Reply to the Reviewers' Comments prof. Picotti Vincenzo (Referee 1)

Formattato: Numerazione: ricomincia ad ogni pagina

General comments

1) This is a novel dataset of peak precipitations in the mountain area of the Northern Apennines of Italy. The authors discuss a well calibrated core and compare it with part of existing data in the region. Although the topic is of paramount interest for the scientific community and the results interesting, the manuscript is poorly written and it requires a deep reworking prior to the final publishing. A first problem is the language, that in some cases is coupled with or it enhances problems in the flow of the arguments. I urge the authors to polish the paper making the reasoning easier to the reader. I have tried to polish the abstract, but, in the text, I did it here and there, and I mostly highlighted some parts where the meaning was obscure.

   Reply: the final version text will be edited by native English translator according to the Reviewer's suggestions.

2) An important general scientific problem is the interpretation of the core deposits. From the map of Figure 2, the Lake Moo spill point has an elevation of 1114.2, the S1 core was drilled at 1121. The authors interpret the deposits as lacustrine until – 0.9 m. This implies a lake level at 1120 m around 200 to 60 years ago. The spill point should have incised 6 m in around 100 years. I think this is not possible, in any case I urge the authors to consider in their manuscript the relationships between the spill point and the lake level, a topic completely overlooked. In my opinion, given the young age and the elevation with respect to the spill point, it is very likely that the units 3 and 4 were formed in a subaerial environment, that is the fan environment visible today. From the point of view of the peak precipitation, this is maybe not changing much, but the sedimentological interpretation, such as the hyperpycnal flows, should be completely changed. Interbedded fine- and coarse-grain deposits is something typical of colluvial fans, where dense flows, such as debris flows and grain flows, are common, but there is always the reworking of previous deposits by running water, that winnows the matrix and brings about fine-grained intervals.

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Reply: This is a good point. Following the Reviewer's observation, we have precisely measured the elevation of key points using Garmin eTrex 10 to improve and better explore the relationship between the spill point, lake level and core stratigraphy. The results are:

- S1: 1120.2 m a.s.l. instead of 1121 m a.s.l.
- Spill point: 1116m a.s.l. instead of 1114.2 m a.s.l..

The difference is about 4m and not about 7m as shown in "CTR."

After a confrontation with the municipality and the Carabinieri forest ranger of Ferriere, it emerged that the area of the emissary was modified by human interventions lowering its altitude to encourage grazing over the years. These activities were carried out by the owners of the area, and there is no official documentation.

We suggest moving the limit of the underwater deposits (now at the base of unit 4) to a depth of 2.3m. Also, unit 3 has been divided into two sub-units: 3a and 3b. Unit 3a retains its depositional characteristics as described in the first version of the article, in a shorezone environment affected by coarse material input through floods. Unit 3b changes its interpretation from a relatively deep lake environment (as shown in Figure_4_new) to a shorezone environment with low coarse debris input due to flooding.

Moreover, we have analysed the palinological content of unit 3 to refine its interpretation better (Table pollen new in SM). In all three samples P12, P13, P14 the presence of typical wetland plants is discretely, particularly herbaceous hygrophytes with values between 11.9 and 19.5%. This group is made up of plants living in marginal lacustrine areas such as cyperaceae and sedges.

3) I also recommend the authors not to use the categories proximal/distal to describe grain size variations in this fan or fan-delta, given they have a spatial meaning, and here the spaces are amazingly tight.

Reply: We have replaced the concept of proximal and distal with that of "mature" and "immature" deposits (Mutti, 1992)

4) Another problem is the missing correlation of pollens with the good record of the Lake del Greppo of Vescovi et al. (2010), located in a similar setting (high elevation counterslope related to deep landslide, Northern Apennines) around 100 km to the southeast. This correlation is

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also hampered by the author’s choice to merge data of Pinus and Abies into a common group, therefore making it impossible to appreciate the decline of Pinus and the growth of Abies during the HTM.

Reply: this is a good point. Following the Reviewer’s suggestion, we have referred to the pollen record of the Lake del Greppo (Vescovi et al., 2010) in the discussion and we have distinguished *Pinus* from *Abies* in our record. For what concerns the correlation of the two pollen records, we are inclined to proceed with caution because of the different stratigraphic/depositional context and the highly different degree of resolution of the two dataset (Figure_7_new).

5) Finally, the authors announced in the text and the abstract the occurrence of 2 cores and an interesting trench. These data are not presented, only located in the Fig. 2 small version, but not reported in the Fig. 2 larger version. What is the reason for this? A trench would help a lot understanding the sedimentary processes!

Reply: In order to optimise the activities, we have focused our attention on the S1 core because it is the most representative and complete of the sedimentary succession. The other core (S2) and the trench were used in support to the stratigraphic and sedimentological study (and a consequence of the second point) of the selected core (S1), on which all the laboratory analyses were undertaken.

6) On the other hand, what is the role of Table 1? Does the forest composition play any role in the story? The pollen data are not referring to it!

Reply: For the sake of clarity, we deleted Table 1 and moved all the available data about the present-day vegetation cover of Lake Moo in text (section 2.1). In our opinion these data, which represent a general overview potentially useful to the readers, cannot be directly compared with the pollen record as they derived from a botanic study.

Specific comments

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- Geographic coordinates and elevation of the drilling are missing.

Reply: done and the data has been added to the text.

S1 elevation: 1120.2 m

S1 geographic coordinates: 44° 37’ 25”N - 9° 32’ 43”E

- Fig. 1 Middle frame, graphic scale is wrong.

  Reply: the figure has been modified according the Reviewer’s suggestions (Figure_1_new).

- Fig. 2 geologic/geomorphic map: very poor! In the published 1:50000 map, the geology of the catchment is given by large olistoliths of serpentinite embedded into “Complesso di Monte Ragola” an Upper Cretaceous blocky clayshale. This latter unit is not mentioned in the map or in the text. The surficial units are not sound: the hillslopes of the Lake (beside one mapped as serpentinite bedrock) consist of two units.

  The first, a “detritical (it should be detrital) cover, from boulder to granule, Holocene”. Granule is not an official grain size: what does it correspond to? (valid for the colluvium too). Does granule imply mud, or should it be something larger? Is there any mud in this detritus? Second, most of this field is mapped as serpentinite in the published small-scale map. Finally, if this is detritus, where is it coming from? If not transported, then it could be the in-situ weathering of the substrate. In fact, the weathered blocky clayshales of the Complesso di Monte Ragola, when removing the fines, would make it visible on the surface only the blocks of any size, without the clay, transported toward the Lake Moo. In any case this field should not be named “detritus”, but eluvial or colluvial cover, or simply weathered bedrock, if the thickness is less than 1 m or so.

  The second surficial unit in Fig. 2 consists of a large field named “Complex landslide, from cobble to silt”. Again, strange there is no clay in this unit, whereas in the depression it is full of clay. In any case, does this field refer to a landslide body? Coming from where, the south? And what created this topography? Is this the original landslide topography? Or has it been subsequently eroded? The steep wall on the eastern margin of the map is steep, suggesting bedrock. I think the two fields represent the same feature: a deeply weathered bedrock, but I never was there in the field.

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In the northwest side of the depression three alluvial fans are mapped that are missing a supplying channel. This is odd: they are clearly fan and wedges of colluvium, not alluvium. Actually, given the size and the mass flow processes, also the fans mapped at the end of channels should be considered colluvial, but this is a matter of debate, therefore I could accept them mapped as they are, except for the small sign of fan to the west of the main fan: this is clearly part of the main fan and there is no feeding channel, therefore it should be cut. Finally, the classic symbol for the fan are fanning lines that should be perpendicular to the contour: in the main fan they are badly drawn. The author should better map the area.

Reply: the figure 2 has been modified as follows (Figure_2_new): we used the latest update of the geological database of the Emilia-Romagna Region, scale 1:10.000 (available at the following link: https://geo.regione.emilia-romagna.it/cartografia_sgss/user/viewer.jsp?service=geologia) and on this geological basis, the flood deposits of 13 - 14 September 2015 have been reported. In this way we have also simplified the map and made it functional to the objectives of the article.

- Fig. 5 scale is missing

  Reply: Done (Figure_5_new)

- Fig 6 It would be interesting to have the stratigraphic units plotted in the figure, since the change in sedimentation rate at the end of unit 2 should be better placed at the unconformity.

  Reply: the figure will be modified as required (Figure_6_new). The limit between unit 2 and 3, placed on the basis of the facies analysis, is in accordance with the change in the sedimentation rate observed in the age-depth model.

- Fig. SUP1. In the profile BB', the core S1 is wrongly reported at 22 m at depth, instead of 12.5 m. Unclear why the authors did not calibrate the profile with the core. After a simple graphic correlation, one can appreciate that the substrate starts at around 1800 m/sec, therefore providing a much simpler and more likely geometry of the substrate/ sediment contact. Please reconsider your interpretation.

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Reply: the figure has been modified according the Reviewer’s suggestions (Figure_1_New).

- Literature cited

  Vescovi, E., B. Ammann, C. Ravazzi,and W. Tinner. 2010 a. A new Late-glacial and Holocene record of vegetation and fire history from Lago del Greppo, northern Apennines, Italy. Vegetation History and Archaeobotany 19: 219– 233.

  Reply: Included in references

Specific comments on the annotated manuscript

- **Line 18 to 19:** As consequence, several geomorphological processes, like widespread debris flows along the slopes and hyperconcentrated flood in the stream channels….

  Referee: why putting debris flows in the slopes and hyperconcentrated flows in the channel? This subdivision is odd! Debris flows require channels! On the other hand hyperconcentrated flows are defined by the density contrast with ambient fluid, being fresh- or marine water. But in the continent every flow is denser than air! Therefore, I urge the authors to make it clearer the definition and nomenclature of flow regimes.

  Reply: The sentence “like widespread debris flows along the slopes and hyperconcentrated flood in the stream channels” has been replaced as follows:

  …like debris avalanches and debris flows (Hungr et al., 2013), ……

- **Line 27:** flows into the plain.

  Referee: which plain?

  Reply: …..flows into the Lake Moo plain.

- **line 27 to 30:** Our main assumption is that, in such a small drainage basin (area <2 km2), with favourable geologic and geomorphic characteristics implying advantageous sediment transfer into lake, high density flood can be triggered only by high intensity precipitation events (HIP) lasting enough time for water to infiltrate and mobilize large quantities of debris.

  Referee:

  1) Unclear concept. Or unclear wording. Or both;

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2) The concept of threshold precipitation is well established in the literature. Why do the authors present it as their assumption? what's different/new?

Reply: the paragraph has been modified according the Reviewer's comment as follows:

In accordance with the literature (Milliman and Syvitski, 1992; Mulder and Syvitski, 1995; Mutti et al., 1996), in such a small drainage basin (area <2 km^2), high density flood can be triggered only by high intensity precipitation events (HIP) lasting enough time for water to infiltrate and mobilize large quantities of debris.

- **line 49**: In particular, on the northern Apennines, more than sixty percent of total precipitation of the year is concentrated in days with moderate to high-intensity precipitation (Isotta et al., 2014).

  <u>Referee:</u> few days? unclear!

  Reply: The sentence has been replaced as follows:

  In particular, on the northern Apennines, more than sixty percent of total precipitation of the year is concentrated in a few days of moderate to high-intensity precipitation events (Isotta et al., 2014).

- **line 86**: ….. generated by a small stream that flow into the plain.

  <u>Referee:</u> which plain?

  Reply: The sentence has been replaced as follows:

  …..generated by a small stream that flow into the Lake Moo plain.

- **line 90 to 97**: In the Trebbia-Nure case, a detailed analysis of precipitation (Grazzini et al., 2016) 90 over Lake Moo site microbasin showed that the observed debris flow occurred with a peak intensity of 112mm/3h. This is a very high value compared to shallow landslide and debris flow thresholds find in literature for nearby areas, like the Apuane and Garfagnana regions (Giannecchini et al., 2012), which can be explained by the dense vegetation cover present now in the area. In addition, the absence of surrounding anthropic activities, the vicinity of the lake to the main Apennines crest, very exposed to maritime moist airflow coming from the central Mediterranean Sea, make this site particularly 95 suitable for a detailed reconstruction of HIP events over the Holocene in terms of frequency, sedimentary expression and forcing factors.

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Referee: the phrasing is unfortunate here… I suggest to split the long sentences and make it clear what conditions occur in the study area with respect to the other areas. F.i the Apuane are a crest even close to the sea.

Reply: the paragraph has been modified as follows:

In the Trebbia-Nure case, a detailed analysis of precipitation (Grazzini et al., 2016) over Lake Moo site microbasin showed that the observed debris flows occurred with a peak intensity of 112mm/3h.

The absence of surrounding anthropic activities, the vicinity of the lake to the main Apennines crest, very exposed to maritime moist airflow coming from the central Mediterranean Sea, make this site particularly suitable for a detailed reconstruction of HIP events over the Holocene in terms of frequency, sedimentary expression and forcing factors.

- **line 126**: HIP conditions are more frequent in Autumn months due to a particular synergy of higher frequency of synoptic disturbances and mesoscale convective systems which could still develop in high thermodynamic unstable environment (Grazzini et al., 2019).

  Referee: unclear phrase

  Reply: We rephrased in the following way. "HIP conditions are very favourable in Autumn months due to a particular synergy of mid-latitude synoptic disturbances, which are more frequent towards the cold season, and strong convective systems, which could still develop at the end of summer and in Autumn over the warm Mediterranean sea (Grazzini et al., 2019)".

- **line 143 to 145**: From this point of view, the main factor controlling the morphological evolution of the area of Lake Moo, is the river incision produced by the Nure stream during the Holocene (Gunderson et al., 2014). This incision triggered the development of gravitational phenomena on the slopes

  Referee: unclear citation: No Holocene incision in Gunderson et al., 2014

  Reply: citation has been replaced by Elter et al., 1997.

- **line 185 and 187**:

  1) the position in the facies tract with respect to the whole fluvial-hyperpycnal system;

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2) relative flood event magnitude;

3) expected related facies types in more proximal and distal areas

<u>Referee:</u>

1) unclear, please reword it

3) expected based on what? it seems circular…

Reply: points 1, 2 and 3 have been deleted and replaced by the following sentence:

The facies tract approach is important because allows, along the vertical of the S1 core, to recognize and reconstruction how the flood deposits change in time at a fixed location.

- **line 264**: high density flood

  Reply: replaced with debris flows

- **line 309**: ……is like to the infill of a structural depression produced by gravitational block sliding that was induced by post-glacial fluvial incision (Gunderson et al., 2014).

  <u>Referee:</u> odd quotation! again, Gunderson et al., 2014 do not deal with Holocene incision

  Reply: citation has been replaced by Elter et al., 1997.

- **line 314 to 316**: The 27 deposits interpreted as instantaneous events representing a total of 374.5 cm were removed, the remaining were used to build an event-free 315 sedimentary record.

  <u>Referee:</u>

  1) what percentage of the fine-grained deposits belong to the "instantaneous deposits"?

  2) The authors should better explain why they built these two curves… (scope and methods);

  Reply:

  Initially, we proposed two age-depth model curves, with and without the coarse-grained levels ("instantaneous events"). During the review of the article we reflected on the following:

  1) Within the stratigraphic interval with radiometric data, there are many different stratigraphic intervals without sediment data, for a total thickness of 107cm;

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2) The difficulty in putting the top limit of the "instantaneous events" in an objective way. This limit marks the passage to regular lake sediments. It is therefore subject to interpretation because it is often transitional.

The set of these factors do not allow us to evaluate the validity of the curve without the coarse levels. For these reasons, we have chosen the age-depth model curve with "istantaneous events" for caution reasons.

All this will be included in the material and methods chapter.
However, it is interesting to observe that in the age-depth model curve with "istantaneous events", the change in sedimentation at the end of unit 2 is at a depth of 500cm, while it is at a depth of 403cm in the age-depth model curve without coarse-grained levels. Based on the analysis of facies, the limit of the end of unit 2 was placed at a depth of 445cm.

- **line 317 to 319**: Four radiocarbon dates were rejected: one (LTL18275Abis code) because it was not possible to date the sample for poor presence of organic matter, the others (LTL18275A, LTL18575A and LTL18272A codes) because it was not possible to identify a calibrate age.
  Referee:
  1) in this case, this is not rejected…;
  2) unclear without the measured data in a table.
  Reply: Text and the table TS2 have been modified according the Reviewer's comments

- **line 337**: ……and June (red) - December (blue) insolation values records reported for 45° Nord.
  Referee: source missing
  Reply: done. From Samartin et al., 2017.

- **line 341 to 342**: Caption figure 7. The stratigraphic succession of the S1 core compared with the most relevant climate proxy available from literature for the area of interest.
  Referee: here you should recall all the various proxies with sources.
  Reply: done

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- **line 357**: **……..**characterized by a period of apparent inactivity of the fluvial system.

  Referee: why are you calling yours a fluvial system?

  Reply: the sentence has been modified according to the Reviewer's comment as follows:

  ….. characterized by a period of apparent floods inactivity.

- **line 379 to 381**: This rise of temperature is associated also with a comparable unprecedented intensification of fluvial deposition, testified in the core, by the deposition of units 4 and 5, which marks the transition (in a short time) from marshy to fluvial 380 sheet-flood deposits (Fig. 5).

  Referee: why are you calling yours a fluvial system?

  Reply: the sentence has been modified according to the Reviewer's comment as follows: This rise of temperature is also associated with a comparable unprecedented intensification of floods deposition, testified in the core, by the deposition of units 4 and 5, which marks the transition (in a short time) from marshy to sheet-flood deposits (Fig. 5).

- **line 406**: In this section, we introduce the pollen data to fully exploit the multidisciplinary approach.

  Reply: removed sentence

- **line 419**: This occur in response to warmer conditions and pluvial phase, as indicated by Regatieri et al., 2014;

  Referee: phase is not appropriate, I would use warmer and wetter conditions.

  Reply: done. This occur in response to warmer and wetter conditions, as indicated by Regatieri et al., 2014

- **line 430**: These coarse grained deposits are expressing of proximal facies (LM4 to LM6, in Fig. 10).

  Referee: I don't find wise to use proximal/distal categories in this case study of such tiny catchment.

  Reply: Distal and proximal terms are related to the moo lake plain. However we understand that it is not wise to use these categories in such tiny catchment and why Lago

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Moo area is only a step in the evolution of debris flow along its down-slope motion. We have replaced the concept of proximal and distal with that of "mature" and "immature" deposits (Mutti, 1992).

- **line 445 to 446**: **Capttion figure 10.** The stratigraphic intervals I1 and I2 from S1 core compared with the original pollinic data and the relevant climate proxy available from literature for the area of interest.
Referee: also in this caption the authors should recall all the proxies with the sources.
Reply: done

- **line 472 to 481**: HIP increase in response to higher temperature is already detectable in observation series, especially in seasons when moisture availability is not limited, like in Autumn (Brönnimann et al., 2018; Prein et al., 2017). We found evidences that this occurred also in the past, especially during HTM testified by higher deposition of large size sediment in to the lake. A comparison with the past help understanding future projections on the area, although we are aware that past evolution cannot be taken as an analogous for future due to the different forcing and consequent response of climate system (D'Agostino et al. 2019). As temperature will continue to increase on the Mediterranean area precipitation intensity would keep increasing over the Northern Apennine. We hypothesize that precipitation intensity increase will be evident in months with cooler and moist air masses, like in Autumn as it already emerging (see Fig.9), but gradually extending towards Winter. In summer, increasing conditions of moisture limitations will induce a decrease in frequency and intensity of precipitation (Dobrinski et al. 2016a and 2016b)

Reply: we will use uppercase letter for seasons

Captions

Figure 1. (a) Location area stricken by the rainfall event of September 13th and 14th 2015 (red square) and Lake Moo plain position **(b)** The landscape view of the Lake Moo plain taken from the southern side.

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Figure 2. Location of the geognostic investigations, geophysical surveys tracks, and detailed geomorphological mapping of the flood deposit occurs between 13 and 14 September 2015 (upper Trebbia and Nure valleys, province of Piacenza, Italy).

Figure 3. Sediment core description (see legend), radiocarbon dates and samples pollen.

Figure 4. Idealized genetic facies tract interpretation of clastic deposits associated with S1 core.

Figure 5. Though the exposure is quite small, these graded pebble-sand couplets could be interpreted as a sheet-flood deposit (Unit 5).

Figure 6. Right: Age-depth model obtained from radiocarbon dates. Black and grey line represents the two-sigma probability envelope depth without coarse grained events. Red and orange line represents the two-sigma probability envelope depth with coarse grained events. Left: S1 core.

Figure 7. Stratigraphy of core S1, main palynological features and microcharcoal content. Relative abundances of pollen groups, explained in text (sub-section 3.4), are reported along with the frequencies of hygrophilous herbs and aquatics. Asterisks point to samples containing coprophilous fungi and other spores like *Sporormiella*, *Dicrocoelium* and *Ascaris*. These data are compared with the most relevant paleoclimate reconstructions available from literature for the area of interest. Panel (a) Reconstructed mean July air temperature from Lago Verdarolo (from Samartin et al., 2017); Panel (b) δ18O speleothem records and reconstructed precipitation trends (mean anomaly time series) from Renella cave (slightly modified from Combourieu et al., 2013; Regattieri et al., 2014; Zanchetta et al., 2011; Zhornyak et al., 2011) and Panel (c) June (red) - December (blue) insolation values records reported for 45° Nord (from Samartin et al., 2017). Main Holocene climate phases and events are also shown. Available radiocarbon ages are reported as calibrated years BP.

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Figure 10: Sedimentological and palynological features of two key stratigraphic intervals (intervals 1 and 2) from core S1 compared with the most relevant paleoclimate data available from literature for the area of interest (for references please see Figure 7). The Anthropic Index (AI) has been calculated as: (Anthropic indicators/tree percentage)*100 following Accorsi et al. (1998).

Figure SUP1. Seismic tomography of the underground lake Moo basin. For geophysical surveys tracks see Fig.2.

Table TS2. Full list of Radiocarbon sample age and description details.

Reply to the Reviewers' Comments Prof. Willy Tinner (Referee 2)

Main issues

1. Somehow surprisingly an age-depth model is presented but not used to put the data on a time-linear scale, instead depths are preferred throughout the manuscript, which makes it difficult to compare these novel data with existing palaeoclimatic, palaeoecological and palaeoenvironmental records.

   Following the suggestion of the Reviewer we modified accordingly the Figure 10, converting depth in time for the two key intervals of the cored succession using the age-depth model (i.e., the Holocene Thermal Maximum-HTM between ca. 9-7 kyrs BP and the exit of HTM between ca. 6-3 kyrs BP). This is a very useful comment that improve the comparison of our data with those already published (i.e., palaeoclimatic records from the Renella Cave and the Verdarolo Lake). Please see the response to the specific comment N.

2. In some cases, however, the discussion and conclusions need more caution, in particular in regard to mismatches of temporal scales between the different time-series used.

   We modified accordingly, please see the response to the specific comment J.

3. Some factors leading to increased erosion such as human impact and fire are neglected (see detailed remarks) and need attention.

   We agree with the Reviewer and for this purpose we prepared new graphics (revised version of the Figures 7 and 10), including also new analyses (e.g., microcharcoals). Please see the response to the specific comment C2.

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4. The Holocene chronology is based on eight 14C dates, the material is most likely of terrestrial origin but may suffer from in-built ages (e.g. wood).

   We see the point of the Reviewer and we will added text in sub-section 4.2 to better discuss the possibility of bias due to the methodology (radiocarbon) and the materials used (listed in the revised version of Table TS2 – Supplementary Material). Please see the response to the specific comment D.

Detailed remarks

A) The abstract is concise and well written, but some mistakes should corrected ("small ice age" is probably Little Ice Age, LIA).

Done.

B) It is not just (Glur et al. 2013) that have observed increasing flood activity in and around the Alps during cold periods. A comprehensive review is provided by Henne et al. (2018) who emphasize the conflict between the available evidence and the hypothesis of the authors: warmer conditions do not always lead to more floods. Flood increases during the Little Ice have been historically recorded and were the consequence of increased precipitation during cold periods (see e.g. Wanner et al. 2000). It might well be that the Alps and the Apennines have different regional flood histories (at least in the northern Alps and the Central European lowlands) and this could be elaborated by the authors.

We agree with the Reviewer. We added text in the Introduction section to better discuss literature data reporting an increasing flood activity during cool periods over the Alpine region.

Lines 75-90: "Many studies suggest a synchronization of a high frequency of flood events with cooling periods. Flood reconstructions from natural archives show very consistently that the floods on the Alpine area have occurred more frequently in times of cold, wet summers (Glur et al. 2013, Henne et al. 2018). This is clearly recognizable, for example, during the LIA. Other studies reported that in the hot and dry periods the floods have been rarer, but stronger in their intensity (Giguet-Covex et al. 2012 and Brönnimann et al. 2018a, Geographica Bernensia, pag.40). At the same time, no specific flood reconstruction is available, as far as we know, for the Apennine area, which has a different precipitation climatology from the inner Alpine region.
The association between cold summers and high flood frequency may hold more for the Alpine region, which has precipitation maxima in summer while in the Apennine area precipitation maxima are occurring in Autumn. In addition, Alpine data are mostly derived from lacustrine archives that are influenced by a combination of factors involving precipitation intensity, duration, seasonality and changes in atmospheric-circulation, land use. These factors might overshadow the physically based positive correlation between temperature increase and precipitation intensity (Utsumi et al., 2011; Brönnimann et al., 2018b).

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C1) Still in the introduction pollen is declared as a palaeoclimate proxy (line 82). Fortunately, this is not the use the authors make of their (very coarse) pollen record. Actually, pollen is a palaeovegetation proxy that in some cases and under some conditions can be used to reconstruct climate.

We agree with the Reviewer. We changed text accordingly: "Those caveats call for an even more multidisciplinary approach integrating sedimentary archive information and paleoenvironmental data (e.g., pollen-derived paleovegetation patterns) with climatological observations and physical arguments".

C2) Since at latest ca. 5000 cal BP vegetation was strongly altered by humans and land use effects were gradually overruling climate as the main driver of plant community changes. For the Northern Apennine this is discussed in detail in e.g. Vescovi et al. (2010a) and Vescovi et al. (2010b) for Greppo and Pavullo.
At the remote Greppo site in the mountains, pastoral and fire activities increased at ca. 6000 cal BP. At the less remote and warmer site Pavullo, arable farming started around 5000 cal BP. These activities were associated with deforestation (also recorded in the data of the authors, pollen layers P08, P10, P12 with high herb pollen), a process of paramount ecosystem relevance which can also increase erosion and flood activities.
This issue needs more attention given that Glur et al. (2013) correctly emphasize that human impact may affect flood reconstructions deriving from single study sites. However, given the signal observed in the Moo Lake data with reconstructed flood activity peaking during the HTM (when human impact was low) and the post-LIA (when human impact was reduced since ca. 1950 AD), the authors can partly rule out such human effects, which I think is very interesting and should be elaborated in the text.

This is a very good suggestion. We better investigated the role of human impact mainly in terms of pastoral activities and fire on the Holocene vegetation changes, especially in terms of trees cover and then on the reconstructed flood activity. Indeed, we performed: *i)* a focus on the pollen percentages of taxa associated with cultivation, pastoralism or generic human disturbance with the addition of two samples in the uppermost portion of Unit 3, and *ii)* a new analysis concerning the microcharcoal record. Our results highlighted:

i) a generally low amount of taxa indicative of human disturbance (i.e., new group "Anthropic indicators" shown in the new version of Figure 7) characterizes all the samples, with an almost total absence of cultivated taxa (only 3 samples – P9, P13 and P14 – contain few grains of cereals: <4%). One relative "peak" (ca. 8%, mainly) is recorded around 8070-7880 cal. years BP (sample P6) due to the categorization difficulties concerning anthropic spontaneous taxa. More consistent "peaks" of ca. 6.5-8% (mainly *Chenopodium*, *Convolvulus arvensis*, *Plantago* cf. *media*, *Urtica*) occur within the stratigraphic interval 2 (samples P8-P10 and P13) and dated between ca. 5780-5630 (P08) cal. years BP and 1270-1110 cal. years BP.

ii) the concentration of microcharcoals is very low (ranging between ca. 0.2-200 mm^2/g), also considering the data obtained by Vescovi et al. (2010a) and Vescovi et al. (2010b). Interestingly, the coarser microcharcoals (>125 micron), which can be interpreted as the product of local fires, are absent throughout the cored succession, with the exception of the most recent sample P14 (dated 146-14 yrs BP) that, however, contain only ca. 0.05 mm^2/g.

Thus, according to the Reviewer comments, pollen data reasonably suggest a certain degree of human impact on the decrease of tree cover since about 6000-5500 cal. years BP (up to 30% of

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herbs within sample P13). This impact is probably due to pastoral activities as documented by the relative abundance of pollen meadow (pasture) taxa and the sporadic presence of coprophilous fungi and other spores like *Sporormiella*, *Dicrocoelium* and *Ascaris* (asterisks in Fig. 7). However, the integration of stratigraphic and pollen data points to a low degree of impact of both pastoral activities and fire as triggering factors for floods, strongly supporting our hypothesis.

All these results are now shown in the new version of Figures 7 and 10 (attached below). Text of section 5 (in particular sub-section 5.1) will be changed accordingly, taking into account the new pollen and microcharcoal data and the Reviewer's suggestions.

D) The chronology is likely sufficient to support the inferences and conclusions of the authors, however, the authors may state that they assume that all radiocarbon samples had no hard-water effects (e.g. in particular for peat, what is the material in the peat layers mainly? Cyperaceae?). Indeed, there are limestones and breccias in the catchment and dating of bulk sediment material under such conditions can lead to wrong reconstructions (see Finsinger et al. 2019). Similarly, do the authors exclude inbuilt ages or reworking effects for wood samples (e.g. were they small twigs, see discussions in Gavin 2001; Oswald et al. 2005)?

For what concerns wood samples, we sampled exclusively small twigs in order to reduce, as much as possible, potential bias due to long-lived plants following the suggestion of Oswald and colleagues. In our opinion, reworking effects can be considered negligible as samples were collected from fine-grained deposits.
About the peaty samples, the high degree of decomposition prevented material identification in terms of taxa. However, pollen analyses highlight the dominance of Cyperaceae that likely represent the main component of peaty layers.
These issues will be briefly presented/discussed in text (in 4.2 sub-section). We have also changed the Supplementary Table TS2 accordingly (upload separately).

E) The July temperature reconstruction of Verdarolo is in agreement with that of Gemini and several other proxies, this may be stated at line 197 to increase the representativeness and validity of the Verdarolo record (see discussion in (Samartin et al. 2017).

Done.

F) In regard to palynology, did the authors really do all identifications at 1000 magnification? The standard is 400 x (to be efficient), only difficult pollen such as Triticum, Avena or Hordeum types is usually observed at 1000 x (line 216). What is in the pollen sum? Please state (e.g. terrestrial pollen, no aquatics, no spores).

We will correct/add information about pollen and microcharcoal analyses in text (sub-section 3.4) as follows:

3.4 Palynological analyses

Palynological analyses were carried out on 14 samples collected from fine-grained layers of core S1 to refine facies characterization and obtain pollen-derived paleovegetation data. Following the radiocarbon dating, we particularly focused on two key stratigraphic intervals. The oldest one (Interval 1 – ca. 11-9 m core depth) encompasses the period between ca. 7300 - 9600 cal yr BP

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centred on the Holocene Thermal Maximum (HTM). The youngest one (Interval 2 – ca. 5.5-4 m core depth) records the final stages of HTM and the following period between ca. 5500 - 3800 cal yr BP. In these two stratigraphic intervals, the mean sampling resolution is ca. 30 cm.

Palynological analyses were carried out applying a methodology already tested for pollen substrates with some minor modifications (Lowe et al. 1996). The method includes the following phases: about 8-10 g were treated in 10% Na-pyrophosphate to deflocculate the sediment matrix. A Lycopodium spores tablet was added to calculate pollen concentration (expressed as pollen grains per gram = p/g). The sediment residue was subsequently washed through 7 micron sieves and then re-suspended in HC1 10% for remove calcareous material and subjected to Erdtman acetolysis; heavy liquid separation, method was then introduced using Na-metatungstate hydrate of s.g. 2.0 and centrifugation at 2000 rpm for 20 minutes. Following this procedure, the retained fractions were treated with 40% HF for 24 h and then the sediment residue was washed previously in distilled water and after in ethanol with glycerol; the final residue was desiccated and mounted on slides by glycerol jelly and finally sealed with paraffin.

This method preserves the slides for many years after preparation and therefore it is suitable for pollen extractions from geological and paleo-archeological samples. Identification of the samples was performed at 400 magnification and only difficult pollen such as *Triticum*, *Avena* or *Hordeum* types at 1000 magnification.

Determination of the pollen grains was based on the Palinoteca of our Laboratory, atlases and a vast amount of specific morpho-palynological bibliography. Names of the families, genus and species of plants conform to the classifications of Italian Flora proposal by Pignatti (2017-2019) and European Flora (Tutin et al. 1964-1993). The pollen terminology is based on Berglund and Ralska-Jasiewiczowa (1986), Faegri and Iversen (1989) and Moore et al. (1991) with slight modifications that tend to simplify nomenclature of plants. The term “taxa” is used in a broad sense to indicate both the systematic categories and the pollen morphological types (Beug 2004). Identified pollen groups (at least 500 pollen grains) have been expressed as percentages of the total (usually between 500 pollen grains). The component of the pollen sum includes only terrestrial pollen, no fern spores and no aquatic plants.

The following groups were identified: Conifers (*Pinus/Abies alba*), Decidous trees (this group includes quercetum taxa – *Quercus*, *Carpinus betulus*, *Corylus avellana*, *Fraxinus*, *Ostrya carpinifolia*, *Tilia* and *Ulmus* + other Deciduous trees), Meadow (this group mainly comprises Fabaceae and Asteroideae, Caryophyllaceae, Cichorioideae and Poaceae), Anthropic indicator (e.g. Cerealia, *Chenopodium*, *Convolvulus arvensis*, *Plantago*, *Urtica*) and Alia that includes all taxa excluded from previous groups. The hygro + aquatic plants, which includes hygrophilous herbs (e.g., Cyperaceae) and helophytes and hydrophytes (i.e., *Lemna*, *Junchus*, *Nymphaea*, *Phragmites*, *Potamogeton* and *Sparganium*), are considered proxy of humid conditions typical of wetlands.

3.5 Microanthracological analysis

The same samples prepared for pollen analysis were also investigated for the identification of microcharcoals. Microanthracological analysis has been used to understand past fire events mostly connected to anthropogenic activities. Point count estimation of microscopic charcoal abundance was carried out, and charcoal fragments encountered during pollen counting were recorded in four size classes, based on long axis length (10–50, 50–125, 125–250, >250 µm) (Whitlock, Millspaugh 1996; Clark 1982, 1997; Patterson et al. 1987; Whitlock, Larsen 2001). The former two classes are thought to be wind-blown transported hence giving information concerning the regional fire events, whereas the latter two are considered the result of local vegetation burning.

G) The discussion starts with a figure description over 6 lines (332-337), this is not

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really exciting, is actually very descriptive (and may stay confined to the figure caption). Why not starting more dynamically with lines 345 (and following text), stating that high flood activity occurred during the HTM? This would make the text more appealing.

We agree with the Reviewer and we shifted part of the text in figure 10 caption:

Figure 10: Sedimentological and palynological features of two key stratigraphic intervals (intervals 1 and 2) from core S1 compared with the most relevant paleoclimate data available from literature for the area of interest (for references please see Figure 7). The Anthropic Index (AI) has been calculated as: (Anthropic indicators/tree percentage)*100 following Accorsi et al. (1998).

H) Model simulations confirm that the HTM was more humid during the summer. This outcome is mainly driven by (orbitally forced) summer insolation and the resulting mid latitude (i.e. Mediterranean and European) evaporation. It seems unlikely that enhanced tropical monsoon activity may have led to wetter climate as far north as the Northern Apennines by vapor transport or related phenomena deriving from the monsoons (see e.g. discussion in Tinner et al. 2009). On the contrary, the strong highpressure field resulting from monsoonal activity north of the ITCZ at ca. 30 N was particularly active during the Early Holocene (causing very dry conditions over the Mediterranean), to become weaker during the Mid Holocene including the HTM, which likely allowed westerlies to reach the Mediterranean, thus creating more humid conditions.
Please discuss and refine, Skinner and Poulsen 2016 is about tropical air masses and related humidity changes, not mid-latitudes.

Studies have documented how mid-latitude extreme precipitation events are very often linked to the transport of remote tropical air masses, in the form of strong confluent airflows, ahead of polar cold fronts, which concentrates water vapour into narrow and very elongated (>2000km) plumes (Atmospheric rivers). Atmospheric rivers have been found to be responsible for more than 90 % of the total poleward atmospheric water vapor transport through the middle latitudes (Ralph and Dettinger 2011). Krichak et al. 2015, documented how this mechanism is also relevant also for Mediterranean extreme precipitation events, especially the ones occurring in autumn, in addition to local evaporation from the Med sea. In that context the study of Skinner and Paulsen 2016 shows that "the atmospheric environment associated with mid-Holocene fall rainfall resembles that of the tropical-extratropical interactions, or tropical plumes, observed in present-day northwest Africa [*Geb*, **2000**; *Nicholson*, **2000**; *Knippertz et al.*, **2003**]. Specifically, tropical convection carries moisture into the midlevels of the troposphere where it is transported northward into the Sahara within strong southerly flow between an upper level trough and anticyclone [e.g., *Knippertz*, **2003**]." In that context an increase in frequency or intensification of tropical plume export could also have had an effect of increasing water vapour availability over the Mediterranean for heavy precipitation events.

I) Lines 361-364: which Alpine lakes do the authors mean? The new one by the authors? Are the authors referring to summer temperatures and more intense summer precipitation (the proxies are about that, see Samartin et al. (2017), please refine.

Done. We refined the paragraph to be more specific. "In Fig.7 we observe a positive correlation (at the millennial scale) between reconstructed (July) temperatures at Verdarolo site, precipitation intensity from nearby speleothem records from Apuane caves (Regattieri et al., 2014; Zanchetta et al., 2011) and high HTM flood activity recorded in S1 core. Our findings support the evidence from other authors (for example Marcott et al. 2013, Giguet-Covex et al., 2012), which are

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associating greater warmth with more extreme precipitation events, probably rarer and more concentrated at the end of Summer/Autumn, when conditions are more favourable."

J) It is true that July temperature during the period 1961-2018 increased by about +4.3 C in the data of the authors (lines 366-378, 11 yr running average). However, this is at an intermediate level between weather and climate. At climatic temporal scales > 30 years for July means, the increase might be more similar to +2 C (14 vs 16 C). Why is this important? The proxies involved have in the best case multidecadal resolutions, in the case of Samartin et al. (2017) ca. 80 years for the past 1000 years and ca. 250 years for the YD/Holocene transition. Caution is therefore needed. No way to reconstruct rates of climate change at decadal scales with such data, they were instead designed to study multi-centennial trends such as the HTM. Where resolution of multiproxy studies was high enough (reaching decadal scales) the early Holocene warming in proximity of the Northern Apennines was estimated to ca. 3-4 C within 48 years (Schwander et al. 2000; von Grafenstein et al. 2000). Please refine to avoid mismatches of temporal scales.
M) Lines 462-465 see remark J and please refine to consider mismatches of temporal scales of time-series involved.

The value +4.3°C (in 100 years) refers to the temperature trend estimated with a linear regression (Mann_Kendal_Test method used for significance) from the Eraclito ER dataset, covering the period 1961-2018. It has not to be confused with the actual increase in the same period which is lower, near +2°C. The trend is computed from the row July monthly averages while the 11yr running average is used only in Fig.8 to smooth the curve in the graph. The idea of calculating the trend over 100yr is an attempt to make comparison feasible with proxies with a multidecadal temporal resolution. As you pointed out, this comparisons paraphs hold in the first 1000 year of proxy reconstruction while, for the YD/Holocene transition, the comparison is less meaningful. Although we agree, we could not draw firm conclusions, the observed recent trend it is very high and similar or superior to estimated trends from other studies, including Henne et al. 2018, which report as a maximum trend +3–4 °C in 50–100 years at the onset of the Holocene. We realize that in the earlier version of the manuscript, we were only briefly mentioning the problem of contrast instrumental data with reconstructed temperature data (line 377-378). We will argument better this comparison and be less firm in our conclusion.

K) Discussion of pollen, what kind of conifers were involved? I assume Abies alba mainly during the HTM. This implies that Abies alba reached its peak during the warmest period of the Holocene, in sample P7 (which chronologically coincides with the HTM peak of Samartin et al. 2017). Thus the sentence at lines 423-424 should be "In the P7 sample we observe a further increase in conifers (75%, mainly Abies alba) and a consequent reduction in deciduous trees (10%) during warmest HTM conditions." This finding might be explained by the fact that Abies alba is a warm-temperate tree (not a boreal conifer) that prefers rather moist conditions (see discussion in Tinner et al. 2013), which is in full agreement with the interpretation of the authors.

We better explained in Figure 7 the encountered conifer taxa and their trends within the two intervals of interest (i.e., Interval 1 and Interval 2 in Figs. 7, 10). We agree with the Reviewer's comments about *A. alba*, as the highest relative abundances characterise the HTM (derived from the temperature curve of Lake Verdarolo; Samartin et al., 2017) and the most humid Holocene period (from the δ18O curve of Renella Cave; Zhornyak et al. 2011; Zanchetta et al., 2011; Combourieu et al., 2013; Regattieri et al., 2014). Interestingly, a peak of ca. 60% occurs at sample

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P7 dated around 7300 cal. years BP in correspondence of the maximum temperature values (please see also Figs. 7, 10). We will accordingly add text about these data in section 5.

L) Lines 436-439. The creation of openland and grassland was a consequence of land use, not climate. To reduce the forest cover to 30 %, semi-desert conditions would be needed, even in hot coastal Sicily arboreal pollen was at ca. 80% during the Late Holocene, when land use was low. The authors should cite relevant literature from the Northern Apennines (e.g. Vescovi et al. 2010a and Vescovi et al. 2010b) that permits attributing such changes to human impact through high taxonomic resolution (e.g. increase of Rumex acetosa and R. acetosella at Greppo as proxies of pastoral farming, of Plantago lanceolata and Cerealia at Pavullo as proxies of arable farming).

We see the point of the Reviewer as explained in response to comment C2.
Specifically, pastoral activities are quite well documented by pollen data and spores in samples P9-P13, however no evidences of significant local fire are detected by means of the microcharcoal analysis (as explained in the response to comment C2).

N) Figure 7: A pity the new Moo record is not on a time scale. How will future research be able to compare this with new results on a depth scale? Figure 10: x-axis label for pollen is missing. Is this 100%?

We modified figures 7 and 10 in order to plot our data firstly against core depth (i.e., Figure 7, where we added the label for the horizontal scale) and then selected index/data against a time scale (i.e., Figure 10).

Figure 7. Stratigraphy of core S1, main palynological features and microcharcoal content. Relative abundances of pollen groups, explained in text (sub-section 3.4), are reported along with the frequencies of hygrophilous herbs and aquatics. Asterisks point to samples containing coprophilous fungi and other spores like *Sporormiella*, *Dicrocoelium* and *Ascaris*. These data are compared with the most relevant paleoclimate reconstructions available from literature for the area of interest. Panel (a) Reconstructed mean July air temperature from Lago Verdarolo (from Samartin et al., 2017); Panel (b) δ18O speleothem records and reconstructed precipitation trends (mean anomaly time series) from Renella cave (slightly modified from Combourieu et al., 2013; Regattieri et al., 2014; Zanchetta et al., 2011; Zhornyak et al., 2011) and Panel (c) June (red) - December (blue) insolation values records reported for 45° Nord (from Samartin et al., 2017). Main Holocene climate phases and events are also shown. Available radiocarbon ages are reported as calibrated years BP.

Changes in high--intensity precipitation on the Northern Apennines (Italy) as revealed by multidisciplinary data over the last 9000 years

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Abstract. Several record-breaking precipitation events have stricken the mountainous area of Emilia-Romagna Region (~~northern~~Northern Apennines, Italy) over the last years. As a consequence, ~~several~~severe geomorphological processes, like ~~widespread~~ debris avalanches and debris flows ~~along the slopes and hyperconcentrated flood in the stream channels~~, shallow landslides and overbank flooding affected the territory, causing ~~serious~~severe damages to ~~man~~human-made structures. The unusual intensity ~~and wide spatial scale~~ of these phenomena ~~leads us to investigate~~prompted an investigation on their frequency in the past, beyond the instrumental time. ~~A detailed study of~~Are these ~~recent deposits compared with fossil peat~~phenomena unprecedented in the region?

Peat bog and lake ~~paleodeposits~~ deposits can provide useful ~~insight~~elements to reply to ~~support a strong match between precipitation intensity~~ this question and ~~warm climatic phases~~to infer the frequency of extreme precipitation events occurred in ~~antecedent climatic periods, as expected by~~ the ~~increase air water vapour holding capacity at higher temperatures~~past.

Here we present the results of ~~the~~a dedicated field campaign performed in summer 2017 at Lake Moo ~~a 0.15km^2~~in the Northern Apennines, a 0.15 km^2 peat bog located at an altitude of ~~1130m~~1130 m a.s.l. ~~The chosen area has been affected, during~~During the ~~flooding of the upper Trebbia and Nure valleys~~ extreme precipitation event of 13-14 September 2015, ~~by~~ several ~~high-density~~debris flows, generated by ~~the stream that flow into the~~small streams, have affected the Lake Moo plain. ~~Our main assumption is that, in~~In such a small drainage basin ~~(area <2 km^2), with favourable geologic and geomorphic characteristics implying advantageous sediment transfer into lake, high density~~ (< 2km^2), high-density flood can be triggered only by high ~~-~~intensity precipitation events ~~(HIP) lasting enough time for water to infiltrate and mobilize large quantities of debris~~.

The sedimentary succession (ca. 13 m-thick) was studied through the ~~extraction~~drilling of two cores and one trench. ~~The facies/paleoenvironmental interpretation of the sedimentary succession, characterized~~The sequence, characterised by clusters of coarse-grained alluvial deposits interbedded with organic-rich silty clays and ~~peaty~~peat layers, was ~~achieved~~analysed combining sedimentological ~~and~~, pollen ~~data with~~, microanthracological, pedological data and radiocarbon dating (AMS ^{14}C~~).~~), in an innovative multidisciplinary approach for this area.

~~Observed depositional cycles~~Original data acquired during the field campaign were ~~put in relation~~also correlated with other specific paleoclimatic proxies available in the literature for the ~~North Apennine~~Northern Apennines area. ~~This~~

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~~comparison illustrates~~We discover that the increase of extreme paleoflood~~ (~~, associated with coarse-grained deposits similar to the ones observed recently~~)~~, correlates well with the warm phases ~~with a maximum activity during~~of the Holocene ~~thermal maximum~~Thermal Maximum and ~~from the small ice age to the present day.~~with the ongoing warming trend observed which started at the beginning of the last century.

Keywords

extreme precipitation, Holocene flood ~~history, northern~~activity, Northern Apennines, climate change, water cycle, global warming

1. Introduction

~~The frequency of high~~ High-intensity precipitation (HIP~~),~~) events, also known as torrential ~~rainstorm~~rainstorms for their capacity to generate flash flood ~~of~~on small streams, ~~is~~represents a ~~key aspect~~significant component of the ~~water cycle of~~ Mediterranean ~~climate since a significant amount of~~water cycle. More than half of the annual precipitation is often concentrated in a few major precipitation events (~~see for example~~e.g., Frei and Schär 1998; Isotta et al., 2014). ~~for the Alpine area). Therefore, the~~A better knowledge of ~~the~~their expected frequency (and ~~their~~ maximum intensity~~), in present and future climate, is a very important constraint~~) is crucial for planning adequate hydraulic defences and sustainable water resources ~~managing. In particular, on the northern Apennines, more than sixty percent of total precipitation of the year is concentrated in days with moderate to high-intensity precipitation (~~management in the present and future climate. ~~Isotta et al., 2014).~~ ~~Restricting the analysis to the Emilia-Romagna region (Northern-Italy; Fig. 1), over the last years there we have been observed an increase in interannual variability of torrential rainfall, with marked or even exceptional droughts such as those occurring in 2012 and 2017 (Grazzini et al., 2012), followed by years with record rainfall (2014 and 2018). Moreover, between September 2014 and September 2015, the region has been affected by three events of exceptional intensity, estimated to have return period of several centuries (Grazzini et al., 2016).~~

Under the threat of the global warming, a growing number of studies ~~are investigating~~have investigated the link between ~~current~~a temperature rise of air masses and intensity of extreme precipitation~~ intensity. A consistent increase in long-term trend of extreme daily precipitation has been already detected for the northern extratropics since 1980, although this is largely changing with the area of the~~ , highlighting spatial and seasonal differences across the globe ~~considered (~~(e.g., Lehmann et al~~.~~., 2015~~,~~; Papalexiou and Montanari, 2019). There is a consensus that HIP events are increasing with global warming, more than mean precipitation which paradoxically could instead decrease in some regions (Berg et al., 2013). Myhre et al. (2019) show that HIP precipitation over Europe almost doubles per degree of warming, due to the combined effect of increasing frequency (the major driver) and an increase in intensity.

At the local scale, different responses of weather patterns and limitations in moisture availability can alter the uniform expected raise of HIP due to the increase of saturation water vapour pressure (6-7% K^{-1}) (e.g., Westra et al., ~~2019). On the Alpine domain~~2014; Prein et al., 2017). For example, on the Swiss Alps Scherrer et al. (2016) found a significant ~~increases~~increase in daily extreme precipitation indices ~~over Switzerland (~~since the beginning of the last century (i.e., between 1901-2014~~).~~) while Brugnara and Maugeri (2019~~), through the analysis of newly digitized data of the last 150 years~~) documented regional differences in HIP trends across the

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whole Alpine area~~, found regional differences in the trend of the extremes suggesting~~. These results suggest that instrumental data ~~are~~do not ~~covering~~cover a ~~sufficient~~suitable period ~~of time~~ to infer reliable local changes in HIP frequency.

The investigation of sedimentary archives, like peat bogs and lakes, allow testing the robustness of the hypothesised linkage between extreme ~~events frequency. Although there is a consensus, based on physical arguments, that precipitation intensities are expected to increase with higher temperatures (see the review paper by Westra et al., 2014) limitations in moisture availability can prevent the potential for increased~~ precipitation ~~from being realized (Prein et al. 2017) explaining spatial and seasonal differences observed in the trends.~~ and temperatures in the distant past, widening substantially the period where we can verify this relation.

~~In this context, the stratigraphic record of current and fossil peat bogs and lakes can provide useful insights to verify/test the hypothesized strong linkage between precipitation intensity and warm phases during the present interglacial (i.e., Holocene). In literature~~In literature, there is ample documentation of the use of these sedimentary archives to reconstruct chronologies of past flood events ~~chronologies (Ahlborn~~(Zavala et al., ~~2018; Anselmetti~~2006; Zavala et al., ~~2014~~2011; Giguet-Covex et al., 2012; Gilli et al., 2013; ~~Giraudi, 2014;~~ Glur et al., 2013; Stoffel et al., 2013; Wirth, 2013; Wirth et al., 2013; Anselmetti et al., 2014; Longman et al., 2017; Schillereff~~,~~ et al., 2014; Stoffel et al., 2016; Swierczynski et al., 2017; Ahlborn et al., 2018; Wilhelm et al., 2012, 2018; ~~Wirth, 2013; Wirth et al., 2013;~~ Zavala and Pan, 2018~~; Zavala et al., 2006; Zavala et al., 2011~~), alongside others as tree rings (Ballesteros-Cánovas et al., 2015~~; Stoffel et al., 2013~~), speleothems (Regattieri et al., 2014; Zanchetta et al., 2011) and torrential fans and cones (Schneuwly-Bollschweiler et al., 2013).

~~Contrary to our hypothesis, some studies suggest a synchronization of high~~ Interestingly, over the Alpine area a synchronisation between increasing flood frequency ~~of flood events with~~ and Holocene cooling periods~~. For example,~~ characterised by cold and wet summers, like the Little Ice Age-LIA, has been documented by a large number of studies (e.g., Glur et al~~. (~~., 2013~~), presenting results from a multi-archive flood reconstruction based on sediments~~; Henne et al., 2018). Other authors reported that under warm paleoclimate conditions floods in the Alps became rarer but stronger in intensity, highlighting the complexity of ~~ten~~this issue (Giguet-Covex et al., 2012; Brönnimann et al., 2018a). Alpine ~~lakes, found periods of high frequency of sediment deposition in concomitance with summer cool temperatures. However, those results needs a careful interpretation since lake sediments depositions~~data mostly derive from lacustrine sedimentary successions that are known to be influenced by a combination of factors ~~which involves~~(e.g., precipitation intensity, duration, seasonality~~,~~ and changes in atmospheric-circulation ~~which~~ and land use) that might overshadow the physically~~-~~based ~~positive correlation~~relation between temperature increase and extreme precipitation ~~intensity~~events (Utsumi et al., 2011; Brönnimann et al., ~~2018). Those caveats call for an even more multidisciplinary approach integrating paleoclimate (pollen), sedimentary archive information~~2018b).

In contrast, less attention was paid on the Holocene flood activity in the Northern Apennine area (N Italy in Fig. 1), which has a different precipitation climatology compared to the inner Alpine region. Indeed, the link between cold summers and high values of flood frequency appears more logical for the Alpine region, which shows a precipitation maximum in the Summer. In contrast, in the Northern Apennine area, precipitation maxima occur in Autumn with more than sixty per cent of the annual total precipitation concentrated in few

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days characterised by severe meteorological events (Isotta et al., 2014).

Focusing the analysis on the Emilia-Romagna Region (ER Region; Fig. 1), an increase in interannual variability of torrential rainfall has been observed over the last ten years with marked or even exceptional droughts, such as those occurring in 2012 and 2017 (Grazzini et al., 2012), followed by years of record-breaking rainfall (2014 and 2018). Between September 2014 and September 2015, the ER Region has been affected by three events of exceptional intensity with an estimated return period of several centuries (Grazzini et al., 2016).

To consolidate HIP trends on the N Apennine area, we analysed the Holocene sedimentary succession of a small-size peat bog (Lake Moo in Fig. 1) through the application of a multidisciplinary approach that integrates sedimentological and environmental data (e.g., pollen-derived paleovegetation patterns) with climatological observations and physical arguments. ~~In this study, we aim to fill this gap, extending and reinforcing observed trends with information from the past, beyond instrumental times, coherently derived from the same region during a specific field campaign.~~

The ~~study area was chosen because, during the flash-flood of the upper Trebbia and Nure valleys 13-14 September 2015, it has been affected by several high-density floods generated by a small stream that flow into the plain. Our main assumption is that, in such a small drainage basin (area <2 km^2), which has favourable geologic and geomorphic characteristics to achieve substantial sediment transfer into lake (Schillereff, 2014), high magnitude flood events can be reconducted only to HIP, necessary to mobilize large quantities of debris (Milliman and Syvitski, 1992; Mulder and Syvitski, 1995; Mutti et al., 1996). In the Trebbia-Nure case, a detailed analysis of precipitation (Grazzini et al., 2016) over Lake Moo site microbasin showed that the observed debris flow occurred with a peak intensity of 112mm/3h. This is a very high value compared to shallow landslide and debris flow thresholds find in literature for nearby areas, like the Apuane and Garfagnana regions (Giannecchini et al., 2012), which can be explained by the dense vegetation cover present now in the area. In addition, the absence of surrounding anthropic activities, the vicinity of the lake to the main Apennines crest, very exposed to maritime moist airflow coming from the central Mediterranean Sea, make this site particularly suitable for a detailed reconstruction of HIP events over the Holocene in terms of frequency, sedimentary expression and forcing factors.~~Lake Moo is located in the proximity of the main N Apennines crest that is very exposed to moist maritime airflow coming from the central Mediterranean Sea. The dimension of the drainage basin is small (total area <2 km^2) and the anthropic impact is low as the site belongs to the Natura 2000 network (site code and name: IT4020008 - Monte Ragola, Lago Moo, Lago Bino). Moreover, the activation of debris flows (*sensu* Hungr et al., 2013) during the severe flash flood event occurred on 13th-14th September 2015, with an estimated rainfall intensity of 112 mm/3h over the Lake Moo basin (Segadelli et al., 2020; Grazzini et al., 2016), offers the unique opportunity to use these recent deposits as the archetype of past events. According to literature (Milliman and Syvitski, 1992; Mulder and Syvitski, 1995; Mutti et al., 1996), in such a small drainage basin high-density floods can be triggered only by HIP events lasting enough time for the water to infiltrate and mobilise large quantities of debris. All these geomorphological features make the Lake Moo an ideal site to investigate past changes in HIP events in terms of sedimentary expression, frequency and forcing factors, and to address the following research questions:

~~Through the analysis of the data acquired in on the field campaign, in this paper we want to address the following research questions:~~

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a) Could we consider ~~these~~the recent events unprecedented ~~over longer time-scales?~~on a millennial timescale (i.e., the Holocene period)?

b) ~~If yes, is~~Is the frequency of ~~these~~HIP events coupled with (paleo)temperature variations?

~~The paper is organised as follows. The study area is presented in section 2 with a description of the basin, its morphology and vegetation. In sections 3 source of instrumental data and methods for collecting data during the fields campaign are described. In section 4 stratigraphic results of the field campaign are commented while in section 5 we develop a full multidisciplinary discussion. Finally, in section 6, conclusions are drawn.~~

2. The study area

2.1. Geographic and ~~climatic~~climate context

The Lake Moo plain (44°37’29”N, 9°32’25”E~~) has a surface area of~~), about 0.~~15Km^2. It~~15 Km^2 wide, is located near the boundary between Emilia-Romagna and Liguria regions (Piacenza province, Italy~~),~~; Fig. 1a) in the ~~high~~upper valley of the Nure stream at an ~~average~~ altitude of ~~1130m~~ 1130 m above sea level (a.s.l~~. (Fig. 1). Nowadays,~~.). A high tree cover density characterises the present-day catchment area ~~of~~(i.e., the ~~Lago Moo is characterized by a dense forest cover (~~total woodland cover ~~of ca.~~is 65.55%; Corticelli et al., 2011), with a high ~~vegetational~~ richness of plant species and an exceptional concentration of protected mountain ~~species~~taxa with a ~~high~~particular phytogeographical interest. The vegetation landscape shows the widespread ~~presence~~occurrence of ~~the~~ *Fagus sylvatica* ~~is~~, locally interrupted by grazing ~~land~~ areas and blueberry ~~moorland~~moorlands with the presence of ~~the~~ rare *Juniperus nana* and *Sorbus chamaemespilus*. Reforestation of *Pinus nigra* is also ~~present (Table 1 and~~ documented (Fig. ~~1~~1b).

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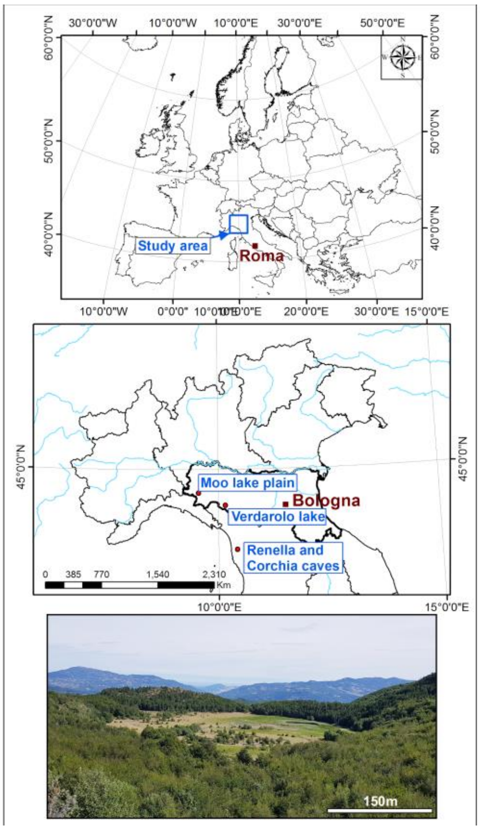

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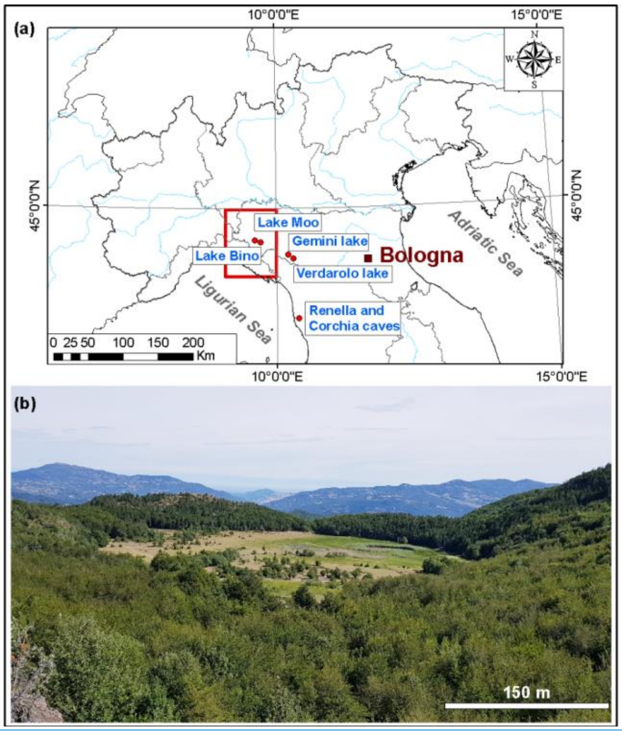

Figure 1. (a) Location ~~and photo~~map of the Lake Moo ~~site~~

~~Tree type specie~~	~~Cover area (km^2)~~	~~Woodland cover (%)~~	~~Forest cover classification in the catchment area of Lago Moo~~
~~*Fagus sylvatica* forest~~	~~1.17~~	~~63.00~~	~~Moderately dense forest~~
~~Reforestation of *Pinus nigra* forest~~	~~0.02~~	~~1.00~~	~~Scrub~~
~~Mixed wood forest (*Pinus nigra, Fagus sylvatica* and *Carpinus* genus)~~	~~0.03~~	~~1.55~~	~~Scrub~~
~~Total~~	~~1.22~~	~~65.55~~	~~Moderately dense forest~~

~~**Table 1** - Actual vegetation cover of Lake Moo area deducted~~plain. The area affected by the extreme precipitation event of September 13th and 14th 2015 is highlighted by ~~Corticelli et al., 2011~~

~~The climate~~the red rectangle. **(b)** View of the ~~area is characterised by~~Lake Moo landscape from the ~~altitude~~southern side.

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Present-day climate conditions primarily reflect the interaction of the prevalent atmospheric flow and the mountain range~~, with enhanced humidity given the short distance~~ surrounding the Lake Moo plain. The proximity to the ~~Tyrrhenian~~Ligurian Sea (~~Nistor, 2016). The months with the~~ about 40 km SW) makes the location particularly favourable to orographic precipitation enhancement in case of moisture-laden southerly-flow. The largest ~~amount of~~ precipitation ~~are~~is usually observed in ~~the transition seasons (~~Spring and the Autumn~~)~~,, with a ~~predominant~~marked peak in early ~~autumn (see Fig. 9). HIP conditions are very favorable in Autumn months due to~~ Autumn. In this period we observe a particular synergy of ~~higher frequency of~~mid-latitude synoptic disturbances ~~and mesoscale~~, becoming more frequent towards the cold seasons, and strong convective systems ~~which could still develop in high thermodynamic unstable environment~~ still developing over the warm Mediterranean Sea at the end of Summer and in Autumn (Grazzini et al., ~~2019).~~2020); a situation very favourable the genesis of extreme precipitation events in the area.

2.2. Geological and geomorphological setting

The study area mainly consists ~~mainly~~ of ~~strongly serpentinized ultramafites~~ extensively fractured ~~and representing the original oceanic crust~~serpentinites that represent the accreted fragments of the Ligure-Piemontese oceanic basin, ~~developed in the Middle to Upper Jurassic, which separated the Europe plate from the~~ separating the European and Adria ~~plate~~plates during the Middle-Upper Jurassic (Marroni et al., 2010). ~~Due to the compositional heterogeneity of its vertical sequence, the ultramafic medium is made of lithological units, tectonically overlapped.~~ The ultramafites are bordered by ~~deposits which are predominantly characterized by~~ polygenic breccias ~~(Casanova complex, early Campanian age, Vescovi, 2002),~~, made of blocks of limestones or marly limestones ~~immersed in~~embedded within a fine-grained matrix ~~or a mineral cement.~~(Mt. Ragola Complex, Late Santonian Early Campanian; Elter et al., 1997).

The ~~morphology of the area~~geomorphological landscape includes flat areas and steep slopes located at different ~~altitude that some authors (Elter et al., 1997~~altitudes. On the former, marshy environments commonly occur recording the last filling phases of small lacustrine basins, some of which still exists as the Lake Moo and the Lake Bino (Figs. 1-2). However, the origin of the Lake Moo is still a matter of debate as some Authors point to a glacial origin (Elter et al., 1997; Marchetti and Fraccia, 1988; Carton and Panizza, 1988~~) interpret as originated from the phase of last glacial retreat. On these morphological flat areas, marsh deposits have developed originated from the filling of small glacial lakes some of which still exist as the Lago Moo plain and Bino lake. Other authors such as the~~), while others have interpreted the basin as the expression of Holocene deep-seated gravitational slope deformations (Geological, Seismic and Soil Service of the Emilia-Romagna Region~~– Inventory Map of landslides at 1:10000 scale of the Emilia-Romagna Region (available at: http://ambiente.regione.emilia-romagna.it/geologia/temi/ dyseste-hydrogeological / the-paper-inventory-of-landslides, 2019) have interpreted the Moo lake plain as the product of gravitational processes that affect the entire slope area (available at: http://ambiente.regione.emilia-romagna.it/geologia/temi/ disruption-hydrogeological / the-paper-inventory-of-landslides,~~, 2012) mainly controlled by changes in the ~~2019). From this point of view, the main factor controlling the morphological evolution of the area of Lake Moo, is the river~~ incision ~~produced by~~rates of the Nure stream ~~during the Holocene (Gunderson~~(Elter et al., ~~2014). This incision triggered the development~~1997). The complexity of

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~~gravitational phenomena on the slopes. These complex~~past and present morphological ~~features of the area is also influenced~~processes are likely enhanced by the ~~presence~~superposition of lithological ~~elements~~units with ~~a~~ strong mechanical contrast, such as ophiolites ~~superimposed on~~and the underlying a predominantly clayey ~~substrate~~unit (Elter et al., 1997).

3. Data and methods

3.1. Field investigation

~~The selection of the study site has been obtained following~~ Taking into account the criteria indicated by Gilli et al. (2013) and Schillereff et al. (2014~~). In this respect,~~), the Lake Moo ~~site presents~~shares several advantageous characteristics ~~to~~for the ~~archiving~~reconstruction of ~~paleo~~the Holocene flood ~~deposits~~activity:

- ~~Steep relief~~steep slopes (average inclination of 24°) ~~with slopes~~ composed of ~~poligenic and monogetic braccias in clay matrix,~~deposits highly susceptible to erosion (~~Monte~~i.e., polygenic and monogenic breccias with a pelitic matrix – the Mt. Ragola Complex, Elter et al., 1997~~) are present;~~; Fig. 2);
- ~~No lakes~~ absence of lacustrine basins in the upstream ~~in~~part of the catchment;
- ~~Small~~small drainage basin area (1.94 km^2);
- ~~One~~one dominant inflow into the lake;
- ~~Absence~~lack of regulated flow structures;
- ~~Absence~~lack of natural pre-lake sediment storage zones.

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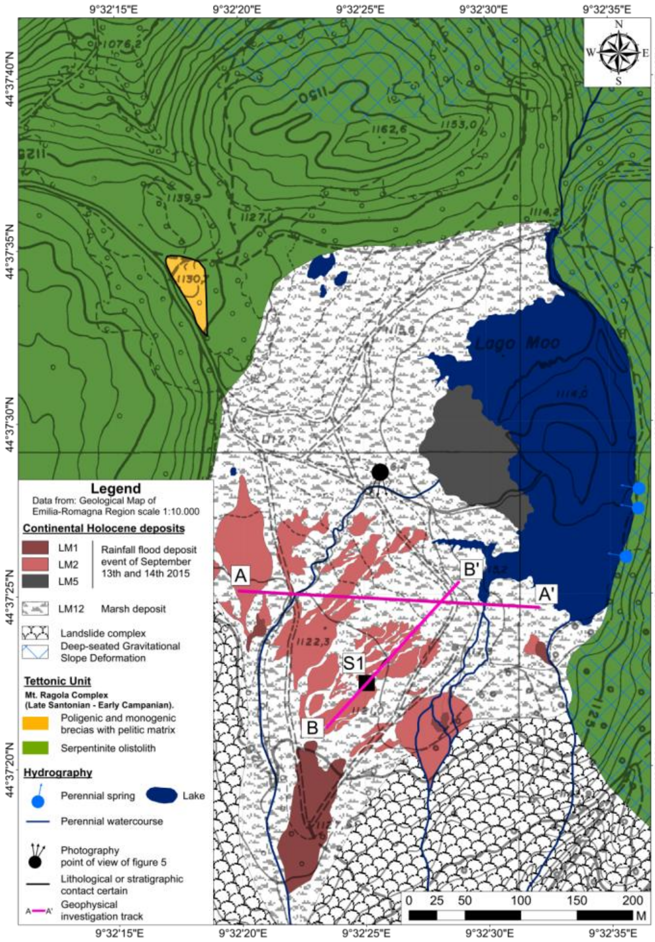
The field campaign led to the acquisition of two sedimentary cores (S1 and S2~~)~~), 14m and 6m-long respectively, and one trench~~, investigating~~ (T1), undertaken to investigate the sedimentary succession capped by the high-density flood ~~deposit~~deposits formed during the ~~last~~recent HIP event (~~14~~13th-14th September 2015). The location of the cores and the trench ~~was planned on the basis of a high-~~benefited from a detailed geomorphological map (Fig. 2) and a high-resolution reflection seismic survey (Fig. SUP1 ~~of~~in the supplementary material~~) and a detailed geomorphological map,~~), both ~~of them~~ originally produced for this ~~purpose (Fig. 2).~~research. The ~~former~~latter provided useful information ~~on~~about the lake ~~basinfloor~~basin-floor morphology and the thickness of the infilling succession.



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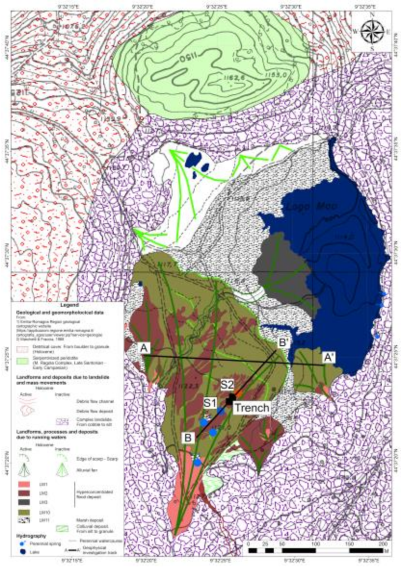

Figure 2. ~~Location~~Geomorphological map showing the main geological units and the hydrological elements of the Lake Moo plain. The detailed mapping of flood deposits formed during the recent HIP event (13th-14th September 2015), the location of the geognostic investigations, and the geophysical surveys tracks~~, and detailed geomorphological mapping of the flood deposit occurs between 13 and 14 September 2015 (upper Trebbia and Nure valleys, province of Piacenza, Italy).~~ are also reported.

The two cores, S1 and S2, ~~14 and 6 meters long respectively,~~ were ~~performed through~~ undertaken using a continuous ~~perforating~~drilling system~~, which~~ that guaranteed an undisturbed ~~core~~ stratigraphy and a high recovery percentage (~~S1~~about 90~~% and S2 91%). The~~ %). A trench~~, carried out in~~ (6m long, 3m wide, 2m depth) was excavated between the two cores~~, reached the depth of 2 meters, the length of 6 meters and the width of 6 meters. The subsurface succession was stratigraphically analysed, and the~~ allowing a detailed analysis of the most recent deposits.

We focused our attention on the longest core (S1) ~~was selected~~ that shows the complete record of the Lake Moo infilling succession, as ~~reference and sampled for~~ it reaches the ophiolite bedrock. Therefore, all the laboratory analyses (grain size, radiocarbon and palynological analysis) were undertaken on core S1, while the other core (S2) and the trench were used in support to the stratigraphic reconstruction. Elevation and geographic coordinates of reference core S1 were acquired using Garmin eTrex 10 GPS receiver: 1120.2 m. a.s.l. and 44° 37’ 25’’N – 9° 32’ 43’’E, respectively.

3.2. *Facies analysis and chronology*

~~A facies characterization~~Facies characterisation of the Lake Moo sedimentary succession ~~has been~~was mainly performed ~~on basis of~~integrating the observable macroscopic physical characteristics (i.e., grain size,

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sedimentary structures, Munsell chart colour and types of bounding surfaces~~), and granulometric~~) with the grain-size data~~, the latter~~ available for the reference core S1.

~~Relatively to the different coarse-grained levels recognized, we follow~~ The interpretation in terms of depositional environments also benefited from the precise position of the core(s) with respect to the spill point of the Lake Moo and the application of the facies tract concept. ~~A~~ The latter strongly supported the interpretation of the coarse-grained intervals encountered throughout the studied succession. Specifically, a facies tract is defined as the association of genetic facies ~~tract here means all facies~~that can be observed within the ~~same deposits relative of the same~~ flood ~~undergoing transformations~~deposits along ~~its~~with the down-slope motion transformation (Lowe, 1982; Mutti, 1992; Mutti et al., 1996). ~~The~~Thus, the application of the facies tract ~~approach is important because allows to recognize the following important information like:~~concept, if framed into the core(s) stratigraphy, may allow reconstructing how flood deposits changed through time at a fixed location (Figs. 3, 4).

~~1) the position in the facies tract with respect to the whole fluvial-hyperpycnal system;~~
~~2) relative flood event magnitude;~~
~~3) expected related facies types in more proximal and distal areas.~~

The abundance of wood remains and ~~peat levels in~~ peaty layers within the sedimentary ~~cores allowed ^{14}C~~ succession under examination supported the reconstruction of a robust chronological framework. Twelve samples were selected from the reference core S1 and radiocarbon ~~twelve samples that were analysed~~dated at the CEDAD Laboratory of the University of Salento (~~Province of Puglia,~~ Italy). The data are collected ~~in~~within the Table ~~TS2 of the~~TS1 (in supplementary material~~. The~~) and the conventional ^{14}C ages were converted into calendar years using the OxCal software version 3.10 ~~software~~ (Reimer et al., 2013).

~~3.3~~An age-depth model was also constructed applying a linear interpolation. Coarse-grained intervals were not excluded from the processing because of the difficulty to evaluate the exact thickness of the deposits interpretable as instantaneous events. Indeed, the upper limit of coarse-grained intervals commonly appears transitional toward finer sediments and, in few cases, some intervals for a total thickness of 107 cm were not recovered.

3.3. Pollen and microanthracological analysis

In order to refine facies characterisation and highlight past vegetation changes at the study site, pollen analyses

~~*Temperature reconstruction and modern climatological dataset*~~

~~Central to our analysis is the availability of a reliable temperature reconstruction for the chronological period explored through the coring. In this respect the chironomid analysis of the nearby Lake Verdarolo conducted by Samartin et al. (2017), represent a unique opportunity. Lake Verdarolo site is located at 1390m a.s.l., 270m higher and 54km south from Lake Moo (Fig. 1), in a very similar climatic context. They reconstructed the mean July air temperature using a chironomid-based inferenced model developed from a combination of data of over 200 lakes from Norway and Swiss~~

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~~Alps (Heiri et al., 2011). This represent the first vegetation independent holocenic temperature reconstruction of the Northern Apennine.~~

~~Modern temperature and precipitation time series (1961-2018) of Lago Verdarolo and Lake Moo are derived from the gridded high-resolution dataset of Emilia-Romagna (Eraclito4), described in Antolini et al. (2016). Trend estimation and Mann Kendall significance trend test are computed with the pyMannKendall package (Hussain et al., 2019).~~

~~*3.4* Pollen analysis~~

~~Palynological analyses~~ were carried out on 14 samples collected from ~~core S1 to refine facies characterization of fine-grained deposits and obtain vegetation-derived~~ the core S1. We focused the analyses on two key stratigraphic intervals, formed during periods of well-known different paleoclimate ~~data (Fig. 3). After the radiocarbon dating, a further choice was made using only 11 samples falling into two stratigraphic intervals of our interest: the first one (I_1),~~(and paleotemperature) conditions: i) Interval 1 (ca. 10.5-9 m core depth) covering ~~10.77m to 9.33m depth and with temporal resolution 7300 -~~the period between ca. 9600-7300 cal yr BP and, thus centred on the Holocene Thermal Maximum ~~(HTM), the second one (I_2) from 5.48m to 4.55 depth and corresponding to the exit of HTM (3900 -~~-HTM (Renssen et al., 2012) and ii) Interval 2 (ca. 5.5-4.5 m core depth) recording the final stages of HTM and the following cooling period between ca. 5500-3800 cal yr BP~~).~~. In these two stratigraphic intervals, ~~the~~samples were collected from fine-grained layers following a mean sampling resolution ~~is 28cm. The choice of these two periods ensure a significant thermal/climatic~~of ca. 30 cm.

A standard methodology already tested for pollen substrates was applied with some minor modifications (Lowe et al., 1996). The method includes a series of laboratory treatments: about 8-10 g were treated in 10% Na-pyrophosphate to deflocculate the sediment matrix; a Lycopodium spores tablet was added to calculate pollen concentration (expressed as pollen grains per gram = p/g) and the sediment residue was subsequently washed through 7 micron sieves. The sample was re-suspended in HC1 10% for remove calcareous material and subjected to Erdtman acetolysis; heavy liquid separation ~~and at the same time the samples were taken~~method was then introduced using Na-metatungstate hydrate of s.g. 2.0 and centrifugation at 2000 rpm for 20 minutes. Following this procedure, the retained fractions were treated with 40% HF for 24 h and then the sediment residue was washed previously in distilled water and after in ethanol with glycerol; the final residue was desiccated and mounted on slides by glycerol jelly and finally sealed with paraffin.

This method preserves the slides for many years after preparation and therefore it is suitable for pollen extractions from ~~predominantly lacustrine fine layers where the stratigraphic series shows characteristics of continuity of sedimentation.~~

geological and paleo-archeological samples. Identification of the ~~pollen grains~~samples was performed at ~~1000 light microscope~~400 magnification and ~~based on the~~only difficult pollen such as *Triticum*, *Avena* or *Hordeum* types were observed at 1000 magnification.

Determination of pollen grains was based on the Palinoteca of the "Centro Agricoltura Ambiente – CAA G. Nicoli" laboratory (Italy), atlases and a vast amount of specific morpho-palynological bibliography ~~stored at the CAA Laboratory (S. Giovanni in Persiceto, Italy).~~. Names of the families, genus and species of plants

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conform to the classifications of Italian Flora ~~proposal~~proposed by Pignatti (2017-2019) and European Flora (Tutin et al., 1964-1993). The pollen terminology ~~is~~was based on Berglund and Ralska-Jasiewiczowa (1986), Faegri and Iversen (1989) and Moore et al. (1991) with slight modifications that tend to simplify plants nomenclature ~~of plants~~. The term “taxa” is used in a broad sense to indicate both the systematic categories and the pollen morphological types (Beug ~~2004). Identified pollen groups (between 300 and 400 pollen grains) have been expressed as percentages of the total (usually between 300 and 400 pollen grains). Pollen percentages are computed on the basis of the total pollen sum. All samples are characterized by fairly high concentration, ranging from 1,072 -30,659 p/g, and good conservation status. The discreet pollen biodiversity (60 pollen types: 22 woody, 32 herbaceous and 6 Monolophyta) found, suggests that flood deposits formed in a rich vegetal environment, with high floristic biodiversity. Pollen groups are defined on the basis of common biological characteristics of the plants, useful to reconstruct vegetation dynamics due to climate fluctuations. In particular groups composition are described in Fig. 10.~~ , 2004). For each sample, at least 500 pollen grains were counted, and the identified taxa have been expressed as percentages of the total pollen sum that includes only terrestrial pollen, no fern spores and no aquatic plants.

On the basis of vegetational and ecological characteristics, the following main pollen groups were identified: Conifers (*Pinus/Abies alba*), Deciduous trees (this group includes quercetum taxa – *Quercus, Carpinus betulus, Corylus avellana, Fraxinus, Ostrya carpinifolia, Tilia* and *Ulmus* + other Deciduous trees), Meadow (this group mainly comprises *Fabaceae* and *Asteroideae*, *Caryophyllaceae*, *Cichorioideae* and *Poaceae*), Anthropic indicator (e.g. *Cerealia, Chenopodium, Convolvulus arvensis, Plantago, Urtica*) and Alia that includes all taxa excluded from previous groups. The group of hygro + aquatic plants was also distinguished. It includes hygrophilous herbs (e.g., *Cyperaceae*), helophytes and hydrophytes (i.e., *Lemna, Junchus, Nymphaea, Phragmites, Potamogeton* and *Sparganium*), which are considered good proxy of humid conditions typical of wetlands.

The 14 samples prepared for pollen analysis were also investigated for the identification of microcharcoals. Microanthracological analysis has been used to track past changes in fire history, likely connected to anthropogenic activities (Vescovi et al., 2010). Point count estimation of microscopic charcoal abundance was carried out, and charcoal fragments encountered during pollen counting were recorded in four, size classes based on the long axis length: 10–50, 50–125, 125–250, >250 µm (Whitlock and Millspaugh 1996; Clark 1982; Patterson et al., 1987; Whitlock and Larsen 2001, Fisinger et al., 2008). The former two classes were interpreted to be wind-blown transported, hence giving information about the regional fire events, whereas the latter two were considered the result of local vegetation burning (Vittori Antisari et al., 2015).

Pollen and microcharcoal results are presented in section 5, to support facies stratigraphy and to discuss controlling factors on floods activation.

3.4. Temperature reconstruction and modern climatological dataset

Central to our study is the availability of a reliable (paleo)temperature dataset for the chronological period recorded by the Lake Moo sedimentary succession. In this respect, the Holocene paleoclimate reconstruction conducted by Samartin et al. (2017) on the nearby Lake Verdarolo represents a very important reference. The Lake Verdarolo site is located at 1390 m a.s.l., 270 m higher and 54 km SE from Lake Moo

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(Fig. 1), in a very similar climatic context. The Authors reconstructed the mean July air temperature using a chironomid-based inference model, developed through a combination of data extracted from more than 200 lakes of Norway and Swiss Alps (Heiri et al., 2011). This vegetation-independent paleotemperature reconstruction is the first for the Northern Apennines and it agrees with that of the Gemini Lake (1350 m a.s.l. elevation and 48 km SE from Lake Moo) as well as several other records coming from central Italy (Samartin et al., 2017).

Modern temperature and precipitation time series (1961-2018) at Lago Verdarolo and Lake Moo were derived from the gridded high-resolution dataset of Emilia-Romagna (Eraclito4), described in Antolini et al. (2016). Trend estimation and Mann Kendall significance trend test were computed with the pyMannKendall package (Hussain et al., 2019).

4. Results

~~4.1 Stratigraphical data and their geological context~~

4.1. Holocene stratigraphy

4.1.1. Sedimentary facies

~~The stratigraphic distribution in the core profiles and the synthetically description facies are shown in Fig. 3. Thirteen different facies types have been identified and named from LM1 to LM13:~~

Fourteen lithofacies (LM1 to LM14) have been identified within the infilling succession of the Lake Moo basin. Detailed lithological description of each lithofacies is reported below.

- LM1 to LM2: Clast-supported deposit with a thickness ranging ~~from~~between 5 ~~to~~ -15 cm. ~~Extremely~~ Fine boulders to coarse ~~(LM1) to medium pebbles (LM2)~~ cobbles with abundant coarse to fine grained ~~sandstone~~sand matrix, showing a low degree of sorting, occur. Polygenic clasts have low sphericity and a very angular shape. ~~Occasional fragments~~ Wood fragments locally occur. The basal and top contacts are sharp; the basal one occasionally shows evidence of erosion;
- LM3 to LM4: Clast-supported deposit with a thickness ranging between 5-15 cm. It is composed of fine cobbles to coarse pebbles with a very fine sand to silt matrix. Polygenic clasts have low sphericity and a subangular shape. Scraps of wood are encountered. The basal and top contacts are sharp; the basal one occasionally shows evidence of erosion;

~~LM3~~

- LM5: Massive matrix-supported deposit composed of medium pebbles to granules ~~with~~embedded within a very fine sand to silt matrix. Polygenic clasts have low sphericity and a subangular shape. ~~Sharp~~Scraps of wood are encountered. The basal and top contacts ~~with evidence of~~ are sharp; the basal one occasionally shows evidence of erosion ~~along the basal one. Presence of fragments of wood~~;

~~LM4 to~~

- LM6 ~~General~~to LM8: Generally clast-supported, poorly sorted deposit with a thickness ranging ~~from~~between 10 ~~to~~ -30 cm. Polygenic clasts, massive or crudely graded angular\subangular ~~medium~~fine pebbles to very fine granules. Crudely horizontal laminae ~~at the top. Sharp basal and top contacts with~~

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~~evidence of occasionally erosion along the basal one. Occasional fragments of wood~~ are locally recorded atop. Fragments of woods can be encountered at the base of the layers. The basal contact is sharp and occasionally shows evidence of erosion; the upper boundary is transitional;

~~LM7 to~~

- LM9 to LM10: Massive or crudely fining-upward graded~~, poorly sorted~~ very coarse to fine sands, showing a low degree of sorting. The total thickness ranges between 5-20 cm ~~thick. The top part of the detrital layer consists of the finest particles with~~ . Evidences of a planar lamination~~. Sharp basal~~ and ~~top contacts. Occasional~~ scattered wood fragments ~~of wood at~~occur close to the ~~top of the layers~~upper boundary, which is transitional. The basal contact is sharp;

~~LM10 Sandy~~

- LM11: Fine sandy loam to clayey loam~~. Presence of polygenic~~ showing a dark grayish brown color (10YR 4/2 or 10YR 3/2). Polygenic fine to medium pebbles aligned with low sphericity and a very angular shape~~. Dark grayish brown color (10YR 4/2 or 10YR 3/2). Sharp~~ occur. Both basal and top contacts are sharp;

~~LM11 Peat layer and~~

- LM12: Silty deposit of dark color (10YR 3/1) with a high content of decomposed organic ~~rich clay layers. Fine~~matter. Occasional fine to medium pebbles aligned with low sphericity and very angular shape~~. Dark color (10YR 3/1);~~ occasionally occur;

~~LM12~~

- LM13: Loam to silty clay deposit showing a coarse angular blocky structure and dark olive gray color (5Y3/2), with yellowish-brown (10YR5/6) due to the presence of iron oxides. The deposit is deprived of calcium carbonate and a field pH 5.5 value is recorded;

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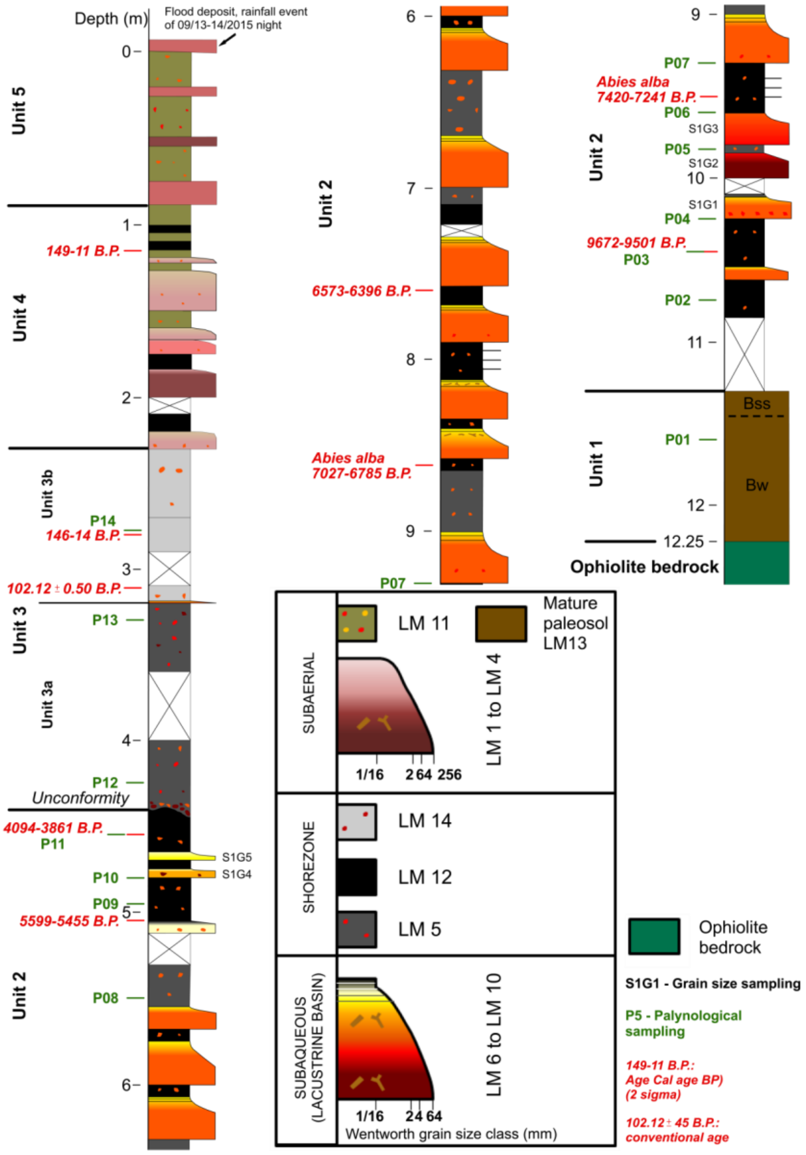
- LM14: Massive clayey silts with ~~rare~~a low amount of decomposed organic matter~~. Occasional~~ and a dark greenish gray color (5G 4\1). Scattered polygenic clasts (fine pebbles) ~~have~~with low sphericity and a very angular shape~~. Sharp~~ are recorded. Both basal and top ~~boundaries. Dark greenish grey color (5G 4\1);~~contacts are sharp.



~~LM13 Loam to silty clay texture, strong coarse angular blocky, dark olive gray dry color (5Y3/2) with yellowish brown redox concentrations (10YR5/6), no carbonate, field pH 5.5.~~

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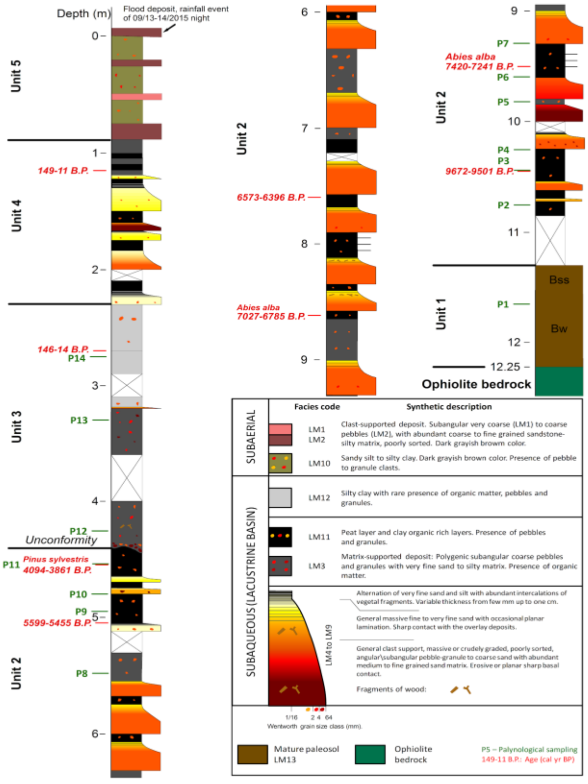

Figure 3. Sedimentological features and lithofacies characterisation of the reference core S1. Radiocarbon dates, palynological and grain-size samples as well as stratigraphic units (described in

~~**Figure 3.** Sediment core description (see legend) and radiocarbon dates.~~

~~Relatively to~~ the ~~Lake Moo site~~section 4.2.) are also reported.

In terms of sedimentary processes, the ~~different~~ coarse-grained ~~facies from~~ LM1~~ to LM9~~-LM10 lithofacies have been interpreted as ~~the extreme~~ flood ~~events~~deposits triggered ~~only by high-intensity convective rainfall~~ by HIP events in the catchment area ~~that flow into the Lake Moo as hyperpycnal flow. Our main assumption is that, with favourable sediment transfer into lake and small catchment area (<2km^2), high density flood can be triggered only by HIP due to erosion of material from the drainage system network (~~following Milliman and Syvitski~~,~~ (1992~~;~~), Mulder and Syvitski~~,~~ (1995~~;~~) and Mutti et al~~.,~~ . (1996). ~~The facies from LM1 to LM9~~Particularly, the identified lithofacies were grouped according to ~~the genetic approach and therefore on the basis of~~ their features (i.e., grain-size, color, sedimentary structures) and the facies tract concept ~~as described in Fig. 4~~ (Lowe, 1982; Mutti, 1992; Mutti et al., 1996~~).~~), distinguishing three main depositional setting along an idealised transect (Fig. 4): subaerial (LM1 to LM4), marginal (LM5) and subacqueous/lacustrine (LM6 to LM10).

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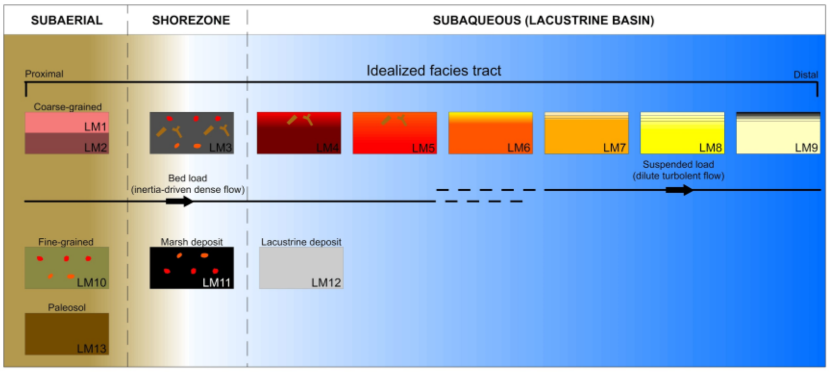
~~Fine~~The fine-grained facies~~, from LM10 to LM13,~~ (LM11-LM14 in Figs. 3, 4) are ~~subdivided~~also gathered into two main groups. ~~In the~~The first group ~~belong the facies~~ includes LM11 and LM13 (paleosol) that are characterised by features indicative of subaerial conditions; the second group consists of LM12 ~~expression of environment shorezone and subaqueous lacustrine~~(i.e., peaty deposits ~~respectively. The second group includes~~) and LM14, deposited along the marginal zone of the ~~facies LM10~~(paleo)lake under low-energy conditions and ~~LM13 expression of subaerial deposits~~different degree of organic-matter enrichment.



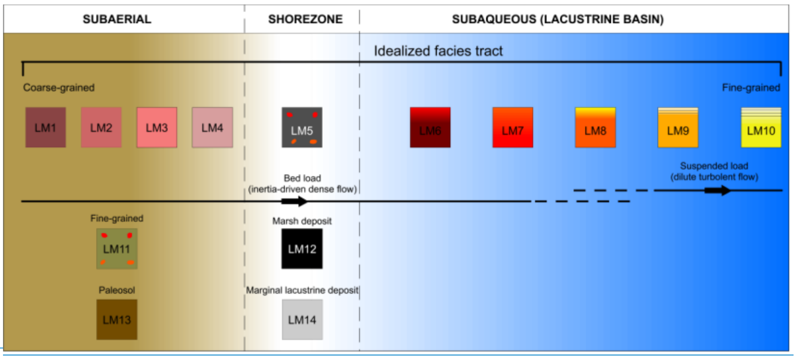


Figure 4. ~~Idealized~~Idealised genetic facies tract ~~interpretation of clastic deposits associated with S1 core~~showing the fourteen lithofacies (LM1-LM14) identified within the reference core S1, whose stratigraphy is reported in Fig. 3.

4.1.2. Stratigraphic units

~~The sedimentary succession of the reference core S1 is subdivided into~~Above the ophiolite bedrock, five informal ~~units,~~ stratigraphic units have been distinguished within the S1 cored succession and described ~~below~~as follows, from the bottom to the top (Fig. ~~3):~~3). Each unit has also interpreted in terms of depositional environment.

Unit 1~~:~~ (12.25-11.30 m core depth) - This unit, 95 cm-thick, is exclusively represented ~~only~~ by the LM13 ~~facies. Two levels can be distinguished: from 11.30 m to~~ lithofacies that is, in turn, composed of two main horizons

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indicative of a mature paleosol. The lowermost horizon (Bw), recorded between 12.25-11.60 m core depth ~~is present a~~, corresponds to weathered deposits overlain by 30 cm-thick slickensides horizon (Bss~~), while from 11.60 m to 12.00 m core depth is present a weathered horizon (Bw).~~). This unit is interpreted as a ~~mature paleosol, likely developed on a~~residual pedogenized colluvium ~~forming~~marking the base of a structural depression produced by gravitational block sliding;

Unit 2 (11.30-4.4 m core depth) - This ca.7 m-thick unit is characterised by the presence of several, very coarse intervals (LM6-LM8) showing a thickness of about 10-30 cm and locally capped by sandy layers (LM9-LM10). Silty deposits with a variable organic-matter content, accompanied by a scarce (LM12) or moderate (LM5) occurrence of pebbles/granules, separate the coarse-grained intervals. This unit, which is capped by a marked unconformity surface, is interpreted as a relative shallow lacustrine environment subjected to several flood events of remarkable intensity;

Unit 3 (4.4-2.3 m core depth) - This unit, ca. 2 m thick, shows sharp boundaries and the occurrence of two sub-units (3a and 3b). The lowermost sub-unit 3a, ranging between 4.4-3.2 m of depth, is exclusively represented by silty deposits with scattered pebbles/granules, several wood fragments and a mottled-like appearance corresponding to the LM5 lithofacies. These deposits are attributed to a marginal lacustrine environment subject to sporadic floods. Upwards, marginal lacustrine clayey deposits (LM14) capped the sequence (sub-unit 3b), documenting a period of apparent flood inactivity;

Unit 4~~Unit 2: This unit is 6.9 m thick and ranging from 11.30 m to 4.4 m core depth, and is characterized by the presence of several layers of~~ (2.3-0.9 m core depth) - This unit, 1.4 m-thick, is composed of alternating coarse (LM3-LM4) and fine-grained deposits (LM12 and LM11) that record:

- the disappearance of truly lacustrine deposits replaced by subaerial ones through an erosional surface that marks the lower boundary of the Unit 4. The stratigraphic depth of this boundary is in accordance with the altitude of the spill point of Lake Moo (1116 m a.s.l.);
- the return of several, cm-thick flood deposits (LM3-LM4).

Unit 5 (uppermost 0.9 m) - This unit is characterised by the presence of several layers of very coarse sediments (~~LM3~~LM1-LM2) separated by ~~deposits with a predominantly fine composition (LM11). The thickness of coarse layers, belonging to facies LM4-LM6 ranges from 10 cm to 30 cm. To the top of the succession and if age dating is reliable, the unit is closed by an unconformity surface recording a important time gap. The same surface is the base of a lacustrine transgression which make up the unit 3~~finer deposits (LM11). An erosional contact separates Unit 4 from Unit 5.~~;~~

~~Unit 3: This unit is thick 2.1 m and ranging from 4.4 m to 2.3 m of depth. Sharp basal and top boundaries. The basal portion of this unit (from 4.4 m to 3.2 m of depth) present matrix-supported deposit with several fragments of wood which we attribute to the shorezone environment. Only this portion of core show a characteristic mottledling-like appearance.~~

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~~From the 3.2 m of depth follows a lacustrine deposit that closed the unit. This unit is characterized by a period of apparent inactivity of the fluvial system, until its reactivation documented in the uppermost part of the core (unit 4 and 5).~~

~~Unit 4~~~~: This unit is thick 1.4m and ranging from 2.3m to 0.9m of depth and registers the return of several coarse-grained levels,~~ which ~~are in general less thick and less coarse than those present in unit 2. These levels are prevalent separated by marsh deposits. Sharp basal and top unit contacts.~~

~~Unit 5: This unit is thick 0.9m, ranging from 0.9m of depth to land surface and records the disappearance of lake deposits replaced by fluvial ones through an erosional contact. The~~includes the flood deposits produced by the rainfall event ~~of~~occurred on September 13th and 14th 2015 ~~closes the sequence (Fig. 5).~~

~~**Figure**~~(Figs. 3, 5~~. Though the exposure is quite small, these graded pebble-sand couplets could be interpreted as a sheet-flood deposit (Unit 5).~~).

As a whole, we interpret the ~~local~~ lacustrine succession ~~(units 1, 2, 3 and 4) is like to the~~as an infill of a structural depression produced by gravitational block sliding that was induced by post-glacial fluvial incision (~~Gunderson~~Elter et al., ~~2014~~1997).

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Figure 5. Representative photograph of the trench (see Fig. 2 for location), showing the uppermost 50 cm-thick sedimentary succession. Though the exposure is quite small, the graded pebble-sand couplets belonging to the Unit 5 can be interpreted as a sheet-flood deposit.

4.2. Age-depth model

~~The age model for the S1 core is based on eight ^{14}C dates (Fig. 6). Coarse levels are removed from the sediment record when constructing the age-depth model because represent instantaneous deposits. The 27 deposits interpreted as instantaneous events representing a total of 374.5 cm were removed, the remaining were used to build an event-free sedimentary record.~~

~~Four radiocarbon dates were rejected: one (LTL18275Abis code) because it was not possible to date the sample for poor presence of organic matter, the others (LTL18275A, LTL18575A and LTL18272A codes) because it was not possible to identify a calibrate age.~~

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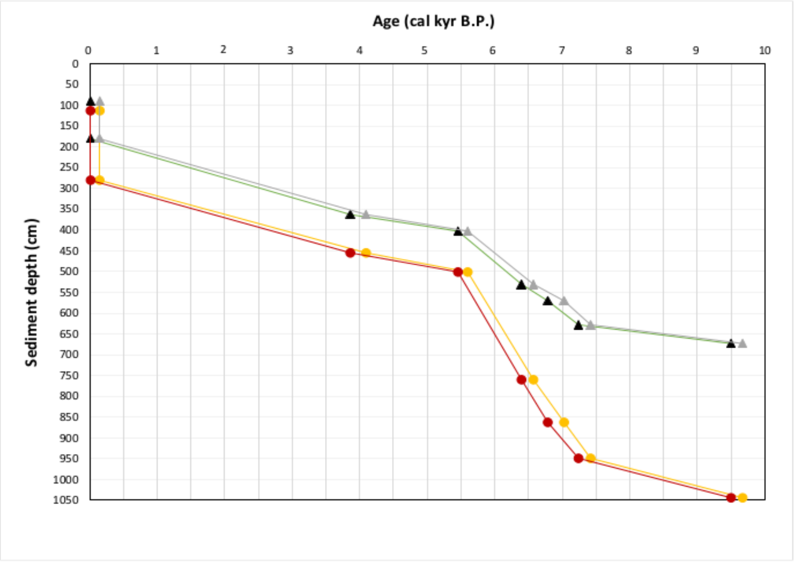

The age-depth model, based on eight out of twelve ^{14}C dates available for the S1 core (Table TS1 in the supplementary material), indicates that the sedimentary succession above the bedrock encompasses almost all the Holocene period (about the last 10 kyrs; Fig. 6). Three ages (at ca. 9.60 m, 3.10 m and 2.40 m core depth) were excluded because resulting younger than 1950 AD, while one sample collected at 2.35 m core depth resulted not datable due to a very low organic matter content. The selected calibrated ages are stratigraphically coherent and mainly derived from wood fragments and peaty deposits. In order to reduce the potential bias due to long-lived plants and reworking processes, small twigs were selected (Oswald et al., 2005) from fine-grained deposits and identified when possible (e.g., *Pinus* and *Abies alba*). Due to the small dimension of the basin and the ophiolites prevalence in the drainage area (Fig. 2), we consider negligible the hard-water effect on peats.

The resulting age-depth model suggests the occurrence of four main stratigraphic intervals in terms of sedimentation rates. The lowermost interval (about 9.5-7.3 cal kyr BP) denotes a mean accumulation rate of ca. 0.50 mm/yr that strongly increases up to ca. 2.38 mm/yr within the overlying section dated around 7.3-5.5 cal kyr B.P. An important change in the accumulation rate occurs around at 5 m of the core depth with a drop to ca. 0.3 mm/yr between the 5.5-4.0 cal kyr BP interval. Above, between ca. 4.5-3 m, the deposit shows an uncertain chronology due to the lack of reliable radiocarbon dates and the occurrence of an unconformity surface around 4.5 m, at the contact between Units 2-3 (Figs. 3, 6). During recent times (the last 146-14 cal yr BP), the accumulation rate strongly increases, reaching the remarkable value of ca. 12 mm/yr.

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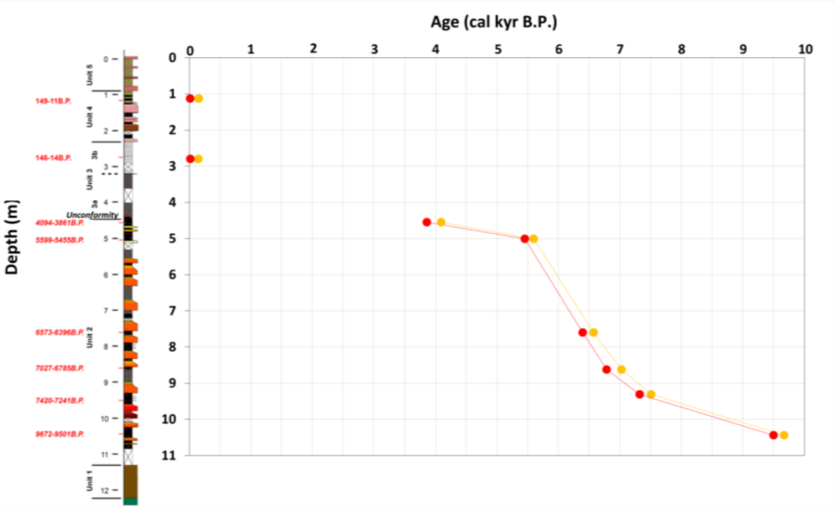

Figure 6. ~~Age~~S1 core stratigraphy and the age-depth model obtained from radiocarbon dates. ~~Black~~Red and ~~grey line represents~~orange lines represent the two-sigma probability envelope ~~depth without coarse grained events. Red and orange line represents the two-sigma probability envelope depth with coarse grained events~~.

5. Discussion

~~Figure 7 shows~~As a basis for discussion we assemble, and temporally synchronise, the ~~stratigraphic succession of the S1 core compared~~ Lake Moo data with the most relevant ~~climate~~paleoclimate proxy available from literature, focusing on the N Apennines paleoarchives (Figs. 1, 7). As a whole, the Holocene infilling succession of the lacustrine basin (i.e., Units 2-3) is composed of an alternation of cm to dm-thick, coarse-grained flood deposits and silts characterised by a variable amount of organic matter (sub-sections 4.1. and 4.2.; Figs. 3, 4, 7). The coarse intervals are particularly well-developed and frequent within the portion of the stratigraphic Unit 2 chronologically correspondent to the HTM (Holocene Thermal Optimum), constrained between ca. 9-5 kyr cal BP in the nearby Verdarolo Lake (Samartin et al., 2017 in Fig. 7A; section 3.4.). Interestingly, stable oxygen isotope records from the nearby Apuan Alps (Corchia caves; Fig. 1) document, within the same time interval, the wettest conditions interpreted as precipitation increases in the Northern Apennine (I and II humid periods in Fig. 7B) with a peak between ca. 8500 and 7500 cal yr BP (I humid period; Regattieri et al., 2014; Zanchetta et al., 2011). This peak is in phase with a clastic layer, dated back to 8.2 and 7.1 cal kyr BP, indicative of a period of enhanced cave flooding triggered by high-magnitude precipitation events (Zhornyak et al., 2011). The Authors attribute this maximum fluvial activity to an increase of strong convective episodes, like the one that affected the Versilia region in 1996 (Cacciamani et al., 2000 for a description of the Versilia flood event).

Models simulations on Northern Apennine, are showing higher precipitation in Autumn in response to the intense Summer heat of the HTM period, (e.g., Tinner et al., 2013). We speculate that the precipitation

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increase, reflected also in high frequency of flood activity, could have occurred during a phase of a progressive reduction of the Hadley cell, paralleled by a reduction of the subtropical high-pressure after the insolation peak (Fig. 7C). This would lead to an enhanced meteorological activity over the Mediterranean area, due to the mid-latitude weather systems, especially at the transition towards the cold season. Although in decline, the presence of African Monsoon (Skinner and Poulsen, 2016) could also have contributed to enrich sub-tropical air masses in the water vapour potentially extractable by mid-latitude synoptic disturbances. Accordingly, Krichak et al. (2015) documented how this mechanism is relevant for Mediterranean extreme precipitations nowadays; moreover, the events occurring in the autumn seasons are characterised by a greater transport of water vapour from the subtropical Atlantic even across North Africa.

With the end of the HTM, a drastic decrease in flood activity is documented at the Lake Moo, as the coarse intervals abruptly reduce in number and thickness within the uppermost portion of Unit 2 dated to ca. 5.5-3.8 kyr BP. This stratigraphic trend is reasonably interpretable as the expression of a decrease in frequency of HIP events over the study area under cooler and less humid climate conditions (Fig. 7). The limit between Unit 2 and Unit 3 corresponds to an unconformity that marks the passage to a marginal lacustrine succession of uncertain age, at least for the lowermost portion (sub-unit 3a). This facies interpretation is supported by palynological data, which show remarkable values of herbaceous hygrophytes (mainly Cyperaceae) and aquatics typical of wetlands.

The upper portion of Unit 3 (i.e., sub-unit 3b), dated around 146-14 cal yr BP, is almost deprived of coarse materials documenting a period of apparent floods inactivity at the Lake Moo (Figs. 3, 7). This is followed by a reactivation of flood processes during recent times (i.e., coarse-grained flood deposits within Units 4-5; Figs. 3, 7) with a minimum of five events to a maximum of twelve events every 100 years, as the confidence range associated with the calibrated age at 2.80 m core depth is rather wide (146-14 cal yr BP; Fig. 7). Despite the low degree of precision affecting radiocarbon ages younger than 200 years, this renewed increase in flood activity fits well with the instrumental record that points to a high frequency of HIP events during the last decades over the Northern Appennine (Libertino et al., 2019). These phenomena seem to be also responsible for the replacement of lake deposits by subaerial ones through an erosional contact (Unit 4 lower boundary).

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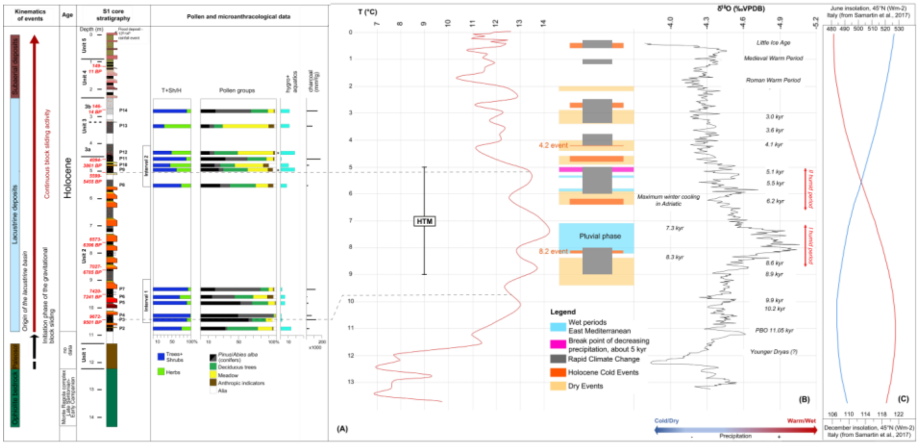
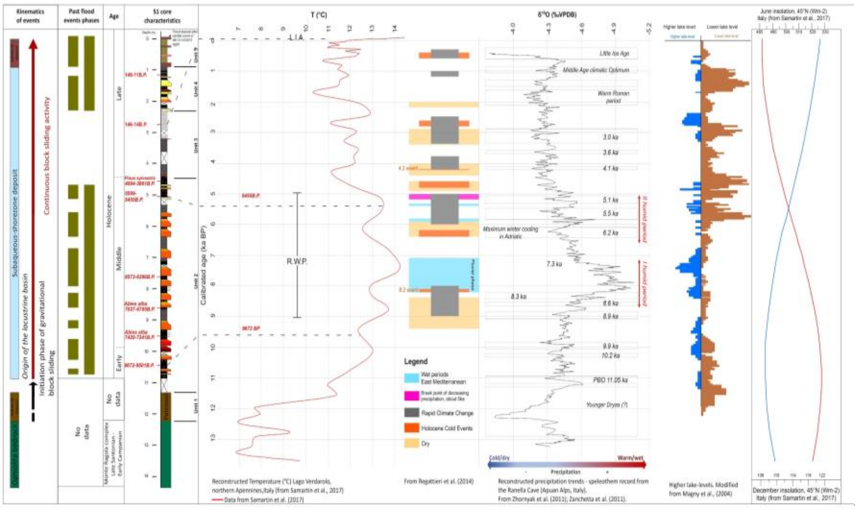


Figure 7. Stratigraphy of core S1, main palynological features and microcharcoal content. Relative abundances of pollen groups, explained in text (sub-section 3.3), are reported along with the frequencies of hygrophilous herbs and aquatics. Asterisks point to samples containing coprophilous fungi and other spores like *Sporormiella*, *Dicrocoelium* and *Ascaris*. These data are compared with the most relevant paleoclimate reconstructions available from literature for the area of interest. ~~These includes: reconstructed~~Panel (A) Reconstructed mean July air temperature from Lago Verdarolo (from Samartin et al., 2017~~),~~); Panel (B) δ^{18}O speleothem records and reconstructed precipitation trends (mean anomaly time series) from ~~Renella~~Corchia cave (~~data~~slightly modified from Combourieu et al., 2013; ~~Regattieri et al., 2014;~~ Zanchetta et al., 2011; Zhornyak et al., 2011~~), distribution of the higher lake levels event reconstructed in Jura)~~ and ~~Pre Alpine mountains (modified from Magny, 2004), and~~Panel (C) June (red) - December (blue) insolation values ~~records~~ reported for 45° Nord (from Samartin et al., 2017). Main Holocene climate phases and events are also shown (Regattieri et a., 2014). Available radiocarbon ages are reported as calibrated years BP.



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~~**Figure 7.** The~~ In order to compare the most recent stratigraphic ~~succession of the S1 core compared~~units (Units 4-5) with ~~the most relevant~~quantitative climate ~~proxy available from literature for the area of interest.~~

~~The lake Moo stratigraphic sequence (Fig. 3) is showing the presence of several coarse grained layers separated by deposit with a predominantly fine composition. These coarse levels are particularly developed within unit 2 (between 5 and 10.5m in depth) and correspond chronologically to range of the HTM of the Verdarolo curve and with the wet/high intensity phase reported at the nearby Renella and Corchia Cave (Fig. 7, Unit 2). Zhornyak et al. (2011) attributed this high fluvial activity, which reached levels of the caves flooded only during extreme events, to an increase of strong convective events like the one that affected the region in 1996. Other authors confirm, through model simulations, higher precipitation accumulations during HTM over the Mediterranean area, especially at end of summer/autumn seasons. This has been linked with a greater expansion of the African Monsoon which contributed to enrich of water vapour air masses extracted from north-Africa by mid-latitude synoptic disturbances (Skinner and Poulsen, 2016 and Tinner et al., 2013 in their Climatic simulations section, Fig. 4). With the end of the HTM a drastic decrease of the coarse deposit levels is observed which we are assuming attributed to a decrease in frequency of HIP. In particular, the transition between unit 2 and 3 is marked by an important unconformity contact. This unconformity is followed by deposits of shorezone environment and subsequently at the top of unit 3 by lacustrine deposits. The top of the unit 3 sequence has a calibrated age that is approximately 146-14 BP and is characterized by a period of apparent inactivity of the fluvial system, until its reactivation documented in the units 4 and 5 due to hypothesized new increase of HIP in recent times. The upper most part of the unit 4 has an age of about 149-11BP. Finally, the disappearance of lake deposits replaced by fluvial ones through an erosional contact is marked by unit 5.~~

~~From this first qualitative comparison we can affirm that there is a positive correlation (at the millennial scale) between temperatures and precipitation peak deducted from nearby speleothem records and the level of alpine lakes. This confirms findings from other authors (for example Marcott et al. 2013, Giguet-Covex et al., 2012), which are associating greater warmth (in the northern hemisphere) with periods of more intense precipitation.~~

~~Instrumental~~ data, the instrumental temperature values, available since the second half of the last century from the Eraclito ER dataset, has been added to the Verdarolo curve ~~to allow a comparison between geological time and recent instrumental data.~~. The overlap with the latest part of Verdarolo ~~reconstructed~~ curve ~~suggests a~~confirms the good accuracy of the reconstruction technique in this region (Fig. 8). The recent temperature increase is striking if compared with the previous period, and the current July temperature is comparable with the maximum temperature reached at HTM over ~~this~~the study area. The actual trend of July temperature, estimated over the period 1961-2018 from monthly mean values, is +4.3°C in 100 years. ~~This value~~The trend is highly statistically significant, with a p-value=0.0004 (see section 3.~~3 for a description of the method and significance). The recent trend is~~ 4.), and more than double of the maximum temperature gradient found in the Verdarolo curve, +2°C/~~100y, found, for a short period of time~~100 years, at the end of the Little Ice Age 1850-1900. ~~While the maximum positive temperature gradient found at the end of Younger Dryas age is about +1°C/100y. Is therefore clear that summer (July) temperature is increasing very rapidly, with an unprecedented rate in the whole Holocene. Such a large difference in increase rate can hardly be explained~~From Fig. 6 and 7 we observe a flood intensification corresponding to periods of rising temperatures. This is testified by the ~~lower frequency sampling~~

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~~of the Verdarolo reconstructed curve although uncertainty in comparison~~exceptionally high accumulation rate estimated on the recent period for the Units 4-5 (Fig. 6; section 4.3.), a rate of about 1 m/100 years calculated since ca. 1800 AD. The recent increased in flood activity is also supported by instrumental data ~~with reconstructed temperature data has been discussed before (Marcott et al. 2013).~~from Fig. 9, where we also observe an emerging trend (not yet significant though) of precipitation intensity increase (both as daily maximum and as monthly cumulative values) in the autumn months.

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~~This rise of temperature is associated also with a comparable unprecedented intensification of fluvial deposition, testified in the core, by the deposition of units 4 and 5, which marks the transition (in a short time) from marshy to fluvial sheet-flood deposits (Fig. 5). In fact, the recent sedimentation rate (computed from the core S1) is 1.27m/100y since 1850, that is 10 times higher than HTM (0.124 m/100y from 5455-9672 BP). In particular, whether the lower or upper end of the 2 sigma confidence level associated with the dating at 280cm depth (146-14 B.P.) is considered, the frequency of the coarse grained deposits (Unit 4 and 5 in figure kk), triggered hence by HIP, varies from a minimum of 5 events every 100 years to a maximum of 12 events every 100 years, respectively. This observation reinforces the trend of increasing precipitation intensity (both as daily maximum and as monthly cumulative values) that is already emerging in the autumn months from the instrumental data as shown in Fig. 9.~~

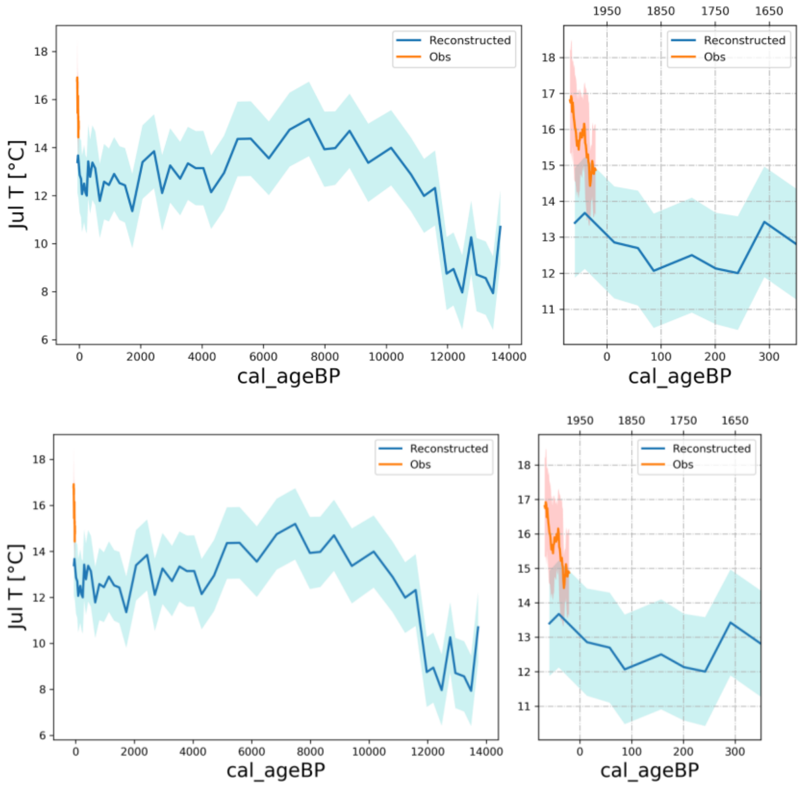

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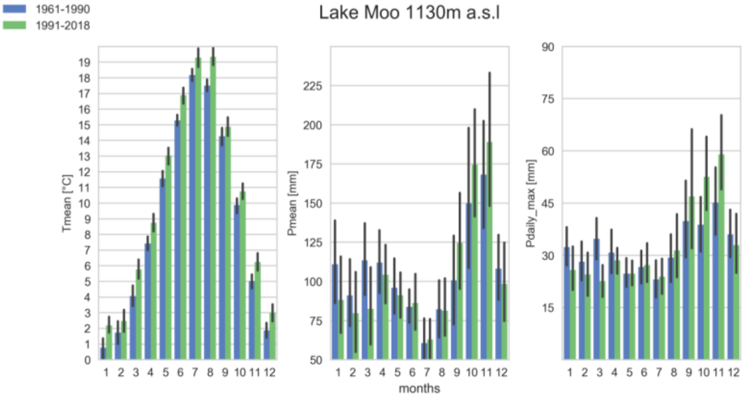
Figure 8. Comparison of current data and reconstructed July mean temperature at the Lake Verdarolo site~~.~~ (see Fig. 1 for location). The blue line is the reconstructed temperature and the shaded area is the sample-specific estimated standard error associated with the temperature reconstruction based on chironomid assemblage from Samartin et al. (2017). The orange line ~~represent~~represents the July mean temperature (1961-2018) retrieved for the grid cell of Lago Verdarolo from Emilia-Romagna climate reanalysis ERACLITO (11 years running average). The shaded orange area is +/- one standard deviation. ~~On the left the~~The full available period is reported on the left, while ~~on the right~~ a zoom on the most recent period ~~from~~(since 1600 AD~~ up to now~~) is shown on the right.



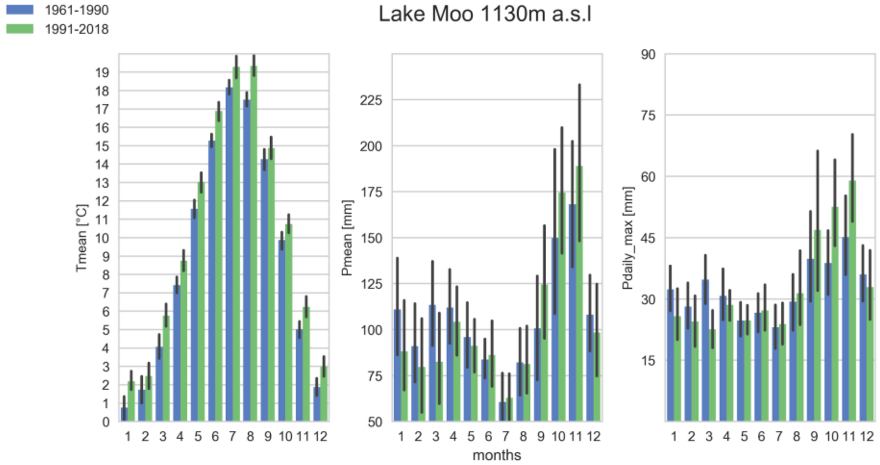


Figure 9. Monthly mean, 2m temperature (a), accumulated precipitation (b), maximum daily precipitation (c), for 1961-1990 (blue) and 1991-2018 (green) computed over Lake Moo site grid cell of Eraclito reanalysis (grid cell 258, Ferriere Municipality). Confidence intervals at 95% significance (black vertical segments) are computed with a bootstrapping method (1000 iterations) as part of the Seaborn python library.

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~~5.1 Detailed comparison on~~ *5.1. Holocene flood activity, paleotemperature changes and HIP events*

A positive link emerges correlating Holocene (July) paleotemperatures, precipitation intensity reconstructions and flood history (Fig. 7) at the study site, as the stratigraphic units showing the highest frequency of coarse-grained flood deposits (i.e., Units 2, 4 and 5) invariably fall into periods of higher temperatures (i.e., HTM and the post-LIA time). This strongly supports the hypothesis that a greater warmth favours the occurrence of extreme precipitation events, probably more frequent at the end of the Summer/Autumn as already reported by other authors (e.g., Marcott et al., 2013; Giguet-Covex et al., 2012). Although the process attribution and the geographical uniformity of the HTM wet phase are still matter of debate, the abundance of coarse-grained flood deposits within the Lake Moo record around 9.5-5.5 kyr BP suggests a precipitation increase also identified in other sites of the central and southern Mediterranean (Magny et al., 2012b).

However, local factors as changes in vegetation cover (i.e., tree cover percentage) due to human disturbance and fires could have significantly contributed to enhancing slope erosion and then influenced the Lake Moo sedimentary record, partly weakening our reconstruction of the temperature-HIP-flood activity relationship at the Holocene scale. In order to overcome this issue, we explored and compared the pollen and microcharcoal content of two key intervals ~~of the Holocene~~

~~In this section, we introduce the pollen data to fully exploit the multidisciplinary approach. As discussed in section 3.4, we focus on two specific intervals, (~~I_1 and I_2~~, synthesizing all available data for these periods in Fig.~~ in Figs. 7, 10~~.~~) that are characterised by a different flood record (high *versus* low flood activity) formed during consecutive periods of distinct climate conditions: the HTM and the following cooling. The difference in mean temperature between I_1 and I_2, obtained averaging the corresponding ~~samples~~chronological intervals in the ~~reconstructed temperature curve from~~ Verdarolo ~~site,~~ paleotemperature curve, is +1.3°C while the maximum difference ~~reach~~reaches +3.1°C~~.~~ (Fig.8).

For what concerns the post-LIA interval, and in particular since the 1950 AD, no significant contribution on debris mobilisation can be attributed to vegetation landscape changes along the slopes as the Lake Moo is a protected area characterised by dense forests (Corticelli et al., 2011; section 2.1.). Consistently, the most recent pollen sample (P14 yielding an age of 146-14 cal yr BP; Fig. 7) shows a tree cover of about 80%.

The main considerations arising from ~~this comparison are the following:~~

the in-depth analysis of I_1~~)~~ and I_2 are the ~~arboreal~~following:

- I_1 (ca. 9.5-7 kyr BP; 10.5-9 m core depth): the woody component ~~is always~~(i.e., tree cover %) is invariably higher than the herbaceous one~~, with an average~~ and it shows the remarkable value of 80~~.1%.~~% on average. The ~~presence of conifers with a prevalence of~~ Conifers, mainly represented by pines and silver fir ~~is significant compared~~, are dominant with respect to the deciduous ~~hardwoods. Conifers reach~~trees (e.g., *Corylus avellana* and *Quercus*), reaching a maximum of 95% ~~in P4 sample. The peak~~

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~~occurs during a relative cooling, just before the 8.2 event, in accordance with the bibliography (Allen et al., 2007; Kofler et al., 2005; Matero et al., 2017; Tinner and Lotter, 2001). Subsequently, samples P5 and P6 (HTM) show a decrease in the presence of conifers, respectively 64% and 45%, with a corresponding increase in deciduous species, from 1.5% in P4 to 20% in P5 and P6. This occur in response to warmer conditions and pluvial phase, as indicated by~~ within the P4 sample dated between 9.3-9.1 cal kyr BP. Interestingly, *Abies alba* shows the highest percentages (ca. 15-55%) within the chronological interval that corresponds to the warmest period of the HTM (Figs. 7, 10; Samartin et al., 2017). Moreover, *A. alba* reaches the peak of ca. 55% during the HTM wettest conditions (around 7.5-7.3 cal kyr B.P.; I_1 humid period in Fig. 7), as reconstructed by several Authors (Regatieri et al., 2014; ~~Zhornyak et al., 2011;~~ Zanchetta et al., 2011~~. It should also be noted the absence of species typical of umid environment (hygro+hydro in Fig.10), which suggests a high stationing of the lake-level. This confirms~~; Zhornyak et al., 2011) from the Apuan Alps speleothems. This trend is consistent with the fact that *A. alba* is a warm-temperature tree with a preference for high moisture availability (Tinner et al., 2013), as clearly documented within the nearby Lake Greppo record (Vescovi et al., 2010, confirming higher rainfall accumulation ~~in the period, in accordance with~~already highlighted by lake-level ~~evidence~~dynamics from Jura Mountains and the central-northern Italy ~~Magny et al. (2004, 2009, 2012). In P7 sample, we observe a new increase in conifers (75%) and a consequent reduction in deciduous trees (10%). These results~~(Magny et al., 2004, 2009, 2012). Although no specific inferences can be made on past water levels of the Lake Moo, it is interesting to note that the low amount of hygrophytes and aquatics (Fig. 7) is fully consistent with highstand conditions. Anthropic indicators taxa (Fig. 7), as well as the Anthropic Index (AI; Fig. 10), show very low values throughout the interval, documenting a negligible human impact on the area in accordance with the extremely low content in microcharcoals (0.01-0.13 mm^2/g; Fig. 10). Besides, the coarser microcharcoals (>125 micron) are not recorded suggesting no significant local fires. A slightly higher amount of anthropic indicators taxa occurs within the sample P6, dated between 8070-7880 ca yr BP; this is interpreted as an effect of categorisation difficulties about spontaneous taxa as *Artemisia vulgaris* type, *Chenopodium*, *Plantago*, *Urtica*, etc.

Palynological data, combined with the stratigraphic interpretation of the S1 core, ~~suggest that pluvial phase, in this period, had been characterized by a~~ support our hypothesis that warmer and wetter conditions typical of the HTM led to a high component of HIP~~. This can be deduced from the characteristics of~~ and then high flood activity in the basin ~~and~~, independently by local factors. Actually, the presence of an extensive vegetation cover ~~which~~along the slopes implies the need of even more intense rainfall to ~~able to trigger high flood activity (as recorded in~~ trigger a debris mobilisation that leads to the deposition of thick, coarse-grained layers containing pebble of remarkable diameters (LM6, LM7 and LM8 in Fig. 10).

- I_2 (ca. 5.5-3.8 kyr BP.; 5.5-4.5 m core depth): tree cover reduction (ranging between ca. 87.4-45.1 %; Figs. 7, 9), in favour of grassland expansion, characterises this interval that sees a fall in *A. alba* percentages (commonly less than 10%) and a remarkable amount of meadow taxa (mainly *Poaceae*,

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Cichorioideae and *Asteroideae*; Fig. 7). The growth in hygrophytes and aquatics (up to ca. 18.2%) is consistent with a marginal lacustrine environment and then a relative lowering of the water level. Both anthropic indicators taxa and AI increase, up to ca. 7.3% and 16.2% respectively (Figs. 7, 9), suggesting a moderate degree of human impact on the vegetation cover (i.e., tree cover changes). This impact is reasonably due to pastoral activities more than agriculture ones (few grains of cereals, less than 4%, are locally encountered), as documented by the abundance of meadow (pasture) taxa and the sporadic occurrence of coprophilous fungi and other spores (*Sporormiella*, *Dicrocoelium* and *Ascaris*; Figs. 7, 9). By contrast, microcharcoals remain very low in amount, pointing to a low fire activity. Although pollen-derived vegetation features (i.e., decrease in tree cover and a moderate degree of human impact) document local conditions more favorable for the debris flows activation with respect to those characterising I_1, this interval~~) in a dense vegetated area, with forest coverage that ranges from 65 to 97%.~~ shows a low past flood activity with few and thin (<5 cm) sandy deposits (LM9 to LM10 in Fig. 10). Integrating the I_2 stratigraphic record with pollen data, such a low flood activity reasonably reflects low frequency (and intensity) of HIP events during a cooler and less humid period (Figs. 7, 9).

The ~~thickness of coarse grained layers range from 30 and 13 cm with pebble-sands, crudely graded characterised by basal and top sharp contact. These coarse grained deposits are expressing of proximal facies (LM4 to LM6, in Fig. 10).~~paleoenvironmental-paleovegetation features characterising the Interval 2 persists upcore, in correspondence of the Unit 3 that records apparent flood inactivity (Figs. 3, 7). The uppermost sample P14 likely tracks a strong increment of *A. alba*.

- ~~I_2 instead is characterized by LM7 to LM8 distal facies from hyperpycnal flows, as a result of a low flood activity. The thickness layers do not exceed 5 cm and they are medium-fine sands. From a bibliographic point of view, this time interval is characterized by a cooling trend and dry conditions over the Mediterranean region occurred approximately between 4.2 – 3.9 ka BP (Regatieri et al., 2014; Zhornyak et al., 2011; Zanchetta et al., 2011, 2016), recently confirmed by a review paper of Bini et al. (2019). Further supporting these evidences low pluvial activity, pollen samples highlight a significant reduction of forest, whose coverage falls to a minimum of 30% (in P10 sample), in favour of a growth of grassland area (with maximum extension of 31% in P10) and hygro+hydro species (13.2%).~~

~~The increase of hygrophilous species, which double their presence, supports the hypothesis of reduction of the lake level, due to colonization of swampy areas which were forming as the lake level drop. Although the conditions in I_2 interval are favourable for the activation of hyperconcentrated flows (due to the lower vegetation cover), the low flood activity observed suggests a low frequency of HIP events.~~

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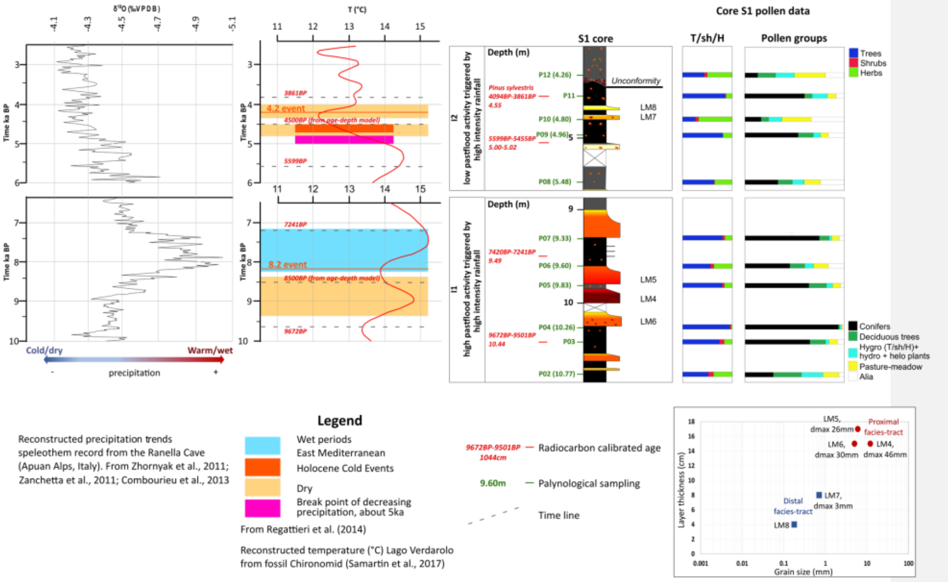

~~**Figura 10**. The stratigraphic intervals I_1 and I_2 from S1 core compared with the original pollinic data and the relevant climate proxy available from literature for the area of interest~~

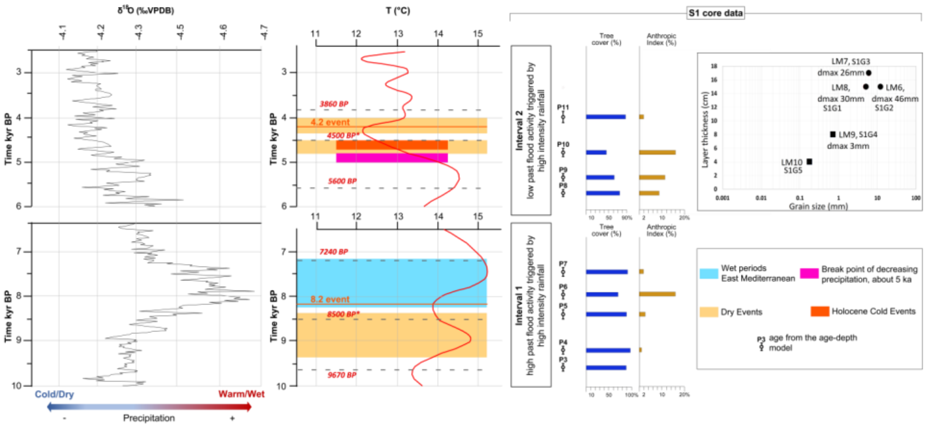

Figure 10. Sedimentological and palynological features of two key stratigraphic intervals (Intervals 1 and 2) from the reference core S1. These features are compared with the most relevant paleoclimate data available from literature for the area of interest (for references, please see Figure 7). The Anthropic Index (AI) has been calculated as: (Anthropic indicators/tree percentage)*100 following Accorsi et al. (1999). Asterisks point to samples containing coprophilous fungi and other spores like *Sporormiella*, *Dicrocoelium* and *Ascaris*. Core S1 sample ages derive from the age-depth model reported in Figure 6. P samples correspond to the pollen samples; LM labels refer to the lithofacies explained in text (section 4.1.) and in Figures 3-4; dmax corresponds to the maximum diameter.

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6. Conclusions

Placing present climate conditions into a geological perspective time, beyond the instrumental ~~record~~era, is ~~important~~essential for understanding changes in the hydrological cycle induced by anthropogenic climate warming, complementing projections of model ~~climate~~ simulations. Physical reasons and regional climate reconstructions are consistently pointing to an increase ~~of~~in precipitation intensity when water vapour is not limited ~~(Prein et al., 2017).~~. In the last decade, record-breaking rainfall events have ~~occurred~~ frequently occurred around the world~~, this~~. This trend is emerging with ~~different~~variable strength in different ~~area, and often, on the~~areas. The short timescale of the instrumental series~~,~~ doesn't allow yet to draw firm ~~conclusion.~~reconstructions. Therefore, in the attempt to consolidate confidence about the extreme precipitation trend, we extended our analysis, passing from the instrumental ~~time scale~~ to the geological time~~.~~ scale (i.e., the Holocene period). This choice implies a ~~strong~~robust multidisciplinary approach, which includes, in addition to climate and meteorological data, proxy and ~~competences~~competencies coming from geological, geomorphological, ~~stratigraphical, paleobotanical area.~~stratigraphic and palynological-microanthracological area. We acquired original data during a field ~~survey the months of June and July~~campaign performed in Summer 2017.

~~Here we can summarize the principal results:~~

The major outcomes of our work can be summarized as follows:

1) The matching of instrumental temperature data and ~~the~~ paleoenvironmental data allow us to affirm that ~~recent~~ current summer temperature ~~trends (over the period 1961-2018), and in particular those of the summer months (July), are in absolute terms the highest ever~~ is comparable with the temperature recorded in the Northern ~~Apennines with an estimated of~~Apennine during the HTM. The current temperature trend computed from the monthly values of July temperature at Lake Verdarolo site over the period 1961-2018 is +4.3°C/100y (highly statistically significant), ~~which~~and it is ~~four time higher than~~likely to be one the ~~maximum~~highest recorded ~~at~~in the ~~exit of last ice age (Younger Dryas).~~Holocene;

~~2) The~~

2) The stratigraphic units showing a high frequency of coarse-grained flood deposits are Units 2, deposited in the HTM, and Units 4 and 5 which belongs to the post-LIA time. Both periods are characterized by higher temperatures. The human impact is almost absent in the HTM and very low in the post-LIA time, especially in the last part of the 20th century. This strongly supports the hypothesis that a greater warmth favours the occurrence of extreme precipitation events. In particular, the recent sedimentation rate ~~(1.27m/100y~~computed since ~~1850) is 10 times higher than that observed during the HTM (0.124~~c.a. 1800 AD (post-LIA) is at least 1 m/~~100y from 5455-9672 BP) and therefore higher the previous warmer period. The observed~~ 100yr. This high value of the sedimentation ~~increase, and higher frequency of high flow discharge~~rate has to be correlated to the presence of numerous coarse-grained levels within Units 4 and 5, after a period of absence of floods deposits in unit 3b. This difference in flood layers must be linked to an increase of HIP over the Lake Moo basin, since we could not attribute it to any other changes in physiographic and vegetation ~~factors. The~~

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~~afforestation~~dynamics (i.e., tree cover). During HTM and current time, the forested area ~~for example, during HTM and in current time~~ coverage around Lake Moo persisted on high ~~percentage, a factor which should be detrimental for the mobilization of debris.~~ values and this factor is considered disadvantageous for debris mobilisation. On the contrary, during about 6-4 kyr BP we did not find any increase of coarse-grained layers from flood events, even though the forested area declined significantly and the anthropic impact increased;

3) HIP increase in response to higher temperature is already detectable in observation series~~, especially in seasons when moisture availability is not limited, like in Autumn (Brönnimann et al., 2018; Prein et al., 2017).~~. We found ~~evidences~~evidence that this also occurred ~~also~~ in the past, especially during HTM testified by higher deposition of ~~large size sediment in to the lake.~~coarse-grained levels. A comparison with the past ~~help understanding~~helps to understand future projections on the area~~, although~~. However, we are aware that past evolution cannot be taken as ~~an analogous~~a perfect analogy for the future due to the different forcing and consequent response of the climate system (D'Agostino et al~~.~~., 2019). As temperature will continue to increase ~~on~~in the Mediterranean area, precipitation intensity would keep increasing over the Northern ~~Apennine~~Apennines. We ~~hypothesize~~hypothesise that precipitation intensity increase will be more evident in months with cooler and moist air masses, like in Autumn ~~as it~~and in Winter, when moisture availability is not limited. An increase in precipitation maxima in Autumn months is already emerging ~~(see Fig.9), but gradually extending towards Winter. In summer, increasing conditions of moisture limitations will induce a decrease in frequency and intensity of precipitation (Dobrinski et al. 2016a and 2016b)~~on the Northern-Apennine.

~~4) The concept of facies tract (Lowe, 1982; Mutti et al., 1996; Zavala and Pan, 2018) applied here, may represent an important approach for activity flood~~

Finally, we would like to remark that Lake Moo basin represents an ideal study area to achieve a reconstruction ~~dynamics and may be applied to other peat-bog deposits to further strengthen and regionalize the signal.~~

~~Lake Moo site, in the Northern Apennine, was chosen~~between high-intensity precipitation and debris flow, for its ~~strategic geographical~~ position ~~with respect~~ to the dominant atmospheric flow ~~associated with heavy precipitation events. In addition to this, the site has the right~~and the favourable and undisturbed geological, geomorphological~~,~~ and vegetation characteristics~~, basin size (< 2 km^2), to achieve a strong and clear response between high intensity precipitation and debris flow triggering. For these reasons, Lake Moo basin represents an ideal study area which~~. We think this site deserves further ~~investigation~~investigations and, in association with other analogous sites along the Northern Apennine crest, could be used in the future to provide a multisite assessment on the ~~relation between past climatic conditions and the~~ dynamics of past ~~flood.~~ extreme precipitation events in relation with temperature variations.

Data availability: Original data concerning pollen and radiometric data are available on the open data repository of ARPAE Emilia-Romagna (https://arpaeprv.datamb.it/dataset/lake-moo)

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Author contribution: SS and FG developed the idea and the research activity planning and execution. SN, MA, MTDN have taken care of the administrative aspects. All authors, except for SN and MTDN, have contributed to field activity. Granulometric analysis has been conducted by AC. Pollen analysis have been conducted by SM and MM, data elaboration and figures were performed by VR, SM and MM. SS and FG and VR prepared the manuscript with contributions from all co-authors, FG management and coordination.

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