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1 **Improving the design and implementation of sediment fingerprinting studies:**
2 **Summary and outcomes of the TRACING 2021 Scientific School**

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28 **Abstract**

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

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

35 **Results.** First, we suggest a better use of geomorphological information to improve study design.
36 Researchers are invited to scrutinize all the knowledge available on the catchment of interest, and to
37 obtain multiple lines of evidence regarding sediment source contributions. Second, we think that

38 scientific knowledge could be improved with local knowledge and we propose a scale of participation
39 describing different levels of involvement of locals in research. Third, we recommend the use of state-
40 of-the-art sediment tracing protocols to conduct sampling, deal with particle size, examine data before
41 modelling and accounting for the hydro-meteorological context under investigation. Fourth, we
42 promote best practices in modelling, including the importance of running multiple models, selecting
43 appropriate tracers, and reporting on model errors and uncertainty. Fifth, we suggest best practices to
44 share tracing data and samples, which will increase the visibility of the fingerprinting technique in
45 geoscience. Sixth, we suggest that a better formulation of hypotheses could improve our knowledge
46 about erosion and sediment transport processes in a more unified way.

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

49 **Keywords**

50 Sediment tracing; catchment; basin; watershed; source-to-sink; Critical Zone; local knowledge;
51 sediment fingerprinting.

52

53 **1. Introduction**

54

55 Sediment fingerprinting or tracing (both terms will be used interchangeably throughout the article) is
56 a relatively recent technique developed in the 1970s and 1980s that allows quantification of sediment
57 contributions from catchment sources by relying on the conservativeness of soil and sediment
58 properties (Loughran et al. 1982; Peart and Walling 1986). After a first descriptive phase the
59 implementation of un-mixing modelling opened the way to quantitative approaches calculating
60 sediment source contributions in target material (Walling and Woodward 1992; Collins et al. 1997).
61 The technique has received increased attention during the last three decades, which is demonstrated
62 by the sharp increase in research articles and several review papers describing its potential, the
63 associated drawbacks, and discussing potential implications for catchment management (Haddadchi
64 et al. 2013; Koiter et al. 2013; Walling 2013; Owens et al. 2016; Collins et al. 2017, 2020 ; Laceby et al.
65 2017). So far, sediment fingerprinting research has mainly focused on methodological issues or on the
66 use of fingerprinting results to support soil conservation and catchment restoration (Smith et al. 2015;
67 Laceby et al. 2019).

68 Although sediment fingerprinting has been applied with reasonable success, the deployment of
69 sediment fingerprinting methods remains associated with many issues (e.g., spatial and temporal
70 representativity of source and sediment sampling, conservative behaviour of tracers, particle size
71 correction, number of tracers incorporated into un-mixing models, validation of model outputs). To
72 move forward and improve the design and the implementation of sediment fingerprinting procedures,
73 discussions have been initiated in the framework of international conferences (e.g., Fall Meeting of the
74 American Geophysical Union (AGU) in December 2017). Following up on these, an International

75 Scientific School entitled "*Emerging strategies of sediment and contaminant tracing in catchments and*
76 *river systems*" (initial suggested acronym "TRACING2020") was scheduled to be organized at the
77 University Paris-Saclay, France, in May 2020. Participants from across the globe, involving both early-
78 career and experienced researchers, were expected to gather and discuss sediment fingerprinting
79 issues (see the full School programme in the Supplementary Information, Fig. 1). Unfortunately, the
80 outbreak of the COVID-19 pandemic disrupted those plans and, after several postponements, the
81 School could finally take place in October 2021 in Saint-Lambert-des-Bois, France (and was eventually
82 referred to as "TRACING2021"). Only those participants working in European countries and possessing
83 a valid European Union-compatible COVID vaccination certificate were able and allowed to attend the
84 event. Although the group of attendants was restricted to a geographical region, the meeting was
85 fruitful and led to several outputs, including the current feedback article. The main objective of the
86 School was to update the participants' knowledge on state-of-the-art techniques and methodological
87 issues associated with sediment fingerprinting. Most of the experienced researchers participating to
88 the Thematic School were invited to share their knowledge in their primary field of expertise. We are
89 sharing here the main issues discussed and the most important take-home messages. Of note, the idea
90 is not to duplicate previous recommendations nor to take away the merit of recent review articles on
91 the technique, but instead to share ideas and suggestions that may go beyond those described in the
92 publications mentioned above. In addition, we aim to stimulate discussions and encourage the use of
93 what was identified as good practices by the participants. Our suggestions are described in the next
94 sections, and they are organised around the following topics (Fig. 1): (section 2) a better use of
95 geomorphological information to improve study design; (section 3) improving scientific knowledge
96 with local knowledge; (section 4) recommending the use of state-of-the-art sediment tracing
97 protocols; (section 5) promoting best practices in modelling; (section 6) promoting best practices to
98 share tracing data and samples; and (section 7) further thoughts on hypothesis testing using sediment
99 tracing methods.

100

101 **2. Using geomorphological information to improve study design**

102

103 With the aim of understanding the provenance of sediment and that of mapping hotspots of soil
104 erosion, sediment fingerprinting studies strongly benefit from an in-depth understanding of the
105 catchment geomorphology and, more specifically, soil erosion and sediment connectivity. Seasonal
106 changes in hydro-meteorological conditions (e.g., glacial, nival or pluvial) or land use and cover may
107 translate into distinct soil erosion patterns and processes, and consequently, a seasonality in sediment
108 provenance and yield. Such relationships are often well understood (Lemma et al. 2019, 2020) and are

109 very important for the interpretation of sediment fingerprinting results and the associated
110 uncertainties (Stutenbecker et al. 2019). Furthermore, sediment provenance can also be variable over
111 short time scales. For example, soil erosion and sediment connectivity may vary with rainfall type and
112 pattern. As shown by Navratil et al. (2012a), widespread rainfall events tend to produce more
113 homogeneous sediment signatures than localized rainfall events such as heavy storms. Sediment
114 provenance between flood events can, therefore, vary significantly (Navratil et al. 2012a, 2012b). The
115 timing of sediment sampling along the flood hydrograph may also have an impact on sediment
116 fingerprinting results, as sediment sources transiting at catchment outlets were shown to vary
117 considerably during runoff events (Duvert et al. 2010; Legout et al. 2013). Capturing this variability,
118 therefore, requires frequent temporal measurements (Poulenard et al. 2012). This is also supported
119 by the careful examination of flood hysteretic patterns and their relationship with erosion processes
120 (Navratil et al. 2012b). A targeted fingerprinting approach is thus important, focussed on the
121 environmental issues of interest (Battista et al. 2020).

122 Geomorphological information can also provide guidance for tracer selection or potential sediment
123 source classification. For instance, in catchments with homogeneous lithologies, it will sometimes be
124 complex to use elemental geochemistry to discriminate between different land uses (Tiecher et al.
125 2017), and other – more straightforward – tools such as the bulk analysis of organic matter
126 composition (Fox 2009) or Compound Specific Stable Isotope (CSSI) signatures may be used instead
127 (Reiffarth et al. 2016, 2019; Lizaga et al. 2021). In contrast, in catchments with heterogeneous
128 lithologies, an approach relying on geochemical concentrations will likely be meaningful to
129 discriminate between contrasted sources that align with distinct terrains (e.g., steep headwaters on
130 resistant lithology vs. erodible hills on weaker rocks) (Sellier et al. 2021). However, such an approach
131 may be complicated when addressing specific environments where mixed sediment deposits occur,
132 such as high mountain areas where glacial till covers a large part of the catchment.

133 Besides supporting the design of fingerprinting studies, complementary information can also be
134 collected using other geomorphological methods. This includes topographic surveys, the analysis of
135 aerial photographs or satellite images (Foucher et al. 2021b), sediment facies surveys (Minella et al.
136 2008; Navratil et al. 2010; Vandromme et al. 2017), hydro-sedimentary monitoring (Navratil et al.
137 2012b; Gateuille et al. 2019), the calculation of connectivity indices (Borselli et al. 2008; Chartin et al.
138 2017), hydro-sedimentary modelling (Launay et al. 2019; Dabrin et al. 2021) and soil erosion modelling
139 (Palazón et al. 2016). Recent methodological developments relying on cutting-edge devices may
140 enable a more flexible approach in collecting complementary information, such as the deployment of
141 uncrewed aerial vehicles to map sediment connectivity patterns with a high spatial and/or temporal
142 resolution (Heckmann et al. 2018) across hillslopes and catchments (Estrany et al. 2019; Hooke et al.

143 2021). The analysis of contrasted types of sediment matrices (e.g., lag deposits, suspended matter,
144 sediment cores, riverbed sediment) or that of multiple particle size fractions can also provide
145 information on various aspects of the environmental problem under consideration (Navratil et al.
146 2012a; Laceby et al. 2017). The deployment of tracing strategies relying on multiple lines of evidence
147 (i.e., those obtained with different methods) may be facilitated in catchments where long term
148 monitoring is being conducted, which is more frequent for water gauging than for sediment
149 observations. These long term monitoring units are increasingly connected in the framework of
150 regional (Rhone Sediment Observatory; www.graie.org/osr/spip.php?rubrique62), national or
151 international networks (e.g., Critical Zone observatories; [https://czo-](https://czo-archive.criticalzone.org/national/)
152 [archive.criticalzone.org/national/](https://czo-archive.criticalzone.org/national/); <https://www.lter-europe.net/>) (Brantley et al. 2017).

153 **3. Improving scientific knowledge with local knowledge**

154

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

169 During the TRACING2021 School, several arguments were given in favour of better integration of
170 scientific and local knowledge. First, the collection of multiple sediment source samples across the
171 catchment is often challenged by access restrictions. A closer collaboration with local communities
172 might facilitate access to private properties and remote locations. Despite that it takes time to build
173 good relationships and gain trust, in some situations, this might also be needed to avoid conflicts
174 between stakeholders, or the generation of new conflicts. Second, the integration of scientific and
175 local knowledge also allows for a rapid briefing of the situation of interest and allows for a rapid
176 refinement of the sampling strategy. Locals' knowledge of erosion/sedimentation processes can help

177 identifying key locations of erosion/sedimentation and may make short fieldwork more efficient and
178 relying on a limited number of samples. Locals may also provide crucial context-specific knowledge,
179 which is not made available in any document (e.g., occurrence of major floods leading to massive
180 sediment deposition when gauging stations are not available), and allow cross-checking of multiple
181 sources of information. Third, when scientific and local knowledge are not sufficiently integrated,
182 catchment management efforts may prove to have limited success (Frankl et al. 2018). Fourth, the
183 involvement of local communities in the research process contributes to local development and
184 provides local experts with opportunities to become active players in research and natural resource
185 management (Blaikie 2006; Frankl et al. 2016). Moreover, it can offer an opportunity to raise
186 awareness regarding the potential of sediment fingerprinting and generate synergistic collaborations
187 with local environmental managers. During this collaboration, a didactic task could be to train local
188 managers on why/how/when applying sediment fingerprinting. This will likely facilitate the future use
189 of the sediment tracing results for river and catchment management (e.g., Collins et al. 2017). For
190 instance, the organisation of focus groups and interviews would allow all the stakeholders to be
191 brought around the table to participate in the selection of potential sources and sampling sites (as
192 already tested for flood risk management by Lane et al., 2011). The sampling plan could also be
193 integrated into a citizen science project. From an ‘action research’ perspective (i.e., research
194 methodology widely applied in social science seeking to obtain a transformative change through the
195 simultaneous process of taking action and doing research) aimed at making a diagnosis and at
196 transforming local practices over the medium to long terms, the concerted stage of defining the
197 sediment sampling plan would appear to be as important as the ultimate results of the un-mixing
198 models. Fifth, in a context of conflicts among stakeholders, the integration of these different levels of
199 knowledge could avoid discrediting the results of a sediment fingerprinting study carried out by a team
200 of scientists working in isolation or in collaboration with only a part of the stakeholders.

201 These arguments making the case for better integrating of scientific and local knowledge may open a
202 new avenue for sediment fingerprinting, although – as already analysed in social science, these
203 approaches are not free of critiques (Belisle, 2018). The first critique is that many scientists are
204 sceptical regarding the validity of informal knowledge because it may be perceived as subjective and
205 lacking rigour (Chalmers and Fabricius 2007). Indeed, local inhabitants often have an excellent
206 understanding of local and recent events, but processes occurring at wider spatial and longer temporal
207 scales might not be obvious to them (i.e., pluri-decadal or centennial scales). Local and scientific
208 knowledge should thus be complementary. A second critique deals with deontological perspectives.
209 The lack of recognition of the significance of fieldwork and interview techniques may lead to a lack of
210 knowledge of the basic ethical rules to be aware of when conducting fieldwork with local stakeholders

211 (i.e., helicopter research) (Minasny et al. 2020). A third critique may be associated with the difficulty
212 in involving all local stakeholders. Indeed, if only one group of locals (e.g., male, senior) or one group
213 of stakeholders participates, the collected information may be biased, and the results may lose
214 credibility in front of the non-represented stakeholders. Therefore, it is essential to approach all
215 stakeholders and to avoid any instrumentalisation of the results or our role of scientists in the
216 stakeholders' interactions.

217 Thus, considering the arguments and limitations identified above, a question asked during the
218 TRACING2021 School was: what could be the levers to promote a better integration of local and
219 scientific knowledge for sediment fingerprinting? A first suggestion is to set up
220 interdisciplinary/transdisciplinary projects as accessing and understanding local knowledge calls upon
221 concepts and methods from both environmental and social sciences. Based on what can be proposed
222 in the framework of ethnographic fieldwork, sediment collection guides could thus describe ethical
223 recommendations to be followed in the field when collecting sediment samples and local knowledge
224 on erosion processes. Another suggestion was to recognise the role of local knowledge in our work
225 thoroughly. In order to gain academic legitimacy, it may be important to better define at the onset of
226 a project the level of involvement that is sought from each stakeholder (e.g., during empirical data
227 collection only or throughout the entire project as co-researchers). The level of involvement will
228 depend on the main issue of interest, research funding and the social and political contexts. Based on
229 citizen science literature, we propose herein a first "scale of participation and engagement" for
230 sediment fingerprinting, with six levels (from the lowest to the highest; Fig. 1). Level 1 corresponds to
231 a field assistance for site access for source and sediment sampling; level 2, to the collection of river
232 sediment during floods; level 3, to the definition of source and sediment sampling locations and timing;
233 level 4, to the discussion of model results with all the stakeholders; level 5, to the participation in the
234 definition of the problem, the objectives and the identification of sediment sources; level 6, to the
235 analysis, validation and discussion of the modelling results (e.g., uncertainties, sampling choices). We
236 argue that the level of involvement of local communities should be explicitly mentioned in our
237 scientific productions in the "Materials and Methods" section and further discussed. Scientific
238 publications on sediment fingerprinting would thus gain in better outlining the limits and biases that
239 may arise during fieldwork, rather than sweeping this sediment problem – i.e., the scientists/local
240 community interactions and knowledge hybridization – under the carpet!

241

242 **4. Recommending the use of state-of-the-art sediment tracing protocols**

243

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

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

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

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

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

302 Second, one of the main issues that the researchers implementing sediment fingerprinting approaches
303 have been dealing with is that of the particle size effects on result interpretations (Smith and Blake
304 2014). The particle size of the sediment load may be variable as a result of different processes being
305 activated in the catchment, which are size-selective. Surface erosion may for example lead to pulses
306 of finer sediment (Gateuille et al. 2019). Furthermore, particle sorting also occurs along the fluvial
307 network (Walling et al. 2000), with the finest particles being detached first and transported the farthest
308 from the source (Knighton 2014; Lacey et al. 2017). The most widely applied technique to deal with
309 particle size is to sieve both source and target material to a given threshold (often $< 63 \mu\text{m}$), although
310 corrections of tracer concentrations have also been widely applied based on the analyses of potential

311 tracers and particle size distributions on bulk material (Collins et al. 1997; Gellis and Noe 2013).
312 Nevertheless, the effectiveness of these corrections was shown to be limited in certain cases (Smith
313 and Blake 2014; Koiter et al. 2018). A recommendation that could be made for future research is that
314 of analysing the particle size of target material before selecting the threshold retained for analysis.
315 With the increasing availability of granulometers, providing the distribution curves of particle size in
316 both source and target material or the associated metrics (e.g., d10, d50, d90) should be considered.

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

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

343 **5. Promoting best practices in modelling**

344

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

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

367
368 However, there are many situations in which un-mixing models can provide useful quantitative
369 information regarding source provenance. For instance, managers might be interested in quantifying
370 the effectiveness of soil conservation measures to reduce the sediment delivery from a given source
371 (Patault et al. 2019). Of note, un-mixing models provide estimates of proportional source contributions.
372 A reduction in the sediment load from a source due to conservation measures may produce a decrease
373 in the proportional contribution from that source, but this will correspond with an apparent increase
374 in the proportional contribution from other sources even if these remain unchanged in load terms
375 (given proportional source contributions sum to 100%). Unless before/after sediment load data is
376 available to convert proportional information into source-specific loads, it will not be possible to
377 meaningfully assess the before and after effect of soil conservation measures using proportional
378 source data alone. This should be taken in consideration when interacting with managers. When un-

379 mixing models are to be used for source attribution, we would also like to emphasize the importance
380 of reporting the uncertainty in the model outputs (Cooper et al. 2015; Sherriff et al. 2015). Current
381 modelling approaches provide multiple solutions, to which confidence or credible intervals can be
382 attributed. Hence, fingerprinting source apportionments should ideally be reported as a measure of
383 central tendency alongside measures of dispersion and include distribution plots of model outputs.
384 We believe it is important to embrace the uncertainty in the modelled source apportionments to
385 interpret and identify flaws in our data. Reducing the uncertainty in modelled source apportionments
386 through modelling artifacts will likely not lead to knowledge improvements or more informed decision
387 making. Instead, it should be acknowledged that the quality of the input data (e.g., number of samples,
388 discriminative power and conservativeness of the tracers) and decisions related to how we treat that
389 data and the associated modelling procedures (e.g., possible removal of outliers, application of data
390 corrections, selection of tracers, choice of model error structures) can affect the accuracy of model
391 outputs and the associated levels of uncertainty.

392 Tracer selection approaches were also discussed in the Tracing School. Generally, un-mixing models
393 require $n-1$ tracers to determine the contributions of n sources to the mixture, where ideally, each of
394 the sources should have at least one tracer that strongly discriminates it from the other sources. In the
395 last decades, there has been no general agreement in the community regarding the different tracer
396 selection methods. Current approaches to tracer selection rely on i) a three-step procedure, starting
397 with a range test to identify the tracers outside of the mixing polygon, a Kruskal-Wallis test to identify
398 tracers that provide discrimination between at least one of the sources, and a linear discriminant
399 analysis to define a tracer suite that maximizes source distinction; ii) maximizing the number of tracers
400 by only excluding non-conservative fingerprints; iii) process- or knowledge-based frameworks
401 considering the interpretation of the bio-physico-chemical properties of the sources; and iv) novel
402 methods for identifying consistent tracers, i.e., which do not produce mathematical inconsistencies in
403 the potential model solutions. A debate exists on the reliability of the most widespread methods such
404 as the three-step procedure or the mixing polygon. As an alternative, recently Lizaga et al. (2020c) and
405 Latorre et al. (2021) developed the new methods of consensus ranking and consistent tracer selection
406 that produce similar outputs in un-mixing with either frequentist or Bayesian models. These methods
407 detect the non-conservative, non-consensual and non-consistent tracers, display and inform on the
408 effect of each tracer into the fingerprinting models and extract if there are multiple solutions in a
409 dataset. In our opinion, this lack of consensus stems from the difficulties in testing/replicating tracer
410 selection approaches in comprehensive datasets (i.e., full databases comprising all the tracing
411 properties analysed in both the potential source and target material) for a range of contrasted
412 catchments, as these are almost non-existent. Hence, we would like to reemphasize the importance

413 of sharing raw data in our publications and promote the idea of shared datasets, which is discussed in
414 the following section (section 6). In addition, we encourage the community to run different tracer
415 selection procedures and compare the resulting tracer selections (or analyse them all) and the
416 corresponding mixing model outputs to better understand the sensitivity of results to tracer selection.

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

441

442 **6. Promoting best practices to share tracing data and samples**

443

444 A recent review on the use of ^{137}Cs as a tracing property showed that very few studies provided the
445 raw data used in the publication and key catchment information, including the size of the drainage
446 area, the outlet coordinates, etc. (Evrard et al. 2020a), most of the articles reporting the summary

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

477 Once the dataset has been uploaded onto a data repository, the associated Digital Object Identifier –
478 DOI can be used to refer to the dataset in manuscripts submitted for publications or in data papers,
479 and referenced in the project's Data Management Plan (DMP) as a data product. Examples of these
480 databases can be found online (Evrard et al. 2020b). Of note, additional information should be added

481 to fully describe the sampling protocol and facilitate the inter-comparison and aggregation of results
482 between studies, including information on the sediment matrix, the soil layer depth sampled, the
483 particle size (fraction of interest or the outputs of the particle size analysis if available), the reference
484 date for decay-correction of radionuclide activities typically, etc.

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

499

500 **7. On hypothesis testing using sediment tracing methods**

501

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

515 gradually improved by changing assumptions and/or modifying the tracer data set. This has also
516 hampered a rigorous comparison of methods and results.

517 On the contrary, the scientific method involves making hypotheses about how nature works, deriving
518 predictions from them as logical consequences, and then carrying out experiments based on those
519 predictions to determine whether the original hypothesis was correct (Blöschl 2017). As described by
520 Pfister and Kirchner (2017), the consequences of the hypotheses should be deduced for things that
521 you can observe or measure (if a particular hypothesis is true, what should we observe? If it is false,
522 what should we observe?), and a decision rule to determine whether the observations support or
523 refute the hypothesis should also be defined beforehand. However, the scientific method assumes
524 that observations are never in doubt (Pfister and Kirchner 2017), while this is not the case in sediment
525 tracing (nor in other environmental sciences). As a result, our observations are often ambiguous, our
526 measurements are associated with errors, and the quality of the data has to be carefully checked
527 before using it to support or refute a hypothesis. Similarly, prevailing theory on the origin and the
528 dynamics of suspended sediment is scarce (e.g., in drylands, gully erosion contributes a minimum of
529 10% and up to 94% of the total sediment yield) (Poesen et al. 2003). One of the reasons for the scarce
530 prevailing theories is the large variability in the physiographical characteristics of the investigated
531 catchments, and the diversity and complexity of erosion and sediment mobilisation driving factors.
532 How can we then formulate hypotheses using the sediment tracing method to better understand how
533 nature works? The answer to this question is not simple.

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

543 The sediment fingerprint approach may be considered to have reached a certain level of maturity (see
544 the analogy with Burns (2002) on the stormflow-hydrograph separation based on isotopes). We argue
545 that applying the sediment fingerprinting method yet in another catchment will most probably have a
546 limited impact on the advancement of science (although sediment tracing studies might be of great
547 value in unexplored environments or to decipher emerging environmental problems, as it has recently

548 been shown for mountainous catchments) (Frankl 2022). On the contrary, by better organising and
549 compiling all our available datasets, we might, for instance, be able to use mixing models to formulate
550 hypotheses about sediment sources in different regions or anthropogenic contexts and contribute in
551 a more unified and visible way to improve our understanding of sediment transfer processes. If this is
552 possible and if it allows establishing some generic characterisation of source contributions in different
553 regions and contexts and at different scales remains to be further investigated. Similarly, we call for
554 further discussions and ideas on how to overcome the case-study dependency when using the
555 sediment fingerprinting approach.

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

574

575 **8. Concluding remarks**

576

577 In the current feedback article, we have synthesized the opinions shared by the participants to the
578 TRACING 2021 School. Recommendations to the sediment fingerprinting community were organised
579 around the main following topics: (1) a better use of geomorphological information to improve study
580 design; (2) improving scientific knowledge with local knowledge; (3) recommending the use of state-
581 of-the-art sediment tracing protocols; (4) promoting best practices in modelling; (5) promoting best

582 practices to share tracing data and samples; and (6) further thoughts on hypothesis testing using
583 sediment tracing methods. In addition, it is timely to recognize again the potential of sediment tracing
584 techniques for improving our knowledge of hydro-sedimentary processes across a wide range of spatial
585 and temporal scales. This was the original focus of sediment fingerprinting research from the late
586 1970s to the late 1990s before the main focus switched towards quantifying sediment source
587 contributions to guide management interventions. As already suggested by Laceby et al. (2019), we
588 should return to the early focus of the technique, which was initially used to investigate erosion and
589 sediment delivery processes through the formulation of generic hypotheses on these. At a time when
590 universities and research agencies around the world promote interdisciplinarity to meet the challenges
591 of global change, we believe that sediment tracing has a major card to play. At the crossroads of
592 geomorphology, hydrology, soil science and social science, the sediment fingerprinting tools are
593 interdisciplinary in nature, and we believe that they should be used to their full potential.

594

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609

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613

614

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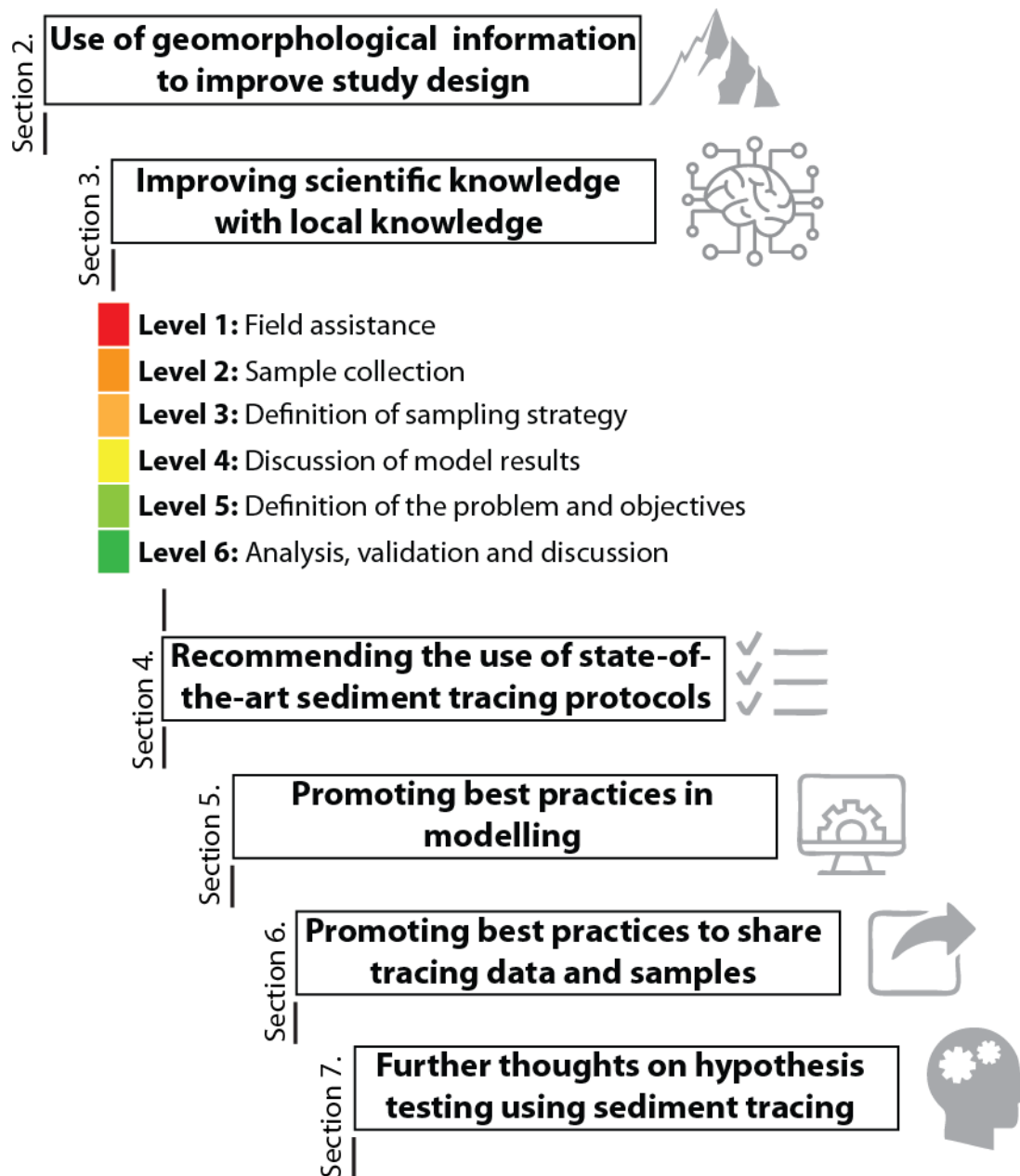
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916 **Figures**

917 Figure 1. Organisation of the main recommendations proposed and discussed during the TRACING
918 2021 School to improve the design and implementation of sediment fingerprinting studies.



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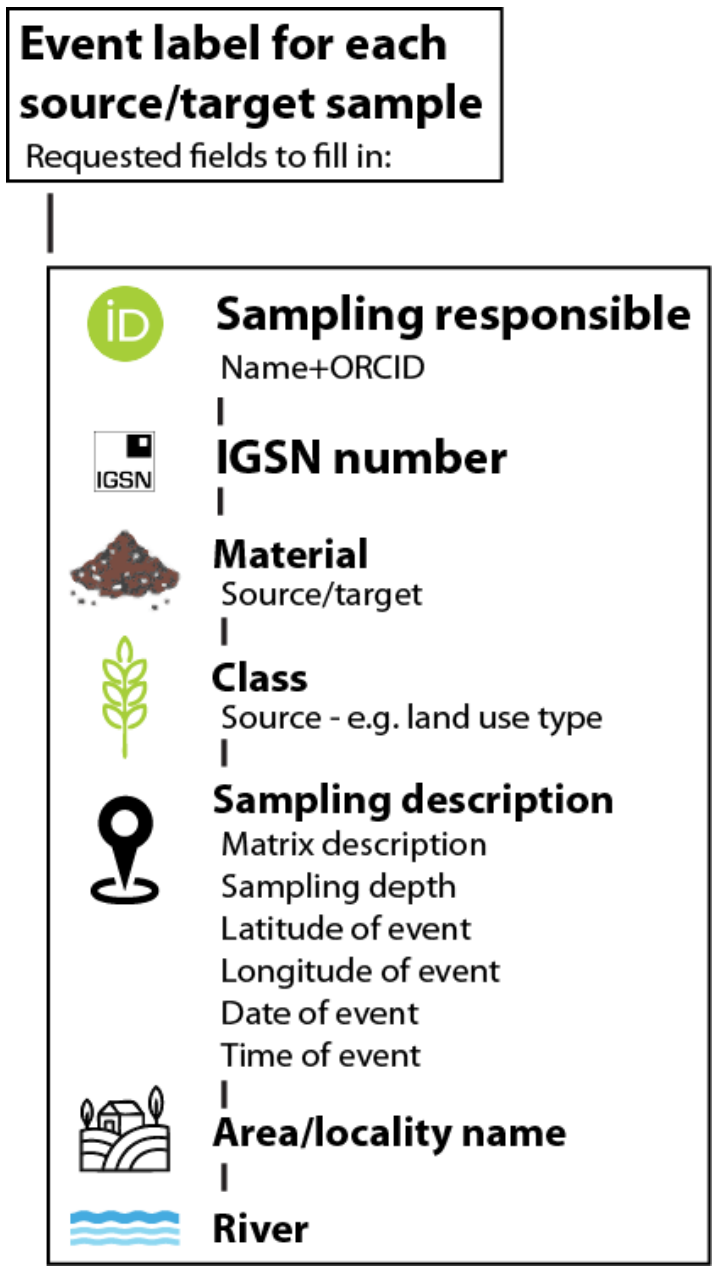
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926 Figure 2. Recommendations regarding information to provide when sharing sediment fingerprinting
927 datasets.



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