UNIVERSITY of York

This is a repository copy of *Long-term trajectories of mountain agro-ecosystems in the North-Western Alps.* 

White Rose Research Online URL for this paper: <u>https://eprints.whiterose.ac.uk/id/eprint/198043/</u>

Version: Accepted Version

#### Article:

Giguet-Covex, Charline, Manon, Covex, Chen, Wentao et al. (13 more authors) (2023) Long-term trajectories of mountain agro-ecosystems in the North-Western Alps. Regional Environmental Change. 58. ISSN 1436-3798

https://doi.org/10.1007/s10113-023-02030-5

#### Reuse

Items deposited in White Rose Research Online are protected by copyright, with all rights reserved unless indicated otherwise. They may be downloaded and/or printed for private study, or other acts as permitted by national copyright laws. The publisher or other rights holders may allow further reproduction and re-use of the full text version. This is indicated by the licence information on the White Rose Research Online record for the item.

#### Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.



- 1 Mountain agroecosystems long-term trajectories in the North-Western Alps
- Auteurs: Charline Giguet-Covex <sup>1</sup>, Manon Bajard <sup>2,3</sup>, Wentao Chen <sup>4</sup>, Kevin James Walsh <sup>5</sup>,
- 4 Pierre-Jérôme Rey<sup>1</sup>, Erwan Messager<sup>1</sup>, David Etienne<sup>6</sup>, Pierre Sabatier<sup>1</sup>, Francesco Gentile
- 5 Ficetola <sup>4,7</sup>, Ludovic Gielly <sup>4</sup>, Claire Blanchet <sup>1</sup>, Christophe Guffond<sup>8</sup>, Patricia Chiquet<sup>9</sup>, Fabien
- 6 Arnaud <sup>1</sup>, Jérôme Poulenard <sup>1</sup>
- 7
- 8 1- EDYTEM, UMR 5204 CNRS, Univ. Savoie Mont Blanc, Pôle Montagne, 73376 Le Bourget du Lac, France
- 9 2- Centre for Earth Evolution and Dynamics, University of Oslo, PO Box 1028, Blindern, 0315 Oslo, Norway
- 10 3- Department of Geosciences, University of Oslo, Oslo, Norway
- 11 4- Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, LECA, 38000 Grenoble, France
- 12 5- BioArch-Department of Archaeology, University of York, York, YO10 5DD, UK
- 13 6- UMR INRA 42 CARRTEL, Univ. Savoie Mont Blanc, 73376 Le Bourget du Lac, France
- 7- Department of Environmental Science and Policy, Università degli Studi di Milano. Via Celoria 26, 20133
   Milano, Italy
- 16 8- Unité Archéologie et Patrimoine Bâti du Département de Haute-Savoie, 74000 Annecy, France
- 17 9- Muséum d'histoire naturelle, Secteur Vertébrés, Route de Malagnou 1, 1208 Genève
- 18

## 19 Abstract

20 Past trajectories of alpine agroecosystems are legacies that we should consider to improve

- 21  $\,$  our understanding of current responses to global environmental changes. By integrating
- 22 archaeology, history and lake sediment-derived ancient DNA records, we reconstructed the
- 23 nature and intensity of agropastoral activities in the Northwestern French Alps. We
- 24 investigated their spatiotemporal trajectories and interactions with the erosion dynamic and
- 25 vegetation cover between 880 and 2440 m a.s.l. Climatic conditions in the upper altitude case
- 26 study site predominantly controlled plant community composition and erosion. In contrast,
- 27 the other sites were influenced mainly by (agro-)pastoral activities. There, the first significant
- 28 human-driven changes in plant community composition occurred earlier (Mid-Late Bronze
- Age or Iron Age) above ca. 2000 m a.s.l. than below (Early to High Middle Ages). This pattern
- 30 mirrors the altitudinal temporal trajectory of (agro-)pastoral activities development.
- 31 Regarding erosion trajectories, all sites show stable non-degraded and degraded states 32 separated by a transition phase caused by (agro-)pastoral activities. However, this does not 33 necessarily occur when the first significant or the most intense activities develop due to the 34 different sensitivities of the systems. From the High Middle Ages or Late Middle Age/Modern 35 Period, resistance or resilience phases relative to erosion are evidenced for all agroecosystems 36 (other than the upper site). These patterns highlight adaptations of agrarian socio-37 ecosystems, possibly thanks to soil management strategies with soil protection and/or just 38 being the consequence of changes in practice for other purposes. Whether in terms of plant 39 community composition or erosion, our trajectories evidence the vulnerability of systems 40 above ca. 2000 m a.s.l. to changes in human activities and variations in climate.

#### 41 Keywords

42 Alpine agro-ecosystems, soil erosion, landscape, trajectories, lake sediment ancient DNA

43 (sedaDNA), inter-disciplinarity

- 44 6628 text+ 258 abstract
- 45 6 figures 1800 words
- 46 8686 words in total

#### 47 1 Introduction

48 Since prehistoric times, mountain environments such as the Alps, have attracted 49 human populations; hunting, gathering, pastoralism, arable agriculture and mining 50 constituting key activities (Walsh and Giguet-Covex 2019). People have been attracted to 51 these a priori "hostile territories". While complex topography and harsh climates render 52 access and mobility difficult, these physical characteristics also result in a significant diversity 53 of ecological niches across short horizontal distances, primarily due to the altitudinal gradient 54 (Archipiélago vertical in the Andes, Murra 1976; Guillet et al. 1983; Lomolino 2001). This 55 diversity within mountain ecosystems facilitates the production of a wide range of goods and 56 services (Grêt-Regamey et al. 2012). These physical characteristics also render landscapes 57 highly susceptible to slope processes (i.e. rockfalls, avalanches, erosion) and other natural 58 risks such as torrential floods (Giguet-Covex et al. 2012; Wilhelm et al. 2013). Furthermore, 59 climate changes are often exacerbated in mountain areas, as we see in the context of current 60 global warming (Beniston 2006; Hock et al. 2019). Consequently, mountain ecosystems are 61 susceptible to natural or human-driven environmental and climatic changes. Environmental 62 and climate conditions can influence lifeways, land use, and landscape management (Guillet 63 et al. 1983; Balée 2006). We might consider how these conditions influence the choices made 64 by alpine farmers and societies: Such choices might comprise adaptation by developing new 65 subsistence strategies (activities/practices) and/or migration to establish settlements 66 elsewhere. In a worst-case scenario, a society might "disappear", not a choice but a 67 consequence. Characteristic forms of adaptation to erosion include the construction of 68 terraces for crops, which also increase water storage in soils. Another form of adaptation that 69 overcomes seasonal grass/fodder shortages is transhumance (as defined in Gilck and Poschlod 70 2019), where herds and flocks pasture at high-altitude during the summer and stay in the 71 valleys or more remote lowlands during winter.

72 The concept of "trajectories" is an interesting framework that facilitates the analysis 73 of these complex systems (Dearing 2008). By definition, in physics, a trajectory is a pathway 74 that is influenced by several multiscalar factors. The path of the considered entity is defined 75 as a function of position in the reference system and momentum. By analogy, we assume that 76 the trajectory of any socio-environmental system is in part conditioned by initial physical 77 properties (geology, topography, climate, soils, hydrology) and that its subsequent pathway 78 and speed of change are also influenced by multiscalar factors that are likely to change over 79 time (Toulouse et al. 2017). The representation of such trajectories can then be used to 80 evidence shifts in system functioning, such as degradation, resilience and resistance phases or 81 adaptation processes and the legacy of past human activities on the current ecosystem state 82 (Dearing 2008; Scheffer et al. 2012).

Historical archives, archaeological research, and lake-sediment analyses provide
 complementary data for investigating complex human-climate-environment interactions

85 (Dearing et al. 2008; Gilck and Poshold 2019). Despite the large number of multi-proxy and 86 interdisciplinary studies focused on alpine societies and their environmental impacts (Wick 87 and Tinner 1997; Schmidt et al. 2002; Koinig et al. 2003; Giguet-Covex et al. 2011; Vannière et 88 al. 2013; Roepke and Krause 2013; Brisset et al. 2013; Dietre et al. 2014; Walsh et al. 2014), 89 questions about the precise nature of agropastoral activities, their spatiotemporal trajectories 90 and their interactions with environmental/climatic changes have not yet been fully resolved. 91 This is primarily due to the lack of suitable proxies for the precise documentation of human 92 activities at local scales and over long periods. However, in the current context of 93 unprecedented global changes (climate, land-use, pollution, decline of biodiversity), detailed 94 studies with long-term perspectives of these agrarian socio-ecosystems are of primary 95 importance.

96 Here we present an interdisciplinary synthesis that documents the altitudinal 97 variability in the history of agro-(sylvo)-pastoral activities and the trajectories of mountain 98 agroecosystems. The synthesis encompasses five sites covering the altitudinal range between 99 874 to 2447 m a.s.l. in the North-Western Alps. The dataset is derived from lake sediment 100 ancient DNA (sedaDNA) analyses focused on plants and mammals and sedimentological or 101 geochemical analyses for local-scale reconstruction of the precise nature of agropastoral 102 activities and their impacts on plant community composition and erosion dynamics. Analyses 103 of coprophilous fungi spores and selected pollen taxa are also included where available to 104 help constrain the history of agricultural and pastoral activities. By integrating all indicators of 105 agropastoral activities, we propose a synthetic index of the (agro-)pastoral intensity to 106 facilitate the analysis of the agroecosystem trajectories. Moreover, some study sites have 107 benefited from archaeological and historical research.

## 108 2 Study sites

109

110 Mountain societies have developed specific activities across the different vegetation 111 belts (Guillet et al. 1983). The valley bottoms and sub-montane to montane belts can be 112 exploited for cultivation, hay/fodder production, livestock farming and forestry, whereas 113 subalpine areas are dedicated to pastoralism and, on occasion, haymaking. This specificity of 114 mountain landscapes has led to the development of seasonal vertical mobility from the 115 valleys, or other regions, such as lowland Provence, to the high-altitude pastures, i.e. the 116 "Alpages". Our study sites are distributed across these vegetation belts, from the montane to 117 the alpine/nival belts (Fig. 1; Table 1). They cover different massifs and valleys from the 118 external to the internal Alpine zones, i.e. with different accessibility, geological and thus 119 topographical features and climatic conditions (internal massifs are drier and warmer than 120 external massifs; Theurillat and Guisan 2001). The external subalpine massifs comprise the 121 Bauges massif with Lake La Thuile (874 to 1209 m a.s.l.) and the Haut-Giffre massif with lakes 122 Gers (1540 to 2385 m a.s.l.) and Anterne (2063 to 2494 m a.s.l.), the Vallon de Sales (1600 m 123 to 2733 m a.s.l.) and Anterne-Pormenaz massifs (1700 to 2700 m a.s.l.). Lakes Verney (2088 124 to 2930 m a.s.l.) and Savine (2447 to 3312 m a.s.l.) are in the inner massifs of Grand Paradis in 125 the Aoste Valley (Italie) and Mont-Cenis in the Maurienne Valley (France), respectively. More 126 details on geology, current vegetation cover and human activities are provided in 127 Supplementary material 1. The period covered by the records varies between 4600 years at 128 Verney and Gers, and 6000 to 6500 years at La Thuile, Anterne and Savine. 129

# 130 3 Material and methods

131

### 132 **3.1. (agro-)pastoral activities and activity intensity**

133 The sedaDNA data from the five lakes were produced following similar laboratory 134 protocols. There are, however, some differences in the extraction procedure and the number 135 of PCR replicates across certain lakes (Supplementary table 1). The same treatment procedure 136 (bioinformatic and subsequent filtering) was applied to high-throughput sequencing data 137 (Giguet-Covex et al. 2019). Taxa used for the reconstruction of (agro-)pastoral history for each 138 lake are shown in Fig. 2. Taxonomic, taphonomic or methodological gaps from the DNA record 139 were compensated via reference to selected pollen taxa from La Thuile and coprophilous fungi 140 spore analyses from Gers and Verney (Supplementary table 1, Supplementary figure 3). 141 Details regarding the strengths and weaknesses associated with each method are provided in 142 Supplementary material 2.

143 To analyse agroecosystem trajectories, we also developed a synthetic index reflecting 144 the intensity of (agro-)pastoral activities. The proposed index is the aggregation of all (agro-145 )pastoral activity proxies (Supplementary table 1). The selected markers are standardised via 146 Z-scores. Then, the synthetic index is obtained by calculating the mean of the standardised 147 proxies. The hypotheses underpinning this index are 1) the different sensitivities of the proxies 148 due to taphonomic/methodological issues (Sporormiella more sensitive to low-intensity 149 activities than animal DNA; Giguet-Covex et al. 2019) and 2) ecological preferences related to 150 the intensity of activities (Plantago sp. for extensive and intensive activities and Rumex sp. for 151 intensive activities and/or the presence of resting places). Moreover, this index considers that 152 the more diversified the activities, the greater the intensity of the activities. One criticism of 153 this index, when it comes to assessing human impact on plant community composition and 154 soil stability, is that it does not consider deforestation due to difficulties in discriminating 155 human- and climatic-induced forest cover loss on sites around the tree line. Therefore, we 156 note that the intensity of human activity reflected in our index is underestimated for some 157 periods.

158

160

## 159 **3.2.** Plant community composition

161 To assess the overall trajectories of plant communities, we performed nonmetric 162 multidimensional scaling (NMDS) using the Bray-Curtis dissimilarity indices with the function 163 metaMDS from the VEGAN package v2.5.6 in R (Oksanen et al., 2013; Kruskal 1964; Legendre 164 and Legendre 2012). The dataset is based on the number of DNA copies (i.e. the number of 165 DNA reads) for each taxon (N.B. cultivated plants at La Thuile were not included in the NMDS 166 as we analyse the impact of agropastoral activities on plant communities). PCR replicates were 167 grouped with two replicates by sample, i.e., by age. This treatment reduces "noise" in the 168 dataset due to PCR stochasticity and yields a more robust analysis. A colour code was used to 169 discriminate the different cultural periods, and a spatial median for each phase was 170 determined using the function ordispider from the VEGAN package. The position of this 171 median was then used to draw the trajectory of plant communities. This NMDS analysis and 172 representation facilitate the identification of similarity or dissimilarity in plant community 173 composition between the samples of different ages: the closer two points are, the more 174 similar the composition and vice versa.

175

#### **3.3. Erosion proxies**

177 For the reconstruction of erosive processes, we selected different erosion indicators 178 (Supplementary table 1); these depend on each study area's geomorphologic and sedimentary 179 contexts. Other than Lake La Thuile, the lakes presented in this study are dominated by detrital 180 clastic and organic matter. In lakes Savine, Anterne and Gers, many of these detrital inputs 181 are transferred to the lake during flood events. These events result in specific sedimentary 182 deposits characterised by fining-upward facies from well-sorted coarse particles at the bottom 183 to a clayey cap (Arnaud et al. 2002). Consequently, in these contexts, the flood deposit 184 frequency and the total sedimentary accumulation, i.e., the continuous sedimentation rate 185 and the flood deposit thickness, are pertinent erosion proxies. Their signal will depend on the 186 precipitation frequency and intensity and sediment availability, which is greatly influenced by 187 human land use (Giguet-Covex et al. 2012). To integrate the entire erosion dynamic and assess 188 the complexity of the underlying mechanisms, mean values for the different cultural periods 189 of each of these proxies were assessed (detailed discussion in Supplementary material 6). In 190 lake Verney, where flood deposits are absent, the sedimentation rate represents a reliable 191 proxy of the erosion dynamic (Bajard et al. 2017a). However, in Lake La Thuile, where bio-192 precipitation of carbonates and aquatic organic matter were also significant during certain 193 periods of low erosion (Bajard et al. 2017b), titanium is preferred because it is a purely detrital 194 element not affected by weathering processes. To analyse the erosion trajectories in response 195 to the intensity of (agro-)pastoral activities, these site-specific erosion proxies were 196 standardised (Z-scores), and mean and standard deviation values for each cultural period were 197 calculated.

- 198
- 199

#### $200 \qquad \textbf{3.4. Archaeological and historical research}$

201

202 Archaeological surveys and excavations have been carried out in or close to three of the 203 lake catchments (Fig. 1; 4). Between lakes Gers and Anterne in the Vallon de Sales, a research 204 program has documented human occupation from the Late Middle Ages to the contemporary 205 period (Guffond and Mélo 2018), including zooarchaeological analyses (Fig. 4; Supplementary 206 table 2). This research is supplemented by interpreting historical documents (land registries, 207 old photographs, texts), which facilitate understanding human occupation and land-use. 208 Adjacent to this area, in the massifs of Anterne and Pormenaz, archaeological investigations 209 identified several phases of activity from the Neolithic to the Modern Period (Rey et al., 2022; 210 Fig. 4). Around Lake Verney, on both sides of the Petit Saint-Bernard pass (Fig. 1), from 700 to 211 2500 m a.s.l., the archaeological fieldwork discovered sites dating from the Neolithic to the 212 Middle Ages (Crogiez-Pétrequin 2016; Rey and Moulin 2019; Rey and Collombet 2020).

213

# 214 4 Results and interpretations

- 215
- 216 217

#### 4.1. Detailed history of agropastoral activities: an altitudinal evolution

The synthetic index of (agro-)pastoral activities, represented by box plots for each cultural phase and lake, outlines an altitudinal trajectory over time with different activity intensities across the different vegetation belts (Fig. 3). This evolution is discussed in the light of proxies indicating the nature of activities inferred from, lake sediments (Fig. 2,

- 222 Supplementary figure 3) along with archaeological (Fig. 1, 4) and historical research carried out
- in the vicinity of the lakes or from neighbouring Alpine landscapes.
- 224

225 Late Neolithic Period. In mid to high-altitude areas, evidence for pastoral activities is 226 negligible or uncertain, leaving the debate open regarding the existence of high-altitude 227 pastoralism during this period (Schwörer et al. 2015; Dietre et al. 2017, 2020; Hafner and 228 Schwörer 2018). Indeed, the low level of Bos DNA (genus of wild and domestic cattle) detected 229 at Savine and Anterne at 3300 and 2900 BC, respectively, might be attributed to; the actual 230 presence of cattle, sporadic contamination, or the presence of Aurochs (Fig. 2). Moreover, at 231 Anterne, the decrease in tree cover (Pinus sp. DNA) and increase in erosion during this period 232 could be due to pastoral developments and the transition toward the Neoglacial Period. At 233 Gers, the low concentration of Sporormiella sp. spores could also reflect low levels of pastoral 234 activity or the presence of wild herds, as Sporormiella sp. develops on herbivores' faeces 235 (Davis and Shafer 2006). The absence of archaeological evidence, whether in the subalpine 236 Bauges and Haut-Giffre massifs or around the Petit Saint-Bernard Pass (Fig. 4; Rey 2016; Rey 237 et al. 2022; Rey and Moulin 2019), supports the absence or low intensity of pastoral activities 238 in the high altitudinal zones during the late Neolithic. In these areas, as in other subalpine 239 massifs (e.g. Chartreuse, Martin et al. 2012), artefacts are often instead associated with 240 hunting and gathering activities or the collection of mineral resources.

241 In the montane belt at La Thuile (Bauges massif), the landscape was dominated by fir and 242 alder forest, probably comprising some forest clearings as suggested by the decrease in Abies sp 243 DNA (Supplementary figure 3). In this context, the detection in several samples, but few 244 replicates, of Bos and Ovis DNA might suggest the development of a sylvo-pastoral system. This 245 extensive practice (a system with relatively few animals spread across a relatively large area) is 246 expected to have a low impact on erosion (titanium, Supplementary figure 3), which, in turn, is 247 not conducive to DNA transfer to the lake. Moreover, such a practice reduces animal DNA 248 production. These conditions can explain the low animal DNA detection and low intensity of 249 pastoral activity (Fig. 2, 3). In another subalpine massif (Vercors, Fig.1 star 1), archaeobotanical 250 and zooarchaeological analyses from a sheepfold cave at 580 m a.s.l. also evidence cattle and 251 caprine fodder derived from trees and shrubs from the pastures and/or within the shelter 252 (Delhon et al. 2008). Sheepfold caves also exist in the Bornes subalpine massif (La Balme de Thuy, 253 620 m a.s.l; Fig. 1 star 2; Ginestet et al. 1984; Remicourt 2009) and in the Haute Maurienne (Les 254 Balmes à Sollières-Sardières, 1350 m a.s.l.; Fig. 1 star 3; Vital and Benamour 2012; Martin and 255 Lundström 2012). In the Tarentaise area, pastoral activities are also evidenced by 256 zooarchaeological remains of sheep, goat and cattle as early as the mid-Neolithic (4300-3300 BC, 257 Le Chenet des Pierres at Bozel, 940m a.s.l.; Fig. 1 star 4; Chiquet 2019).

258

259 Mid to Late Bronze Age. At all high-altitude sites (Savine, Verney and Anterne), 1600-1000 260 BC corresponds to the start of significant pastoral activities (Figs. 2, 3). This is mainly evidenced 261 by the high and regular detection of DNA from the ruderal *Plantago sp.* (Fig. 2). At Anterne, this 262 hypothesis is strengthened by the presence of Ovis DNA, albeit in low quantities, probably due 263 to taphonomic issues (Supplementary material 2.1.) and a tipping point recognised in the erosion 264 dynamic, characterised by a permanent increase in flood deposit frequency and thickness 265 (Supplementary Fig. 3; Giguet-Covex et al. 2011). At Verney, the concentration of Sporormiella 266 sp. spores suggests extensive pastoral activities as early as 2250 BC, but more intensive activities from 1100 BC. Similarly, in a Swiss lake located in the upper subalpine belt (Sulsseewli at 1922 m
a.s.l.; Fig. 1), the first occurrence of sheep DNA is dated to 1850 BC, while significant sheep DNA
detections appear from 1450 BC (Garcés-Pastor et al. 2022).

271 Unlike the Southern French Alps, where several high-altitude enclosures have been 272 discovered (Walsh and Mocci 2011), the equivalent archaeological evidence is limited in the 273 North. The remains of a wooden structure dated to the mid (1630-1450 BC) and late Bronze Age 274 (1410-1220 BC) have been excavated close to Anterne at Le Laouchet (1950 m a.s.l., Fig. 3; Rey 275 et al. 2022). An ethnoarchaeological study in the Italian Alps showed that non-dairying 276 pastoralists are less visible in the landscape than dairying pastoralists (Carrer 2016). This 277 ethnoarchaeological analogy might help explain the relative dearth of archaeological evidence 278 for pastoralism in some areas.

279

270

280 At lower altitudes, at Gers and La Thuile, low-intensity pastoral activities are apparent 281 (Fig. 3). They are evidenced at Gers by low numbers of *Sporormiella sp.* spores and low detection 282 of *Plantago sp.* DNA. A similar pattern in the pollen record of *Plantago sp.* is observed at La Thuile 283 (Supplementary figure 3; Bajard et al. 2016). However, no specific pastoral indicators are 284 available for this period (no sedaDNA was detected for taphonomic reasons, and no Sporormiella 285 sp. analyses were undertaken). Combined, these results from the low-to-mid altitudes suggest 286 small-scale pastoral activities or practices that differ from those seen at higher altitudes (Fig. 2, 287 3).

288

289 Iron Age and Roman Period. During the Iron Age, (agro-)pastoral activities reemerge at high 290 altitude (Savine, Verney, Anterne), while they remain low at lower altitude (Gers and La Thuile) 291 (Fig. 3). At Anterne and Verney, sheep and/or cattle DNA is detected along with *Plantago sp.* (Fig. 292 2). At Verney, there are also high levels of Sporormiella sp. spores and DNA from Rumex sp., a 293 nitrophilous plant which may indicate the presence of significant herds/flocks and/or stalling 294 areas. In the Eastern Swiss Alps, high-altitude dairy practices have been inferred from the 295 analyses of lipids in Iron Age pots (Carrer et al. 2016). Together, these results support the notion 296 of the increasing value of "Alpages" and may reflect the economic development of alpine 297 societies.

298 The Roman Period is characterised by an intensification of pastoral activities from the 299 subalpine to the alpine/nival belts (Savine, Verney, Anterne and Gers), i.e. over a wider altitudinal 300 range (Fig. 3). Both sheep and cow are present in the records from Anterne and Savines (Fig. 2). 301 However, only cow DNA is recorded at Verney, Gers, and La Thuile, which might reflect the 302 increased economic importance of this domesticate (Fig. 2). Such a pattern is also observed at 303 Sulsseewli (Garcés-Pastor et al. 2022). The synthetic index may underestimate the intensity of 304 pastoral activities at Gers and Anterne due to taphonomic issues affecting the DNA records 305 (Supplementary material 2.1.).

Archaeological data from some of our study areas attest to significant levels of human activity and movements into the "Alpages" during the Iron Age. A trend that increased during the Roman Period. Around Anterne, several archaeological structures were dated to the Iron Age and Roman Period (Fig. 4; Rey et al. 2022). At Verney, ruins of Roman buildings, a possible road station of the "Via Romana" (Crogiez-Pétrequin 2016), indicate the movement of people across the Petit Saint-Bernard pass, perhaps engaged in trade activities. Indeed, the integration of our study area into the Roman Empire triggered the growth of commercial activities and networks due to the significant requirement of the Roman Empire for wool and meat and its appetite for alpine cheese
(Frayn 1984; Segard 2009; Pliny the Elder, "Natural History" 77-79 AD, book XI, XCVII.).

315

The low levels of cattle DNA, *Plantago* and *Rumex sp.* at La Thuile (montane belt) reflect lower pastoral pressure than that seen in the higher altitudes during the Iron Age and Roman Period (Fig. 2). However, other activities, i.e. the cultivation of fruit trees (*Prunus sp.*) and some cereals, are recorded, revealing the development of an agropastoral system (Fig. 2). The disappearance of fir DNA is also notable.

321

322 End of the Roman Period and Early Middle Ages. During this period, in the alpine/nival 323 and upper subalpine areas, pastoral activities decline (Fig. 2, 3). A trend characterised by the 324 absence or low detection of animal DNA (Bos or Ovis) (Fig. 2). Short phase(s) of pastoral revival 325 are suggested at all sites, but they are not always contemporary. Around Anterne, 326 archaeological excavations have revealed new cabins, some with enclosures, but only below 327 1950 m a.s.l., i.e. lower than Lake Anterne (Fig. 4; Rey al. 2022). Below, at Gers, coprophilous 328 fungi spores, *Plantago sp.* and *Rumex sp.* DNA suggest significant activity during the Early 329 Middle Ages (500 to 900 AD; Fig. 2). In the same vegetation belt, around Lake Bénit (Fig. 1), the 330 coprophilous fungal spore record also suggests a high level of pastoral activity (Bajard et al. 331 2018). In the montane belt at La Thuile, this period corresponds to a significant development 332 in agricultural activity (Fig. 3). We see cereal cultivation, broad beans, and hemp, which may 333 reflect retting activities and a decline of forest cover affecting fir, alder and beech (Fig. 2; Bajard 334 et al. 2017b).

335 Interestingly, the apparent post-Iron Age/Roman period movement of economic 336 activity towards the lower altitudes, i.e. in the montane and lower subalpine belts, is also 337 reflected in the medieval toponomy of farms and pastures and terms associated with alpine 338 farming in the Austrian Alps (Gilck and Poschlod 2019). The first half of the Early Middle Ages 339 corresponds to the so-called "Dark Ages Cold Period" (Helama et al. 2017). These climatic 340 conditions may have partly explained the focus of more intense activities toward lower 341 altitudes. The probable shorter summer season might explain the apparent decrease in 342 activities in the highest mountain pastures.

343

344 High Middle Ages to the Early Modern Period. This period corresponds to a new 345 intensification of human activity across the montane to the alpine belts (Fig. 2, 3). At La Thuile 346 (montane zone), activities diversified with the cultivation of fruit trees, such as pears, walnuts, 347 plum or cherries, and grapes, along with the intensification of livestock farming (Fig. 2). During 348 the coldest phase of the Little Ice Age (LIA), from 1500 AD, grapes disappeared from the DNA 349 record but not the pollen signal, which indicates that these cultures still existed regionally 350 (Supplementary figure 3). As the sedaDNA represents a local signal, this result can be 351 interpreted as reflecting the impact of climate cooling on the choice of suitable crops and on 352 the development of the wine-growing "terroirs". At this time, the cultivation of other fruit 353 trees also decreased.

Higher up, in the upper subalpine/alpine areas, the lake *seda*DNA signals from *Bos, Ovis* and *Capra hircus* evidence a new phase of intensive grazing activity (Fig. 2). The presence of cattle, sheep and goats, the latter only detected in the sediments from Gers, is also attested by archaeozoological evidence from excavations in the Vallon de Sales (Fig. 4, Supplementary table 2). Bones from pigs and equids were also identified. Interestingly, DNA from all lake sediment records indicate the predominance of cattle over sheep from the High/Late Middle 360 Ages; the moment at which the proportion of cattle/sheep change varies across each lake 361 catchment, but the dates have to be considered with caution due to uncertainties in the age-362 depth models and non-continuous sampling (Fig. 2). Other than at Verney, this change seems to be progressive, with a transition phase characterised by a decrease of sheep DNA and an 363 increase of cattle DNA between the 11<sup>th</sup> and 13<sup>th</sup> (La Thuile, Anterne) or 13<sup>th</sup> and 15<sup>th</sup> centuries 364 365 (Gers). The total disappearance of sheep in the DNA records follows this. This pattern of change 366 in the composition of domesticates is reflected in fifteenth-century historical documents in the 367 Northern French Alps (Carrier, 2013; Dodgshon, 2019). In the Swiss Alps, this change in 368 composition is also recorded in historical archives dating to the end of the 13<sup>th</sup> century (Aerni 369 1991) and lake sediments between the 11th and 13th centuries, with a total disappearance of 370 sheep DNA from the 17th century (Sulsseewli, Garcés-Pastor et al. 2022). Socioeconomic 371 demands can explain this change in animal composition. Indeed, from the 11<sup>th</sup> to the 372 12<sup>th</sup> centuries, monks, lay landlords, and wealthier peasants developed commercial sheep 373 farming, primarily due to the expanding market for wool (Dodgson, 2019). Then, from the 13<sup>th</sup>-374 15<sup>th</sup> centuries, the predominance of cattle herds is explained by the increasing lowland-urban 375 demand for alpine cheeses, butter, and milk (Aerni, 1991; Dodgson, 2019). Around Anterne, 376 this change in animal composition coincides with the appearance of complex structures 377 composed of cabins with several rooms and contiguous enclosures of different sizes (Fig. 4; 378 Rey et al. 2022). These structures may reflect the development of mountain pasture farms, 379 where the milk is processed to make cheese and other secondary products. In the Vallon de 380 Sales, there was a change from large pastoral cabins to smaller, contiguous cabins between the 14<sup>th</sup> and 16<sup>th</sup> centuries (Fig. 4), which also suggests a change in the pastoral organisation 381 382 of this small valley (Guffond and Mélo 2018). This correlated with the faunal remains that show 383 lower numbers and reduced diversity in the post-medieval period (15<sup>th</sup>-16<sup>th</sup> centuries) (Fig. 4; 384 Supplementary table 2). Here, we see heterogeneity in the development and evolution of 385 mountain pastoral systems at small spatial scales (Vallon de Sales vs Anterne/Pormenaz).

386

From the 10<sup>th</sup> century, we can distinguish three peaks of enhanced pastoral activity 387 388 across all palaeo-records based on the synthetic index and/or animal DNA detection (Fig. 2, 389 grey areas a, b, c). They are not all synchronous, possibly due to dating uncertainties and the 390 different sampling resolutions, but overall, the first peak runs from the 10<sup>th</sup> to 13<sup>th</sup> centuries, 391 the second from the 13<sup>th</sup> to 16<sup>th</sup> centuries, and the last from the 17<sup>th</sup> to 19<sup>th</sup> centuries. This last 392 peak is associated with an increase in the number of contiguous cabins and zooarchaeological 393 remains at Sales, along with hamlets of chalets around Anterne (Fig. 4, Supplementary table 394 2). All these data mirror the increase in communities constituted by families and their livestock, 395 attested to in the historical documents associated with the commune (Sixt-Fer-à-Cheval) (Mélo 396 pers. Com.; Supplementary figure 4). This demographic increase is not an isolated event, with 397 population increases apparent across the Northern French Alps (Crook et al. 2004; Elleaume 398 et al. this issue). While all data types suggest increases in settlement and economic activities 399 during this period, activity intensity is not very high, especially when compared with previous 400 peaks. Different practices or a period of summering reduced by the colder conditions of the 401 LIA (Büntgen et al. 2006) might explain this apparent contradiction.

402

403 **Late Modern to Contemporary Periods**. From the 19<sup>th</sup>/20<sup>th</sup> centuries, all sites 404 show a decline in pastoral activity intensity (Fig. 2, 3). The decline is seen in the records of cattle 405 DNA and *Sporormiella sp.* spores (Fig. 2). Furthermore, in the montane belt, arable activities 406 decrease. These reduced levels of agropastoral activity correspond to a demographic decline 407 (Supplementary figure 4) due to industrialisation, technological developments, improvements in
408 modes of transport, world wars, and urbanisation. These trends were seen across the entire
409 Alpine arc (Carrer 2016; Andres 2016). Global climate warming and agropastoral decline allowed
410 forest recovery across low to mid-altitude areas (Supplementary figure 3; Bajard et al. 2016;
411 Tasser et al. 2017; Elleaume et al. this issue).

- 412
- 413

#### 414 **4.2.** Relationships between agropastoral activities and landscape trajectories

415 In order to assess the impact of human activity on changes in plant community 416 composition trajectories, the NMDS analysis and mean values of the synthetic index of (agro-417 )pastoral activities were combined (Fig. 5; Supplementary figure 5). The spatial median for 418 each cultural phase in the NMDS is used to position a circle of proportional size relative to the 419 mean intensity of (agro-)pastoral activities. We also compare erosion proxies with the intensity 420 of agropastoral activities to assess the impacts of the agropastoral activities and practices on 421 the erosion trajectory (Fig. 6; Supplementary figures 7, 8). This approach facilitates the 422 assessment of similarities and differences in the evolution and functioning of the different 423 landscape systems through time and allows the proposition of a testable general model for 424 future research.

425

426 Plant composition trajectories. At Savine, i.e. in the alpine/nival belt, no clear temporal 427 trajectory appears in the NMDS analysis (Fig. 5). However, the samples corresponding to the 428 "pre-anthropic" period on the one hand, and those corresponding to the Modern Period, on the 429 other, form two obvious different sample groups. These periods match the two climatic extremes 430 of the Holocene, i.e. the Holocene Climatic Optimum (HCO, 8000 to 5400 cal. BP) and the LIA 431 (1300-1850 AD). Moreover, the points corresponding to the Late Neolithic represent a transition 432 between the HCO and the Neoglacial period. These results suggest that climate played an 433 important role in shaping plant community changes in these alpine/nival areas (see more details 434 in Supplementary material 5.2.), which agrees with our understanding of high mountain 435 ecosystems (Theurillat and Guisan, 2001; Körner 2003; Lamprecht et al. 2018). The scattered 436 distribution corresponding to the other periods, mainly from the mid-Bronze Age, suggests the 437 presence of a mosaic landscape, possibly promoted by the development of pastoral activities. 438 For the other study sites, the plant community composition trajectories follow the cultural 439 phases characterised by changes in the intensities of (agro-)pastoral activities (Fig. 5, 440 Supplementary figure 5). As a general trend, we observe that the dissimilarity between the initial 441 plant communities, and those communities in later periods, usually increases with time. The 442 primary shifts in plant composition in the upper part of the subalpine and alpine belts occurred 443 during the Middle Bronze Age at Verney and the Late Iron Age at Anterne. Other significant shifts 444 in the plant composition trajectory are recorded later, i.e. during the Roman Period, Early Middle 445 Ages, High Middle Ages and Late Middle Ages or the Modern Period (Fig. 5, Supplementary figure 446 5). At lower altitudes, in the montane to the lower subalpine belts, the principal shifts in plant 447 composition trajectories occurred later, from the Early or Late Middle Ages. More subtle changes 448 are also seen in the Iron Age and Roman Period as well as the Early Middle Ages at Gers (Fig. 5, 449 Supplementary figure 5). As with the evolution of human occupation and land use, the principal 450 vegetation composition changes are first recorded in the upper mountain areas and then in the 451 mid to low altitudes. A more detailed assessment of plant community composition trajectories 452 reveals rare and minor "resilience" phases. They are characterised by return paths toward 453 previous plant community composition after a decline in human disturbance (Fig. 5). A resilience

454 phase is recorded from the Contemporary Period in the montane and lower subalpine belts (i.e. 455 at La Thuile and Gers). They are attributed to forest recovery, which had not (yet) reached the 456 highest vegetation belts (Supplementary figure 6). At Verney in the upper subalpine/alpine belt, 457 minor resilience phases are observed at the end of the Roman Period/beginning of the Early 458 Medieval Period and from the Contemporary Period.

- 459
- 460

461 Erosion trajectories. Our records show a diversity of erosion trajectories, despite some 462 similar trends in human land use (Fig. 6A; Supplementary figure 7). This may be explained by 463 variations in the sensitivity of landscapes to climate and human-triggered erosion due to initial 464 physical and related biological (vegetation cover) characteristics. Lakes, where flood deposits are 465 recorded, are naturally sensitive to climate-triggered-flood deposits due to the steep slopes, bare 466 soils or glacial deposits that produce easily erodible materials. When the catchment has always 467 been above the treeline (with no possible soil destabilisation due to deforestation) and does not 468 comprise extensive good quality pasture attractive to grazers but does comprise steep slopes, 469 bare soils, or glacial deposits, we expect climatic changes to act as the primary drivers of erosion 470 dynamics throughout the record. This scenario is illustrated at Savine, where the development of 471 significant grazing activities during the Roman Period did not strongly influence flood deposit 472 frequency. Only the total sediment accumulation, i.e. flood deposit thickness and continuous 473 detrital sedimentation, record substantial increases, largely due to continuous sedimentation 474 (Supplementary figure 8 and comments; Sabatier et al. 2017). However, the LIA strongly 475 impacted this site, pushing the system toward a new and degraded steady-state (Fig. 6A; Dearing 476 2008). At Anterne and Gers, the catchments also present steep slopes and bare soils, making 477 these systems naturally susceptible to erosion processes as at Savine (Giguet-Covex et al. 2012; 478 Bajard et al. 2020). However, because these systems comprise good-quality pastures, the 479 pastoral activities pushed them toward new and degraded steady-states (Fig. 6A, Supplementary 480 figure 7). Conversely, the slopes around Lake Verney are mostly gentle with highly developed 481 vegetation cover (also due to the more internal massif location). This type of system is expected 482 to be very resistant to climate and human-triggered erosion, which is what we observe here 483 (Supplementary figure 7). However, possibly due to long-term human disturbance combined with 484 climatic degradation, this system was finally pushed toward a degraded steady-state. Indeed, the 485 first human disturbances may have started to degrade and destabilise the soils, but the 486 potentially mobilised sediments must have been temporarily trapped in intermediate sinks. La 487 Thuile, which was in a densely forested area with moderate slopes, is not naturally sensitive to 488 erosion processes and does not, therefore, constitute a useful record for climate-driven erosion. 489 Significant human disturbance via deforestation and agricultural activities was crucial in 490 rendering the system sensitive to erosion, thereby pushing it toward a degraded steady-state 491 (Fig. 6A).

492

493 Although the erosion trajectories differ across the sites, we can identify four trajectory 494 patterns. The most "classical" patterns correspond to the expected increase in erosion due to 495 human (agricultural activities, deforestation, cutting or burning of shrubs) or climatic 496 disturbances, followed by a tendency to return to the initial state after the disturbance has 497 ceased. Alternating "degradation" and "resilience" phases are represented by oblique and 498 vertical feedback loops for human and climatic disturbances, respectively (Fig. 6B). Two other 499 less frequent trajectory types, termed "unusual patterns", are also observed. They correspond 500 to 1) an increase of agropastoral activities with no erosion response (rightward horizontal 501 arrow), i.e. to a "resistance" phase, and 2) a decrease in erosion while human activities remain 502 steady or see a slight increase (vertical/oblique downward arrow), i.e. to an "adaption" phase. 503 A "resistance" phase is recorded between the Neolithic and Iron Age at Verney, probably due 504 to the site's initial physical and biological conditions considered above (Supplementary figure 505 7). Another "resistance" phase appeared at Anterne during the Iron Age, but it is only visible 506 in the total sediment accumulation (Supplementary figure 8) and not in the flood frequency. 507 This apparent discrepancy reflects the complexity of erosion mechanisms, probably due to 508 interactions between climatic conditions, human activities and practices, and initial 509 environmental conditions (see Supplementary material 6 for more details). Otherwise, the 510 other "resistance" and "adaptation" phases occurred from the High Middle Ages at Anterne 511 and La Thuile, the Late Middle Ages at Gers, as well as Bénit (Bajard et al., 2018), and from the 512 Late Middle Ages and the Early Modern Period at Verney (Fig. 6A; Supplementary figures 3, 513 7). Also, all these resistance and adaptation phases developed after an anthropic erosive 514 "crisis". At La Thuile, Gers and Anterne, the erosive crises are characterised by the progressive 515 disappearance of soil surface horizons and then the deeper horizons (Bajard et al. 2017b; 516 2020; Giguet-Covex et al. 2011; Pansu et al. 2015). Moreover, at La Thuile, Bajard et al. (2017b) 517 show that the agricultural system reached a point where soil loss exceeded soil formation, i.e. 518 when the system became unsustainable. Then, the system returned to a sustainable situation. 519 This shift occurred during the phase of activity diversification, with the development of fruit 520 tree cultivation (Fig. 2). Also, fir, alder, beech and oak increased in the DNA and pollen records 521 (Bajard et al. 2016; Supplementary figure 3). The combination of these results leads us to 522 consider the role of land use management, such as tree plantations, forest management, and 523 possibly terrace construction (observed in soil profiles but undated), in reducing erosion. 524 Some have suggested that terracing in the Alps was initiated by monasteries (see Scaramellini 525 and Varoto 2008). Furthermore, this period corresponds to the start of land division based on 526 inheritance from one generation to another (Mouthon 2009). The associated development of 527 parcel limits possibly led to a topography modification and reduced erosion. Moreover, this 528 observed "adaption" pattern raises the question of farmers' awareness of erosion problems 529 linked to their activities. This "awareness" appears in historical archives from Cistercian monks 530 installed in 1132 AD in the Abbey of Tamié (Bauges Massif), which avoided cutting trees on 531 steep slopes and mountain tops to limit erosion (Crook et al. 2004). At higher altitudes, the 532 unusual erosion patterns correspond to the increased size of cowherds relative to sheep 533 flocks. This evolution was also probably associated with changes in pastoral practices, perhaps 534 in herd management. For example, such herds might have been concentrated near farms for 535 milking, i.e. for our study sites in areas downstream from the lakes or outside the lake 536 catchments.

537

538 Lakes in the lower part of the subalpine belt and the montane belt show higher resilience 539 than lakes in the upper part of the subalpine belt. Indeed, in the Contemporary period, when we 540 see a decrease in pastoral/agropastoral pressure at all altitudes, only lower sites (Gers and La 541 Thuile) show significant reductions in erosion (Fig. 6A, Supplementary figure 7). This pattern may 542 be explained by the permanent presence of trees in lower altitude catchments combined with 543 warmer conditions facilitating forest regeneration and expansion after disturbance, quite 544 different to the sparse woodland or treeless landscapes in the upper and colder altitudes. As for the plant community composition, these belts are more resilient due to their altitudinal position 545 546 and, thus to the initial conditions of the systems. 547

548

# 549 Conclusion and perspectives

550

551 The combined palaeoenvironmental, archaeological and historical evidence facilitated 552 the characterisation of broad-scale and long-term trajectories of human activities, including 553 their intensities, across our altitudinal gradient. Significant pastoral activities first developed in 554 the high-altitude zones during the Mid-Late Bronze Age. During the Roman Period, they saw 555 significant developments across the lower subalpine to the alpine/nival belts. In the montane 556 belt, while the first arable cultures appeared during the Late Iron Age/Roman periods, 557 intensification of these activities was recorded in the Early Middle Ages. During the High and 558 Late Middle Ages, all the vegetation belts were used for pastoral activities, while in the montane 559 belt, we see the diversification of crops.

560

561 This altitudinal evolution of human activities is mirrored in the trajectory of the plant 562 community composition, with earlier impact recorded in the upper subalpine and alpine areas 563 than in the lower subalpine and montane belts. Rare and minor resilience phases were observed, 564 demonstrating how modern mountain landscapes are a legacy of human land use and 565 management cumulated over millennia. When we look at erosion histories, trajectories differ 566 from one site to another due to variations in their sensitivity to erosion processes. However, we 567 can recognise similar response patterns to disturbances. Interestingly, "unusual patterns", 568 characterised by the absence or a reduced impact of agropastoral activities on erosion, are 569 observed everywhere after 1000 AD. Finally, whether in terms of plant community composition 570 or erosion, our trajectories evidence the vulnerability of systems above ca. 2000 m a.s.l. to 571 changes in human activities and practices, as well as variations in climate. This vulnerability must 572 be considered in the capacity of these environments to support the current changes.

573

574 The altitudinal model of agropastoral developments and their interactions with 575 landscapes should now be tested across more sites. In particular, our study sites are 576 concentrated on the north-facing slopes; it would also be interesting to investigate sites with 577 the greatest exposure to the sun, where cultivated land could develop at higher altitude 578 (Elleaume et al. this issue). The model could also integrate perialpine areas to elucidate the 579 organisation of land use across an entire territory, thus highlighting interactions between the 580 lower and upper zones. Moreover, developing our approach in other parts of the Alps, or other 581 mountains in the world, would allow the assessment of locally specific or shared characteristics 582 of mountain agroecosystems.

# 583 Acknowledgments

584 This paper is the outcome of more than ten years of collaborative and interdisciplinary works 585 led in several research programs, which were initiated under the leadership of Fabien Arnaud 586 (PYGMALION program supported by the French National Research Agency ANRblan07-587 2\_204489) and Pierre Taberlet (in the framework of the DiPEE between the LECA and EDYTEM 588 which funded the Retromont program), that we warmly thank here. The work was then 589 continued within the framework of a Marie Slodowska Curie fellowship (PALEO-AGRI project, 590 EC grant number 655331) and via the PhD projects of Manon Bajard, Wentao Chen and Claire 591 Blanchet funded by the Fondation Montagne Vivante, the Universities of Savoie Mont-Blanc 592 and Grenoble-Alpes and the French Agence Nationale pour la Recherche project 593 Investissements d'avenir CDP TRAJECTORIES (ANR-15-IDEX-02). We also benefited from 594 discussions with Alain Mélo and Patricia Chiquet about historical and zooarcheological data 595 from the Vallon de Sales. Finally, we thanks the Réserve Naturelles de Haute-Savoie managed 596 by ASTER who made significant contributions to the archaeological and coring fieldwork 597 campaigns in the Anterne and the Vallon de Sales study areas.

# 598 Author's contribution

599 CGC, MB, WC, DE, FGF, LG, PS, PC, CG, FA, EM, PJR and CB contributed to the sampling and/or 600 data production. CGC, JP, KJW, contributed to the design of the study. All authors contributed 601 to the writing of the manuscript.

602

## 603 **References**

604

605Alsos IG, Lammers Y, Yoccoz NG, et al (2018) Plant DNA metabarcoding of lake sediments: How does it606representthecontemporaryvegetation.PLoSONE13:e0195403.607https://doi.org/10.1371/journal.pone.0195403

Alsos IG, Sjögren P, Edwards ME, et al (2016) Sedimentary ancient DNA from Lake Skartjørna, Svalbard:
 Assessing the resilience of arctic flora to Holocene climate change. The Holocene 26:627–642.

Aerni K (1991) 1000 Jahre Siedlung und Verkehr im schweizerischen Alpenraum. Voraussetzungen und
Ergebnisse. In Aerni, K., Egli, H.-R. and Fehn, K., editors, Siedlungsprozesse an der Höhengrenze
der ökumene. Am Bespiel der Alpen. Referate der 16. Tagung des 'Arbeitskreises für genetische
Siedlungsforschung in Mitteleuropa' vom 20. bis 23. September 1989 in Spiez. Bern/Bonn: P.
Burggraaff, 9–42.

615Andres B (2016) Alpine huts, livestock and cheese in the Oberhasli region (Switzerland): Medieval and616early modern building remains and their historical context. In Summer Farms: seasonal617exploitation of the Uplands from Prehistory to the Present. Edited by Collis J, Pearce M, Nicolis618F.

- 619Arnaud F, Lignier V, Revel M, et al (2002) Flood and earthquake disturbance of 210Pb geochronology620(Lake Anterne, NW Alps). Terra Nova 14:225–232. <a href="https://doi.org/10.1046/j.1365-3121.2002.00413.x">https://doi.org/10.1046/j.1365-</a>6213121.2002.00413.x
- 622Bajard M, Etienne D, Quinsac S, et al (2018) Legacy of early anthropogenic effects on recent lake623eutrophication (Lake Bénit, northern French Alps). Anthropocene 24:72–87.624https://doi.org/10.1016/j.ancene.2018.11.005
- Bajard M, Poulenard J, Sabatier P, et al (2017a) Long-term changes in alpine pedogenetic processes:
  Effect of millennial agro-pastoralism activities (French-Italian Alps). Geoderma 306:217–236.
  https://doi.org/10.1016/j.geoderma.2017.07.005
- 628Bajard M, Poulenard J, Sabatier P, et al (2017b) Progressive and regressive soil evolution phases in the629Anthropocene. CATENA 150:39–52. https://doi.org/10.1016/j.catena.2016.11.001

- 630Bajard M, Poulenard J, Sabatier P, et al (2020) Pastoralism increased vulnerability of a subalpine631catchment to flood hazard through changing soil properties. Palaeogeography,632Palaeoclimatology, Palaeoecology 538:109462. https://doi.org/10.1016/j.palaeo.2019.109462
- Bajard M, Sabatier P, David F, et al (2016) Erosion record in Lake La Thuile sediments (Prealps, France):
  Evidence of montane landscape dynamics throughout the Holocene. The Holocene 26:350–364.
  https://doi.org/10.1177/0959683615609750
- 636Balée W (2006) The Research Program of Historical Ecology. Annu Rev Anthropol 35:75–98.637https://doi.org/10.1146/annurev.anthro.35.081705.123231
- 638Beniston M (2006) Mountain Weather and Climate: A General Overview and a Focus on Climatic Change639in the Alps. Hydrobiologia 562:3–16. <a href="https://doi.org/10.1007/s10750-005-1802-0">https://doi.org/10.1007/s10750-005-1802-0</a>
- 640Birks HJB, Birks HH (2016) How have studies of ancient DNA from sediments contributed to the641reconstruction of Quaternary floras? New Phytologist 209:499–506.642https://doi.org/10.1111/nph.13657
- 643Bremond L, Favier C, Ficetola GF, et al (2017) Five thousand years of tropical lake sediment DNA records644from Benin. Quat Sci Rev 170:203–211. https://doi.org/10.1016/j.quascirev.2017.06.025
- 645Brisset E, Miramont C, Guiter F, et al (2013) Non-reversible geosystem destabilisation at 4200 cal. BP:646Sedimentological, geochemical and botanical markers of soil erosion recorded in a647Mediterranean alpine lake. The Holocene 23:1863–1874.648https://doi.org/10.1177/0959683613508158
- Büntgen U, Bellwald I, Kalbermatten H, et al (2006) 700 Years of Settlement and Building History in the
   Lötschental, Switzerland (700 Jahre Siedlungs- und Baugeschichte im Lötschental, Schweiz).
   Erdkunde 60:96–112
- Capo E, Giguet-Covex C, Rouillard A, et al (2021) Lake Sedimentary DNA Research on Past Terrestrial and
   Aquatic Biodiversity: Overview and Recommendations. Quaternary 4:6.
   https://doi.org/10.3390/quat4010006
- 655Carrer F, Colonese AC, Lucquin A, et al (2016) Chemical Analysis of Pottery Demonstrates Prehistoric656Origin for High-Altitude Alpine Dairying. PLOS ONE 11:e0151442.657https://doi.org/10.1371/journal.pone.0151442
- 658Carrer F (2016) The « invisible » shepherd and the "visible" dairyman: Ethnoarchaeology of alpine659pastoral sites in the Val di Fiemme (eastern Italian Alps). In Summer Farms: seasonal exploitation660of the Uplands from Prehistory to the Present. Edited by Collis J, Pearce M, Nicolis F.
- 661 Carrier N, Mouthon F (2010) Paysans des Alpes. Les communautés montagnardes au Moyen Age. (Eds.)
   662 Presses Universitaires de Rennes. Book pp 420
- 663 Carrier N (2013) Malthus à la montagne ? Les Alpes dans la conjoncture économique de la fin du Moyen
   664 Âge (XIIIe-XVe siècle). 245–262
- 665 Chen W (2019) Approches quantitatives de l'analyse de l'ADN sédimentaire pour comprendre la biodiversité et le fonctionnement des écosystèmes dans le passé. PhD Thesis
- 667Chiquet P (2019) Économie animale et territoire au Néolithique dans les Alpes occidentales : un même668son de cloche ? Les sites de La Grande Rivoire (Sassenage, Isère, France), Le Chenet des Pierres

- (Bozel, Savoie, France) et La Soie (Savièse, Valais, Suisse). In: Deschamps M, Costamagno S,
  Milcent P-Y, et al. (eds) La conquête de la montagne : des premières occupations humaines à
  l'anthropisation du milieu. Éditions du Comité des travaux historiques et scientifiques
- 672 Clarke CL, Edwards ME, Brown AG, et al (2018) Holocene floristic diversity and richness in northeast
   673 Norway revealed by sedimentary ancient DNA (*sed* aDNA) and pollen. Boreas.
   674 https://doi.org/10.1111/bor.12357
- 675Crogiez-Pétrequin S (2016) Alpis Graia (col du Petit-Saint-Bernard, Savoie et Val d'Aoste) : découvertes676anciennes et recherches récentes. gallia 73:113–118. https://doi.org/10.4000/gallia.498
- 677 Crook DS, Siddle DJ, Dearing JA, Thompson R (2004) Human Impact on the Environment in the Annecy
   678 Petit Lac Catchment, Haute-Savoie: A Documentary Approach. Environment and History 10:247–
   679 284. <u>https://doi.org/10.3197/0967340041794312</u>
- David F (2010) Expansion of green alder (Alnus alnobetula [Ehrh] K. Koch) in the northern French Alps: a
   palaeoecological point of view. Comptes Rendus Biologies, 333(5):424–428
   doi:10.1016/j.crvi.2010.01.002
- 685Davis OK, Shafer DS (2006) Sporormiella fungal spores, a palynological means of detecting herbivore686density.Palaeogeography,Palaeoclimatology,Palaeoecology237:40–50.687<a href="https://doi.org/10.1016/j.palaeo.2005.11.028">https://doi.org/10.1016/j.palaeo.2005.11.028</a>
- 688Dearing JA (2008) Landscape change and resilience theory: a palaeoenvironmental assessment from689Yunnan, SW China. The Holocene 18:117–127. <a href="https://doi.org/10.1177/0959683607085601">https://doi.org/10.1177/0959683607085601</a>
- 690 Dearing JA, Jones RT, Shen J, et al (2008) Using multiple archives to understand past and present climate–
   691 human–environment interactions: the lake Erhai catchment, Yunnan Province, China. J
   692 Paleolimnol 40:3–31. https://doi.org/10.1007/s10933-007-9182-2
- 693Della Casa PhD (2005) Lithic resources in the early prehistory in the early prehistory of the Alps.694Archaeometry 47:221–234. https://doi.org/10.1111/j.1475-4754.2005.00198.x
- 695Delhon C, Martin L, Argant J, Thiébault S (2008) Shepherds and plants in the Alps: multi-proxy696archaeobotanical analysis of neolithic dung from "La Grande Rivoire" (Isère, France). Journal of697Archaeological Science 35:2937–2952. https://doi.org/10.1016/j.jas.2008.06.007
- 698Dietre B, Walser C, Kofler W, et al (2017) Neolithic to Bronze Age (4850–3450 cal. BP) fire management699of the Alpine Lower Engadine landscape (Switzerland) to establish pastures and cereal fields.700The Holocene 27:181–196. <a href="https://doi.org/10.1177/0959683616658523">https://doi.org/10.1177/0959683616658523</a>
- Dietre, B., Walser, C., Lambers, K., et al. (2014) Palaeoecological evidence for Mesolithic to Medieval
   climatic change and anthropogenic impact on the Alpine flora and vegetation of the Silvretta
   Massif (Switzerland/Austria). Quat. Int. 353:3–16. https://doi.org/10.1016/j.quaint.2014.05.001
- Dodgshon R (2019) Farming Communities in the Western Alps, 1500–1914: The Enduring Bond. Springer
   International Publishing, Cham pp 168
- 706Elleaume N, Lachello R, et al. (this issue) An interdisciplinary approach to reconstruct the multi-century707trajectory of a socio-ecological system in the French Alps. Regional Environmental Changes

708Etienne D, Destas M, Lyautey E, et al (2015) Two thousand-year reconstruction of livestock production709intensity in France using sediment-archived fecal Bacteroidales and source-specific710mitochondrialmarkers.711https://doi.org/10.1177/0959683615585836

Etienne D, Wilhelm B, Sabatier P, et al (2013) Influence of sample location and livestock numbers on
 Sporormiella concentrations and accumulation rates in surface sediments of Lake Allos, French
 Alps. J Paleolimnol 49:117–127. https://doi.org/10.1007/s10933-012-9646-x

- 715Ficetola GF, Pansu J, Bonin A, et al (2015) Replication levels, false presences and the estimation of the716presence/absence from eDNA metabarcoding data. Mol Ecol Resour 15:543–556.717https://doi.org/10.1111/1755-0998.12338
- 718Ficetola GF, Poulenard J, Sabatier P, et al (2018) DNA from lake sediments reveals long-term ecosystem719changes after a biological invasion. Sci Adv 4:eaar4292. https://doi.org/10.1126/sciadv.aar4292
- 720Frayn JM (1984) Sheep-rearing and the wool trade in Italy during the Roman period. Francis721Cairns Publications
- 722Garcés-Pastor S, Coissac E, Lavergne S, et al (2022) High resolution ancient sedimentary DNA shows that723alpine plant biodiversity is a result of human land use. Nat Com 13(1).724https://doi.org/10.1038/s41467-022-34010-4
- Giguet-Covex C, Messager E, Blanchet C, et al (accepted) A 4600 years' history of vegetation and
   pastoralism in a subalpine landscape as revealed by pollen, coprophilous fungal spores and DNA
   from Lake Gers (Northern French Alps). The Holocene
- Giguet-Covex C, Arnaud F, Enters D, et al (2012) Frequency and intensity of high-altitude floods over the
   last 3.5 ka in northwestern French Alps (Lake Anterne). Quaternary Research 77:12–22.
   https://doi.org/10.1016/j.yqres.2011.11.003

Giguet-Covex C, Arnaud F, Poulenard J, et al (2011) Changes in erosion patterns during the Holocene in
 a currently treeless subalpine catchment inferred from lake sediment geochemistry (Lake
 Anterne, 2063 m a.s.l., NW French Alps): The role of climate and human activities. The Holocene
 21:651–665. https://doi.org/10.1177/0959683610391320

- 735Giguet-Covex C, Ficetola GF, Walsh K, et al (2019) New insights on lake sediment DNA from the736catchment: importance of taphonomic and analytical issues on the record quality. Sci Rep7379:14676. https://doi.org/10.1038/s41598-019-50339-1
- 738Giguet-Covex C, Pansu J, Arnaud F, et al (2014) Long livestock farming history and human landscape739shaping revealed by lake sediment DNA. Nature Communications 5:.740https://doi.org/10.1038/ncomms4211

741Gilck F, Poschlod P (2019) The origin of alpine farming: A review of archaeological, linguistic and742archaeobotanical studies in the Alps. The Holocene 095968361985451.743https://doi.org/10.1177/0959683619854511

744Ginestet J-P, Bintz P, Chaix L, et al (1984) L'abri sous roche de la Vieille Église, La Balme-de-Thuy (Haute-745Savoie), premiers résultats. bspf 81:320–342. <a href="https://doi.org/10.3406/bspf.1984.8595">https://doi.org/10.3406/bspf.1984.8595</a>

- Graham RW, Belmecheri S, Choy K, et al (2016) Timing and causes of mid-Holocene mammoth extinction
  on St. Paul Island, Alaska. Proc Natl Acad Sci 113:9310–9314.
  https://doi.org/10.1073/pnas.1604903113
- 752Guédron S, Tolu J, Delaere C, et al (2021) Reconstructing two millennia of copper and silver metallurgy753in the Lake Titicaca region (Bolivia/Peru) using trace metals and lead isotopic composition.754Anthropocene 34:100288. https://doi.org/10.1016/j.ancene.2021.100288
- Guffond C, Mélo A (2018) Une institution collective dans l'histoire : l'alpage de Sales (Sixt-Fer-à-Cheval,
   Haute-Savoie, fin XIVe-fin XIXe siècles). 14
- 757Guillet D, Godoy RA, Guksch CE, et al (1983) Toward a Cultural Ecology of Mountains: The Central Andes758and the Himalayas Compared [and Comments and Reply]. Current Anthropology 24:561–574
- Hafner A, Schwörer C (2018) Vertical mobility around the high-alpine Schnidejoch Pass. Indications of
   Neolithic and Bronze Age pastoralism in the Swiss Alps from paleoecological and archaeological
   sources. Quaternary International 484:3–18. https://doi.org/10.1016/j.quaint.2016.12.049
- Helama S, Jones PD, Briffa KR (2017) Dark Ages Cold Period: A literature review and directions for future
   research. The Holocene 27(10):1600–1606. https://doi.org/10.1177/0959683617693898
- 764 Hock R, Rasul G. Adler C, et al (2019) Chapter 2. High Mountain Area. pp 202 www.ipcc.ch.
- Koinig KA, Shotyk W, Lotter AF, et al (2003) 9000 years of geochemical evolution of lithogenic major and
   trace elements in the sediment of an alpine lake the role of climate, vegetation, and land- use
   history. 14
- Körner C. 2003. Alpine plant life: functional plant ecology of high mountain ecosystems. Berlin, Germany:
   Springer.
- Kruskal JB (1964) Multidimensional scaling by optimising goodness of fit to a nonmetric hypothesis.
   Psychometrika 29:1–27. <u>https://doi.org/10.1007/BF02289565</u>
- Lamprecht A, Semenchuk PR, Steinbauer K, et al (2018) Climate change leads to accelerated
   transformation of high-elevation vegetation in the central Alps. New Phytologist 220:447-459
   doi: 10.1111/nph.15290
- 775Legendre P, Legendre L (2012)Numerical Ecology.Amsterdam: Elsevier.pp852eBook776ISBN: 9780080523170
- Levy-Booth DJ, Campbell RG, Gulden RH, et al (2007) Cycling of extracellular DNA in the soil environment.
   Soil Biology and Biochemistry 39:2977–2991. https://doi.org/10.1016/j.soilbio.2007.06.020
- Lomolino MV (2001) Elevation gradients of species-density: historical and prospective views. Global
   Ecology and Biogeography 10:3-13.
- Longman J, Veres D, Finsinger W, Ersek V (2018) Exceptionally high levels of lead pollution in the Balkans
   from the Early Bronze Age to the Industrial Revolution. Proc Natl Acad Sci USA 115:E5661–
   E5668. <u>https://doi.org/10.1073/pnas.1721546115</u>

- Madeja J (2015) A new tool to trace past human presence from lake sediments: the human-specific
   molecular marker *Bacteroides* strain HF 183: PAST HUMAN PRESENCE FROM LAKE SEDIMENTS.
   Journal of Quaternary Science 30:349–354. https://doi.org/10.1002/jqs.2783
- Madeja J, Wacnik A, Wypasek E, et al (2010) Integrated palynological and molecular analyses of late
   Holocene deposits from Lake Miłkowskie (NE Poland): Verification of local human impact on
   environment. Quaternary International 220:147–152.
   https://doi.org/10.1016/j.guaint.2009.09.008
- Martin L, Delhon C, Thiébault S, Pelletier D (2012) Plant exploitation and diet in altitude during Mesolithic
   and Neolithic: Archaeobotanical analysis from a hunting camp in the Chartreuse massif (l'Aulp du-Seuil, Isère, France). Review of Palaeobotany and Palynology 185:26–34.
   https://doi.org/10.1016/j.revpalbo.2012.07.011
- 795Martin L, Jacomet S, Thiebault S (2008) Plant economy during the Neolithic in a mountain context: the796case of "Le Chenet des Pierres" in the French Alps (Bozel-Savoie, France). Vegetation History and797Archaeobotany 17:113–122. <a href="https://doi.org/10.1007/s00334-008-0191-5">https://doi.org/10.1007/s00334-008-0191-5</a>
- Martin L, Lundström-Baudais K (2012) Analyses carpologiques : agriculture et alimentation végétale. In:
  Vital, J. & Benamour, P. (Ed.). *Economies, sociétés et espaces en Alpe : la grotte des Balmes à Sollières-Sardières (Savoie) du Néolithique moyen 2 à l'âge du Fer*. Lyon : ALPARA et Publications
  de la Maison de l'Orient et de la Méditerranée, 2012. p. 234-245. (Documents d'Archéologie en
  Rhône-Alpes et en Auvergne; 36) <u>https://archive-ouverte.unige.ch/unige:23823</u>
- 803 Mouthon F (2009) Les Bauges médiévales. Université de Savoie, « Collection Sociétés, Religions,
   804 Politiques » 11, pp 242 <u>https://doi.org/10.4000/peme.5528</u>
- 805 Mura J (1976) Los limites y las limitaciones del archipielago vertical en los Andes. Universidad del Norte,
   806 pp 75-79
- Nicod P-Y, Picavet R, Argant J, et al (2010) Une économie pastorale dans le Nord du Vercors : analyse
  pluridisciplinaire des niveaux néolithiques et protohistoriques de la Grande Rivoire (Sassenage,
  Isère). In: Beeching A, Thirault É, Vital J (eds) Économie et société de la fin de la Préhistoire :
  Actualité de la recherche. Alpara, pp 69–86
- Niemeyer B, Epp LS, Stoof-Leichsenring KR, et al (2017) A comparison of sedimentary DNA and pollen
   from lake sediments in recording vegetation composition at the Siberian treeline. Molecular
   Ecology Resources 17:e46–e62. https://doi.org/10.1111/1755-0998.12689
- 814 Oksanen J, Blanchet FG, Kindt R, et al (2013) *Package 'vegan,'*. http://cran.r-815 project.org/web/packages/vegan/index.html
- 816Ortu E, Brewer S, Peyron O (2006) Pollen-inferred palaeoclimate reconstructions in mountain areas:817problems and perspectives. J Quaternary Sci 21:615–627. https://doi.org/10.1002/jqs.998
- 818 Pansu J, Giguet-Covex C, Ficetola GF, et al (2015) Reconstructing long-term human impacts on plant
   819 communities: an ecological approach based on lake sediment DNA. Molecular Ecology 24:1485–
   820 1498. https://doi.org/10.1111/mec.13136
- Parducci L, Bennett KD, Ficetola GF, et al (2017) Ancient plant DNA in lake sediments. New Phytologist
   214:924–942. https://doi.org/10.1111/nph.14470

Parducci L, Matetovici I, Fontana SL, et al (2013) Molecular- and pollen-based vegetation analysis in lake
 sediments from central Scandinavia. Molecular Ecology 22:3511–3524.
 https://doi.org/10.1111/mec.12298

Pedersen MW, Ginolhac A, Orlando L, et al (2013) A comparative study of ancient environmental DNA
 to pollen and macrofossils from lake sediments reveals taxonomic overlap and additional plant
 taxa. Quaternary Science Reviews 75:161–168.
 https://doi.org/10.1016/j.guascirev.2013.06.006

- Remicourt M (2009) Nouvelles données sur la couche 5B de l'abri-sous-roche de la Vieille Église, La
   Balme-de-Thuy (Haute- Savoie). Néolithique ancien ou Mésolithique final ? bspf 106:15–23.
   https://doi.org/10.3406/bspf.2009.13827
- Rey P-J (2016) Archéologie du Massif des Bauges du Néolithique à l'Age du Bronze. Les Dossiers du
  Musée Savoisien. Revue numérique 1. https://hal.archives-ouvertes.fr/hal02499479/document
- Rey P-J, Affolter J, Arnaud F et al (2022) De la Préhistoire aux temps modernes dans les Alpages
  d'Anterne et Pormenaz, une première approche de l'occupation de la moyenne montagne entre
  les Fiz et les Aiguilles Rouges. Résultats du programme de sondages 2008-2011. Actes de la table
  ronde de Clermont-Ferrand, novembre 2019.
- Rey P-J, Moulin B (2019) L'occupation des versants du col du Petit-Saint-Bernard au Néolithique: premier
  bilan des données acquises lors des campagnes de sondages du programme Alpis
  Graia.Collection EDYTEM. Cahiers de géographie, Laboratoire EDYTEM pp. 241-255.
- Roepke A, Krause R (2013) High montane–subalpine soils in the Montafon Valley (Austria, northern Alps)
  and their link to land-use, fire and settlement history. Quaternary International 308–309:178–
  189. https://doi.org/10.1016/j.quaint.2013.01.022
- 846Sabatier P, Wilhelm B, Ficetola GF, et al (2017) 6-kyr record of flood frequency and intensity in the847western Mediterranean Alps Interplay of solar and temperature forcing. Quaternary Science848Reviews 170:121–135. <a href="https://doi.org/10.1016/j.quascirev.2017.06.019">https://doi.org/10.1016/j.quascirev.2017.06.019</a>
- 849 Scaramellini G and Varoto M (2008) Terraced landscapes of the Alps. Atlas book. 850 https://www.alpter.net/IMG/pdf/ALPTER\_Atlas\_ENG\_small.pdf.
- Scheffer M, Carpenter SR, Lenton TM, et al (2012) Anticipating Critical Transitions. Science 338:344–348.
   https://doi.org/10.1126/science.1225244

Schmidt R, Koinig KA, Thompson R, Kamenik C (2002) A multi proxy core study of the last 7000 years of
 climate and alpine land-use impacts on an Austrian mountain lake (Unterer Landschitzsee,
 Niedere Tauern). Palaeogeography, Palaeoclimatology, Palaeoecology 187:101–120.
 https://doi.org/10.1016/S0031-0182(02)00511-4

857Segard M (2009) Pastoralism, rural economy and landscape evolution in the western Alps. Journal of858Roman Archaeology 22:170–182 <a href="https://doi.org/10.1017/S104775940002064x">https://doi.org/10.1017/S104775940002064x</a>

Sjögren P, Edwards ME, Gielly L, et al (2017) Lake sedimentary DNA accurately records 20 <sup>th</sup> Century
introductions of exotic conifers in Scotland. New Phytologist 213:929–941.
<u>https://doi.org/10.1111/nph.14199https://doi.org/10.1111/1365-2745.12354</u>

Tasser E, Leitinger G, Tappeiner U (2017) Climate change versus land-use change—What affects
the mountain landscapes more? Land Use Policy 60:60–72.
https://doi.org/10.1016/j.landusepol.2016.10.019

Theurillat J-P, Guisan A. 2001. Potential impact of climate change on vegetation in the European Alps: a
 review. Climatic Change 50: 77–109.(Lamprecht et al. 2018)

867 Toulouse TA, Zimmerman ME, Gladstone J (2020) Introduction: Environmental Trajectories: 55:1–8

Vannière B, Magny M, Joannin S, et al (2013) Orbital changes, variation in solar activity and increased
 anthropogenic activities: controls on the Holocene flood frequency in the Lake Ledro area,
 Northern Italy. Clim Past 9:1193–1209. https://doi.org/10.5194/cp-9-1193-2013

- 871 Vital J, Benamour P (2012) Economie, sociétés et espaces en Alpe : La grotte des Balmes à Sollières872 Sardières Savoie, du Néolithique moyen 2 à l'âge du Fer, Lyon ALPARA, Maison de l'Orient et de
  873 la Méditerranée. Documents d'archéologie en Rhône-Alpes 36, pp 388.
- Walsh K, Court-Picon M, de Beaulieu J-L, et al (2014) A historical ecology of the Ecrins (Southern French
   Alps): Archaeology and palaeoecology of the Mesolithic to the Medieval period. Quaternary
   International 353:52–73. https://doi.org/10.1016/j.quaint.2013.08.060
- Walsh K, Giguet-Covex C (2019) A History of Human Exploitation of Alpine Regions. In: Reference Module
   in Earth Systems and Environmental Sciences. Elsevier

Walsh K, Mocci F (2011) Mobility in the Mountains: Late Third and Second Millennia Alpine Societies'
 Engagements with the High-Altitude Zones in the Southern French Alps. European Journal of
 Archaeology 28

- Walsh K, Mocci F, Palet-Martinez J (2007) Nine thousand years of human/landscape dynamics in a high
   altitude zone in the southern French Alps (Parc National des Ecrins, Hautes-Alpes). 14
- Wick L, Tinner W (1997) Vegetation Changes and Timberline Fluctuations in the Central Alps as Indicators
   of Holocene Climatic Oscillations. Arctic and Alpine Research 29:445.
   <u>https://doi.org/10.2307/1551992</u>
- Wilhelm B, Arnaud F, Sabatier P, et al (2013) Palaeoflood activity and climate change over the last 1400
   years recorded by lake sediments in the north-west European Alps. Journal of Quaternary
   Science 28: 189-199. https://doi:10.1002/jqs.2609
- Willerslev E, Davison J, Moora M, et al (2014) Fifty thousand years of Arctic vegetation and megafaunal
   diet. Nature 506:47–51. https://doi.org/10.1038/nature12921
- Yoccoz NG, Bråthen KA, Gielly L, et al (2012) DNA from soil mirrors plant taxonomic and growth form
   diversity: DNA FROM SOIL MIRRORS PLANT DIVERSITY. Molecular Ecology 21:3647–3655.
   <u>https://doi.org/10.1111/j.1365-294X.2012.05545.x</u>
- 895
- 896
- 897
- 898

901	sites indicated by the stars are located in the Vercors subalpine massif (1: La Grande Rivoire 580 m a.s.l.), the
902	Bornes-Aravis subalpine massif (2: La Balme de Thuy 620 m a.s.l.), the Haute-Maurienne Valley (3: Les Balmes à
903	Sollières-Sardières, 1350 m a.s.l.) and the Tarentaise Valley (4: Le Chenet des Pierres à Bozel, 940 m a.s.l.). The
904	altitudinal positions in the different vegetation belts of all the sites are also presented on the right side of the
905	figure.
906	
907	Figure 2. Synthesis of (agro-)pastoral activity histories in the Northwestern Alps from the montane to the
908	alpine/nival belts. For each site, ruderal taxa are presented in order to compare these with mammal DNA data
909	(herbivorous domestic animals) and, when available, with coprophilous fungi. At La Thuile, cultivated taxa
910	recorded by DNA and pollen for cereals are also presented. In addition to these data indicating the nature of the
911	activities and practices, a synthetic index representing the intensity of (agro-)pastoral activities has been
912	calculated for each site. The grey areas show the phases of intense pastoral activities discussed in the text during
913	the High/Late Middle Ages, and the black dotted lines the medieval transition in animal composition.
914	
915	Figure 3. Box plot by cultural periods evidencing the temporal and altitudinal trajectory of the intensity of (agro-
916	)pastoral activities in the Northwestern Alps.
917	
918	

Figure 1. Location of the main sites (lakes and archaeological sites) discussed in the manuscript. The Neolithic

Figure 4. Synthesis of archaeological sites and composition of zooarchaeological remains for the different periods
 in The Vallon de Sales and around Anterne. Positions of the palaeoenvironmental records available close to these
 sites.

923
924 Figure 5. Temporal trajectories in plant composition evidenced through NMDS analyses from lake sedDNA data
925 in different vegetation belts. The stress values for the ordinations are relatively high (0,17 at Gers and 0,19 at
926 Savine, Anterne).

Figure 6. Erosion trajectories in response to agropastoral and pastoral activities in the northwestern Alps. A) Specific
 trajectories for the different studied sites. B) Representation of generic patterns of the erosion trajectory in response
 to human activities.