A millennium-long perspective of flood-related seasonal sediment yield in Mediterranean watersheds.

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Abstract:

Mediterranean mountains have been extremely vulnerable to land degradation and soil erosion due to climate factors (summer hydric stress, high storminess) and the long history of human pressure on these terrestrial ecosystems. The short-time span of instrumental monitoring datasets **limits our ability to obtain a full depiction of** the long-term drivers controlling flood intensity and frequency and soil erosion in Mediterranean watersheds. Here we have applied a novel methodology based on detailed microfacies analyses on annually-laminated (varved) lacustrine sediments to reconstruct floods and seasonal sediment yield and denudation rates in a mountainous Mediterranean watershed during the last 2775 years. The sediment yield reconstruction in this study agrees reasonably well with soil erosion rates from Pyrenean experimental watersheds supporting the validity of this methodology to assess the soil erosion and sediment production from a long-term perspective. The comparison with instrumental precipitation datasets demonstrates the different seasonal **sensitivity** of sediment yield to heavy rainfall magnitudes mostly depending on soil moisture conditions, soil and regolith erodibility and vegetation cover. During periods of reduced human impact in the watershed, the seasonal

maxima in sediment production occurred in autumn, which corresponds to the season with more frequent and intense heavy rainfall in the region. The highest soil erosion rates occurred during periods with higher human impact in the watershed due to sustained burning, overgrazing and cereals cultivation that modified the seasonal sediment yield distribution, with the highest sediment production happening in winter. The most significant periods of increased sediment yield occurred during the Middle Ages (1168-1239 CE) and the 19th century (1844-1866 CE) due to an interplay between increased frequencies and magnitudes of heavy rainfall and intensive agropastoral activities in the lake's watershed. This study highlights the potential of seasonally-resolved archives to adequately evaluate the environmental drivers and mechanisms controlling flood dynamics and soil erosion at decadal to centennial time-scales in areas with strong seasonality.

KEYWORDS: soil erosion, paleofloods, Mediterranean watershed, seasonality, sediment budget

HIGHLIGHTS:

-First Late Holocene seasonal yield reconstruction in W Mediterranean

-Sediment yield variability is driven by an interplay between land use changes and heavy rainfall.

-Fires and overgrazing have a significant impact on long-term soil erosion

-Human activities have modified the seasonality of natural sediment yield variability

-Large spatial and temporal sediment yield heterogeneities in W Mediterranean karstic watersheds

INTRODUCTION:

Land degradation due to soil erosion is a main environmental consequence of extreme floods in Mediterranean watersheds, since sediment yield in these regions mostly occurs during flood-related run-off events (González-Hidalgo et al. 2007, Nadal-Romero et al. 2012, Nadal-Romero et al. 2012, Rodríguez-Lloveras et al. 2017). The projected increase in heavy rainfall events would cause an increase in surface runoff and soil erosion and redistribution of water within watersheds that may reduce crop yield and impact water security in western Mediterranean watersheds (Eekhout et al. 2018). Therefore, a detailed understanding of the hydro-sedimentary processes controlling soil erosion under different anthropogenic and environmental scenarios is needed in the Mediterranean. To tackle this issue, monitoring of experimental watersheds in Mediterranean mountains have significantly contributed to the evaluation of the main drivers controlling soil erosion and their relationships with hydroclimate and land use changes (Cerdà and Lasanta 2005, González-Hidalgo et al. 2007, García-Ruiz et al. 2008, García-Ruiz 2010, Nadal-Romero and Regüés 2010, Nadal-Romero et al. 2012, Nadal-Romero et al. 2012, Lana-Renault et al. 2014, Garcia-Ruiz et al. 2015). However, these locations have only been monitored over the last few decades, impeding adequate assessment of the long-term hydroclimate evolution and drivers of soil erosion under different environmental scenarios. The few attempts to provide temporal rates (since the late 19th century) of sediment yield in Mediterranean regions were based on hydro-sedimentary modelling approaches and/or paleolimnological studies in artificial reservoirs (Valero-Garcés et al., 1999; Diodato et al. 2012, Rodríguez-Lloveras et al. 2017). These studies show the critical role of the inter-annual variability of heavy rainfall events on reactivating erosion and sediment connectivity through the watersheds, in addition to the enhancing erosion effects of historical land use changes.

Natural sedimentary archives have been used in different Mediterranean regions to evaluate the millennial-scale sediment yield variability following climate and human-driven land use changes (Bonneau et al., 2014; Walsh et al., 2019) as well as to reconstruct flood variability

beyond the instrumental period (Woodward et al., 2001; Benito et al., 2015; Wilhelm et al., 2019). Lacustrine sedimentary archives stand as a valuable tool to investigate long-term sediment yield related to extreme flood events in mountainous watersheds prior to the instrumental period (Einsele and Hinderer 1998, Arnaud et al. 2016, Roberts et al. 2018). Mountainous watersheds strongly contribute to global sediment yields mainly due to the connection between local relief and denudation and the reduced sediment storage on high gradient and rugged hillslopes (Ahnert, 1970; Milliman and Syvitski, 1992). In the Iberian Peninsula, only a few paleolimnological studies in small mountainous watersheds have been investigated as natural laboratories to understand how sediment dynamics have responded to a variety of factors at decadal to centennial time-scales, including geomorphologic processes, major flooding events and vegetation cover changes (Corella et al. 2011, Barreiro-Lostres et al. 2017). Moreover, the sedimentological information at the investigated sites is restricted to decadal to centennial averages of annual sediment yield, which is not sufficient to depict adequately the hydro-sedimentary processes and flood variability in climates with a marked seasonality such as the western Mediterranean. To overcome these limitations, annually-laminated (varved) sediments provide information of past human-climate-environment interactions (Valero-Garcés and Corella et al., 2018) such as the occurrence of flood-related runoff events with seasonal resolution (Mangili et al. 2005, Czymzik et al. 2010, Swierczynski et al. 2012, Czymzik et al. 2013, Vannire et al. 2013, Wirth et al. 2013, Roberts et al. 2018).

In this study, we use a varve record to reconstruct the long-term sediment yield evolution related to extreme floods in a Western Mediterranean watershed where the long history of human impact has played a major role in the dynamics of soil erosion and landscape transformations during the last millennia. This novel approach comprises detailed microfacies and sedimentological analyses on the Lake Montcorts varved record (NE Iberian Peninsula) to reconstruct the Late Holocene seasonal sediment yield in the lake's watershed. The comparisons of the seasonal sediment yield evolution with detailed documentary and palynological archives

of land use changes in the watershed (Rull et al. 2011, Rull and Vegas-Vilarrúbia 2015, Montoya et al. 2018, Trapote et al. 2018a) have allowed the role of the main drivers (climate, land cover, land use) controlling sediment yield to be evaluated.

2. REGIONAL SETTING

2.1 Lake Montcortès. The lake (42°19.50'N, 0°59.41'E, 1027 m a.s.l.) is located in the southern Central Pyrenees (NE Spain) between *Les Nogueres* and the *South Pyrenean* structural units, composed of Mesozoic and Tertiary carbonate and conglomeratic sedimentary units tectonically thrust southwards. The watershed has a total surface area of 1.39 km² lying mostly on Oligocene conglomerates and siliciclastic, carbonate and evaporitic Mesozoic rocks (Keuper and Muschelkalk facies). Hypovolcanic ophite outcrops can be found in the southern areas of the watershed while Quaternary sediments (i.e. ancient lake shore terraces) are present around the lakeshore (Rosell, 1994; Corella et al. 2011). The lake was formed by karstic processes on evaporite-bearing formations (Corella et al. 2011). Lake Montcortès (LM) has a surface area of 0.14 km² and a maximum water depth of 32 m (Fig. 1). Lake margins are very steep, particularly in the northern shores, limiting their sediment production into the lake. The central deepest area (>18m water depth, 0.07 km²) is almost flat and represents the lake's main sediment sink area. The lake can be considered as a closed basin with a small ephemeral outlet in the northern shore. The lake's water column has permanent annual stratification that allows the preservation of biogenic varves. These varves are composed of calcite layers that precipitate due to enhanced bioproductivity during the warm season (June-September) algal blooms, and organic detritus deposited throughout the year (Corella et al. 2012, Trapote et al. 2018b). Two ephemeral streams in the southern margin of the lake reactivate during heavy rainfalls draining the lake watershed and eventually providing water and sediments to the lake basin. The sediment-laden flows enter the lake via i) over and/or interflows through low-density currents or ii) as underflow events when the hypopycnal currents are denser than the ambient lake

water (Corella et al. 2014). These **inorganic** sediment-laden flows are recorded as clastic laminae interbedded within the carbonate and organic couplets (Corella et al. 2014).

Fig. 1. (A) Location of Lake Montcortès (red circle) in the Iberian Peninsula and location of other sites discussed in the text (black circles correspond to other karstic sites and the grey square to experimental **watersheds** in the central Pre-Pyrenees). 1: Lake Estanya; 2: Lake Arreo; 3: Lake La Parra; 4: Lake El Tejo; 5: Lake Zoñar. (B) Photograph of the lake (source: Teresa Vegas-Vilarrúbia) (C) Land use map – Corine (EEA 2000) of Lake Montcortès **watershed** area. (D) Bathymetric map of Lake Montcortès and coring sites. In red the reference core of this study.

2.2 Vegetation and land use evolution in the lake watershed. The present-day landscape in the watershed mainly consist of cereal crops, meadows and pasture in the lowlands (60% of the

total area) and deciduous and conifer forests in elevated areas (30%) (Corella et al. 2014) (Fig. 1). Meadows and pastures around the lake are characterized by hay meadows and calcicolous, mesophilous and xerophilous grasslands. Shrublands are primarily represented by *Buxus*, *Genista* and *Thymus*. Forested areas in the watershed are dominated by *Quercus* species while *Fraxinus*, *Populus* and *Salix* species are also present. Hygrophytic communities colonize the lakeshore. Human-modified landscapes consist of intensive pastures, crop fields, fruit-tree orchards and ruderal communities (see detailed description of vegetation around the lake in (Mercadé et al. 2013, Rull et al. 2017). Cultivation of wheat, oat, barley, olives, rye, hemp and legumes as well as livestock husbandry (cattle and sheep) have varied through time during the last few centuries (Rull et al. 2011, Rull and Vegas-Vilarrúbia 2015, Montoya et al. 2018, Trapote et al. 2018a).

Two main agricultural phases A1 (9th–14th centuries) and A2 (16th–19th centuries) have been documented in the LM watershed. A1 was characterized by a decline of arboreal pollen from ~60 to ~30 % and the cultivation of *Secale* and *Triticum/Avena* cereals, alternating with pastures dominated by *Artemisia*, in a ca. 60 years land use rotation scheme (Rull and Vegas-Vilarrúbia 2015). This phase also coincided with a transition from intensive agriculture to shifting cultivation practices (Rull and Vegas-Vilarrúbia 2015). The onset of A2 was characterized by hemp cultivation, which attained a maximum in the post-modern age, as well as increases in cereals, ruderals and nitrophilous taxa from approximately 1500 to 1900 CE (Trapote et al. 2018a). Three phases of increased charcoal influx to the lake indicating widespread loss of woodland by fire occurred at B1 (830-970 CE), B2 (1670-1830 CE) and B3 (1850-1900 CE). Additionally, four main periods of high grazing pressure in the lake watershed have been characterized by increases of coprophilous fungi in the lake's sedimentary record (G1: 830–865 CE, G2: 1120–1290 CE, G3: 1530–1795 CE and G4: 1865–1880 CE) (Montoya et al., 2018). On the other hand, the pollen record shows different periods with low to moderate human impact (LHI) in the region. LHI1 (8th century BCE–8th century CE) experienced a subtle intensification of cereal cultivation in the lowlands of the Pre-Pyrenees, although stockbreeding and grazing pressure

were greatly reduced (González-Sampériz et al. 2017). LHI2 (15th century) coincided with the onset of the Little Ice Age, when a great social crisis with wars and plagues led to the depopulation of the area and the recovery of the forest (Rull et al. 2011, Rull and Vegas-Vilarrúbia 2015). LHI3 (20th century) coincided with massive emigration to large cities, promoted by growing industrialization with the subsequent reduction of agro-pastoral activities and field abandonment in the LM watershed (Trapote et al. 2018a).

2.3 Climate. The study area is located within the sub-Mediterranean bioclimatic domain, between the Mediterranean lowlands and the Middle Mountain belt (Rull et al. 2011). The climatic regime is characterized by a strong seasonality with the warmest temperatures occurring in July (mean temperature 23.3 °C) and the coldest in January (mean temperature 2.9 °C) (Corella et al. 2014, Trapote et al. 2018b). The mean annual rainfall is 825 mm, with the largest storms (>100 mm) occurring mainly in autumn and secondly in winter (Martin-Vide et al. 2008). Heavy rainfall events (> 80mm Maximum Daily Precipitation (MDP) during the cold season (October-May) are mostly associated with i) mesoscale convective systems fed by Mediterranean moisture and enhanced by the orography of the eastern pre-Pyrenean Mountains (Llasat and Puigcerver 1994) and ii) frontal Atlantic systems leading to persistent rainfall during the autumn and winter months (Corella et al. 2016). Warm season storminess is mainly caused by localized convective storms, a consequence of thermal related low pressure over the Iberian Peninsula (Campins et al. 2000).

3. MATERIAL AND METHODS

3.1 Bathymetric, seismic and coring surveys. A detailed bathymetric survey was carried out using a SonarMite echosound connected to a DGPS. A total of 8500 depth points distributed in several N-S and E-W depth transects were processed using ArcGIS 10.3 Extension 3D Analyst. The seismic survey was conducted with an Edgetech 424-SB sub-bottom multi-frequency profiler using a frequency range of 2–10 kHz for 20 ms. Fifteen seismic profiles were obtained although

penetration was limited to the upper meter in the northern distal area due to gas blanking. In the upper 1m of sediment, seismic profiles displayed parallel reflectors indicating undisturbed sediments. Long Kullenberg cores (MON04-1A-1K, MON04-1A-3A and MON04-1A-4A) and UWITEC gravity cores (MON12-3A-1G, 78 cm length, and MON12-2A-1G, 106 cm length) were retrieved from the deepest part of the lake using the coring equipment from the Limnological Research Center (University of Minnesota, USA) and the Pyrenean Institute of Ecology (IPE-CSIC) in 2004 and 2012 respectively (Corella et al. 2011, 2014).

3.2 Core correlation and sediment microfacies description. The cores were split in two halves lengthwise and imaged with a DMT core scanner and correlated using physical properties and sedimentary facies (lithological units and well-visible layers; Fig. 2). Cores MON12-3A-1G, MON12-2A-1G, MON04-3A-1K and MON04-4A-1K were selected to conduct microfacies analyses and to obtain an undisturbed composite sedimentary sequence (Corella et al. 2011; 2014). Microfacies analyses were carried out by detailed inspection of thin sections using the MNCN-CSIC microscopy lab. For this purpose, large-scale thin sections (120 mm × 35 mm) were prepared from a composite sequence of 543.5 cm after sampling in aluminium trays, freeze-drying and impregnation in Epoxy resin (Corella et al. 2012). Sediment compositional parameters and layer thickness measurements were performed using a *Nikon Eclipse E600* microscope.

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214 **Fig. 2.** Stratigraphical correlation between cores MON04-1A-1K, MON04-3A-1K and MON04-4A-
 215 1K. Light grey bands indicate the main lithostratigraphic units and grey lines represent the well-
 216 visible layers. Dark grey squares represent slumped material

217

218 **3.3 Age-depth model.** Varve counting performed on thin sections throughout the 543.5 cm-long
 219 composite sedimentary sequence resulted in an independent absolute varve chronology from
 220 2012 CE to B 763 BCE and was previously presented in (Corella et al. 2012; 2014; 2016). The
 221 varve chronology is in agreement with two independent dating - based on AMS ^{14}C (Corella et
 222 al. 2011) and ^{210}Pb (Corella et al. 2014) - supporting the robustness of the varve chronology (see
 223 above-mentioned references for further details on the Lake Montcortès age-depth chronology).

224 **3.4 Calculation of seasonal sediment fluxes and denudation rates in the Lake Montcortès**
 225 **watershed.** Clastic sediments are mainly delivered from the watershed by flood runoff flowing
 226 to the lake and they are deposited as detrital layers intercalated between the annual biogenic
 227 sediment (calcite and organic layers). The relative position of detrital layers within biogenic
 228 varve couplets makes it possible to constrain the seasonality of the detrital layers (Corella et al.

2016). Since calcite precipitates during the warm period (Trapote et al. 2018b), detrital layers intercalated within calcite layers are related to summer run-off events. In contrast, detrital layers embedded beneath, within and/or above the organic layer represent sediment fluxes during the cold season floods occurring in autumn, winter and spring, respectively.

The calculation of sediment fluxes originating from soil erosion in the watershed has been carried out following the approach proposed by (Einsele and Hinderer 1998) and (Barreiro-Lostres et al. 2017). Sediment volume delivery for annual and seasonal runoff (Vol_{DL}) has been estimated considering the thickness of detrital layers and the lake depositional surface. The lake depositional area (A_d) has been defined as the distal, flat areas below 18 m water depth to avoid overestimation due to some sediment focusing (i.e. sediment remobilization) on the bypass talus areas. Detrital layer thickness in the lake mostly depends on the sediment delivery although some variability in the deposited thickness may depend on the core location. Core correlation performed in the upper 4 m of sediment of Kullenberg long-cores highlighted that mean sedimentation rates in core MON04-3A-1K were 7.5 and 25% higher with respect to cores MON04-1A-1K and MON04-4A-1K (Fig. 2). Therefore, correction factors have been applied to estimate mean detrital layer thickness in the lake. In the estimation of Mass Denudation rates (DR) in the watershed, we assume that the annual mass denudation (M_d) equals the mass accumulated in the lake (M_l) per year, since the lake is a closed system. However, we have not considered minor fractions of terrigenous material that might be trapped in the vegetated littoral lake's shores and/or lowlands in the watershed. Therefore, sediment delivery efficiency will not reach the 100% and estimated DR values only reflect minimum thresholds. The minimum M_d was estimated based on the annual sediment volume deposited in the detrital (minerogenic) layers and their mean density ($\rho = 1 \text{ g cm}^{-3}$; Corella et al. 2017) that may resemble the mineral fraction of the surface soil in the lake's watershed. Area specific sediment yield (S_y) from the watershed (hereafter defined as sediment yield *sensu lato*) is subsequently calculated from M_d

and the watershed area (W_a) while lowering rates or denudation rate (DR_t) variability in the watershed is calculated considering only Vol_{DL} and W_d .

$$Md > MI / A_d = Vol_{DL} \times \rho = [t \text{ yr}^{-1}]$$

$$S_y = MI / W_a = [t \text{ km}^{-2} \text{ yr}^{-1}]$$

$$DR_t = Vol_{DL} \times W_d \text{ [mm yr}^{-1}]$$

4. RESULTS

4.1 The seasonal sediment yield in Lake Montcortès during the Late Holocene

The analyses of the different variables (Md , S_y , DR_t) related to the sediment remobilization in the lake watershed and subsequent storage in the lacustrine basin have been applied to the 1220 clastic layers distributed over the 819 years within the studied period (last 2775 years) that represent Late Holocene sediment-laden flood events during heavy rainfall events in the area. The mean Md , S_y and DR_t during the Late Holocene are 43.9 t yr^{-1} , $31.5 \text{ t km}^{-2} \text{ yr}^{-1}$ and $3.1 \times 10^{-2} \text{ mm yr}^{-1}$ respectively. These values hide a large variability during the main climate periods described for the North Atlantic region. All these variables show maximum values during the warm Medieval Climate Anomaly (MCA, 900-1350 CE (Moreno et al. 2012)) – and during the Industrial Period (1850-Present day) with mean annual sediment yield of 94.7 and $54.6 \text{ t km}^{-2} \text{ yr}^{-1}$, respectively (Fig. 3). Short phases of very high annual sediment yield occurred during these periods at 921-989, 1030-1046, 1070-1107, 1168-1239, 1256-1261, 1278-1285, 1299-1315, 1340-1362 and 1844-1866 CE. The highest sediment yield occurred at 1168-1239 CE with a mean annual sediment yield of $197.4 \text{ t km}^{-2} \text{ yr}^{-1}$. During this period, the most extreme event in terms of sediment yield occurred in 1182 CE mobilizing 1704.7 t of sediment that were deposited in the lake basin. A significant decrease in annual sediment yield occurred during other past well-known climatic periods in NE Spain such as the Little Ice Age (LIA, 1300-1850 CE; Morellón et al. (2012)), the Dark Ages Cold Period (DACP; 450-900 CE; Corella et al. (2013)), the Late Antiquity Little Ice Age (LALIA; 536-660 CE; Buntgen et al. (2016); Corella et al. (2016)) and the Ibero-

279 Roman Humid Period (IRHP; 650 BCE- 350 CE; Martín-Puertas et al. (2009), Corella et al. (2013)
 280 with mean annual sediment yield of 14.6, 30.5, 6.6 and 11.8 $\text{t km}^{-2} \text{yr}^{-1}$ respectively. During these
 281 periods very low sediment yield was recorded at 679-560, 474-347 and 147-17 BCE and 34-139,
 282 257-297, 356-590, 1362-1499, 1540-1563, 1658-1677, 1690-1713, 1755-1838 and 1927-2012
 283 CE. The two periods with the lowest annual sediment yield occurred between 358 and 590 CE
 284 and since 1927 with mean annual sediment yield of 2.5 and 2.7 $\text{t km}^{-2} \text{yr}^{-1}$ respectively.

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287 **Fig. 3.** From left to right: occurrence of heavy-rainfall-induced layers (Maximum Daily
 288 Precipitation events >80mm during the 20th century). Black lines represent the 31-yr running
 289 average of layer occurrence ranging from 0 to 1 (mean values of 0.44 layers/year) (Corella et al.
 290 2016). Lake Montcortès detrital layer thicknesses (DLt); Mass denudation rates (Md); Calculated
 291 annual sediment yield (Sy) and total denudation rates (DRt) in the lake watershed. Vertical
 292 colour bars represent the different land use phases described in section 2.2. Blue (LHI), green
 293 (A), yellow (B) and red bars (G) represent phases of low human impact, intensive agriculture,
 294 burning and overgrazing in the watershed, respectively.

The sediment yield variability is consistent with the different anthropogenic landscape scenarios reconstructed in the area (Rull et al. 2011, Rull and Vegas-Vilarrúbia 2015, Montoya et al. 2018, Trapote et al. 2018a). Thus, the lowest annual sediment yield occurred during periods of low to moderate human impact in the watershed (LHI) with a mean annual sediment yield of 11, 8 t km⁻² yr⁻¹ (mean annual sediment yield of 12, 8.3 and 14.9 t km⁻² yr⁻¹ during LHI 1, 2 and 3 respectively). The highest annual sediment yield is recorded during periods of high human impact associated to agricultural phases (mean annual sediment yield $y = 52,2 \text{ t km}^{-2} \text{ yr}^{-1}$), burning phases (mean annual sediment yield = 80.9 t km⁻² yr⁻¹) and grazing periods (mean annual sediment yield = 84.6 t km⁻² yr⁻¹) (Fig. 3). Mean annual sediment yield shows significant positive correlations with charcoal fluxes and percentages of meadows and pastures ($\rho=0.39$ and 0.40 respectively), and negative correlations with percentages of shrubland and trees ($\rho= -0.438$ and -0.41 respectively).

4.2 Sediment yield seasonality

Seasonality was determined in 41% of the years with detrital layers occurrence, recording 114, 139, 42 and 91 runoff events in autumn, winter, spring and summer respectively. The highest sediment yield corresponded to autumn and winter floods (mean Sy per event of 47.7 and 62.6 t km⁻² yr⁻¹ respectively) while mean SY during spring and summer accounts for a mean annual Sy of 27.3 and 34.2 t km⁻² yr⁻¹ respectively. Nevertheless, the seasonal distribution of sediment yield strongly varied over the past 2775 years in response to different historical land use settings (Figs 4 and 5). During LHI phases, and particularly during the 20th century, autumn runoff produced most of the detrital inputs with up to 58.5% of the total annual sediment delivery, followed by winter (17.9%) summer (14.9%) and spring (8.6%). On the contrary, the highest sediment

production occurred during winter (always more than 50%) during phases of higher human activities, namely grazing, agricultural and burning (Fig. 5).

Fig. 4. From left to right: occurrence and seasonality of detrital layers related to rainfall events per decade; Sediment yield (Sy) during autumn, winter, spring and summer for the last 2775 years. Vertical colour bars represent the different land use phases described in section 2. Blue (LHI), green (A), yellow (B) and red bars (G) represent phases of low human impact, intensive agriculture, burning and overgrazing in the watershed respectively.

Fig. 5. A and B) Mean annual sediment yield (Sy) during the different Late Holocene climatic phases and during the different cultural landscape changes. C) Relative seasonal contribution to annual sediment yield (%).

4.3 Sediment yield from Lake Montcortès watershed during the Instrumental Period

The comparison of the sediment yield associated with heavy rainfall events in the lake watershed with the instrumental daily rainfall record from the Cabdella meteorological station (15 km north of the lake) during the period 1917-1994 CE has shown that floods in the watershed

are related to heavy rainfall and sediment delivery to the lake. Clastic layer deposition has always occurred since 1917 CE when rainfall events exceeded 80 mm MDP (Maximum Daily Precipitation) (Corella et al., 2014). A detailed seasonal analysis set MDP minimum thresholds to 91.5, 80, 84 and 107 mm for autumn, winter, spring and summer sediment yield events, respectively (Fig. 6). The analysis of the annual sediment yield produced by these heavy rainfalls does not show any significant trend (Fig. 6). Nevertheless, the seasonal patterns of these extreme events may suggest an annual sediment yield increase with heavy rainfall magnitudes in autumn, winter and summer (Fig. 6).

Fig. 6. Relation between annual maximum daily precipitation events measured in Cabdella meteorological station (15km north of the lake) and sediment yield during heavy rainfall events in Lake Montcortès watershed. Arrows indicate the sediment yield seasonal trend in relation to heavy rainfall magnitudes.

5. DISCUSSION

5.1 Effects of heavy rainfall events and land use on sediment yield variability

The relation between heavy rainfall variability, vegetation changes and sediment yield in the LM watershed highlights the interplay between hydroclimate and flood variability and human-driven land use changes as the main drivers controlling the sediment yield in mountainous Mediterranean watersheds. A better understanding of the long-term seasonal patterns of sediment yield significantly contributes to elucidate the relative contribution of these drivers during the Late Holocene:

5.1.1. Hydroclimate: The analysis of detrital layers deposited in LM during the time-span of the Cabdella meteorological dataset provides further links between rainfall amount and sediment yield in the context of the low human disturbances that characterize the 20th century. To our knowledge, only a few studies have attempted to compare instrumental hydrological datasets with the amount of sediments deposited in lake basins, highlighting certain relationships between flood events magnitudes and sediment volumes (Schiefer et al. 2011, Kämpf et al. 2015, Wilhelm et al. 2018, Evin et al. 2019). In Lake Montcortès, all runoff events delivering sediment to the lake since 1917 CE occurred during heavy rainfalls > 80 mm MDP (Corella et al., 2014). The 11 events occurring within the instrumental period show a weak statistical correlation between sediment yield and the amount of daily precipitation due to a strong sample dispersion (Fig. 6). A close look at the seasonal subsets suggests a proportional-type response of seasonal Sy to heavy rainfall amount, although these trends are based on a limited number of data points (Fig. 6). This differential behaviour may be explained by the seasonal changes on soil properties, sediment connectivity and erodibility in relation with soil moisture, temperature, sediment availability and vegetation cover. Once again, it shows the paramount interest of considering seasonality in palaeoflood studies using paleolimnological approaches. The percentage-base distribution of seasonal sediment yields during 20th century (autumn: 58.5%; winter: 17.9%; spring: 8.6%; summer: 14.9%) agrees with the recorded heavy rainfall distribution

in the region, namely the highest in autumn (50.0% of the cases), followed by winter (22.1%), spring (13.1%) and summer (14.8%) (Martin-Vide et al. 2008). Interestingly, during the instrumental period the highest and the lowest **sensitivity** of Sy occur in autumn and winter seasons respectively (Fig. 6), which might be explained by more developed and softer regolith favouring hortonian runoff sediment-laden flows at fall while this regolith is mostly washed-out in winter.

On longer time-scales, there is a lack of high-resolution quantitative climatic reconstructions in the Pyrenees that impedes further assessments of the climate effect on **sediment yield**. The higher sediment delivery recorded during the warmer MCA (Moreno et al., 2012) may suggest that climate warming could have accelerated soil erosion by altering soil properties and vegetation coverage in Mediterranean areas. Nevertheless, during the recent global warming sediment delivery has not increased, implying that temperature by itself is not a significant driver for soil erosion in Mediterranean watersheds. Therefore, increased **sediment yield** would be mostly controlled by heavy rainfall variability at decadal to centennial time-scales.

5.1.2. Land use. The sediment delivery and denudation rates in the watershed also agree reasonably well with the anthropic activities phases in the LM **watershed** (Figs. 3, 5 and 7), implying that humans **have had a large** impact on sediment delivery to the lake. The highest sediment yield occurred during burning and grazing phases with an 8-fold increase with respect to low human impact phases. This **correspondence** would suggest that fire incidence and overgrazing had similar impacts on soil erosion at decadal to centennial time-scales. This hypothesis is further supported by the significant positive statistical correlations between annual **sediment yield** and charcoal fluxes and percentages of meadows and pastures in **the LM watershed**.

The impact of overgrazing as a dominant factor in the increase of soil erosion has already been reported in other lake sequences from the Alps from a historical perspective (Giguet-Covex et al. 2012, Giguet-Covex et al. 2014, Arnaud et al. 2016, Doyen et al. 2016). In Mediterranean areas, higher soil erosion rates and run-off episodes coincide with rising grazing activities. Two factors occur synergistically; i) soil compaction by overgrazing trampling, which impedes the development of vegetation cover in meadows and pastures that could even lead to the formation of badlands; ii) Cattle raising feeding, which reduces grassland and vegetation cover protecting the soil and ultimately increasing run-off (e.g Garcia-Ruiz and Lopez-Bermudez 2009). In the Pyrenees, meadows and pastures expansion in steep slopes and above the forest line has historically led to an increase in erosive processes and mass movements (Montserrat, 1992; García-Ruiz and Valero-Garcés., 1998). Fires also have a strong impact on soil properties increasing soil repellence, reducing infiltration rates, degrading the soil structure and eventually increasing soil erodibility (Cerdà et al. 1995, Mataix-Solera and Doerr 2004). The fact that the highest sediment delivery occurred during burning phases points to slash and burn practices as the most critical factors for soil erosion. It also underlines the importance of management practices to adapt agricultural systems to the growing food and water demands. Periods of sustained agricultural practices also had an impact on the sediment delivery to the lake with a 5-fold increase with respect to LHI phases. On the other hand, the strong negative correlation between annual sediment yield and shrubland and forest percentages shows that land abandonment (and shrubland recolonization and forest recovery) are primary drivers to diminish soil degradation and sediment yield in the watershed.

Land use changes also have a significant impact of the seasonal trends of sediment yield. The periods with low human impact in the watershed show a seasonal sediment delivery distribution that parallels the seasonality of heavy rainfall frequencies during the instrumental period (Figs. 4 and 5). On the other hand, the sediment yield seasonality distribution in the different anthropogenic scenarios (grazing, agricultural and burning phases) followed a different

seasonal trend with the highest contribution during the winter season (always more than 50%). Agricultural phases exert a key influence on seasonality of sediment yield since cereal cropping (wheat or barley) involves traditional tillage practices during autumn after the first rains, and once the plants sprout the croplands were cleaned of weeds. These agricultural tasks likely contributed to a greater vulnerability of soil erosion during the winter season, particularly in years with late rains.

5.1.3. Comparison with experimental watersheds in the Pyrenees: Sediment yield recorded in the LM watershed reasonably agrees with recorded sediment production on experimental monitoring stations in the Southern Pyrenees under similar physiographic and hydrometeorological characteristics in terms of mean slopes, precipitation and temperature regimes, watershed areas and elevation ranges and comparable land use changes (Table 1) (Cerdà and Lasanta 2005, García-Ruiz et al. 2008, López-Vicente et al. 2008, García-Ruiz 2010, Nadal-Romero and Regüés 2010, Nadal-Romero et al. 2013, Lana-Renault et al. 2014). Indeed, the comparison of Sy from active shifting agriculture and cereal plots with those from the abandoned meadows and dense shrub cover plots were up to one order of magnitude different in these experimental watersheds (García-Ruiz 2010, Nadal-Romero et al. 2013), in agreement with the LM watershed results. The lower sediment yield values recorded in the LM watershed compared to the San Salvador and Arnás watersheds are expected since the LM watershed sediment yield represents minimum sediment production where sediment trapping and storage in the distal basin does not reach 100%. This sediment delivery delay has been observed in other karstic lakes (Barreiro-Lostres et al. 2017) due to the interplay between several factors, including: i) The littoral vegetation may act as a sediment barrier facilitating the deposition of the finer sediments during low-magnitude flood events along the palustrine areas before reaching the lake's distal basin; ii) sediment trapping in geomorphic barriers disconnected from the main hydrological network as seen in other karstic lacustrine watersheds in the Pyrenees (López-Vicente et al. 2013, Corella et al. 2018) and the Iberian Range (Barreiro-Lostres et al.

2017) and; iii) the LM sedimentary sequence only records sediment yield from heavy rainfall events, but misses sediment produced during low magnitude floods that do not reach the lake. Nevertheless, studies from these experimental stations highlight that extreme events are the main contributors to the annual sediment yield (González-Hidalgo et al. 2007, Nadal-Romero et al. 2012, Nadal-Romero et al. 2012).

In the same hydroclimatic region (Estanya, ca. 50 km from LM), (López-Vicente et al. 2008) estimated annual soil losses in an agricultural landscape using RUSLE model and rainfall records (1997-2006) obtaining rates of $33.4 \text{ t km}^{-2} \text{ yr}^{-1}$, similarly to the LM watershed values ($31.5 \text{ t km}^{-2} \text{ yr}^{-1}$). Mean annual sediment yield during periods of low to moderate human impact in the LM watershed ($9.1 \text{ t km}^{-2} \text{ yr}^{-1}$) have also very similar values to erosion rates of $8.9 \text{ t km}^{-2} \text{ yr}^{-1}$ reported for experimental plots on abandoned farmlands (García-Ruiz et al. 1995, Cerdà and Lasanta 2005). At the event scale, the largest event recorded in the LM watershed during a period of intense human pressure and land degradation estimated to be 1704.7 t km^{-2} compares with a similar exceptional rainfall event in the highly degraded soils and soft regolith of the Araguas experimental station with the total amount of sediment mobilized in the station estimated at 1392.2 t km^{-2} (Nadal-Romero and Regüés 2010, Lana-Renault et al. 2014).

The dense shrub cover from experimental plots in the Aísa experimental station had very moderate hydrological and geomorphologic effects, with little sediment yield (Nadal-Romero et al. 2013). This observation agrees with the negative correlation between shrublands and annual sediment yield in the LM watershed, highlighting that a dense shrub cover enhances infiltration and decreases runoff and erosion. In this experimental station, active shifting cultivation plots also triggered very high sediment yield (Nadal-Romero et al. 2013) as seen in the LM watershed during periods with shifting cultivation in the area (Rull et al. 2011, Rull and Vegas-Vilarrúbia 2015). The 8-fold increase in annual sediment yield measured in LM sedimentary record during burning phases are also in agreement with experimental monitoring stations in the Pyrenees that monitored the long-term erosion rates after fire measuring up to 10 times greater post-

fires erosion rates (Cerdà and Lasanta 2005). In quantitative terms, the mean annual sediment yield ($81 \text{ t km}^{-2} \text{ yr}^{-1}$) during this burning phases are in the same order of magnitude of erosion rates measured in a burn plot from Aínsa Experimental Station one and two years after a fire event ($64.3\text{-}104.1 \text{ t km}^{-2} \text{ yr}^{-1}$ respectively) (Cerdà and Lasanta 2005).

5.2 Late Holocene flood-related sediment yield evolution in Lake Montcortès watershed

The detailed microfacies analyses carried out on the LM sedimentary sequence has contributed to an improved understanding of the evolution of sediment yield and denudation rates in a mountainous Mediterranean watershed during the Late Holocene. Periods with reduced annual sediment yield are interpreted as phases with low sediment production in the watershed due to reduced human impact and/or lowered flood intensity and frequency.

5.2.1 Iberian and Roman period (6th century BCE- 5th century CE): During periods of low human impact in the landscape prior to Roman times, the annual sediment yield variability would mostly reflect the magnitude of heavy rainfall events and the greatest storminess recorded during the onset of the Iron Age (763-672 BCE). The reduced annual sediment yield in Lake Montcortès during the Iberian and the Roman Periods would suggest a moderate human impact in the watershed and relatively lower flood intensity. Nevertheless, there are no vegetation reconstructions for the Montcortès watershed during this period and so, it is not possible to directly explore the relationships between annual sediment yield variability and land use changes at that time. Nevertheless, regional vegetation reconstructions from nearby lake records highlight a relatively low-degree of anthropogenic impact in the Central Pyrenees including reduced pastoral and grazing activities (González-Sampériz et al. 2017).

5.2.2. The Migration period and the Middle Ages (6th century CE- 14th century CE): The lowest sediment yield of the entire studied period occurred at 356-590 CE coinciding with the collapse of the Roman Empire in NE Iberian Peninsula and the Migration period. This time span coincides

with a sharp decline of heavy rainfall events in the area that persisted until the 7th century (Corella et al. 2016) as well as lower flood frequency in western Mediterranean rivers (Benito et al. 2015). The progressive increase in annual sediment yield since 650 CE lasted until 990 CE with the highest values recorded during the 10th century. This period experienced a higher human pressure in the lake's watershed documented from historical sources (Marugan and Oliver 2005), overlapping grazing and burning phases G1 and B1 characterized by shifting cultivation and a peak in local fire incidence that led to an increase in fungal spores *Neurospora crassa*, *Cooniochaeta* and *Gelasinospora* with low dispersion capacity (Montoya et al. 2018). In this period, other studies point out to a dramatic reduction in woodland (Rull and Vegas-Vilarrúbia 2015) and the beginning of livestock farming and pastures activities in the watershed recorded by an increase in coprophilous fungi (Fig. 7) (Montoya et al. 2018).

Sediment delivery and denudation rates remained high during the Middle Ages until 1362 CE coinciding with a phase of agricultural expansion (A1) that began after intensive woodland clearance by fire and lasted until the 14th century (Rull and Vegas-Vilarrúbia 2015). Hydrologically this coincides with the highest frequency of flooding events in NE Iberian Peninsula (Corella et al. 2016). The cultural landscape during this period was characterized by *Cannabis*, cereals and *Castanea* cultivation together with the maximum abundance and diversity of weeds (Rull and Vegas-Vilarrúbia 2015). The highest annual sediment yield of the entire sequence (1168 and 1239 CE) is synchronous with the expansion of cattle farming in the watershed (increase in palynological "dung" indicators; (Montoya et al. 2018) and coincided with the period with the highest population density documented in the area (Marugan and Oliver 2005). During this period, a single event was able to mobilize 1704 tons of sediment because of the severe soil degradation due to the higher human pressure. Indeed, shifting cultivation was replaced at that time by a more controlled and permanent land exploitation. This land use change eventually led to increased soil degradation even though crop rotation was applied to reduce soil impoverishment (Rull and Vegas-Vilarrúbia 2015).

534

535 **Fig. 7.** Comparison between annual sediment yield (Sy) in Lake Montcortès watershed (11 yrs
536 running average) with Lake Montcortès palynological proxies previously published in Rull and
537 Vegas-Villarubia (2015) and Montoya et al., (2018). *Glomus* percentage represents the
538 abundance of this spore indicating higher erosion processes in the LM watershed (Montoya et
539 al., 2018). The different land use phases are also indicated with horizontal and vertical bars. The
540 grey arrow indicates the degree of human disturbance in the LM watershed.

541

542 The progressive decrease in annual *sediment yield* since the mid-13th century also
543 coincided with a decrease in herb crops and a dominance of cultivated trees (Rull and Vegas-
544 Vilarrúbia 2015). During the mid-14th century, the black death pandemic (1348 CE) triggered a
545 depopulation and a drastic reduction in human pressure characterized by the disappearance of
546 cereal cultivation and livestock raising in the lake *watershed* (Rull and Vegas-Vilarrúbia 2015).
547 This reduced human pressure was most likely responsible for the abrupt reduction annual
548 *sediment yield* in the watershed after 1362 CE.

549 5.2.3. Modern period (15th century CE- 18th century CE): The reduced sediment yield during the
550 Modern Age contrasts with an intensification of agricultural practices in the watershed since
551 1500 CE. During this period the LM *watershed* vegetation reconstruction showed a

diversification of land uses in concordance with historical sources that documented slash-and-burn activities to create and maintain agricultural fields and cattle from 1500 to 1700 CE (Marugan and Rapalino 2005, Ferrer Alòs 2017, Trapote et al. 2018a). Therefore, the only plausible explanation for the low annual sediment yield recorded during this period is an abrupt decrease in the frequencies of autumn and winter heavy rainfall events (Corella et al. 2016) (Figs. 5 and 6). The lower frequency or even absence of large floods since mid-17th to mid-18th centuries has also been reported in other Mediterranean watersheds based on palaeoflood (Wilhelm et al. 2012, Machado et al. 2017) and historical records (Barriendos and Martín-Vide 1998).

5.2.4. Industrial period (19th century CE- 20th century CE): A higher number of flood layers during the second half of the 19th century correspond to intensive pastoral activities, higher fire incidence and agricultural practices. High annual sediment yield recorded in the lake between 1844 and 1866 CE also coincided with the highest demographic pressure in most mountain valleys of the Spanish Pyrenees (Ayuda and Pinilla 2002, Fillat et al. 2008) leading to common slash and burn practices, cultivation of steep slopes and shifting cultivation (Lasanta, 1989). The increase in annual sediment yield in the LM watershed is also in agreement with a maximum in river flood frequency and magnitude in NE Spain since the Middle Ages, occurring between 1840 and 1870 CE (Llasat et al. 2005, Barriendos and Rodrigo 2006). The interplay between extreme run-off events, deforestation and grazing activities controlling the increase in sediment yield has also been highlighted in artificial historical reservoir watersheds in western Mediterranean (Puentes and Valdeinfierno reservoirs) (Rodríguez-Lloveras et al., 2017) and the Southern Pyrenees (Valero-Garcés et al., 1999) since the 19th and the early 20th centuries respectively.

Reduced storminess and a significant decrease of human presence indicators in LM record explained by depopulation in the Pallars region (Farràs 2005, Corella et al. 2016, Trapote et al. 2018a) contributed to low annual sediment yield values during the 20th century, and

particularly since 1927 CE. Indeed, the demographic migration to urban areas during the last decades has caused a drastic reduction in human pressure in the lake's watershed with an abandonment of grazing and agricultural activities and a considerable reduction of fire and forest management (Farràs, 2005; García-Ruiz, 2010; Trapote et al. 2018a).

5.3 Sediment yield in other mountainous Mediterranean watersheds

In the Iberian Peninsula, there are several karstic lakes emplaced in small watersheds with similar limnological and physiographic characteristics in terms of water depths and bedrock lithology composition that could be used as a comparison to LM data set: Lake Arreo (Northern Spain; Corella et al., 2013); Lake Estanya (Southern Central Pyrenees; Morellón et al., 2009; 2011); Lakes Tejo, La Parra, Tobar and Taravilla (Iberian Range; Barreiro-Lostres et al., 2015; 2017) and Lake Zoñar (Southern Spain, Martin-Puertas et al., 2009). Sediment delivery to these karstic systems shows a great variability with significant differences in the timing and magnitude of the periods of enhanced sediment delivery to the lake basins.

Sediment yield reported in karstic lake watersheds from the Iberian Range, namely lakes Tejo, La Parra and Tobar with sediment yield values of 69, 103 and 111 t km⁻² yr⁻¹ respectively (Barreiro-Lostres et al. 2017) are higher than the long-term mean Sy in the LM watershed. These three lakes have a large range of watershed/lake surface area ratios, which explain these higher production rates. In addition, it is important to note that a different methodological approach was applied in these systems using mean sedimentation rates to estimate soil erosion-related parameters for the investigated watersheds. This approach does not decouple endogenic lake production from the allochthonous sediment delivery to the lake basins and it may overestimate mean annual Sy values during period of higher bioproductivity in the lakes (Barreiro-Lostres et al. 2017). Other karstic lake from the Iberian Range (i.e. Lake Taravilla) displayed lower sediment yield (7 t km⁻² yr⁻¹) than Lake Montcortès. These lower values are explained by intrinsic factors

of Lake Taravilla watershed with the presence of creeks and large palustrine areas acting as a sediment sink and thus, impeding the coarser material to reach the lake bottom (Barreiro-Lostres et al., 2017).

Fig. 8. Comparison between sediment yield (Sy) in Lake Montcortès watershed (11 yrs running average) with terrigenous input proxies to other karstic lakes in the Iberian Peninsula. From left to right: Lake Montcortès (This study); Lake Estanya (Morellón et al., 2009; 2011); Lake Arreo (Corella et al., 2013); Lakes La Parra y El Tejo (Barreiro Lostres et al., 2015; 2017); Lake Zoñar (Martín-Puertas, Jiménez-Espejo et al. 2010). Blue horizontal bars highlight the highest sediment fluxes to Lake Montcortès.

Besides karstic lakes from the Iberian Range, there is a lack of Late Holocene annual sediment yield reconstructions in the Iberian Peninsula to compare with. Nevertheless, there are several geochemical proxies (Ti/Ca and Rb/Al ratios (Martín-Puertas et al. 2010, Corella et

al. 2013) and/or further statistical treatments of geochemical datasets (e.g. Principal Component Analyses, PCA; (Morellón et al. 2009; 2011; Barreiro-Lostres et al. 2017)) that reconstruct qualitatively the sediment delivery to karstic lake systems (Fig. 8). Thus, karstic sequences from the Pre-Pyrenees and the northern Ebro Basin (i.e. Lakes Montcortès, Estanya and Arreo) show a reasonably similar trend with higher and lower sediment delivery within the Middle Ages and the Modern Age respectively (Fig. 8). The similarities are most likely explained by an analogous hydroclimate regime in NE Spain with higher and lower frequency of heavy rainfalls during the MCA and the LIA respectively and a parallel population and cultural history, with the onset of higher human impact controlled by the advance southwards of Christian kingdoms. Certain differences in periods of higher clastic input shown in these sequences most probably response to the different land uses and convective storms affecting each lacustrine system differently. Particularly, Lake Montcortès shows characteristically lower SY during the 1400 – 1800 CE not shown in Arreo or Estanya. The lower elevation of these two sites likely explains higher human impact during the LIA in the watersheds.

On the other hand, a different trend in sediment [remobilization and delivery to the sink](#) (i.e. [the lake basin depocentre](#)) is observed in Lake Zoñar, located in Southern Spain, and in karstic lakes from the Iberian Range (Martín-Puertas et al. 2010, Barreiro-Lostres et al. 2017) (Fig. 8). Although some phases of high [sediment yield](#) in the Iberian Range occurred during medieval times, the highest [sediment yield](#) occurred later, during the 15th–16th and it was also quite intense during the 18th–19th centuries and continued in the 20th century (Barreiro-Lostres et al., 2017). In southern Spain, [the](#) Lake Zoñar sedimentary sequence showed the highest clastic input during the IRHP (Martín-Puertas et al. 2010). These dissimilarities are probably explained by the different land uses and precipitation regimes recorded throughout the Iberian Peninsula. Indeed, the higher clastic input in Lake Zoñar coincides with the flourishing of the Iberian culture and the Roman conquest that brought and intensification of agropastoral activities in southern Spain (Carrión et al. 2007, Martín-Puertas et al. 2009). Secondly, the IRHP is known as the Late

Holocene's most humid period in Southern Spain (Martín-Puertas et al. 2009) while more arid conditions prevailed in Northern Spain at that time (Corella et al. 2013). These hydroclimate saw patterns coupled with different land use changes at the investigated sites may explain the large differences in the sediment dynamics in southern and northern Iberian karstic watersheds.

In other Western Mediterranean regions such as the French Alps, human-driven influence on erosion at a local scale has been also been documented for the last three millennia (Arnaud et al., 2016). In this region, Lake Bourget can arguably be considered as a reference record of continuous soil erosion fluxes in the Alp (Debret et al., 2010; Arnaud et al., 2012; Evin et al., 2019). This lacustrine record highlights two erosive periods with increase sediment yield in the Rhone river watershed at 350-650 CE and 1150-1900 CE. These results greatly differ from the long-term erosive trends reconstructed in Southern Pyrenean records shown in this study. This difference in sediment yield estimation in western Alps can partially be attributed to the glacier control on the hydrological processes in the Rhone river watershed that ultimately controls the regional soil erosion. An increase in soil erosion has also been reconstructed in Eastern Mediterranean during the last 2500 years using a varved lake record from central Anatolia (Roberts et al., 2018). In this lacustrine records, Roberts et al, (2018) inferred that watershed erosion was mostly controlled by changes in land-cover, with a significant decrease in soil erosion when forest cover expanded between 650 and 950 CE and higher sediment delivery to the lake between 950 and 1250 CE.

The impact of progressive woodland clearance followed by overgrazing in seasonally dry climates has resulted in high soil erosion rates across the Mediterranean (Woodward et al., 1995) with average sediment loads have increased by a factor of 2 to 10 since the onset of human-driven widespread deforestation and farming (Milliman and Syvitsky., 1992). In this study, a large heterogeneity in soil erosion is depicted across the Mediterranean from the comparison between different lacustrine records during the Late Holocene. In the other hand, at longer time-scales, a recent meta-data analyses of soil erosion patterns in the Mediterranean

during the entire Holocene highlights that dominant erosion phases occur contemporaneously across a number of Mediterranean regions during some periods that could be attributed to climate changes (Walsh et al., 2019). Therefore, more homogenised paleoenvironmental reconstructions are still needed to understand the complex patterns and environmental forcings controlling soil erosion in the Mediterranean at different temporal and spatial scales.

6. CONCLUSIONS

The Lake Montcortès sedimentary sequence has recorded flood events related to heavy rainfall at seasonal resolution during the Late Holocene. Sedimentological analyses using varved sediments from Lake Montcortès (NE Spain) have been applied to provide, for the first time, mass accumulation rates in lake basins as well as minimum flood-related sediment yields and denudation rates in a Mediterranean watershed with seasonal resolution during the last three millennia. The agreement between the Lake Montcortès sediment yield reconstruction and the sediment yield variability measured in experimental watersheds in the Southern Pyrenees with similar physiographic and hydroclimate conditions and land use configuration highlight that paleolimnology is a valid approach to estimate watershed sediment yield and denudation rates. Nevertheless, in Mediterranean areas with a strong seasonal hydroclimatic regime and a long history of human occupation, detailed microfacies analyses using annually laminated sediment are required to unravel the long-term sediment yield seasonal patterns.

The interplay between heavy rainfall frequencies and magnitudes, flood events and land use changes are the main drivers controlling long-term soil erosion during the Late Holocene. The comparison of LM watershed sediment yield with the instrumental meteorological datasets indicate that sediment yield show a different sensitivity to heavy rainfall magnitudes at the seasonal scale that is mostly depending on the different seasonal soil properties in terms of soil moisture, available regolith and vegetation cover. On longer time-scales, the highest sediment yield and denudation rates occurred during two periods, the Middle Ages and the 19th century,

whereas the lowest corresponded to the Migration Period (5th -7th centuries) and the 20th century, coinciding with periods of high (low) agropastoral activities in the watershed and higher (lower) heavy rainfall in the region. Burning and grazing activities have triggered an 8-fold increase in **sediment yield** causing severe land degradation in the watershed sustained for decades. Agricultural practices such as shifting cultivation and cereal production have also increased **sediment yield** in the watershed, while land abandonment and forest expansion contribute to reduce soil erosion in the lake's watershed.

Flood events are always needed to remobilize the sediment in the lakes watershed. Nevertheless, the quantitative relation between the magnitude of the extreme hydrological event and the sediment yield in the watershed may vary under different land-use scenarios. The comparison of the sediment production and transport reconstructed from the different karstic sequences from mountainous Mediterranean areas in the Iberian Peninsula highlights a large spatio-temporal **sediment yield** variability. These dissimilarities in the sediment budget are mainly controlled by the hydroclimate **and flood** variability at the regional scale as well as the varied history of the vegetation cover related to land use changes.

7. TABLES

Table 1: Main morphological, geological and hydro-sedimentological characteristics of the Lake Montcortès watershed and Central Pyrenees experimental **watershed**s (data from San Salvador and Arnás watersheds based on García-Ruiz et al., (2008) and Lana-Renault et al., (2014).

Watershed	San Salvador	Arnás	Montcortès
<i>Location</i>	42°37'N, 0°36'W	42°38'N, 0°34'W	42°19'N, 0°59'E
<i>Drainage area (km²)</i>	0.92	2.84	1.39
<i>Maximum elevation (m a.s.l.)</i>	1295	1340	1300
<i>Minimum elevation (m a.s.l.)</i>	830	910	1027

<i>Mean elevation (m a.s.l.)</i>	1063	1125	1120
<i>Mean slope (°)</i>	14	12	
<i>Precipitation (mm/a)</i>	935	926	860
<i>Dominant Geology</i>	Flysh	Flysh	Keuper and Muschelkalk Fm
Land cover (%)			
<i>Woodland</i>	98	20	30
<i>Bare soil</i>	1	2	0
<i>Shrubs or cultivated lands</i>	1	71	60
<i>Lake area (%)</i>			10
Sediment yield			
<i>t km yr⁻¹</i>	140	160	31.5
Periods of high human impact in LM watershed			113.9
Periods of low human impact in LM watershed			9.1
Exceptional rainfall event			
Sed. yield (t km²)		68,9	1704,7 (flood in 1182 CE)

8. ACKNOWLEDGEMENTS

This work was supported by the Spanish Ministry of Science, Innovation and Universities (MICINN) projects LIMNOCAL (CGL 2006-13327.C04-01/CLI), MEDLANT (CGL2016-76215-R) and EPHIMED (CGL2017-86839-C3-1-R) (co-financed with FEDER funds). J.P.C. and EM were supported by Juan de la Cierva – Incorporación postdoctoral contracts funded by MINECO (refs. IJCI-2015-23839 and IJCI-2015-24273 respectively). This study was also partially funded by means of an international mobility grant Jose Castillejo to J.P.C. (CAS18/00348) financed by the Spanish Ministry of Education, Culture and Sports (MECD).

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