Author's response to Laura Sadori - "Holocene aridification trend interrupted by millennial- and centennial-scale climate fluctuations from a new sedimentary record from Padul (Sierra Nevada, southern Iberian Peninsula)"

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Firstly, we would like to thank to Laura Sadori for her comments and constructive suggestions, which will improve the manuscript, and for recommending this study for publication in Climate of the Past. Please find enclosed point by point responses to the comments.

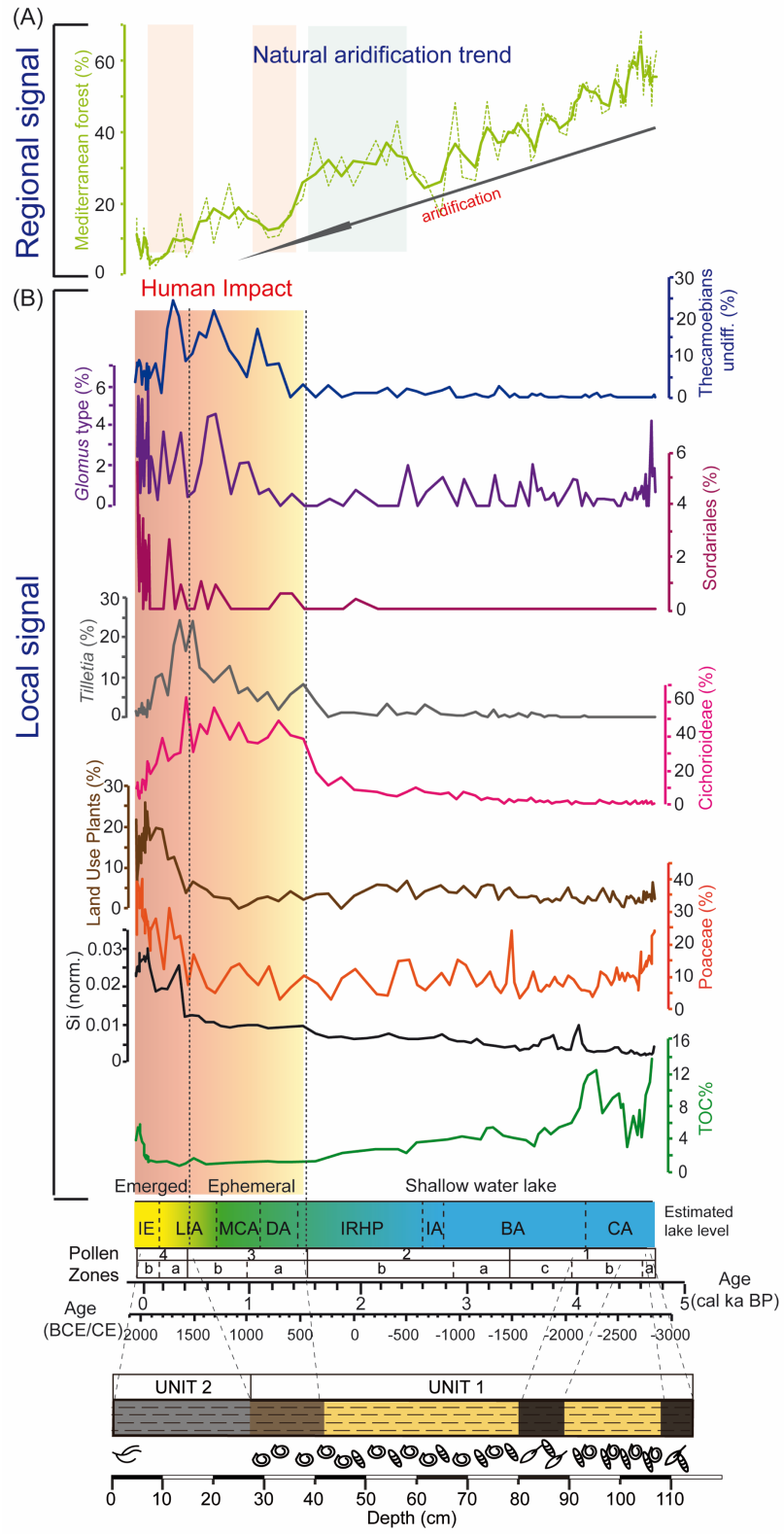
The referee suggestions and comments are displayed in black, and our answers in blue. We marked the lines over the MS that we are going to modify and we show the modifications (in inverted commas). In the case that we do not follow the reviewer suggestions we discuss the reasons.

General

I found the new data from Padul record, presented by María J. Ramos-Román and colleagues, quite important and necessary to improve our knowledge of the environmental history of the last 5000 years.
The chronology is very well assessed and the sediment and pollen data are consistent.
I was very surprised by the fact that such a multidisciplinary dataset is not used to disentangle between the two main drivers of deforestation in the Mediterranean region: human impact and climate forcing. The authors in fact start the interpretation with pollen, embracing the climate party, but they HAVE TO DEMONSTRATE THIS with clear data, and we have to admit that pollen alone is not enough. I suggest re-writing of interpretation and discussion under this light. I just noticed that this is also the main concern of the other reviewer, I totally agree with her. This is in fact a never- ending dilemma of Holocene palaeoecology: is it possible to separate the effects due to climate change and human impact in the pollen records of the last millennia? (see for example the discussion in Marignani et al., 2017. Plant Biosystems).
I want to add that my personal opinion is that climate is the most important factor in shaping the present landscape, but it is just an opinion if it is not clearly supported by data! Sometimes, in my personal experience, charcoal counting together with concentration data seemed to be resolutive (Sadori et al., 2004. The Holocene), but most times it is just the use of independent sediment and geochemical proxies (Giraudi

et al., 2011, The Holocene; Morellon et al., 2016. Quaternary Science Reviews; Sadori et al., 2016 Quaternary Science Reviews) that can disentangle drivers, solving the "dilemma". You have good data from your own record that can be used in this sense! I found that the comparisons with other sites are too many and not always meaningful, so that the reader gets lost. The references are mostly up to date, but the discussion present in the pollen community about the cause of the deforestation (aridification vs. increased land use) is completely ignored. It should be included. I do think that the paper absolutely deserves to be published, and I recommend publication in Climate of the Past, but just after the above mentioned issues will be assessed. Please have a look also at the file with my comments.

Thank you. We agree with your comment about the importance of disentangling human impact and climate forcing in this study. In our opinion the most important process shaping the environment in the area was climate as we do not have clear evidences of human activities in this record until the last 1500 cal yr BP. Humans left their footprint in the area since then, with indications of cultivars and livestock but still when we expect to see a significant forest reduction the deforestation trend continues to be linear and even opposite to what expected with slight increases in forest during the MCA. In this new version of the manuscript we inserted a new figure 8 (see bellow) trying to clarify and separate natural vs. anthropic signals. We hope that with this new figure together with some modifications and reorganizations of the text the reader gets a better idea of what we found in this record. Considering the importance of human activity in the area, notably for the last 1500 years, we modified the title for "Holocene aridification trend and human impact interrupted by millennial- and centennial-scale climate fluctuations from a new sedimentary record from Padul (Sierra Nevada, southern Iberian Peninsula)".



This is new Figure 8 that includes the Mediterranean forest, which we believe is mostly a regional climate proxy, and local human activity indicators such as cultivars (land use plants), fungi related with grain cultivation (*Tilletia*), livestock occurrence (most likely Thecamoebians, Cichoroideae, see text) and soil

erosion (Si, TOC, Glomus). Note the time when we have evidences of humans shaping the environment at ca. 1500 cal yr BP. Previously to that period there does not seem to be clear evidences of human impact in the area.

Comments

1/ Line 22: What is the source?

We try to clarify this later on in the MS:

Lines 410-418: "The decline in forest can be mostly explained as a decrease in winter rainfall as consequence to a reorganization of the general atmospheric circulation with a northward shift of the westerlies - a long-term enhanced positive NAO trend - inducing drier conditions in this area since 6000 cal yr BP (Magny et al., 2012). Furthermore, the decrease in summer insolation would produce a progressive cooling, with a reduction in the length of the growing season as well as a decrease in the sea-surface temperature (Marchal et al., 2002), generating a decrease in the land-sea contrast that would be reflected in a reduction of the wind system and a reduced precipitation gradient from sea to shore during the fall-winter season"

2/ Line 68: see also…

Thank you for the reference.

3/ Line 107-125: I would recommend the addition of species' authors

We appreciate this comment but we had to reorganize this part following one of the reviewer's comment to make it more synthetic and succinct and we believe adding the species' authors would make it too long.

4/ Line 154-170: same as above (vegetation)

See response to previous comment above.

5/ Line 236: here you have to quote the dates obtained for the published interval, that is 8. In the chapter on chronology assessment you have explained what you have used.

Thank you for the suggestion - we added this information in the MS.

Modification Line 235-237: "The age-model of the studied Padul-15-05 core (Fig. 2) shows that the top 115 cm, with an average sedimentation rate of 0.058 cm/yr, continuously cover approximately the last ca. 4700 cal yr BP being the age constrained by seven AMS ^{14}C dates (Table 1)"

6/ Line 269-270: As this work is a part of the complex study you are carrying out on this core, I suggest to number zones from the top to the bottom. In this way in the following you will be able to continue numbering…I also suggest to name the zone PA-1 (PA-1a, PA-1b for subzones). Can you imagine a future quotation of your paper with "zone Padul-15-05-1"? Isn't simpler and more effective PA-1?

It is a good idea. Thank you for the suggestion. We changed the names of the pollen zones throughout the MS.

7/ Line 296: better to use Thecamoebians undiff.

Thank you, we agree it is more appropriate. We will modify this throughout the MS.

8/ Line 341-342: this is true in absence of human pressure…human impact is overlapping to climate signals and the two are quite difficult to disentangle! To distinguish between them, especially in the last 5000 years, palynology needs to be confirmed by other evidences. This should be emphasized and it would explain the multi-proxy approach you used.

We agree with your comment. However, in this part of the text we are only trying to introduce the different proxies and how can they usually help us. Anyhow, we added some more information about how we tried to discriminate human impact in the area using the palynological proxies. We added the following modification to that part of the text:

Line 338-387: "Different proxies have been used in this study to interpret the paleoenvironmental and hydrodynamic changes recorded in the Padul peat bog sedimentary record during the last 4700 cal yr BP. Palynological analysis (pollen and NPP) is commonly used as a proxy for climate change, lake level variations and human impact and land uses (e.g. Faegri and Iversen, 1990; van Geel et al., 1983). Disentangling natural vs. anthropogenic effect on the environment in the last millennia is sometimes challenging but can be persuaded using a multi-proxy approach (e.g. Sadori et al., 2011; Roberts et al., 2011). In this study, we used the variations between Mediterranean forest taxa, xerophytes and algal communities for paleoclimatic variability and the occurrence of nitrophilous and ruderal plant communities and some NPPs for identifying human influence in the study area (Fig. 4). Variations in arboreal pollen (AP, including Mediterranean tree species) have previously been used in the Sierra Nevada records as a proxy for humidity changes (Jiménez-Moreno and Anderson, 2012; Ramos-Román et al., 2016). The abundance of the Mediterranean forest has been used as a proxy for climate change in other studies in the western Mediterranean region, with higher forest development generally meaning higher humidity (Fletcher et al., 2013; Fletcher and Sánchez-Goñi, 2008). On the other hand, increases in xerophyte pollen taxa (i.e., *Artemisia*, *Ephedra*, Amaranthaceae) have been used as an indication of aridity in this area (Anderson et al., 2011; Carrión et al., 2007).
The chlorophyceae alga *Botryococcus* sp. has been described as an indicator of freshwater environments, in relatively productive fens, temporary pools, ponds or lakes (Guy-Ohlson, 1992). The high visual and statistical correlation between *Botryococcus* from Padul-15-05 and North Atlantic temperature estimations (Bond et al., 2001; $r = -0.63$; $p < 0.0001$; between ca. 4700 to 1500 cal ka BP – the decreasing and very low *Botryococcus* occurrence in the last 1500 cal yr BP makes this correlation moderate: $r=-0.48$; $p < 0.0001$ between 4700 and -65 cal yr BP) seems to show that in this case *Botryococcus* is driven by temperature change and would reflect variations in lake productivity (increasing with warmer water temperatures). Nitrophilous and ruderal pollen taxa (*Convolvulus*, *Plantago lanceolata* type, Cannabaceae-Urticaceae type and/or *Polygonum avicularis* type) are also very useful as proxies for human impact (Riera et al., 2004). Amaranthaceae have also been related with enhanced human impact (Sadori et al., 2013). Some species of Cichorioideae have also been described in different studies from the Iberian Peninsula as nitrophilous taxa (Abel-Schaad and López-Sáez, 2013) and as grazing indicator (Sadori et al., 2016; Florenzano et al., 2015; Mercuri et al., 2006). At the same time, NPP taxa such as some coprophilous fungi, Sordariales and thecamoebians are also used as indicators of anthropization and land use (Carrión et al., 2007; Ejarque et al., 2015; van Geel et al., 1989; Riera et al., 2006). Tilletia a grass-parasitizing fungi has been described as an indicator of grass cultivation in other Iberian records (Carrión et al., 2001b). In this study we also used the NPP mycorrhizal fungus *Glomus* sp. as a proxy for erosive activity. This interpretation comes from different studies, which correlated erosive events with elevated percentages of *Glomus* (van Geel et al., 1989; Morellón et al., 2016; Sadori et al., 2016).
the palynological analysis, variations in the lithology, geochemistry and macrofossil remains (gastropod shells and charophytes) from the Padul-15-05 core helped us reconstruct the estimated lake level, local

environment changes in the Padul peat bog and their relationship with regional climate (Fig. 5). Several previous studies on Late Holocene lake records from the Iberian Peninsula show that lithological changes can be used as a proxy for lake level reconstruction (Martín-Puertas et al., 2011; Morellón et al., 2009; Riera et al., 2004). For example, carbonate sediments formed by biogenic remains of gastropods and charophytes are indicative of shallow lake waters (Riera et al., 2004). Furthermore, van Geel et al. (1983), described occurrences of *Mougeotia* and *Zygnema* type (Zygnemataceae) as typical of shallow water environments. The increase in organic matter accumulation deduced by TOC (and Br) could be considered as characteristic of high productivity (Kalugin et al., 2007) in these shallow water environments. On the other hand, increases in clastic input in lake sediments have been interpreted as due to lowering of lake level and more influence of terrestrial-fluvial deposition in a very shallow/ephemeral lake (Martín-Puertas et al., 2008). Nevertheless, in natural environments with potential interactions with human activities the increase in clastic deposition related with other indications of soil erosion (e.g. *Glomus sp.*) may be assigned to intensification in land use (Morellón et al., 2016; Sadori et al., 2016)."

9/ Line 346-347: It's not enough! A strong land-use can produce the same deforestation effect!

10/ Line 350: in the central Mediterranean the increase of Mediterranean vegetation occurring in the second half of the Holocene is taken as either the evidence of aridification (from mesophilous to sclerophylous vegetation) or as the result of increased grazing and cultivation

Yes, we agree and we worked on adding some more information and a new figure (Fig. 8) to clarify this question. See also modifications above and below where we try to clarify this matter. As you will see, this new figure 8 shows that human impact in the area does not seem to be evident until the last 1500 years and the Mediterranean forest dynamics point to a regional climatic signal of aridification that is also affected by millennial-scale climate variability rather than human impact.

11/ Line 352: they could either be the evidence of increased water salinity (Salicornia, Sarcocornia species) or of increased human impact (many Chenopodium species…) …

We agree with your suggestion and we added this to the MS. See modifications in answer to question 8.

12/ Line 362-367: These are the proxies you need to confirm your hypothesis based on pollen!

We clarify this in the modifications inserted related with question 8.

13/ Line 367: Cannabaceae-Urtycaceae type

Thank you. We corrected it.

14/ Line 380: See Mercuri

Thank you for the suggestions. We added this information to the MS. See modifications answering questions 8 and 23.

15/ Line 385-387: This interpretation is confirmed by other proxies in the pollen records from a very different areas such as the coastal ones of Butrint lake, Albania and of the Tiber delta, Italy

Thank you for your suggestions. We added these references to the MS. See previous modifications inserted answering question 8.

16/ Line 396-399: Again, a deforestation can produce the same effects… you need to emphasize climate proxies first, and then interpret the pollen record.

Ok, we worked on this – see previous comments and new Fig. 8 where we believe this is clarified.

Now it says:

"This natural progressive aridification is confirmed by the increase in siliciclastics pointing to a change towards ephemeral (even emerged) environments and became more prominent since the last ca. 1550 cal yr BP and then enhanced again in the last ca. 400 cal yr BP to Present. *Glomus*, a spore from mycorrhizal fungi that occur in soils (van Geel et al., 1989), follows a similar pattern of change, which probably points to enhanced soil erosion in the catchment area related with the decrease in forest in the surroundings during the last 1550 cal yr BP. A clear increase in human land use is also observed during the last 1500 cal yr BP (see below), which shows that humans were at least partially responsible for this sedimentary change."

17/ Line 401-403: you see… the two factors were probably overlapping. Who was the leading and starting one?
In my opinion (and in yours, I guess) it was climate, but this has to be demonstrated by independent data… that you, by the way, have.

In our opinion the most important process shaping the environment in the area was climate and we start recording human activities in this area in the last 1500 cal yr BP. We tried to clarify this matter in section 5.4 "human activity".

18/ Line 408: could be probably

We believe so.

19/ Line 418: what about grazing in such environments?

Yes, a signal of the presence of livestock was described is these alpine environments (i.e., *Sporormiella*) but in those studies there is not a clear signal of grazing affecting the local vegetation.

20/ Line 436-438: the ages appear to be quite different. Again, local human presence can mask climatic driving.

Yes, we agree in that there are age differences between sites but in this section we are talking about aridity pulses between 4.2 and 3.0 ka so those dates fall within those ages.

21/ Line 433: the date is not calibrated!

Thank you. We corrected that error.

22/ Line 446: this is the best global relation you can find! The age correspondance is quite good!

Yes, we agree. Thanks!

23/ Line 496: it's quite long! In other areas independent proxies found also humid pahses. You cannot explain every environmenta change ONLY with climate change!
Cichoriaeae have also other meaning, not just climate! Just think at pasturelands! See:

We agree and changed the title and discussion in this section. We also tried to concentrate everything concerning human impact in the "human activity" section. However, we still believe these changes are mostly produced by natural climate change and its variability. Reviewer#2 also made some questions about Cichorioideae. We have made some modifications in the MS in reference with to this matter.

Modifications-lines (495-498): "Enhanced aridity occurred right after the IRHP in the Padul peat bog area. This is deduced by a significant forest decline, with a prominent decrease in Mediterranean forest, increase in herbs and decline in the estimated water level…
Line (502) … Humans probably also contributed to enhancing deforestation and erosion in the area during this last ca. 1550 cal yr BP. The significant change during the transition from Unit 1 to Unit 2 with a decrease in the pollen concentration and the increase in Cichoroideae could also be due to enhanced pollen degradation as Cichoroideae have been found to be very resistant to pollen deterioration (Bottema, 1975). However, the occurrence of other pollen taxa (e.g. *Quercus*, Ericaceae, *Pinus,* Poaceae, *Olea*) showing climatic trends and a maximum between ca. 1500-400 cal yr BP and a decrease in this taxon in the last ca. 400 cal yr BP when an increase in clastic material occurred, do not entirely support a preservation issue (see section of Human activity; 5.4)."

Line (627 Human activities section): "This is deduced by a significant increase in nitrophilous plant taxa such as Cichorioideae, Convolvulaceae, Polygonaceae and *Plantago* and the increase in some NPP such as *Tilletia*, coprophilous fungi and thecamoebians (Unit 2; Pollen Zone 4; Fig. 4). Most of these pollen taxa and NPPs are described in other southern Iberian paleoenvironmental records as indicators of land uses, for instance, *Tilletia* and covarying Cichorioideae have been described as indicators of farming (e.g. Carrión et al., 2001b). Thecamoebians undiff. also show a similar trend and have also been detected in other areas being related to nutrient enrichment as consequence of livestock (Fig. 8). The stronger increase in Cichorioideae have also been described as indicators of animal grazing in areas subjected to intense use of the territory (Mercuri et al., 2006). Interestingly, these taxa began to decline around ca. 400 cal yr BP (~1550 CE), coinciding with the higher increase in detritic material into the basin. We could then interpret this increase in Cichorioideae by higher livestock activity in the surroundings of the lake during this period, which is supported by the increase in these other proxies related with animal husbandry."

Line (638): "This higher increase in detritic material occurred during an increase in other plants related with human land uses such as Polygonaceae, Amaranthacea, Convolvulaceae, *Plantago*, Apiaceae and Cannabaceae-Urticaceae type (Land Use Plants; Fig. 8) and the increase in Poaceae."

24/ Line 622: you have taken them as an evidence of climate change, see line 497. Again, you should use pollen data to cross check with sediment data. In that way you could be able to distinguish abut the two drivinf forces, humans and climate

Thank you for your suggestions. Yes, we agree in that we can not use the same taxa for explaining different processes and tried to be more consistent. Cichoroideae is now only discussed in the human activity section and only explained as a human activity proxy.

25/ Line 660-662: again, pollen can have a dual interpretation!

Yes, but in this record we strongly believe, and hope it is more clear in this new version of the manuscript, climate is the main factor controlling these changes until ca. 1500 years ago.