomorphological processes. This constitutes the local knowledge as defined by Bélisle et al. (2018). In addition, locals may facilitate site accessibility or assist in sampling and/or indicate the occurrence of specific environmental issues in the study area.

During the TRACING 2021 School, several arguments were given in favour of better integration of scientific and local knowledge. First, the collection of multiple sediment source samples across the catchment is often challenged by access restrictions. A closer collaboration with local communities might facilitate access to private properties and remote locations. Despite that, it takes time to build good relationships and gain trust, and in some situations, this might also be needed to avoid conflicts between stakeholders, or the generation of new conflicts. Second, the integration of scientific and local knowledge also allows for a rapid briefing of the situation of interest and allows for a rapid refinement of the sampling strategy. Locals' knowledge of erosion/sedimentation processes can help identifying key locations of erosion/sedimentation and may make short fieldwork more efficient and relying on a limited number of samples. Locals may also provide crucial context-specific knowledge, which is not made available in any document (e.g., occurrence of major floods leading to massive sediment deposition when gauging stations are not available), and allow cross-checking of multiple sources of information. Third, when scientific and local knowledge are not sufficiently integrated, catchment management efforts may prove to have limited success (Frankl et al. 2018). Fourth, the involvement of local communities in the research process contributes to local development and provides local experts with opportunities to become active players in research and natural resource management (Blaikie 2006; Frankl et al. 2016). Moreover, it can offer an opportunity to raise awareness regarding the potential of sediment fingerprinting and generate synergistic collaborations with local environmental managers. During this collaboration, a didactic task could be to train local managers on why/how/when applying sediment fingerprinting. This will likely facilitate the future use of the sediment tracing results for river and catchment management (e.g., Collins et al. 2017). For instance, the organisation of focus groups and interviews would allow all the stakeholders to be brought around the table to participate in the selection of potential sources and sampling sites (as already tested for flood risk management by Lane et al. 2011). The sampling plan could also be integrated into a citizen science project. From an "action research" perspective (i.e., research methodology widely applied in social science seeking to obtain a transformative change through the simultaneous process of taking action and doing research) aimed at making a diagnosis and at transforming local practices over the medium to long terms, the concerted stage of defining the sediment sampling plan would appear to be as important as the ultimate results of the un-mixing models. Fifth, in a context of conflicts among stakeholders, the integration of these different levels of knowledge could avoid discrediting the results of a sediment fingerprinting study carried out by a team of scientists working in isolation or in collaboration with only a part of the stakeholders.

These arguments making the case for better integrating of scientific and local knowledge may open a new avenue for sediment fingerprinting, although – as already analysed in social science – these approaches are not free of critiques (Belisle 2018). The first critique is that many scientists are sceptical regarding the validity of informal knowledge because it may be perceived as subjective and lacking rigour (Chalmers and Fabricius 2007). Indeed, local inhabitants often have an excellent understanding of local and recent events, but processes occurring at wider spatial and longer temporal scales might not be obvious to them (i.e., pluri-decadal or centennial scales). Local and scientific knowledge should thus be complementary. A second critique deals with deontological perspectives. The lack of recognition of the significance of fieldwork and interview techniques may lead to a lack of knowledge of the basic ethical rules to be aware of when conducting fieldwork with local stakeholders (i.e., helicopter research) (Minasny et al. 2020). A third critique may be associated with the difficulty in involving all local stakeholders. Indeed, if only one group of locals (e.g., male, senior) or one group of stakeholders participates, the collected information may be biased, and the results may lose credibility in front of the non-represented stakeholders. Therefore, it is essential to approach all stakeholders and to avoid any instrumentalisation of the results or our role of scientists in the stakeholders' interactions.

Thus, considering the arguments and limitations identified above, a question asked during the TRACING 2021 School was: what could be the levers to promote a better integration of local and scientific knowledge for sediment fingerprinting? A first suggestion is to set up interdisciplinary/transdisciplinary projects as accessing and understanding local knowledge calls upon concepts and methods from both environmental and social sciences. Based on what can be proposed in the framework of ethnographic fieldwork, sediment collection guides could thus describe ethical recommendations to be followed in the field when collecting sediment samples and local knowledge on erosion processes. Another suggestion was to recognise the role of local knowledge in our work thoroughly. In order to gain academic legitimacy, it may be important to better define at the onset of a project the level of involvement that is sought from each stakeholder (e.g., during empirical data collection only or throughout the entire project as co-researchers). The level of involvement will depend on the main issue of interest, research funding, and the social and political contexts. Based on citizen science literature, we propose herein a first "scale of participation and engagement" for sediment fingerprinting, with six levels (from the lowest to the highest; Fig. 1). Level 1 corresponds to a field assistance for site access for source and sediment sampling; level 2, to the collection of river sediment during floods; level 3, to the definition of source and sediment sampling locations and timing; level 4, to the discussion of model results with all the stakeholders; level 5, to the participation in the definition of the problem, the objectives, and the identification of sediment sources; level 6, to the analysis, validation, and discussion of the modelling results (e.g., uncertainties and sampling choices). We argue that the level of involvement of local communities should be explicitly mentioned in our scientific productions in the "Materials and Methods" section and further discussed. Scientific publications on sediment fingerprinting would thus gain in better outlining the limits and biases that may arise during fieldwork, rather than sweeping this sediment problem – i.e., the scientists/local community interactions and knowledge hybridisation – under the carpet!

4 Recommending the use of state-of-the-art sediment tracing protocols

Once the study design has been refined with all the available information and the potential sediment sources have been determined, a "stratified" sampling strategy is suggested. The number of sources to discriminate should remain limited: a specific suggestion is to limit it to four (Lees 1997). At the same time, there is also a need to consider the minimum number of sources needed to provide meaningful insight into erosion and sediment delivery processes within a catchment. To avoid the merging of sources at a later stage of the sediment fingerprinting procedure, researchers should check during the initial design of their study that the sources considered are sufficiently different in nature to be discriminated against each other. This recommendation may seem obvious, but numerous examples have been found in the literature where the objective is, for instance, to discriminate between cropland and grassland in zones with mixed crop-livestock farming. Both sources will ultimately need to be merged (Lamba et al. 2015; Ramon et al. 2020). A sufficient number of source samples should be collected to characterise each source, and cover its spatial and temporal variability and – as much as possible – the entire extent of the catchment if potential sources are to be found across the entire drainage area.

A compromise is to be found on the number of samples to collect, given the time, budget, field, and logistical constraints. However, the number of samples should be maximised, as a larger number of source samples will always provide a more robust basis for analysis, modelling, and discussion (Clarke and Minella 2016; Du and Walling 2017). As a community, we require a better articulation of this cost–benefit consideration and its implications for the methods adopted and the likely strength of conclusions (e.g., qualitative vs. quantitative estimates of source contributions). In addition, there is a lack of standardised protocols for sampling sediment sources in catchments affected by widespread environmental disturbances. For example, in catchments affected by fires, soil characteristics will change following the incorporation of ashes (García-Comendador et al. 2020). Therefore, in such conditions, the refinement of the sampling protocol (e.g., incorporating the layer of ash or partially or completely removing it to reach the mineral soil surface) and the sampling time (e.g., collecting material immediately after the fire or a few days later) requires further research.

To avoid the multiple difficulties associated when sampling soils across catchments (e.g., field accessibility, safety, and budget limitations), an alternative strategy is to consider sediment deposited in tributaries as potential source material supplied to the main river (Vale et al. 2016; Laceby et al. 2017). This tributary tracing approach will – of course – be facilitated in catchments where tributaries drain very contrasted sub-catchments in terms of lithology or land use (Sellier et al. 2019). In more homogeneous catchments, this strategy may simply be seen as a way to avoid the complex sampling of soils across the entire drainage area.

The main limitations and challenges associated with the deployment of the sediment tracing technique have been detailed elsewhere (Collins et al. 2020). However, to move forward, we want to share some basic principles that should be taken into consideration when designing a sediment fingerprinting study. This may facilitate the future comparison or aggregation of results obtained from different studies.

First, the tracer selection should rely as much as possible on a solid bio-physico-chemical basis (i.e., the analysed tracers provide differentiation between sources relying on meaningful biological, physical, or chemical properties). This will strengthen the basis for discrimination and facilitate the results' interpretation while avoiding running a "blind" statistical approach (Laceby et al. 2015). For instance, when the main objective is to discriminate the contributions of surface cropland and channel bank erosion, the use of ^{137}Cs (Evrard et al. 2020a) or that of bulk organic matter properties (Garzon-Garcia et al. 2017) – both found to be enriched in topsoil layers and depleted in subsoil layers – is likely the best targeted approach. In contrast, the use of geochemical properties to discriminate between land cover types is likely not the best targeted approach whereas these parameters will be more appropriate to discriminate the origin of sediment coming from tributaries with contrasting lithologies. Of note, in regions where strong interactions between plants and the characteristics of the soils on which they grow are found, geochemical properties will likely provide a useful tool for quantifying the sediment supply from areas covered with some target plant types (Darmody et al. 2004; Ji et al. 2009; Cramer et al. 2019). Furthermore, it should be widely encouraged to systematically obtain multiple lines of evidence (i.e., complementary data obtained with different techniques or information deduced from the analyses of various tracer properties) regarding the sediment source contributions (Laceby et al. 2019). As each type of tracer is associated with inherent limitations, the analysis of several types of tracers should be envisaged (Boudreault et al. 2018; Ramon et al. 2020) and limitations arising when combining tracers (e.g., fallout radionuclides, mineral magnetic properties, organic matter bulk, and compound-specific stable isotopes) should be overcome (Guan et al. 2017).

Second, one of the main issues that the researchers implementing sediment fingerprinting approaches have been dealing with is that of the particle size effects on result interpretations (Smith and Blake 2014). The particle size of the sediment load may be variable as a result of different processes being activated in the catchment, which are size-selective. Surface erosion may for example lead to pulses of finer sediment (Gateuille et al. 2019). Furthermore, particle sorting also occurs along the fluvial network (Walling et al. 2000), with the finest particles being detached first and transported the farthest from the source (Knighton 2014; Laceby et al. 2017). The most widely applied technique to deal with particle size is to sieve both source and target material to a given threshold (often < 63 µm), although corrections of tracer concentrations have also been widely applied based on the analyses of potential tracers and particle size distributions on bulk material (Collins et al. 1997; Gellis and Noe 2013). Nevertheless, the effectiveness of these corrections was shown to be limited in certain cases (Smith and Blake 2014; Koiter et al. 2018). A recommendation that could be made for future research is that of analysing the particle size of target material before selecting the threshold retained for analysis. With the increasing availability of granulometers, providing the distribution curves of particle size in both source and target material or the associated metrics (e.g., d10, d50, d90) should be considered.

Third, data should be carefully examined after measuring the selected tracing properties and before running statistical tests and un-mixing models. For instance, this can be achieved visually with boxplots or scatterplots, and such careful examination will indicate whether a source is likely missing or is not well represented, or whether some of the tested properties may not behave conservatively. With these graphs, it can rapidly be visually checked that the tracer values found in the target material lie within the range of properties found in the potential sources, if tracers provide sufficient source discrimination, and will often reveal the main source contributing the target sediment. Of note, conducting a visual check and a range test will not avoid problems related to changes in tracer signatures during sediment transport, mainly in environments characterised by strong physico-chemical gradients (e.g., salinity and redox conditions). A similar problem may occur when applying the sediment fingerprinting procedure to a sediment core covering a long period during which the tracers considered may have been impacted by anthropogenic releases throughout time. In these conditions, it has recently been suggested to use the signature of the non-reactive fraction of sediment for quantifying the source contributions (Begorre et al. 2021).

As for the collection of source samples, the collection of suspended sediment samples is subject to significant costs due to associated workload and laboratory analyses needed (Laceby et al. 2019). Therefore, often, only a limited number of samples are collected and analysed, providing uncomprehensive insights into sediment dynamics, as source contributions may change during storm events as well as throughout the year because of changing land surface characteristics (Walling 2005). The need to better characterise sources with a higher temporal resolution has been well identified in the literature in order to provide better insights into changes of sediment sources over time (Navratil et al. 2012b; Vercruysse et al. 2017; Collins et al. 2020). During the School, options to overcome these issues regarding sampling and laboratory workload were discussed, proposing methods such as the development of low-cost sensors or the use of field-deployable spectrophotometers (Martínez-Carreras et al. 2016; Lake et al. 2021), which could eventually measure sediment fingerprints in situ, at a high temporal frequency and for long periods of time.

5 Promoting best practices in modelling

Since the introduction of un-mixing models in sediment source fingerprinting research (Peart and Walling 1986; Yu and Oldfield 1989; Collins et al. 1997), great progress has been achieved by the tracing community. A major development was the inclusion of bootstrapping and Bayesian approaches to estimate the uncertainty in sediment fingerprinting source apportionments (Franks and Rowan 2000; Rowan et al. 2000). Accordingly, multiple modelling frameworks are available, often with different structures, features, expertise requirements, and code availability (Gorman Sanisaca et al. 2017; Pulley and Collins 2018; Stock et al. 2018; Lizaga et al. 2020b). As a result, models have become more accessible and easy to apply, which is a considerable accomplishment from the community. However, as model utilisation increases, so does the potential for misapplication. In particular, modelled source apportionments may create an illusion of certainty and conceal limitations in the input data, particularly when models are applied as black-boxes. Hence, we would like to suggest some best practices in modelling.

We would like to incentivise researchers to rethink if un-mixing models are always necessary when it comes to sediment fingerprinting (García-Comendador et al. 2021; Pulley and Collins 2021). There are situations in which simply analysing tracer values in source and target material might be sufficient to draw relevant conclusions. For instance, scatterplots often reveal the dominant signal in a mixture without the application of models. Moreover, calculating source contributions might be counterproductive in situations where, for instance, the number of source samples is limited. This is because models will always produce an output, even when the input data is highly flawed. A similar case can be made regarding the use of mineralogical properties (Hein et al. 2013) and environmental DNA (Evrard et al. 2019; Frankl 2022) as sediment tracers, as these fingerprints cannot be used – at this stage – for quantitative source attribution.

However, there are many situations in which un-mixing models can provide useful quantitative information regarding source provenance. For instance, managers might be interested in quantifying the effectiveness of soil conservation measures to reduce the sediment delivery from a given source (Patault et al. 2019). Of note, un-mixing models provide estimates of proportional source contributions. A reduction in the sediment load from a source due to conservation measures may produce a decrease in the proportional contribution from that source, but this will correspond with an apparent increase in the proportional contribution from other sources even if these remain unchanged in load terms (given proportional source contributions sum to 100%). Unless before/after sediment load data is available to convert proportional information into source-specific loads, it will not be possible to meaningfully assess the before and after effect of soil conservation measures using proportional source data alone. This should be taken in consideration when interacting with managers. When un-mixing models are to be used for source attribution, we would also like to emphasise the importance of reporting the uncertainty in the model outputs (Cooper et al. 2015; Sherriff et al. 2015). Current modelling approaches provide multiple solutions, to which confidence or credible intervals can be attributed. Hence, fingerprinting source apportionments should ideally be reported as a measure of central tendency alongside measures of dispersion and include distribution plots of model outputs. We believe it is important to embrace the uncertainty in the modelled source apportionments to interpret and identify flaws in our data. Reducing the uncertainty in modelled source apportionments through modelling artifacts will likely not lead to knowledge improvements or more informed decision making. Instead, it should be acknowledged that the quality of the input data (e.g., number of samples, discriminative power, and conservativeness of the tracers) and decisions related to how we treat that data and the associated modelling procedures (e.g., possible removal of outliers, application of data corrections, selection of tracers, and choice of model error structures) can affect the accuracy of model outputs and the associated levels of uncertainty.

Tracer selection approaches were also discussed in the Tracing School. Generally, un-mixing models require n – 1 tracers to determine the contributions of n sources to the mixture, where ideally, each of the sources should have at least one tracer that strongly discriminates it from the other sources. In the last decades, there has been no general agreement in the community regarding the different tracer selection methods. Current approaches to tracer selection rely on (i) a three-step procedure, starting with a range test to identify the tracers outside of the mixing polygon, a Kruskal–Wallis test to identify tracers that provide discrimination between at least one of the sources, and a linear discriminant analysis to define a tracer suite that maximises source distinction; (ii) maximising the number of tracers by only excluding non-conservative fingerprints; (iii) process- or knowledge-based frameworks considering the interpretation of the bio-physico-chemical properties of the sources; and (iv) novel methods for identifying consistent tracers, i.e., which do not produce mathematical inconsistencies in the potential model solutions. A debate exists on the reliability of the most widespread methods such as the three-step procedure or the mixing polygon. As an alternative, recently, Lizaga et al. (2020c) and Latorre et al. (2021) developed the new methods of consensus ranking and consistent tracer selection that produce similar outputs in un-mixing with either frequentist or Bayesian models. These methods detect the non-conservative, non-consensual, and non-consistent tracers, display and inform on the effect of each tracer into the fingerprinting models, and extract if there are multiple solutions in a dataset. In our opinion, this lack of consensus stems from the difficulties in testing/replicating tracer selection approaches in comprehensive datasets (i.e., full databases comprising all the tracing properties analysed in both the potential source and target material) for a range of contrasted catchments, as these are almost non-existent. Hence, we would like to reemphasise the importance of sharing raw data in our publications and promote the idea of shared datasets, which is discussed in the following section ("Sect. 6"). In addition, we encourage the community to run different tracer selection procedures and compare the resulting tracer selections (or analyse them all) and the corresponding mixing model outputs to better understand the sensitivity of results to tracer selection.

Finally, outputs from sediment fingerprinting applications in general, and modelled source apportionments in particular, require testing. That is, as any model output, fingerprinting-estimated source contributions should be evaluated against independent sources of data in order to assess their ability to provide acceptable representations of a system (Beven 2009). A common thread in our debates in the Tracing School relates to the importance of obtaining multiple lines of evidence to evaluate sediment fingerprinting source ascriptions. Although artificial laboratory or mathematical mixtures can allow us to evaluate the ability of models to un-mix source contributions in a controlled setting (Gaspar et al. 2019), they cannot provide definite information regarding the accuracy of source apportionments in reality (e.g., considering actual target sediments from a catchment, which can be investigated by means of submersion experiments) (Poulenard et al. 2012; Legout et al. 2013; Uber et al. 2019). Hence, it is important to strive for different sources of data to corroborate the results from sediment fingerprinting studies (Navratil et al. 2012b; Palazón et al. 2016). These data might potentially include measurements of sediment fluxes, the outputs of hydro-sedimentary models, modelled catchment erosion (Wynants et al. 2020) and sediment transport rates (Batista et al. 2021), remote sensing information (Lizaga et al. 2020a), local knowledge, and ultimately our own geomorphological interpretation of the catchment dynamics. However, it needs to be acknowledged that this compilation of different sources of data is associated with considerable challenges, not least of which is due to the cost associated with assembling this additional information (given cost is frequently cited as a constraint in sampling/analysis). We can make inferences from sediment load data, but this is rarely collected at multiple locations within a catchment. Catchment models need to be treated with caution given they come with considerable uncertainty. Perhaps what is needed is a more concerted effort to "field test" sediment fingerprinting results. While difficult, this demonstration of performance in natural settings is needed given that lab/numerical mixtures provide an idealised measure of performance by ignoring potential non-conservative tracer behaviour.

6 Promoting best practices to share tracing data and samples

A recent review on the use of ^{137}Cs as a tracing property showed that very few studies provided the raw data used in the publication and key catchment information, including the size of the drainage area and the outlet coordinates (Evrard et al. 2020a), most of the articles reporting the summary statistics of the measurements, or including graphs/tables showing part of their dataset. A similar finding was obtained for data associated with sediment core dating (Foucher et al. 2021a) or gully erosion (Frankl et al. 2021). This does not exempt us from self-criticism, as some of our previous articles failed to comprehensively report raw data. Therefore, the objective of this section is to propose concrete strategies to improve data sharing in the future. A similar initiative has recently been taken in the hydrological science community (Hall et al. 2021). This approach is not only virtuous for our research practice but it is also often imposed by law (e.g., INSPIRE Directive 2007/2/EC of the European Parliament). In the near future, journals may also require the authors to systematically provide their raw data or any mode of open access to this information, and we feel that our research community should anticipate this situation. The ultimate objective to reach would be to comply with the F.A.I.R. principles when sharing our datasets, requiring that they are "Findable, Accessible, Interoperable and Reusable" (https://www.go-fair.org/fair-principles/) (Wilkinson et al. 2016, 2018). Therefore, they must be described as precisely as possible using general or thematic metadata and a controlled vocabulary allowing this interoperability. Tools are available online to assist the community with the upload of this metadata based on sample registration (e.g., SESAR, https://www.geosamples.org/ or other national allocating agents) or existing general or thematic metadata schemes for analytical datasets (e.g., Datacite, Iso19115, EML). The use of data dictionaries to describe column headings in files (with relevant measurement units) will facilitate the good reusability of the data. Field-specific terminology (a list may be found on https://fairsharing.org/) used in publications should strictly follow international guidelines (Pourret et al. 2020). Each sample may then be related to a given sampling campaign and associated with an International Geo Sample Number (IGSN), a unique sample identifier, and related to common metadata in geoscience (e.g., sample type, geographic coordinates of sampling location, altitude of sampling location, sampling date, catchment/river name, and sampling protocol) (Fig. 2). After registering samples and formatting their metadata, the data itself can then be uploaded onto a repository. The most frequently used data repositories in our community are likely Zenodo (https://zenodo.org/) and Pangaea (https://www.pangaea.de/), although other options exist and have been reviewed and compared recently (https://dataverse.org/blog/comparative-review-various-data-repositories). Of note, quality assurance and quality control procedures for analytical data should also be described in publications and reported with the dataset (via a ReadMe file or a data dictionary) using the proper terminology (Pourret et al. 2020).

Once the dataset has been uploaded onto a data repository, the associated Digital Object Identifier – DOI – can be used to refer to the dataset in manuscripts submitted for publications or in data papers, and referenced in the project's Data Management Plan (DMP) as a data product. Examples of these databases can be found online (Evrard et al. 2020b). Of note, additional information should be added to fully describe the sampling protocol and facilitate the inter-comparison and aggregation of results between studies, including information on the sediment matrix, the soil layer depth sampled, the particle size (fraction of interest or the outputs of the particle size analysis if available), and the reference date for decay-correction of radionuclide activities typically.

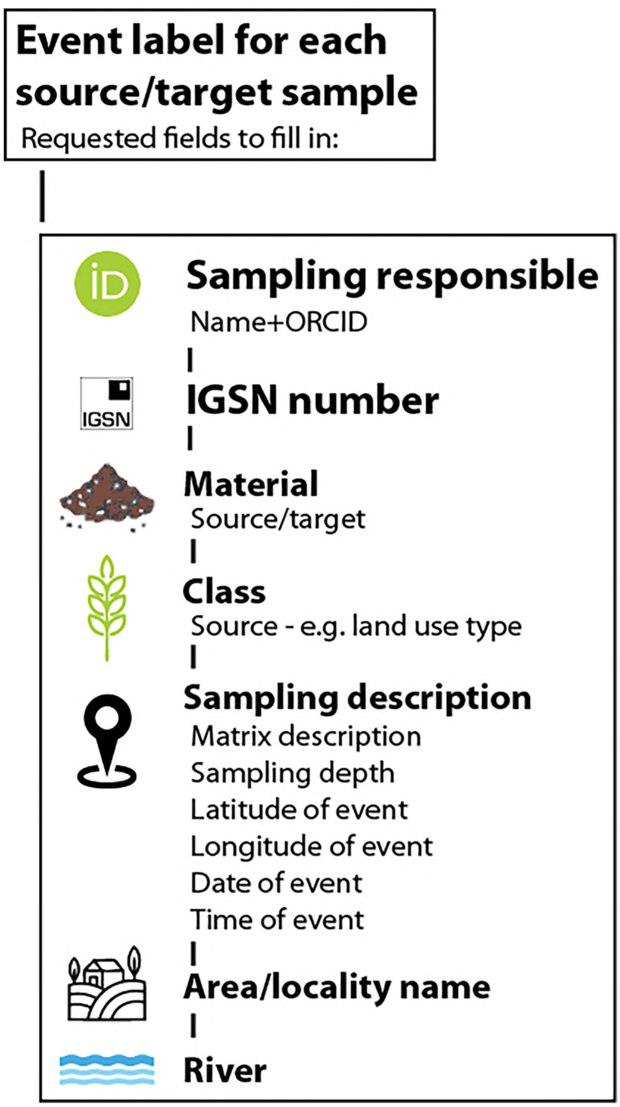

Fig. 2 Recommendations regarding information to provide when sharing sediment fingerprinting datasets

Once well-described and registered databases are available online, novel collaboration modes will likely become facilitated among the community of sediment tracing experts and beyond. For instance, source and target samples could be shared to analyse multiple properties – those that are available in the partners' respective facilities – on aliquots of the same samples, and maybe provide results that will go beyond those of the initial studies. Another suggestion may be to set up an international database on studied catchments through the compilation of metadata (e.g., location, the context of soil erosion, main operational issues, scientific questions, tracing issues/challenges, and research teams involved and papers). Focus would be to compile (meta)data available on catchments where sediment fingerprinting and other techniques (hydro-sedimentary monitoring, geomorphological approaches, erosion models) have been applied. Beyond the scientific interest, this database would allow making the sediment fingerprinting technique better known and more visible to federate a community while raising awareness on the issue of soil erosion to a wider audience. To go one step further in the transition to "open, accessible, reusable, and reproducible research," the reader is referred to the recently published hydrologist's guide to open science (Hall et al. 2021).

7 On hypothesis testing using sediment tracing methods

In each catchment, the authors wanted to understand where sediment was coming from. However, each study was based on different assumptions, parameterisations, and modelling schemes, which were all considered acceptable. In reality, tracing is an inexact science, and the sediment tracing method is often used in an "exploratory modelling" framework (Beven 2018) without going through a specific hypothesis testing process. For instance, in hypothesis-based research for sediment source fingerprinting, a hypothesis should first be stated and then tested through laboratory and field experiments, data analysis, and modelling. The number of potential sediment sources should be defined when designing the research. However, this number will be reduced if the tracer data does not lead to a good discrimination between the initially considered sources, in which case statistical criteria for merging sources can be implemented (Lizaga et al. 2021). Similarly, tracers that do not show a conservative behaviour are discarded, and there may be inconsistencies in the selected tracers when different studies are compared. As part of the process, poor results often do not get reported. Instead, they are considered part of the development of the modelling study (Beven 2018), where results are gradually improved by changing assumptions and/or modifying the tracer dataset.

This has also hampered a rigorous comparison of methods and results.

On the contrary, the scientific method involves making hypotheses about how nature works, deriving predictions from them as logical consequences, and then carrying out experiments based on those predictions to determine whether the original hypothesis was correct (Blöschl 2017). As described by Pfister and Kirchner (2017), the consequences of the hypotheses should be deduced for things that you can observe or measure (if a particular hypothesis is true, what should we observe? If it is false, what should we observe?), and a decision rule to determine whether the observations support or refute the hypothesis should also be defined beforehand. However, the scientific method assumes that observations are never in doubt (Pfister and Kirchner 2017), while this is not the case in sediment tracing (nor in other environmental sciences). As a result, our observations are often ambiguous, our measurements are associated with errors, and the quality of the data has to be carefully checked before using it to support or refute a hypothesis. Similarly, prevailing theory on the origin and the dynamics of suspended sediment is scarce (e.g., in drylands, gully erosion contributes a minimum of 10% and up to 94% of the total sediment yield) (Poesen et al. 2003). One of the reasons for the scarce prevailing theories is the large variability in the physiographical characteristics of the investigated catchments, and the diversity and complexity of erosion and sediment mobilisation driving factors. How can we then formulate hypotheses using the sediment tracing method to better understand how nature works? The answer to this question is not simple.

The sediment fingerprinting approach has now become a more widespread tool. As a community, we underlined many key advances carrying out exploratory research, which has proven to be another form of valuable scientific activity. Exploratory research is often driven by measurements in contrasted catchments with different contexts, or by investigating novel tracers or protocols. However, we should acknowledge that exploratory research often results in the generation of new hypotheses rather than rigorously testing them (Pfister and Kirchner 2017). We should hence be creative in finding new ways to test these hypotheses. We argue that combining the technique with other methods is crucial here and that process-oriented models and independent datasets might eventually help us to develop a better mechanistic understanding of sediment transport processes.

The sediment fingerprint approach may be considered to have reached a certain level of maturity (see the analogy with Burns (2002) on the stormflow-hydrograph separation based on isotopes). We argue that applying the sediment fingerprinting method yet in another catchment will most probably have a limited impact on the advancement of science (although sediment tracing studies might be of great value in unexplored environments or to decipher emerging environmental problems, as it has recently been shown for mountainous catchments) (Frankl 2022). On the contrary, by better organising and compiling all our available datasets, we might, for instance, be able to use mixing models to formulate hypotheses about sediment sources in different regions or anthropogenic contexts and contribute in a more unified and visible way to improve our understanding of sediment transfer processes. If this is possible and if it allows stablishing some generic characterisation of source contributions in different regions and contexts and at different scales remains to be further investigated. Similarly, we call for further discussions and ideas on how to overcome the case-study dependency when using the sediment fingerprinting approach.

In parallel to these efforts to encourage hypothesis testing research, it is also necessary to think actively about improving scientific output transfers to the society (Frankl et al. 2022). The sediment fingerprinting approach proves to be essential to assess the sediment source contributions in catchments. However, in addition to the optimisation of statistical procedures and the unification of sampling and analysis protocols, progress must also be made regarding its wider applicability. Land use managers have a relatively poor understanding of sediment fingerprinting techniques, and they are therefore unaware of the benefits of incorporating such methods into their management framework (Miller et al. 2015). However, this technique could be applied more widely to support the design of effective catchment management plans. Application guides have been proposed to this end (Collins et al. 2017; Gorman Sanisaca et al. 2017). In any case, the development of affordable, simple, and rapid methodologies remains essential to enable the wider application of this technique by local managers. For example, after a wildfire, it is necessary to know quickly where to implement erosion control measures or not, and if they have been applied, to evaluate their effectiveness. Therefore, one of the potential future developments of the technique could also be to design simpler statistical procedures and to propose the measurement of soil and sediment properties that can be collected in a very quick and inexpensive way. Of course, this line of development should be conducted in parallel to the application of more advanced methodologies, since the results obtained must be as rigorous as possible.

8 Concluding remarks

In the current feedback article, we have synthesised the opinions shared by the participants to the TRACING 2021 School. Recommendations to the sediment fingerprinting community were organised around the main following topics: (1) a better use of geomorphological information to improve study design; (2) improving scientific knowledge with local knowledge; (3)

recommending the use of state-of-the-art sediment tracing protocols; (4) promoting best practices in modelling; (5) promoting best practices to share tracing data and samples; and (6) further thoughts on hypothesis testing using sediment tracing methods. In addition, it is timely to recognise again the potential of sediment tracing techniques for improving our knowledge of hydro-sedimentary processes across a wide range of spatial and temporal scales. This was the original focus of sediment fingerprinting research from the late 1970s to the late 1990s before the main focus switched towards quantifying sediment source contributions to guide management interventions. As already suggested by Laceby et al. (2019), we should return to the early focus of the technique, which was initially used to investigate erosion and sediment delivery processes through the formulation of generic hypotheses on these. At a time when universities and research agencies around the world promote interdisciplinarity to meet the challenges of global change, we believe that sediment tracing has a major card to play. At the crossroads of geomorphology, hydrology, soil science, and social science, the sediment fingerprinting tools are interdisciplinary in nature, and we believe that they should be used to their full potential.

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Declarations

Conflict of interest The authors declare no competing interests.

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