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1 Quantitative evaluation of human and  
2 climate forcing on erosion in the Alpine  
3 Critical Zone over the last 2000 years.

4  
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17 **Abstract**

18 Soil erosion is one of the main environmental threats affecting the Critical Zone (CZ) and thus  
19 ecosystem services and human societies. Through time, physical erosion is linked to both climate

20 variations and the landscape evolution under long-term human pressures. In mountainous areas  
21 where erosion is highest a combination of large spatial and temporal approaches allows to assess the  
22 effect of these forcing factors on erosion rates. Here, we apply a retrospective approach based on lake  
23 sediments to reconstruct the long-term evolution of erosion in alpine landscapes. Lake Iseo in the  
24 Italian Alps acts as a natural sink for all the erosion products from a large catchment (1777 km<sup>2</sup>). This  
25 catchment is representative of the southern Italian Alps, where Holocene human activity and climate  
26 fluctuations are well known. The approach combines a source-to-sink method, using isotopic  
27 geochemistry ( $\epsilon\text{Nd}$ ,  $^{87}\text{Sr}/^{86}\text{Sr}$ ) associated to a multiproxy study of a lacustrine sediment section covering  
28 the last 2000 years. The applied method allows us to disentangle the role of climate and land use as  
29 erosion forcing factors through their differential impact on the various rock types present in the  
30 catchment. Indeed, the high-altitude part of the Iseo catchment, where glacier advances and retreats  
31 drive the erosion, presents isotopic signature different from those of the sedimentary rocks located in  
32 the lower part of the catchment, where both human activities and precipitations impacted erosion  
33 through time. A chronicle of glacial erosion over the last 2000 years was produced. Once the climatic  
34 trend was highlighted, the signal of erosion of sedimentary rocks was investigated to understand the  
35 influence of humans. From the Roman Period to the Industrial Age several periods of deforestation  
36 and increased human pressure were documented. The past sediment yield inferred for sedimentary  
37 rocks exhibits the highest values ( $> 80 \text{ t.km}^{-2}.\text{yr}^{-1}$ ) at periods of intense human practices. Hence, since  
38 the late Roman Period, human activities seem to be the dominant forcing factor of the physical erosion  
39 in mountainous environment of northern Italy. This study presents the first reconstruction through  
40 time of sediment yield derived from lake sediments associated with sediment sources identification  
41 and quantitative evaluation of the CZ erosion drivers.

## 42 [Keywords](#)

43 Erosion, Human impact, Lake sediments, Source to sink method, isotopic mixing model

## 44 1. Introduction

45 Erosion is a geological process that, on long timescales, impacts the Earth's topography, tectonics and  
46 climate (e.g. Gayer et al., 2019 and references therein). Currently, erosion is also the main process  
47 leading to the deterioration of the Critical Zone (CZ), defined as the thin active layer at the Earth's  
48 terrestrial surface, which host life forms. Among other impacts, by destroying soils, erosion alters food  
49 production, drinking water quality, ecosystems services, biodiversity, and soil carbon stocks (e.g. Bosco  
50 et al., 2008; Panagos et al., 2015). Erosion also directly affects human societies (Montgomery, 2012),  
51 especially in mountainous environments (Bosco et al., 2008) and has thus become a scientific subject  
52 of prime importance worldwide (Borrelli et al., 2020; FAO, 2015; Panagos et al., 2015; Rusco et al.,  
53 2008). Increasing concern about these deleterious effects has led Europe and the United Nations to  
54 rank soil erosion as one of the main threats to mankind, and to call for quantitative evaluation of soil  
55 loss over large spatial and long temporal scales (e.g. Panagos et al., 2015 and references therein). The  
56 objective of these evaluations is to better assess the relative effects of the main factors controlling  
57 erosion. In particular, climate (for example through the precipitation regimes or glaciers advances and  
58 retreats) and human activities (through land-use and vegetation cover management) have been  
59 identified as major controls on long-term changes in erosion rates (e.g. Panagos et al., 2015).

60 Besides the use of modelling approaches (e.g. Angima et al., 2003; Borrelli et al., 2020; Millward and  
61 Mersey, 1999; Panagos et al., 2015; Renard et al., 1991), this knowledge gap can be filled through the  
62 acquisition of empirical constraints provided by the study of lake sediment archives, in particular with  
63 the aim of evaluating erosion rates over the centennial to millennial time scales over which climatic  
64 and human forcing are the most likely drivers of erosion (e.g. Arnaud et al., 2016). Although regional  
65 syntheses of erosion rates over these time scales exist, in particular for the European Alps (e.g.  
66 Hinderer et al., 2013 and references therein), only a few studies have produced a quantitative  
67 assessment of erosion rates through time (e.g. Bajard et al., 2020), but none on the quantitative  
68 impact of the various factors. The "source-to-sink" approach (e.g. Collins and Walling, 2002) offers the

69 possibility to track the sources of sediment inputs (sub-catchments and/or rock types) to a sink (e.g.,  
70 a lake) through time, making it in turn possible to disentangle the relative impacts of climate and  
71 human activities upon erosion rates, provided that each sediment source is sensitive to a given type of  
72 forcing.

73 For this study, we selected Lake Iseo, located in the Italian Alps, at the downstream end of the Val  
74 Camonica valley, an area where human activities since the beginning of the Neolithic period are well  
75 documented (e.g. Pini et al., 2016 and references therein). Lake Iseo drains a large catchment that can  
76 be split into three main sediment source areas, distinguishable through the means of geochemical  
77 tools, and coinciding with different relative roles of climatic and human forcings on erosion over the  
78 centennial to millennial scales:

- 79 (i) The northernmost, high-altitude part of the catchment underlain by calco-alkaline rock  
80 series and where numerous glaciers have shaped the landscape (Scotti et al., 2013);
- 81 (ii) The mid- to high-altitude part of the catchment underlain by metamorphic Variscan  
82 basement rocks where both glaciers and human activities have impacted erosion (Pini et  
83 al., 2016; Scotti et al., 2013)
- 84 (iii) The southernmost, low- to mid-altitude part of the catchment underlain by Permian to  
85 Cretaceous sedimentary cover, and the locus of most human activities in the Val Camonica  
86 since the beginning of the late Holocene (Pini et al., 2016 and references therein).

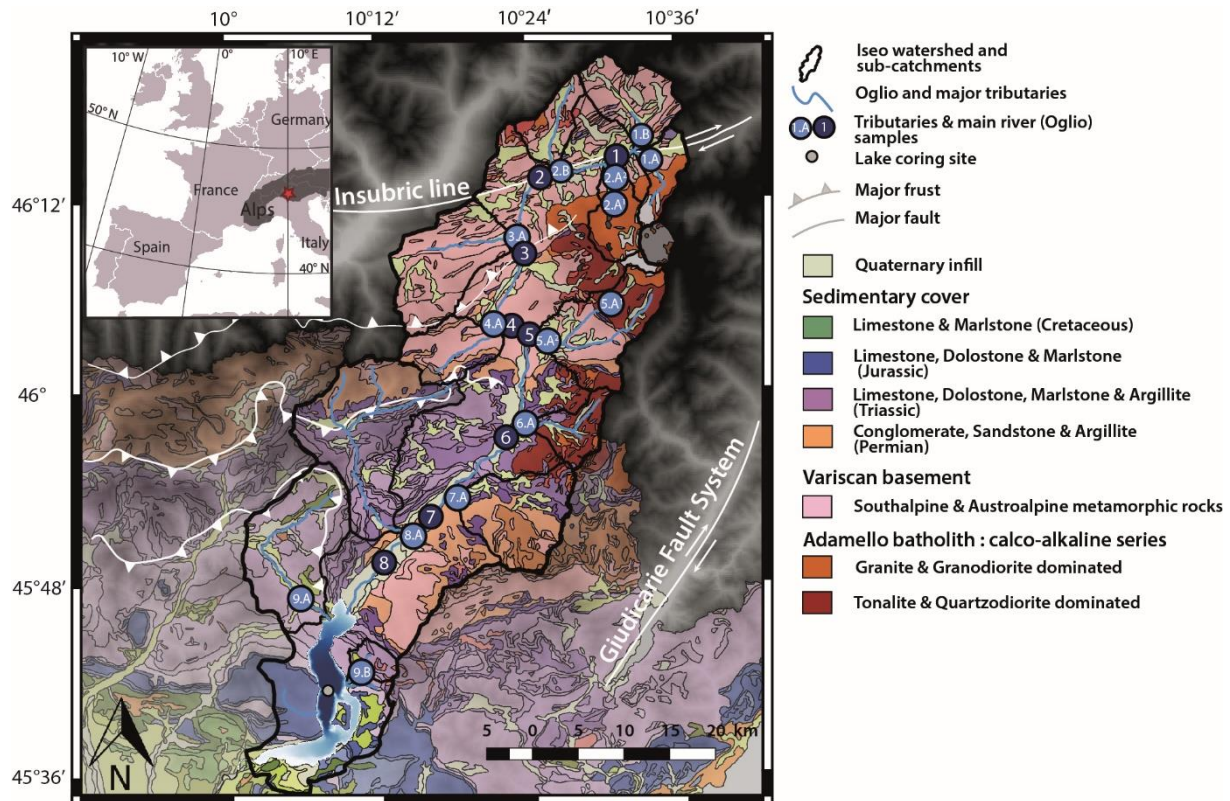
87 To quantify the evolution of erosion in the catchment of Lake Iseo over the late Holocene, we selected  
88 a sediment sequence retrieved in the deep depositional basin of the lake, where most of the fine-  
89 grained sediment inputs from the catchment have been captured. River samples were also collected  
90 from all the sub-catchments directly contributing to Lake Iseo. Neodymium (Nd) and Strontium (Sr)  
91 isotopic compositions and concentrations of river and lake sediments were used to constrain the  
92 results of a mixing model (for discussion of the model please refer to sub-section 4.3). Results from the  
93 model yielded quantitative contributions of each sediment source, allowing us to disentangle the

94 effects of climate fluctuations and human activities on erosion in the Iseo catchment from the Roman  
95 Period to the present day.

## 96 2. Study sites

97 Lake Iseo (45°44.205'N; 10°4.340'E) lies in the Italian Alps, at the southern end of the Val Camonica  
98 valley at an altitude of 185 m a.s.l (above sea level). The lake is 25-km long and has a surface area of  
99 60.9 km<sup>2</sup>.

100 Lake Iseo is fed water and sediment by the Oglio River, which originates in the Adamello Massif, and is  
101 the main lake tributary and unique outlet (**Fig. 1**). Upstream from Lake Iseo, the Oglio River drains a  
102 large catchment of 1777 km<sup>2</sup> with a maximum elevation of 3539 m a.s.l in the Adamello Massif and a  
103 mean altitude of 1400 m a.s.l (Garibaldi et al., 1999). The Oglio catchment is limited to the North and  
104 East by the Insubric line, one of the main lineaments of the European Alpine (Mittempergher et al.,  
105 2021), separating the Austroalpine domain (N) from the southern Alps (S). Rocks of high alpine  
106 metamorphic grade from the Austroalpine unit exist at the extreme northern limit of the catchment  
107 but constitute very small areas (Chiesa et al., 2011; Gosso et al., 2012).



108

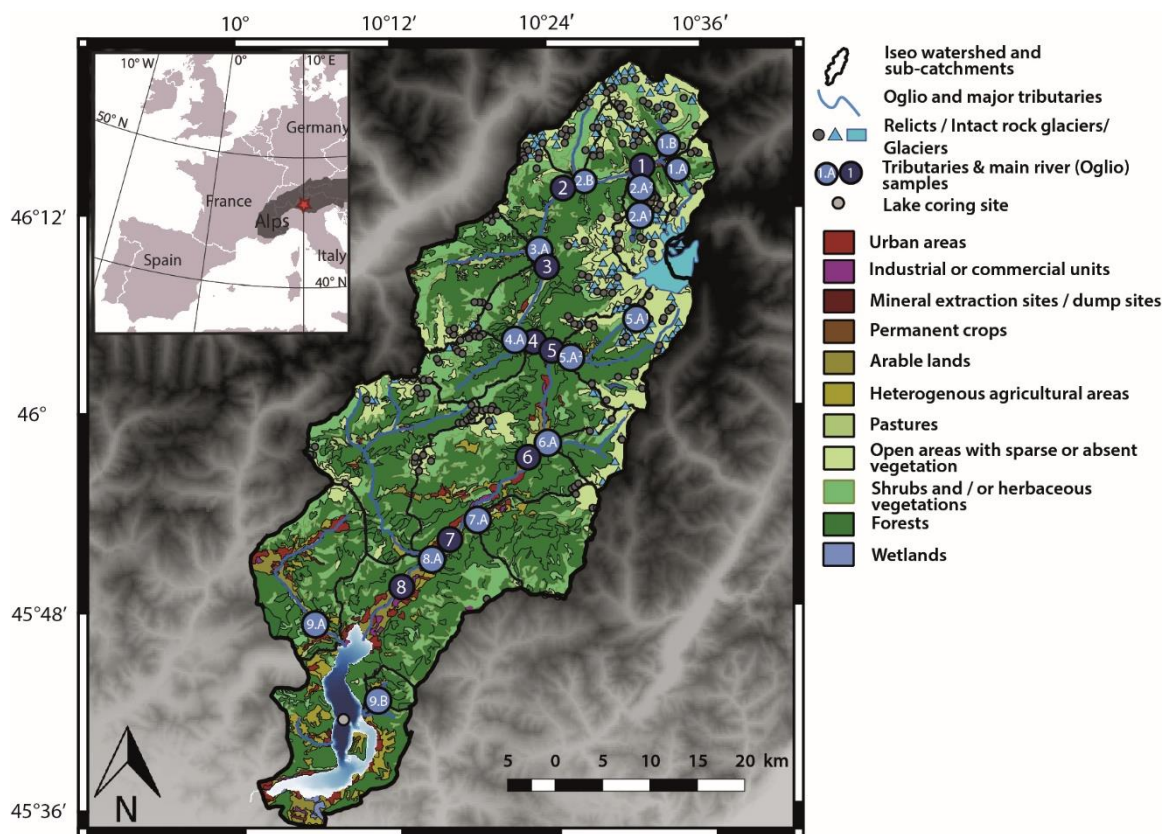
109 *Figure 1 – Geological map of the study area, superimposed on a shaded relief map, and location of sampling sites. The*  
 110 *geological information is modified from the geological map of Lombardy (CARG project;*  
 111 *<https://www.cartografia.servizirl.it/cargviewer/>). The tributaries (blue) and sub-catchments (boundaries in black) of the Oglio*  
 112 *River and the SEB18 lake sediment coring site are also shown (grey circle). Lake Iseo bathymetry is modified from Pilotti et al.*  
 113 *(2013) and is available at [https://hydraulics.unibs.it/hydraulics/attivita-scientifica/laqhi\\_pvbs/lake-iseo-data-set/](https://hydraulics.unibs.it/hydraulics/attivita-scientifica/laqhi_pvbs/lake-iseo-data-set/).*

114 The faulted Variscan basement of the southern Alps is made of low- to high-grade metamorphic rocks  
 115 (pelites, schists, amphibolites, gneiss) visible in the North and West part of the Upper Oglio catchment.  
 116 To the South, the catchment is underlain by the sedimentary cover of the southern Alps, mainly  
 117 composed of Triassic, Jurassic, and Cretaceous marlstones, limestones, and dolostones, associated  
 118 with outcrops of Permian sandstones (Bini et al., 2012).

119 The NE part of the catchment area is underlain by the famous Adamello batholith which is a plutonic  
 120 series of calco-alkaline rocks of Cenozoic age (30 to 40 Ma) that intruded the old southern Alps Variscan  
 121 basement (Mitterpergher et al., 2021). The Adamello massif is mainly composed of felsic plutonic  
 122 rocks such as tonalites, granites, granodiorites, and quartzodiorites, with some minor outcrops of mafic



123 to ultramafic rocks (Brack et al., 2008). Glaciers and rock glaciers are particularly numerous in this part  
 124 of the catchment (Scotti et al., 2013) and are suspected to have strongly impacted erosion in the area.  
 125 In terms of human occupation, the southernmost area, closest to the lake, is located at low to mid  
 126 altitude, and is where human activities are currently concentrated (**Fig. 2**). Archaeological and  
 127 palynological studies also locate the main human settlements and agrarian activities within this area  
 128 since the Neolithic (e.g. Marziani and Citterio, 1999; Pini, 2002; Pini et al., 2016). Human activities in  
 129 the rest of the catchment area are sparse, restricted to herd grazing and only minor urban areas, both  
 130 for modern times (**Fig. 2**) and in the recent past (Pini et al., 2016).



131  
 132 *Figure 2 – Land-use map of the study area, superimposed on a shaded relief map, and location of sampling sites. Land use*  
 133 *information is derived from the CORINE land cover map for Lombardia, available here:*  
 134 *<http://www.geoportale.regione.lombardia.it/>. Locations of glaciers, relicts, and intact rock glaciers are derived from Scotti et*  
 135 *al. (2013).*



## 136 3. Materials and Methods

### 137 3.1. Lake sediment

138 In October 2018, a 15.5-m-long sediment sequence coded “SEB18” (45°43.536'N; 10°3.888'E) was  
139 retrieved from the deep basin of Lake Iseo, at 251 m below the lake surface (b.l.s). This site was  
140 selected as it is supposed (i) to be less influenced by event sedimentation (Bini et al., 2007) and (ii) to  
141 have collected the sediment input from the Oglio River in a continuous way. For this survey, two  
142 UWITEC 90-mm diameter piston corers (Uwitec, Mondsee, Austria) were used, operated from an  
143 UWITEC platform (EDYTEM/LSCE/C2FN). Most of the sections were split, photographed at high-  
144 resolution (20 pixels.mm<sup>-1</sup>), described and logged in detail. The identification of specific layers on the  
145 overlapping sections allowed the creation of the composite sediment sequence.

146 Thirty 1 cm-long sediment samples were collected from the background sedimentation  
147 (**supplementary Table S1 & S2**) using graduated syringes for geochemical analyses (sections 3.4 and  
148 3.5). Due to the presence of multiple event-specific sediment layers, a continuous sampling step was  
149 impossible to apply. Sediment dry bulk density (DBD) was measured using sediment samples of an  
150 invariant 5 mL volume.

151 Loss-on-ignition measurements were conducted on all the sediment samples following the method of  
152 Heiri et al. (2001). The proportion of detrital silicates in the sediment samples was evaluated from  
153 values of non-carbonate residue (NCIR) that is the sediment remaining after the last ignition step (950°  
154 for 2h; Bajard et al., 2016).

155 To produce a precise age-depth model for the sediment sequence, we combined varve counting, short-  
156 lived radionuclides (<sup>210</sup>Pb, <sup>137</sup>Cs, <sup>241</sup>Am), and <sup>14</sup>C. Varves were counted over the first 37 cm of the core,  
157 then 38 samples were collected over the first 48.1 cm of the sequence to measure short-lived  
158 radionuclide activities at the Laboratoire Souterrain de Modane using the well-type germanium  
159 detectors (Reyss et al., 1995). Short-lived radionuclide chronology was carried out using the R code

160 package “serac” (Bruel and Sabatier, 2020). Thirteen samples of vegetal macro-organic remains were  
161 used to perform <sup>14</sup>C measurements at the LMC14 laboratory (CNRS) using AMS. Dates were calibrated  
162 at 2 sigma using the Intcal20 calibration curve (Reimer et al., 2020), and the age-depth model was  
163 performed using R code packages “clam” (Blaauw, 2010) and “bacon” (Blaauw et al., 2021) in R  
164 software.

### 165 3.2. River sediment samples

166 To characterize the source of sediments accumulated in Lake Iseo deep basin, 14 river sediment  
167 samples were collected in May 2018 from flood deposits in all sub-catchments directly contributing to  
168 the Oglio River, close to the confluence with the main river (**Fig. 1; Table S3**). Eight samples were also  
169 collected from flood deposits in the Oglio main valley at several hundred meters downstream of each  
170 confluence to test for the mixing between sub-catchment and main river sediments (**Fig. 1; Table S3**).  
171 Sub-catchments covered by this sampling set represent 52 % of the Iseo catchment total area. Samples  
172 were collected manually, an aliquot of each sample was sieved, and only the fraction finer than 63 µm  
173 was saved for later analysis, to account for the fact that the sedimentation in the studied lake sediment  
174 core is mostly of silty to clayey nature.

### 175 3.3. Sample preparation

176 Even in carbonate-dominated terrains, soil physical erosion occurs mostly through the removal of  
177 silicate phases, as carbonate minerals tend to be removed from soils through chemical dissolution. For  
178 this reason, our analysis focuses on siliciclastic material, and we removed the carbonate component  
179 of the lake and river sediments before geochemical analyses. Although the authigenic carbonate  
180 production is poorly preserved in the deep basin of peri-Alpine lakes (Ramisch et al., 1999), this  
181 procedure also ensures that authigenic lake carbonates do not affect our interpretation. To that effect,  
182 after crushing in an agate mortar and drying at 60°C for 72 h in a laboratory oven, river and lake  
183 sediment samples were decarbonated by two successive 5 mL HCl 0.5N leaching steps to remove  
184 authigenic and detrital carbonate (**supplementary S4**). Major and trace elements of supernatants from

185 each leaching step were measured by Q-ICP-MS (section 3.2) to evaluate the amount of calcium (Ca)  
186 and Sr lost. As discussed below, this leaching procedure did not lead to complete removal of the  
187 carbonate component from the river sediment samples, which might be due to the presence of  
188 dolomite in the sediment.

189 A series of river sediment samples was kept unleached and measured as bulk powder for isotope and  
190 major and trace element concentration measurements. All samples (bulk or residue from the leaching  
191 steps), then underwent a digestion using concentrated acid mixtures of HF, HNO<sub>3</sub>, and HCl.

### 192 3.4. Major and trace elements

193 Major and trace element concentrations were measured using an Agilent 7900 quadrupole ICP-MS (Q-  
194 ICP-MS) at the High-Resolution Analytical Platform (PARI) of the Institut de physique du globe de Paris  
195 (IPGP). Liquid samples were sprayed through a micro-nebulizer in a Scott spray chamber prior to  
196 ionization. Magnesium (Mg), calcium (Ca), and iron (Fe) were measured using a collision-reaction cell  
197 with helium gas (5 mL.min<sup>-1</sup>) to remove polyatomic interferences. Nd and Sr were measured without  
198 collision gas. Signal drift and matrix effects were corrected by injection of scandium, indium, and  
199 rhenium as internal standards after inline mixing with the samples. Two sets of multi-element  
200 calibration standards (one for major and one for trace elements) were analysed to compute the  
201 calibration curves that were used to convert measured counts to concentrations. The reported  
202 uncertainties were calculated using the algebraic propagation of blank subtraction and sample count  
203 standard deviations (n=3). The NIST®SRM®2709a reference material (San Joaquin soil) was processed  
204 as samples and analysed repeatedly during the sequences to evaluate the accuracy of the  
205 measurements. The detection limit was between 0.2 and 0.5 ppt depending on the element, and the  
206 internal errors were 5% on average. The weight loss during carbonate leaching of lake (and river in  
207 some cases) sediments was considered in the estimate of major and trace element concentrations of  
208 the residue, such that the reported concentrations relate to the mass of residue (that is, carbonate-

209 free, and referred to as “silicate” in the following) component of the sediment (**see supplementary**  
210 **S4**).

### 211 3.5. Isotopic composition

212 Isotope measurements were all performed at the PARI analytical platform of IPGP. After powder  
213 digestion, Sr and Nd were separated from the sample matrix by extraction chromatography. We used  
214 an Sr-SPEC resin (Eichrom) for Sr (Hajj et al., 2017) and a combination of TRU-spec and Ln-spec resins  
215 for Nd (Cogez et al., 2015).

216 Sr isotope ratios were measured by multi-collector inductively coupled plasma mass spectrometry  
217 (MC-ICPMS; Neptune, Thermo-Fisher Scientific) with an APEX-Q (ESI) desolvation system as a sample  
218 introduction system. Rubidium (Rb, that was observed in residual amounts in some samples, even after  
219 chromatographic purification) interference on mass 87 and krypton (Kr, present in the argon gas used  
220 to produce the plasma) interferences on masses 84 and 86 were corrected for using the  $^{85}\text{Rb}$  and  $^{83}\text{Kr}$   
221 signals along with the Rb and Kr isotope ratios measured at the beginning of the sequence.  
222 Instrumental and natural mass fractionation on the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio were corrected using an exponential  
223 law, the measured  $^{88}\text{Sr}/^{86}\text{Sr}$  ratio and the “natural” abundance  $^{88}\text{Sr}/^{86}\text{Sr}$  ratio assumed to be equal to  
224 8.3752. Measurement accuracy was checked through repeated measurements of the NIST pure-Sr,  
225 isotope reference material SRM 987 (2 S.D of  $2.9 \times 10^{-5}$ ), and the NIST soil reference material SRM  
226 2709a ( $^{87}\text{Sr}/^{86}\text{Sr} = 0.70823 \pm 0.00002$ ; comparing well with the value provided by Brazier et al., 2020 of  
227  $0.70814 \pm 0.00002$ ). Each sample was measured up to three times during a session. For samples  
228 measured three times, the 95% confidence interval was obtained from Student’s t-distribution and  
229 ranged from  $3 \times 10^{-6}$  to  $8 \times 10^{-3}$ . For other samples measured less than 3 times, the 2 S.D of  $4.9 \times 10^{-5}$   
230 estimated from the repeated measurements of the reference material NIST SRM 2709a (processed  
231 through powder digestion and separation as for samples) was used as an estimate of the 95%  
232 confidence interval.

233 Nd isotope analyses were performed by MC-ICP-MS Neptune using N<sub>2</sub> addition and X-cones with an  
234 APEX-IR (ESI) desolvation system as the sample introduction system. Instrumental and natural mass  
235 fractionation on the <sup>143</sup>Nd/<sup>144</sup>Nd ratio were corrected for using an exponential law, the measured  
236 <sup>146</sup>Nd/<sup>144</sup>Nd ratio and its natural abundance ratio, taken as 0.7218. Accuracy was checked through  
237 repeated measurements of a NIST pure-Nd, isotope reference material (<sup>143</sup>Nd/<sup>144</sup>Nd = 0.511418; Caro  
238 et al., 2006), with a measured 2 S.D of 2.7 x 10<sup>-6</sup>, and the NIST soil reference material SRM2709a  
239 (0.512381 ± 0.000028). For convenience we report Nd isotope ratios as εNd values:

$$240 \quad \epsilon Nd = \left( \frac{(^{143}\text{Nd}/^{144}\text{Nd})_{\text{samples}}}{(^{143}\text{Nd}/^{144}\text{Nd})_{\text{CHUR}}} - 1 \right) \times 10\,000$$

241 with (<sup>143</sup>Nd/<sup>144</sup>Nd)<sub>CHUR</sub> (CHUR standing for “chondritic uniform reservoir”) equal to 0.512638 (Jacobsen  
242 and Wasserburg, 1980). Each sample was measured twice during a session, and the 95% confidence  
243 interval of the measurement was estimated from the 2 S.D. at 0.4 εNd unit from repeated  
244 measurements of the NIST reference material SRM2709a at mass spectrometric signal levels similar to  
245 those of samples.

## 246 4. Results and interpretations

247 All the results of lake (sink) and river (source) sediment geochemistry, dating and sedimentology are  
248 presented in **Figs. 3 and 4** and in **supplementary Table S1, S2, S3 & S5**.

### 249 4.1. Lake sediments

250 In the SEB18 sediment section, background sedimentation accounts for 39 % of the total sediment  
251 accumulation and is composed mainly of grey clay, visually distinguishable from homogenite or  
252 turbidite-type graded layers interpreted as event layers. Over the 15.5 m of sediment, 146 event layers  
253 (≥ 1 mm) have been identified and represent 61 % of the sediment. The material making the  
254 background sedimentation of the lake Iseo deep basin mainly consists of detrital silicates. Indeed, most  
255 of the lake authigenic carbonate is dissolved within the water column whereas the organic matter

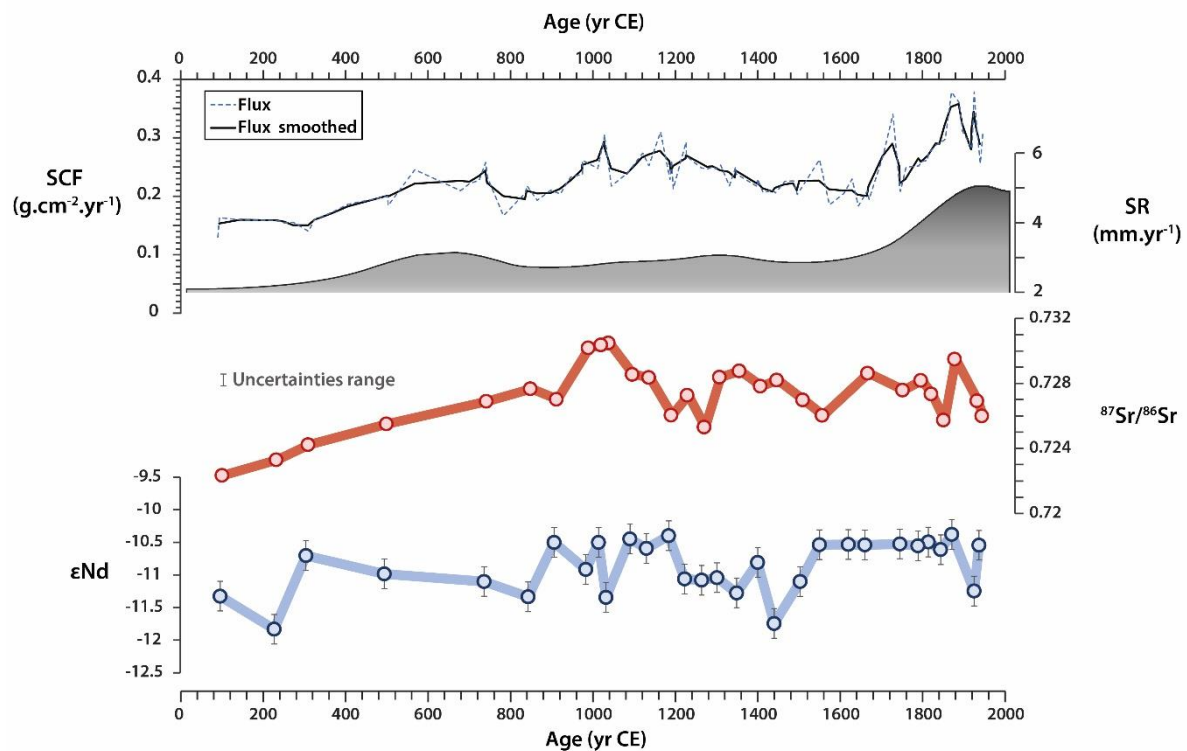
256 content is under 8 %, and detrital carbonates account for less than 18 %. NCIR mean value in the  
257 background sedimentation is 82.5 % and increase progressively towards the bottom of the sequence  
258 **(see supplementary S1)**.

259 The age depth-model of the SEB18 sequence was constrained by a combination of short-lived  
260 radionuclides, varve counting, and  $^{14}\text{C}$  ages, detailed information is presented **in supplementary S5**.  
261 To constrain the upper part (0 – 48 cm) of the sediment section, we used  $^{137}\text{Cs}$  and  $^{241}\text{Am}$  profiles, that  
262 present two peaks (16.7 – 19.7 and 42.5 – 43.5 cm) that are widely attributed to the 1986 CE Chernobyl  
263 accident (e.g., Appleby et al., 1991) and to the maximum nuclear weapon tests at 1963 CE (Appleby et  
264 al., 1991b). These peaks, in good agreement with the varve counting model and the  $^{210}\text{Pb}$  excess profile  
265 ( $^{210}\text{Pb}_{\text{ex}}$ ), are used as chronological markers to construct the age-depth model of the entire SEB18  
266 sediment section. Thirteen samples of terrestrial macro-remains were analyzed to provide radiocarbon  
267 ages for the rest of the sediment section. Once calibrated, 4 of these 13 dates were not used because  
268 they presented ages older than the best-fit age-depth curve of the SEB18 sequence. The thickness of  
269 each event layer was subtracted from the SEB18 sediment sequence depth to create an event-free  
270 depth and to obtain the best age-depth model. The obtained SR was calculated from the event-free  
271 depth and is not influenced by the variation of the event layer occurrence (**Fig. 3**). To reduce the SR  
272 uncertainty linked to the first radiocarbon age, we decided to use only the uncertainty of the short-  
273 lived radionuclides and the other radiocarbon ages.

274 The SEB18 sequence covers the last 2000 yrs (21 – 2018 CE) with a continuous SR that varies between  
275 5.1 and 2.1  $\text{mm}\cdot\text{yr}^{-1}$ , with a mean of 3.1  $\text{mm}\cdot\text{yr}^{-1}$ . Three periods of gradual increase of SR are identified  
276 in the sequence: (i) between 500 and 800 CE (SR max = 3.2  $\text{mm}\cdot\text{yr}^{-1}$ ), (ii) between 1000 and 1400 CE  
277 (SR max = 3.06  $\text{mm}\cdot\text{yr}^{-1}$ ) and (iii) from 1500 CE towards the top (SR max = 5  $\text{mm}\cdot\text{yr}^{-1}$ ).

278 In the siliciclastic fraction of Iseo Lake sediments, the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio ranges between 0.730 and 0.722  
279 with a significant increase from 97 to 1033 CE followed by a decrease until 1265 CE, and then relatively  
280 high values with successive high and lows until the present day (**Fig. 3**). Values of  $\epsilon\text{Nd}$  are relatively

281 invariant and range between -11.8 and -10.4 (Fig. 3), with only two notable excursions towards higher  
282 values from 907 to 1185 CE and from 1551 to 1872 CE.



283  
284 *Figure 3 – Silicate detrital flux (SCF, for siliciclastic flux), sedimentation rate (SR) and Sr and Nd isotope ratios of Lake Iseo over*  
285 *the last 2000 years obtained from lake sediment SEB18 sediment sequence. The siliciclastic flux was obtained from loss on*  
286 *ignition analyses, age-depth modelling and density measurements (supplementary S1). The sedimentation rate was obtained*  
287 *from the age-depth model (supplementary S5). Error bars on the <sup>87</sup>Sr/<sup>86</sup>Sr and εNd curves represent the 95% confidence*  
288 *intervals corresponding to analytical uncertainty.*

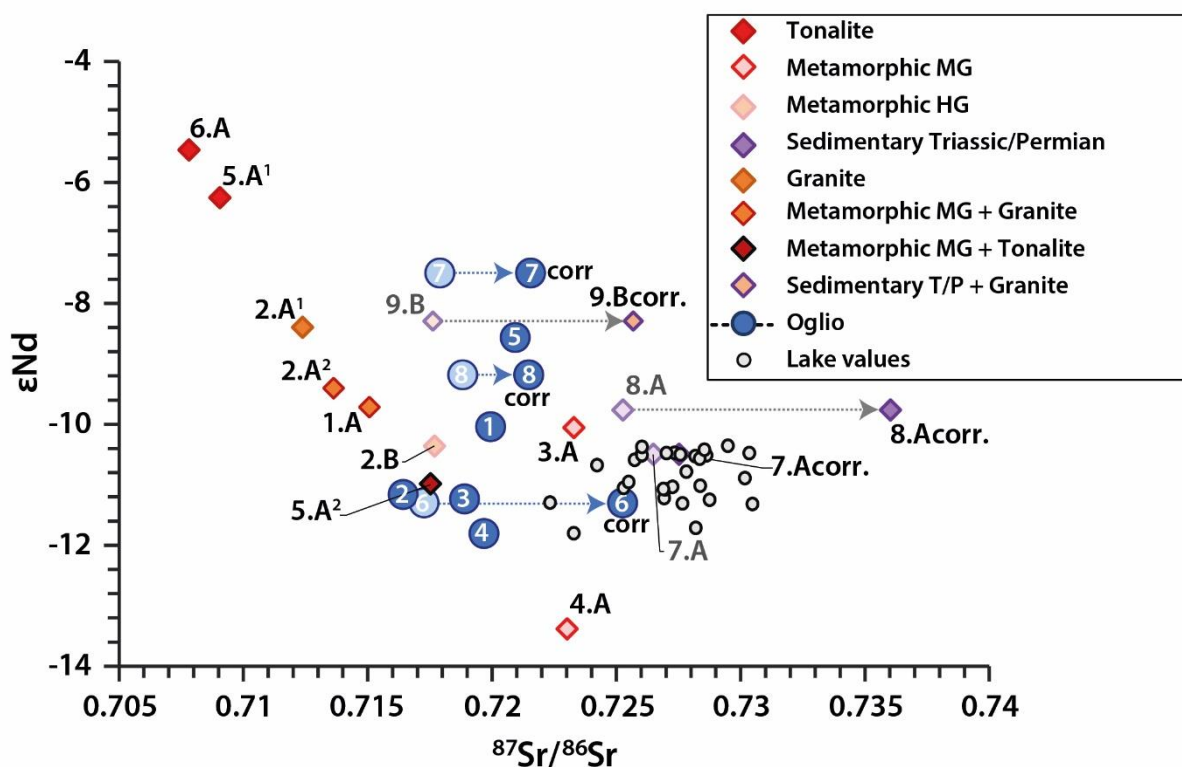
#### 289 4.2. River samples

290 River sediments taken in Oglio sub-catchments are characterized by εNd values ranging from -5.5 to -  
291 13.4 (Fig. 4). Sediment samples from the northern, high-altitude basins, thus reflective of the calco-  
292 alkaline-type rock sources present the most radiogenic values: -5.5 to -6.3 for sub-catchments  
293 essentially underlain of tonalites (6.A and 5.A1) and -8.4 to -9.7 for granite dominated sub-catchments.  
294 Southern sub-catchments draining sedimentary rocks display εNd values ranging from -8.3 to -10.5,  
295 while sub-catchments dominated by Variscan metamorphic rocks present the highest variability in εNd  
296 values, from -10.1 to -13.4.



297  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios for leached river sediment samples range from 0.708 to 0.726. Northern Oglio sub-  
 298 catchments dominated by calco-alkaline series display low  $^{87}\text{Sr}/^{86}\text{Sr}$  values, from 0.708 for tonalite-  
 299 dominated catchments to 0.712 for granite-dominated catchments. Sub-catchments underlain mostly  
 300 by Variscan metamorphic rocks are characterized by  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios ranging from 0.718 to 0.723.  
 301 Southern sub-catchments draining sedimentary rocks present  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios from 0.725 to 0.726. At  
 302 face value, none of the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios from the sampled sub-catchments can explain the most  
 303 radiogenic ratios observed in lake sediments (**Fig. 4**). Bulk values are presented in **Table S3 and Fig.**  
 304 **S6.1** and display systematically lower  $^{87}\text{Sr}/^{86}\text{Sr}$  values for sub-catchments where limestones and  
 305 dolostones crop out.

306 Oglio River samples  $\epsilon\text{Nd}$  values range between -7.5 and -11.8, whereas their  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios range  
 307 from 0.716 to 0.721 (**Fig. 4**).



308

309 *Figure 4 – Nd and Sr isotope composition of Lake Iseo siliciclastic sediment samples (small grey circles), and of river sediment*  
 310 *samples from the Oglio sub-catchments upstream from Lake Iseo (diamonds) and from the Oglio main valley (large blue*  
 311 *circles). Oglio sub-catchments symbols (diamonds) are coloured as a function of the dominant rock types underlying the*  
 312 *catchment. Oglio main valley sediment samples (blue circles) are numbered as in Figs 2 and 3. Dotted arrows represent the*

313 *correction from carbonate contribution performed for river samples originating from sub-catchments underlain by limestone,*  
314 *as constrained by mild acid leaching steps (section 3.1; **supplementary S4**).*

### 315 4.3. Interpreting Sr and Nd isotope ratios in term of sediment source 316 fingerprinting

317 Two main assumptions are made here for the interpretation of the Sr and Nd isotope data from Lake  
318 Iseo and Oglio River in terms of the contribution of each rock source to the detrital sediment input to  
319 the lake:

- 320 - All the major sediment sources contributing to detrital inputs to the lake were sampled.
- 321 - The isotopic signatures of the various potential rock sources have remained constant over the  
322 period considered.

323 Because we removed the carbonate component of the lake and river sediments, the Sr-Nd isotope  
324 signatures of lake samples can be interpreted as a mixture of the identified silicate sources. In order  
325 to quantitatively deconvolve the contributions of the dominant rock sources through time, end  
326 members need to be identified, and their signatures need to be constrained. To that effect, we selected  
327 sediment samples from sub-catchments presenting a homogeneous lithology (**Fig. 5A**). Indeed,  
328 samples from the Oglio River and sub-catchments with heterogeneous lithology (**Fig. 1**) result from a  
329 mixture of several rock sources on their own, such that considering them would not provide  
330 independent constraints on the composition of the end members. River sediment samples for which  
331 only one out of the two isotope signatures was available were not considered either.

332 Out of the remaining 8 samples, three main sources can be identified and summarized into: i) calco-  
333 alkaline rocks ("A"), ii) metamorphic ("B") and iii) sedimentary ("C") rock sources.

334 Sub-catchments draining mainly rocks from the calco-alkaline rock series (6.A, 5.A<sup>1</sup>, 2.A<sup>1</sup>) were  
335 gathered into a single "calco-alkaline rocks" source. Minor marlstone and limestone outcrops are also  
336 present in these areas, especially in 2.A<sup>1</sup> sub-catchment (**Fig. 1**) which may explain the lower  $\epsilon_{Nd}$   
337 values measured for some sub-catchment samples compared to the values reported for the rocks

338 themselves (+3.8 to -4.9; Kagami et al., 1991). This end member is sourced from the high-altitude  
339 Adamello massif (**Fig. 1**). Several glaciers and rock glaciers are currently present in this area (Scotti et  
340 al., 2013). Sr-Nd isotope signatures of the sample 6.A (**Fig. 4**) were selected as a fingerprint of  
341 the contribution of the calco-alkaline rocks source, as this sample is the closest to the Adamello massif  
342 outcrops signature (Kagami et al., 1991).

343 Sub-catchments draining mostly metamorphic rocks were combined into the “metamorphic” source.  
344 We note that these catchments are also partially underlain by sedimentary rock outcrops and  
345 Quaternary deposits. Samples from this source (2.B, 3.A and 4.A) present contrasted Sr-Nd isotope  
346 signatures, linked to their heterogeneous composition (**Fig. 4**). The sub-catchment of sample 4.A  
347 presents the highest proportion of metamorphic rocks (**Fig. 1**;  
348 <https://www.cartografia.servizirl.it/cargviewer/>), which constitutes the only rock source that can  
349 explain the lowest  $\epsilon\text{Nd}$  values observed in lake sediment samples (**Fig. 4**). As a consequence, the  
350 isotope signatures of sample 4.A are used as a fingerprint for the contribution of metamorphic rocks  
351 in the Lake Iseo catchment. Due to the significant heterogeneity of the metamorphic source, the  
352 fractional input from this end member to Lake Iseo sediments over time are discussed with great  
353 caution hereafter.

354 The remaining samples 7.A and 8.A originate from sub-catchments dominated by sedimentary rocks  
355 and were thus gathered into the “sedimentary rock” source. This source shows  $\epsilon\text{Nd}$  values between -  
356 10.5 and -9.7, associated to the highest  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios (> 0.725). However, these  $^{87}\text{Sr}/^{86}\text{Sr}$  values are  
357 not high enough to explain the highest  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios observed in lake sediment samples. This is  
358 because the sub-catchments dominated by sedimentary rocks are actually underlain by marlstones  
359 and limestones/dolostones. Although our decarbonation protocol has likely removed a large fraction  
360 of the carbonate component present in the river sediment, we expect that relatively refractory  
361 carbonate minerals such as dolomite remain in the “silicate” residue of the leaching procedure. As a  
362 consequence, this residue hosts a non-silicate component, most likely characterized by relatively low  
363  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios (Faure et al., 1978), and the contribution of which needs to be corrected for. Details

364 about this correction are provided in **supplementary S6**. After correction, the Sr signature of river  
 365 sediments from sub-catchments draining sedimentary rocks is sufficiently  $^{87}\text{Sr}$ -enriched to explain the  
 366 highest  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios observed in Lake Iseo sediments (**Fig. 4**). Areas corresponding to the  
 367 “sedimentary rock” source are located at low to mid altitude, in the southern part of the Iseo  
 368 catchment, and correspond to places of current intense human activities (**Fig. 2**). The Nd-Sr isotope  
 369 signatures of sample 8.A were selected as a fingerprint of the “sedimentary rock” source as this sub-  
 370 catchment presents the highest proportion of marlstone (**Fig. 1**;  
 371 <https://www.cartografia.servizirl.it/cargviewer/>) and is the only one explaining the most radiogenic  
 372  $^{87}\text{Sr}/^{86}\text{Sr}$  signature observed in lake samples.

373 The fractional contribution of each rock source can be estimated using a mixing model. The lake  
 374 sediment Sr and Nd isotope compositions depend on (i) the Sr-Nd concentration and isotope signatures  
 375 of each rock source, and (ii) the proportion of each contributing source in the mixture. This can be  
 376 summarized by a system of 5 linear equations, expressed as  
 377 follows:

$$378 \quad [\text{Sr}]^M = [\text{Sr}]^A \times f_A + [\text{Sr}]^B \times f_B + [\text{Sr}]^C \times f_C \quad (1)$$

$$379 \quad [\text{Nd}]^M = [\text{Nd}]^A \times f_A + [\text{Nd}]^B \times f_B + [\text{Nd}]^C \times f_C \quad (2)$$

$$380 \quad f_A + f_B + f_C = 1 \quad (3)$$

$$381 \quad \frac{^{87}\text{Sr}^M}{^{86}\text{Sr}^M} \times [\text{Sr}]^M = \frac{^{87}\text{Sr}^A}{^{86}\text{Sr}^A} \times [\text{Sr}]^A \times f_A + \frac{^{87}\text{Sr}^B}{^{86}\text{Sr}^B} \times [\text{Sr}]^B \times f_B + \frac{^{87}\text{Sr}^C}{^{86}\text{Sr}^C} \times [\text{Sr}]^C \times f_C \quad (4)$$

$$382 \quad \varepsilon\text{Nd}^M \times [\text{Nd}]^M = \varepsilon\text{Nd}^A \times [\text{Nd}]^A \times f_A + \varepsilon\text{Nd}^B \times [\text{Nd}]^B \times f_B + \varepsilon\text{Nd}^C \times [\text{Nd}]^C \times f_C \quad (5)$$

383 with the superscript M standing for lake sediment (“mixture”) values, and the superscripts A, B and C  
 384 stand for the three rock sources values (calco-alkaline rocks, metamorphic, and sedimentary rocks,  
 385 respectively);  $f_x$  represents the fractional contribution of each rock source.

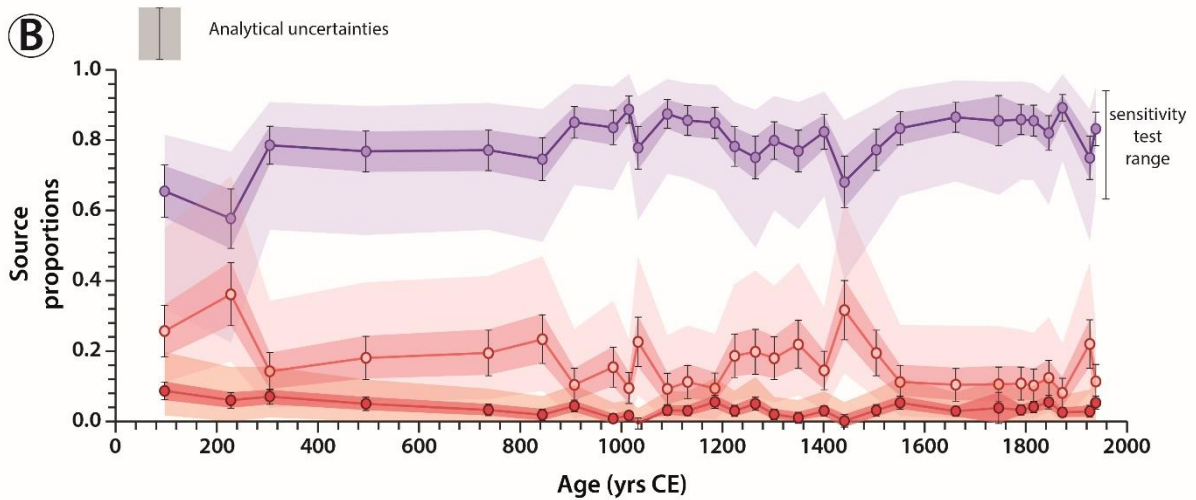
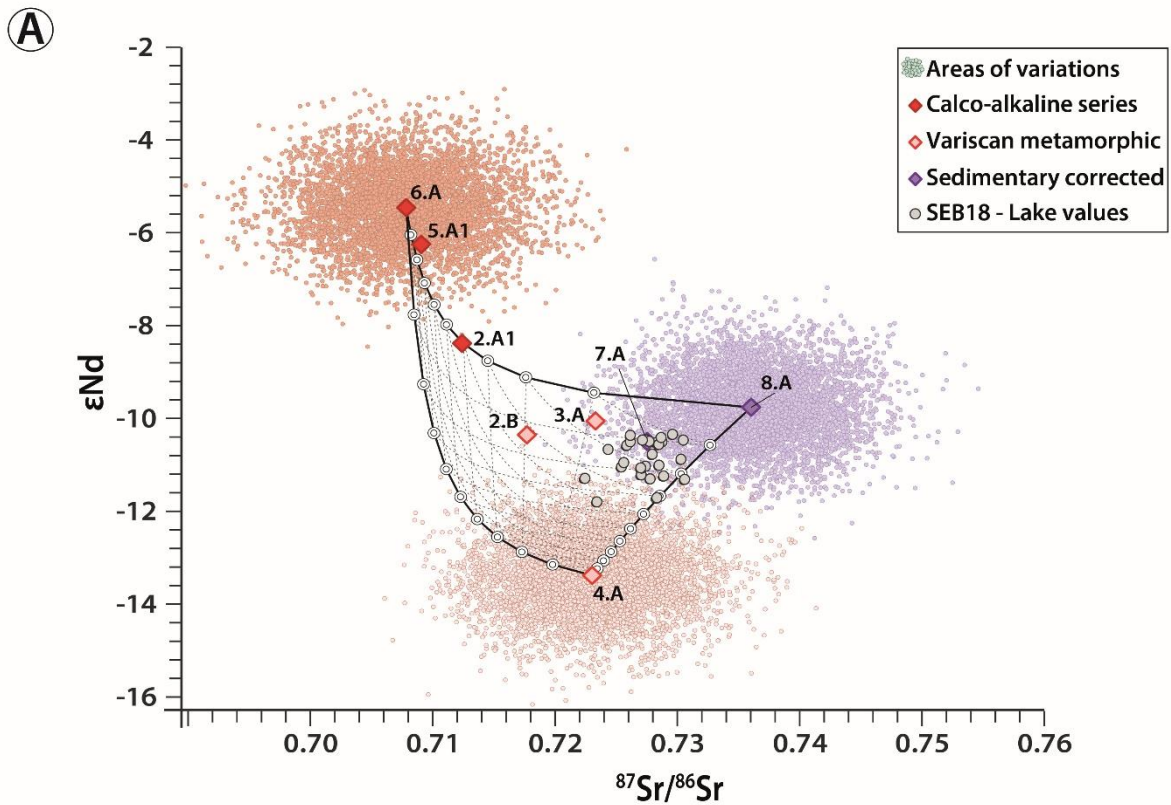
386 Solving this equation system leads to estimates of the relative contributions of sources A, B and C.

387 Analytical solutions for  $f_A$ ,  $f_B$  and  $f_C$  were obtained from Maple software (**see supplementary S7**). A

388 Monte Carlo method was used to compute uncertainties on the fractional contributions. Random  
389 sampling within the analytical uncertainties of each parameter was executed using a Box–Muller  
390 transform (Box and Muller, 1958) for each of the 5000 iterations of the Monte Carlo procedure. From  
391 the simulated parameter distributions, D84, D16, median and standard deviation were obtained for  
392 each proportion  $f_x$  (**Table S8**). The “sedimentary rocks” source contributes on average to  $79.6^{+4.8}_{-5.7}$  %  
393 of the total siliciclastic sedimentation in Lake Iseo deep basin, whereas the calco-alkaline rocks source  
394 is the smallest contributor with a mean contribution of  $3.5^{+1.8}_{-1.5}$  % and the metamorphic source  
395 contribute to  $16.7^{+6.1}_{-5.0}$  % on average (**Fig. 5B**). Through the last 2000 years, the “sedimentary rock”  
396 inputs to Lake Iseo remain predominant and increase progressively towards the Middle Ages and the  
397 Industrial Age.

398 Beyond accounting for analytical uncertainties, an additional sensitivity test was run to evaluate the  
399 impact of the Sr-Nd isotope signatures selected for each rock end member. “Geological” uncertainties  
400 of 0.005 on the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio and of 0.8 epsilon-units on  $\epsilon\text{Nd}$ , together with a 50 % relative uncertainty  
401 on Nd and Sr concentrations were attributed to each end member, and a Monte Carlo procedure was  
402 performed in the same manner as that laid out above (**Table S9** and **Fig. 5B**). Regardless of the exact  
403 composition of the three end members within the ranges given above, the “sedimentary rocks” source  
404 remains the predominant contributor to the continuous accumulation of siliciclastic material over time  
405 in Lake Iseo deep basin. Therefore, results from our mixing model can be reliably used to discuss the  
406 evolution of the contribution of each source in terms of temporal variations in erosion processes in the  
407 catchment.

408



409

410 *Figure 5 – Results from the mixing model. (A) Nd-Sr isotope signatures of the three identified rock sources, used as end*  
 411 *members for explaining the composition of lake sediments. Samples 6.A, 8.A and 4.A are used to constrain the composition of*  
 412 *the rock end members. Lake sediments are shown as grey circles within an array described by mixing hyperbolae. The pink,*  
 413 *red, and purple symbols correspond to the composition of each Monte Carlo iteration used for the sensitivity test. (B) Fractional*  
 414 *contributions of each rock source to Lake Iseo sediment against time (yr CE). The propagation of analytical uncertainties are*  
 415 *represented as error bars and by dark shaded areas, corresponding to the D84 and D16 of the distribution of the parameters*  
 416 *obtained from Monte Carlo simulations. The light shaded areas represent the propagation of the uncertainty associated to*

417 *the composition of the three rock sources, again with the D84 and D16 of the distribution of the parameters obtained from*  
418 *Monte Carlo simulations.*

#### 419 4.4. Evaluation of the sediment yield

420 Once the proportion of each sediment source to lake sediments has been calculated, river loads, and  
421 corresponding sediment yields can be estimated to obtain a quantitative assessment of catchment-  
422 scale erosion rates, for each area in the catchment. Sediment accumulated in a sinking basin, such as  
423 natural lakes, is partly composed of river silt-sized material and of authigenic deposits; sand-sized  
424 material such as river bedload being in general deposited along the sides of the river channel or in the  
425 delta (Hinderer et al., 2013). Few or none of the authigenic carbonates produced in Lake Iseo are  
426 preserved in the deep basin of the lake, as demonstrated in other deep peri-Alpine lakes (Ramisch et  
427 al., 1999), making this lake the ideal candidate to reconstruct the evolution of river suspended load  
428 through time, and thus of erosion rates in the contributing catchment. The time-dependent erosion  
429 flux from the catchment was determined as follows by using the calculation of a siliciclastic flux (SCF;  
430  $\text{g}\cdot\text{cm}^{-2}\cdot\text{yr}^{-1}$ ) from the lake sediment samples:

$$431 \quad SCF = NCIR \times SR \times DBD \quad (6)$$

432 Here NCIR is the fraction of non-carbonate ignition residue of the lake sediments; SR is the  
433 sedimentation rate ( $\text{cm}\cdot\text{yr}^{-1}$ ) derived from the age-depth-model; and DBD is the dry bulk density of the  
434 samples ( $\text{g}\cdot\text{cm}^{-3}$ ). The DBD used in the SCF calculation was smoothed using a weighted arithmetic mean  
435 to reduce the impact of measurement bias in successive samples.

436 The sediment yield is defined as the mass of sediment that, over a given time span, leaves a boundary,  
437 such as the outlet of a catchment. SY is expressed in units of mass per unit of area and time (Hinderer  
438 et al., 2013 and reference therein). This parameter is used here to enable comparison with previous  
439 studies on erosion in the Alps. To calculate SY for the Iseo catchment, the total amount of sediment  
440 stored in Lake Iseo per amount of time ( $Stock_{sed}$ ) needs to be estimated:

$$441 \quad Stock_{sed} = SCF \times Lake\ area \quad (7)$$



442 SR may vary spatially over the surface of a lake. To calculate a consistent  $Stock_{sed}$  for the entire lake  
 443 we consider only the fraction of the total lake area where SR should be commensurate with that  
 444 measured at the coring site. We assume here that this area corresponds to the flat part of the deep  
 445 basin as suggested by the seismic survey (Bini et al., 2007), which lies below the slope discontinuity.  
 446 Based on the lake bathymetry, we consider that the lake area with water depth below 210 m b.l.s  
 447 should be taken into account in the calculation of  $Stock_{sed}$ , corresponding to a total of 18 km<sup>2</sup>  
 448 (**supplementary S10**). The sediment stock is then multiplied by the contribution of each source to the  
 449 lake sediment, in order to calculate changes in the source-specific sediment loads (SL, in t.yr<sup>-1</sup>) through  
 450 time:

$$451 \quad SL = Stock_{sed} \times source\ proportion \quad (8)$$

452 To obtain an area-normalized sediment yield value for each source ( $SY_i$ ), SL is normalized to the  
 453 drainage area of each rock type. A value for total sediment yield ( $SY_{Total}$ ) was also computed from the  
 454 total SL:

$$455 \quad SY_i = \frac{SL}{Source\ area} \quad (9)$$

$$456 \quad SY_{Total} = \frac{SL}{Watershed\ area} \quad (10)$$

457 with  $SY_i$  and  $SY_{Total}$  expressed in t.km<sup>-2</sup>.yr<sup>-1</sup>. For the computation of  $SY_i$  and  $SY_{Total}$ , only the parts of  
 458 the catchment area likely to be subjected to physical erosion are considered. For more detail on these  
 459 calculations, see **supplementary S11**.

460 During the Industrial Age,  $SY_{Sedimentary\ rocks}$  and  $SY_{Calco-alkaline}$ , representing area-specific erosion rates of  
 461 the sedimentary and the calco-alkaline rocks areas in the Iseo catchment, show values around 100 and  
 462 10 t.km<sup>-2</sup>.yr<sup>-1</sup>, respectively (**Fig. 6**).  $SY_{Sedimentary\ rocks}$  values for the recent times are coherent with  
 463 estimates derived from the RUSLE model for similar contexts (Panagos et al., 2015; **supplementary**  
 464 **S12**). Calculated  $SY_{Sedimentary\ rocks}$  values for the twentieth century are also close to present-day sediment  
 465 yield measurements on Alpine rivers (30 – 671 t.km<sup>-2</sup>.yr<sup>-1</sup>; Hinderer et al., 2013). Deviations between

466 our calculations and previously reported values can be explained by storage of sediment in the lake  
467 delta (Hinderer et al., 2013) and by the absence of consideration of the bed load in our calculation.  
468 However, Hinderer et al. (2013) showed that in the southern crystalline Alps, where Lake Iseo is  
469 located, suspended load generally dominates over bed load. Altogether the present-day sediment yield  
470 estimated here for the Lake Iseo catchment is consistent with previously reported figures, lending  
471 support to our estimates of erosion rates through time.

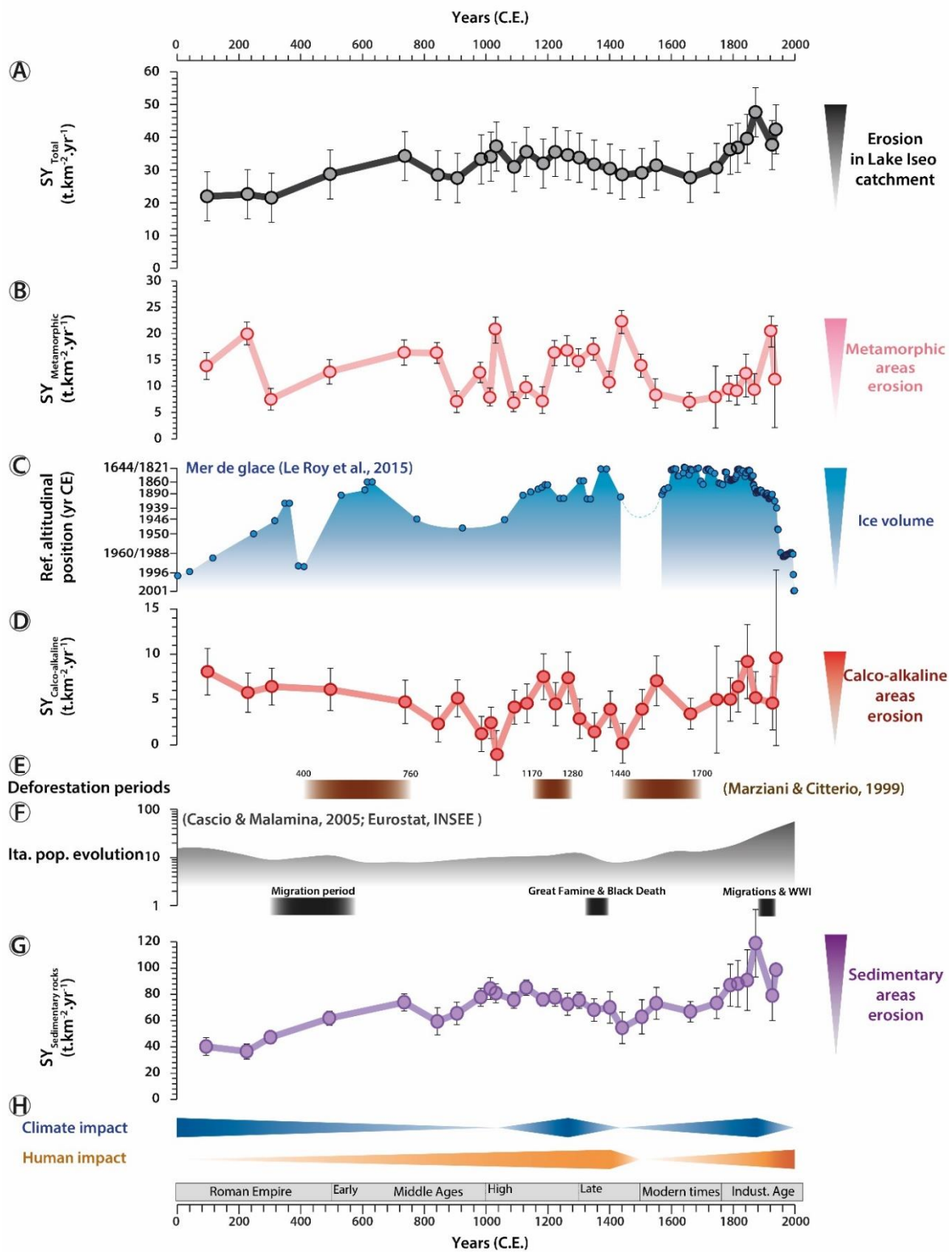
## 472 5. Discussion

### 473 5.1. The record of erosion in Val Camonica

474 The calculated  $SY_{Total}$  is about  $20 \text{ t.km}^{-2}.\text{yr}^{-1}$  during the Roman Period (**Fig. 6A**). From then on,  $SY_{Total}$   
475 values increase nearly two-fold until the Medieval Period, when it reaches values between 30 and 40  
476  $\text{t.km}^{-2}.\text{yr}^{-1}$ . Then,  $SY_{Total}$  values decrease slightly until 1661 CE, prior to a sharp increase again during the  
477 Industrial Age and until the present.

478 Over centennial to millennial time scales, erosion is mainly a result of climate, vegetation, and land use  
479 changes (e.g. Bosco et al., 2008; Panagos et al., 2015), the last two parameters being associated with  
480 human activities. To disentangle the impact of climate and human practices on erosion in the Lake Iseo  
481 catchment, we investigate separately the reconstructed sediment yields of the “sedimentary rock” and  
482 calco-alkaline rocks areas. Indeed, no or very few human activities are reported in the high-altitude  
483 part of the catchment (e.g. Biagi and Starnini, 2015). Conversely, a great number of glaciers and rock  
484 glaciers are present in this area (Scotti et al., 2013), making erosion there highly sensitive to climate  
485 induced glacial fluctuations. In contrast, human activities are widely developed at low- to mid-altitude  
486 levels in the Val Camonica, meaning that human and climate have an unquestioned influence on  
487 erosion rates in the “sedimentary rock” area. No further investigation was conducted here on the  
488 sediment yields of the metamorphic area because of the lack of information about land use over time

489 in this area, which was in addition certainly affected by a combination of glacier fluctuations and  
 490 human activities such as grazing and deforestation (Fig. 6B).



491  
 492 Figure 6 – Erosion in the Lake Iseo catchment and forcing factors evolution over the last 2000 years. From top to bottom: (A)  
 493 total sediment yield obtained from the SEB18 sediment core (black curve); (B) the sediment yield originating from the erosion

494 *of metamorphic areas in the Iseo catchment (pink curve); (C) the advances and retreats of the Mer de Glace glacier (French*  
495 *Alps, 45° 54.9'N and 6° 56.2'E) modified from Le Roy et al. (2015; blue shaded curve); (D) the sediment yield originating from*  
496 *the erosion of calco-alkaline rocks areas in the Iseo catchment (red curve); (E) the attested deforestation periods at a mid-*  
497 *altitude archaeological site of the Val Camonica valley (Marziani and Citterio, 1999; brown shades); (F) the evolution of the*  
498 *Italian population modified from Cascio and Malanima (2005) and Eurostat and INSEE sources (black shaded curve);*  
499 *demographic events that have affected the Italian population (black shades); (G) the sediment yield originating from the*  
500 *erosion of "sedimentary rock" area in the Iseo catchment (purple curve); (H) inferred periods of enhanced impact of climate*  
501 *(blue) and human (orange) activities on the erosion of the Iseo catchment.*

### 502 5.1.1. Climate impact on erosion of high-altitude areas

503 Erosion in the high-altitude area of the Adamello massif is influenced by glacier advances and retreats  
504 and by extreme precipitation events. Glacier volumes depend on summer temperature and winter  
505 precipitation amounts (e.g. Fouinat et al., 2017; Holzhauser et al., 2005; Le Roy et al., 2015), all linked  
506 to Mediterranean climate. Therefore, in order to discuss the impact of climate fluctuations on erosion  
507 in Lake Iseo catchment, we focus on the  $SY_{\text{Calco-alkaline}}$  reconstruction. Currently, glaciers present in the  
508 calco-alkaline rocks area of Lake Iseo catchment correspond to a small glacial tongue (0.7 km<sup>2</sup>) of the  
509 great Adamello glacier (21.6 km<sup>2</sup>) and small glacier bodies (< 0.5 km<sup>2</sup>) south and north of it. By their  
510 sizes, these glacier bodies are thought to be more sensitive to local climate change and present a lower  
511 inertia during glacier retreat than great Alpine glaciers.

512  $SY_{\text{Calco-alkaline}}$  first decreases from 100 to 1000 CE before increasing sharply until 1200 CE. The erosion  
513 from calco-alkaline rocks area remains high (> 6 t.km<sup>-2</sup>.yr<sup>-1</sup>) until 1300 CE before decreasing again until  
514 1450 CE. Another increase is observed until 1550 CE.  $SY_{\text{Calco-alkaline}}$  values remain high until the present  
515 days, with two peaks at 1845 CE and 1940 CE. The comparison of  $SY_{\text{Calco-alkaline}}$  evolution over the last  
516 2000 years with other alpine glaciers advances and retreats such as that of the Mont Blanc valley (**Fig.**  
517 **6C**, Le Roy et al., 2015), or smaller glacial bodies (e.g. Fouinat et al., 2017; Glur et al., 2015) presents  
518 similarities. Except for the Roman Period,  $SY_{\text{Calco-alkaline}}$  increases during periods of major glacier  
519 advances and decreases during retreat periods (**Fig. 7D**). During the Roman Period,  $SY_{\text{Calco-alkaline}}$  present  
520 high values that are not consistent with the relatively low volume of great glaciers in the European

521 Alps (Holzhauser et al., 2005; Le Roy et al., 2015). However, erosion signals from small glacial bodies  
522 in the western French Alps (Fouinat et al., 2017) or in the Central Alps (Glur et al., 2015), present  
523 several peaks of enhanced erosion between 0 to 600 CE in relation to short term temperature  
524 variation, but the sampling resolution presented here do not allow the comparison.

525 From ~500 to 1000 CE,  $SY_{\text{Calco-alkaline}}$  decreases in agreement with the volume of major great Alpine  
526 glaciers (Holzhauser et al., 2005; Le Roy et al., 2015). At that period, climate is warm and dry in the  
527 southern Alps, favouring glacier retreats (Büntgen et al., 2011). From 1000 to 1200 CE, erosion in high-  
528 altitude areas of Lake Iseo catchment increases sharply and remains high until 1300 CE. This period  
529 known as the High Medieval Advance (HMA) corresponds to a general episode of glacier advance in  
530 the Alps (Le Roy et al., 2015 and references therein) despite temperature increase in Europe (Büntgen  
531 et al., 2011). After the HMA,  $SY_{\text{Calco-alkaline}}$  decreases again until 1450 CE before another increase,  
532 observable in every alpine glacier chronicle, and corresponding to the onset of the Little Ice Age (LIA;  
533 **Figs. 6C**). This period is characterized by a globally cold and wet climate, inducing significant glacier  
534 advances that caused intense erosion throughout the alpine area (e.g. Fouinat et al., 2017; Glur et al.,  
535 2015; Holzhauser et al., 2005; Le Roy et al., 2015). The LIA is known to last approximately until the  
536 middle of the nineteenth century, which correspond to the penultimate observed peak in  $SY_{\text{Calco-alkaline}}$ .  
537 Collectively, these observations suggest, as demonstrated elsewhere in the Alps (e.g. Fouinat et al.,  
538 2017; Glur et al., 2015), that even over short time scales, colder periods induced higher erosion rates  
539 in the mountainous parts of the Lake Iseo catchment, implying a strong link between climate and  
540 erosion in high-altitude areas.

#### 541 5.1.2. Human impact on erosion of low-altitude areas

542 At lower altitudes, climate fluctuations are not the only factors responsible for changes in erosion  
543 rates. Indeed, with land use and vegetation cover management, humans play a key role on erosion  
544 (e.g. Bosco et al., 2008; Panagos et al., 2015). However, during periods of high  $SY_{\text{Calco-alkaline}}$ , climatic

545 forcing of the erosion in the low-altitude such as the sedimentary area need to be considered together  
546 with the human forcing as a possible driver of erosion.

547 The  $SY_{\text{Sedimentary rocks}}$  values increase two-fold from the Roman Period until the High Middle Ages. This  
548 increase occurs during dry and warm climate conditions across Europe (Bini et al., 2020; Büntgen et  
549 al., 2011), and is associated with a gradual decrease of the  $SY_{\text{Calco-alkaline}}$  signal (**Fig. 6D**), suggesting that  
550 human practices become the main driver of erosion in the Lake Iseo catchment at that time.  
551 Abandonment of forest management plans until the Migration Period (300 – 570 CE) has been  
552 attributed to a declining influence of the Roman Empire in the Lake Iseo catchment (Comiti, 2012). The  
553 period from the Roman Period until the High Middle Ages is interpreted as a period of enhanced human  
554 pressure on the environment due to:

- 555 (i) Deforestation to allow for instance for increased mining activity, as observable elsewhere  
556 in Europe (Büntgen et al., 2011) and at low- to mid-altitude sites in the Val Camonica (**Fig.**  
557 **6E**, Marziani and Citterio, 1999; Pini, 2002; Pini et al., 2016);
- 558 (ii) A general population increase in Italy towards the Middle Ages (**Fig. 6F**, Cascio and  
559 Malanima, 2005);
- 560 (iii) An intensification of land use and human practices, coupled with replacement of pre-  
561 existent buildings (Büntgen et al., 2011).

562 In the Iseo catchment, the collapse of the forest management system of the Roman Empire should be  
563 at the origin of an enhancement of erosion. During the High Middle Ages and until the Late Middle  
564 Ages,  $SY_{\text{Sedimentary rocks}}$  remains relatively high (**Fig. 6G**). At that time, regional climate is wet (Bini et al.,  
565 2020; Büntgen et al., 2011), extreme precipitations are frequent locally until 1300 CE (Wirth et al.,  
566 2013), and the human pressure remains important, with (i) attested periods of deforestation in the  
567 catchment (Marziani and Citterio, 1999) and (ii) intense land use and pastoralism in the Italian Alps  
568 (Büntgen et al., 2011; Comiti, 2012; Joannin et al., 2014; Pini, 2002). Therefore, disentangling human  
569 and climate forcing over this period is not possible, and it is likely that the combination of the two

570 factors induced intense erosion in the entire Lake Iseo catchment until the Great Famine (1315 – 1317  
571 CE) and the Black Death (1347 – 1351 CE). A slight decrease in  $SY_{\text{Sedimentary rocks}}$  is observed just after  
572 these two (**Fig. 7G, F**). These events are known to have deeply impacted European populations,  
573 resulting in particular in agricultural decline in the Southern Alps (e.g. Büntgen et al., 2011; Joannin et  
574 al., 2014; Ruddiman, 2007).

575 After this trough,  $SY_{\text{Sedimentary rocks}}$  increases progressively until 1800 CE and then strongly until 1872 CE  
576 and the onset of the Industrial Age (**Fig. 6G**). Two hypotheses can be invoked to explain this pattern:  
577 the effect of the Little Ice Age (LIA) following an increase of human activity. Indeed, maximal glacier  
578 advances in the Alps are reported at around 1850 CE (Holzhauser et al., 2005; Le Roy et al., 2015),  
579 before the current period of general retreat. The LIA is also characterized by more frequent extreme  
580 precipitation events in the Southern Alps (Wirth et al., 2013). The effect of LIA climate change on  
581 erosion, through precipitation events and plausible glacier advances, are well visible on  $SY_{\text{Calco-alkaline}}$  at  
582 that time and thus cannot be ignored for the interpretation of the low and mid-altitude part erosion  
583 signal of the Lake Iseo catchment, even if the LIA starts before the increase in  $SY_{\text{Calco-alkaline}}$ .  
584 Synchronously, human pressure on the environment grows sharply in the Italian Alps generally, and in  
585 the Lake Iseo catchment in particular, with an increase of the population (Cascio and Malanima, 2005)  
586 associated to a surge in agricultural practices and a transition towards intensive farming (Federico and  
587 Malanima, 2004).

588 Between 1872 and 1926 CE,  $SY_{\text{Sedimentary rocks}}$  decreases sharply, most likely due to the onset of outward  
589 migration, with more than 11 million people leaving Italy for the New World (Moretti, 1999).  $SY_{\text{Sedimentary}}$   
590  $rocks$  finally increases until 1938 CE (last sample).

591 To summarize, each episode of  $SY_{\text{Sedimentary rocks}}$  increase in the Lake Iseo catchment can be associated  
592 to a period of intense human pressure on the environment (**Fig. 6**). Between 1030 and 1300 CE and  
593 during the LIA, wetter and colder climate favoured erosion not only at high altitudes but also at  
594 intermediate and low altitudes, making it hard to disentangle climate versus human influences.



595 However, from the Roman Period to the Middle Ages and up to the present, erosion at low altitudes  
596 shows a clear increase, asynchronous and decorrelated from the regional climate trend. Therefore,  
597 only human pressure on the environment can be responsible for this trend (**Fig. 6H**). Human activities,  
598 through the development of agricultural practices and deforestation at low- and mid-altitude have  
599 induced a three-fold increase in erosion rates in a large catchment of the Italian Alps. Hence, even in  
600 large mountainous catchments, human activities affect the CZ by increasing erosion, resulting in  
601 damages on ecosystems and in soil and biomass carbon shrinkage. The CZ is deteriorated by human  
602 practices for 2000 years in the Alps, making it highly sensitive to the current anthropization pressure.  
603 Long term erosion chronicles, such as those produced from lake sediments, are critical to quantify the  
604 influence of the different forcing factors impacting CZ erosion through time.

## 605 6. Conclusion

606 Contributions of glacial variability and human activities to erosion were reconstructed from a sediment  
607 core with a stable isotope mixing model. The absolute value of sediment yields signal is highly coherent  
608 with previous work and annual average erosion models, making it possible to interpret its variations  
609 reported in the three main sources. The erosion signal from high-altitude areas, synchronous with the  
610 three main episodes of European glacier advances and retreats, is interpreted to be driven by climatic  
611 fluctuations. From the comparison between the erosion signals of high- and low-altitude areas, we  
612 were able to disentangle the main triggers of the erosion at low-altitude areas in the study area.  
613 Human activities, through deforestation, agricultural practices and grazing become the main forcing  
614 factors affecting erosion between the Roman Period and the Middle Ages, and from the Late Middle  
615 Ages to the present. A three-fold increase, from 36 to 118 t.km<sup>-2</sup>.yr<sup>-1</sup> is observed in anthropized areas.  
616 This is the first time that the impact of human activity on catchment-scale erosion is quantitatively  
617 assessed over time, based on lake sediments. These findings should contribute to enhance modelling  
618 of human impacts on Critical Zone erosion and on carbon shrinkage in soils.

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