We acknowledge the detailed and constructive comments made by the reviewers. We mostly agree with the general views presented by them and we have made substantial changes to the manuscript and figures based on their suggestions. We also note that in some key questions the views presented by the reviewers differ, and we have tried to take such differing comments into account in our response in a balanced way. While revising the paper, we have also tried to control the length of the paper, including the number of citations. This understandably sets some limits to our responses.

First, there are some key issues raised by all three reviewers. We will first explain how we have responded to these and then provide a point-by-point response individually to all reviewers. The reviewer comments are in blue and our responses in black.

Modern pollen samples and the training set (calibration model)

All three reviewers point out that it is important to provide a more detailed description of the modern pollen samples used for the training set (or pollen-climate calibration model) in the paper. Reviewer 2 also stresses that the modern pollen data should be made available

> **R 1**: "I would be interested to read a little more about the training set used. Were the samples collected and analysed specifically for this study, or compiled from previous studies? Were the samples analysed by one person / one research group, or if not, how did the authors deal with harmonisation of pollen taxonomy? Are they confident that critical identifications such as evergreen vs deciduous Quercus have been made and recorded consistently?

> **R 2**: "Training set. The calibration data set is very small (236 samples). The study assumes that the entire Late Glacial to Holocene climate and related vegetation changes are to be found entirely in this sub-set of the current climate and vegetation of Spain. There are many thousands more modern pollen samples available from the European Modern Pollen Database, not only for Spain, but for adjoining areas which may offer more appropriate climate and vegetation analogues for the fossil samples. The authors actually cite the EMPD (Davis et al 2013), but do not provide an explanation as to why the rest of this data was not used..."

> **R 3**: "However, the description of the modern pollen dataset is too short and the discussion on the multi -method approach needs to be improved. The discussion is essentially based on the results of the WAPLS: why? This point must be justified. If the results of the Bayesien method are not robust, then yes, you can only discuss the WAPLS, otherwise you have to discuss both.

RESPONSE: We have added a more detailed description of the modern pollen samples on page 4 in “Data sources”. We explain that we selected modern pollen samples for the training set on the basis of few key criteria to make the training set as harmonized as possible. First, the procedure for sampling these selected modern pollen samples was standardized, so that all modern samples were collected by averaging the results of several moss polsters, as described in the paper. Second, all samples in our training set were treated in the laboratory and studied under the microscope by the same person (JALS), so the harmonization of the pollen taxonomy of these 236 selected pollen samples is ensured. The identification of critical pollen morphotypes, for example those in the Quercus genus, was carried out in a consistent manner. See, for example, the papers by López-Sáez et al. (2010, 2015) in this regard.

As for the number of samples (236) in our calibrating set, we do not consider it particularly small if compared to many other regional calibration sets used in pollen-based climate reconstructions. In such a regional calibration set it is possible to better control the quality of the samples (e.g. taxonomy, sedimentary context) than in datasets including thousands of samples collected from lakes, bogs, soils samples, pollen traps etc. Moreover, the idea of using a regional calibration set is that it is designed to provide a reasonable response model for key pollen types in the calibration set and the fossil data. In other words, the gradient of the climate variable of interest needs to be large enough to reflect the species response model. This should be the case in our Iberian calibration set, given the large gradient in precipitation from NW Spain to southern Spain. The transfer function techniques used in our paper, WAPLS and the Bayesian Bummer model, assume unimodal or Gaussian response models for the pollen types, although both are to some extent robust for other types of response models as well. Including more modern pollen samples from other regions (e.g. Central Europe or northern Europe or other continents) would influence the optima and tolerance values of the pollen types included in the calibration model and be subsequently reflected in the climate reconstruction. It is not clear to us how this would improve the calibration set or the reconstructions in our study.

As for the comment by reviewer 2 about the availability of the modern samples (“If samples were taken from the European Modern Pollen Database, or included in it, please include the full EMPD identity reference codes/numbers so that all of the samples can be identified. For any other samples it would be preferable if the pollen data was made available in the supplementary information or via submission to a public database or repository”), we can tell that all the samples included in this study were included in the EMPD many years ago by one of the authors (JALS). See the work of Davis et al. (2013), in which JALS is a coauthor. The majority of the 963 samples referred to Spain were contributed to the EMPD by JALS. In short, indeed the samples used in our study come from the EMPD but at the same time correspond to our own authorship.

CHANGES: page 4 in “Data sources” we added “All pollen samples in the training set were treated in the laboratory and analyzed under the microscope by the same person (JALS), to ensure the taxonomical harmonization of these 236 selected pollen samples. The identification of critical pollen morphotypes, for example those in the *Quercus* genus, was been carried out in a consistent manner (López-Sáez et al. (2010; 2015))."

Selection of the climate variables:

Second key issue raised by all reviewers is the selection of the climate variables

> **R 1**: "The authors have chosen to focus on precipitation as the target for reconstruction and they present some good reasons why precipitation should be a strong determinant of vegetation cover across the Iberian Peninsula. However, in order to advance the aforementioned debate, it would be helpful to demonstrate that precipitation indeed does a better job than other climatic variables such as summer and winter temperature at explaining the variance in the modern pollen data (variance partitioning)…."

> **R 2**: "You mention the complexity of the response of vegetation to climate. Is annual precipitation a reliable metric? The city of Paris gets around the same annual precipitation as Barcelona (630mm/year). Is it not growing season moisture that is more important in determining the response of vegetation to precipitation in a Mediterranean climate with hot dry summers and cool wet winters? Annual precipitation does not necessarily give any idea of the amount of growing season moisture"

> **R 3**: "Third point: this study does not propose a temperature reconstruction inferred from pollen: why? The authors assume that precipitation is the most important climate parameter, but this is not justified in a statistical point of view. Multivariate analyses would be required to prove the role of annual precipitation."

RESPONSE: This is indeed a crucially important question in our study, and, as a matter of fact, in all quantitative climate reconstructions. We have added some more explanation about the selection of the annual precipitation as the climate variable on page 5 ("Reconstruction of past climate variables") and added a citation to the study of Pasho et al. (2011) to the paper.

In our original paper, we acknowledged the importance of this question by stating that "The selection of the climate variable of interest is a critical step in quantitative climate reconstructions…". We also acknowledge that precipitation is not the only important climate variable influencing the vegetation composition, but that temperature is also important and, in some cases, the primary determinant. We write that "However, the summer temperature may also be an important factor especially at the high altitudes (Vidal-Macua et al., 2017").

There is ample biogeographical and plant ecological evidence for the importance of precipitation for the large-scale features of vegetation composition and structure in the Iberian Peninsula. We cite some of these studies in our paper (Pasho et al. 2011; Vicente-Serrano et al. 2014; Vidal-Maqua et al. 2017), and much more have been published. Many studies have shown previously that especially in xeric Mediterranean areas tree growth is mainly limited by low precipitation, while more humid regions, including the mesic Mediterranean areas and sites at higher altitude where precipitation is generally higher, the main factor constraining growth is low temperature (Vicente-Serrano, 2007; Pasho et al. 2011). Our sites are not from the high altitudes (all below 1.5 km, Table 1 in our paper), which lends support for water availability as an important variable.

As for the selection of annual precipitation instead of some other variables related to water availability, we agree with the reviewers that a more bioclimatic climate variables, such as effective precipitation or even Palmer's drought severity index, can be more informative variable. However, in the relatively small research areas such as the Iberian Peninsula, precipitation and effective precipitation are correlated and aligned with the main vegetation patterns – the highest precipitation and effective precipitation are on the W and NW coast, and the lowest in S and SE Spain. Thus the reconstructed main trends for these two correlated climate variables would be generally similar.

A statistical test about the importance of different variables in the calibration set (as suggested by R 1 and R 3) would be possible, but that would require testing many different climate variables (e.g. summer temperature, winter temperature (or temperature of the coldest month), sum of degree days, summer precipitation, winter precipitation, actual/potential evaporation ratio etc.) using for example constrained ordination techniques and hierarchical partitioning. However, exploring these questions more in detail in our paper would shift the focus of the paper and would thus require a separate paper focusing only on the modern pollen samples and the calibration set based on them.

Finally, it is useful to remind that the starting point for our paper was the fact that a number of lake-level reconstructions have been recently published from the Iberian Peninsula (see Fig 7 in our paper). Our study was designed to test and validate these humidity records with pollen-based precipitation reconstructions. This does not mean that temperature would not be an important factor or that pollen-based temperature reconstructions from the region would be flawed or biased. We thus do not see any disagreement between our selection of annual precipitation as the climate variable and the views presented by the reviewers – our impression is that we all see precipitation as a critically important climate variable in pollen-based climate reconstructions in the Iberian Peninsula, but do not rule out the importance of temperature either.

CHANGES: We have added some more explanation about the selection of the annual precipitation as the climate variable on page 5 ("Reconstruction of past climate variables") and added a citation to the study of Pasho et al. (2011) to the paper.

Selection of the seven fossil sites

The reviewers ask us to provide justification why these seven fossil records were selected for climate reconstructions

> **R 1**: "Finally, I would be interested to know why the authors chose these seven sites for this study and not a wider set."

> **R 2**: "Both Mauri et al 2015 and Tarroso et al 2016 used many more pollen sites from the region to reconstruct precipitation, since many more are available from the EPD. Can you explain why and how you chose your sites, and the basis of you reasoning for excluding the ones that you did."

> **R 3**: "The choice of the 7 fossil pollen data should be explained and justified; for example, why did you only choose Quintanar de la Sierra, as the sequence which cover the Lateglacial while other pollen records are available in the EPD?"

RESPONSE: We have added a more detailed description on the selection of the fossil records (page 4 in "Data sources"). We now explain that the idea of this work, from its beginnings, was to make a palaeoclimatic reconstruction following a north-south transect in the Iberian Peninsula, to be able to compare humidity trends between the wetter territories of the north and what currently are semi-desert conditions in the southeast. Such a steep precipitation and humidity gradient is exclusive to the Iberian Peninsula on a European scale. Of the Iberian fossil records included in the EPD, we chose the pollen diagrams with a reasonably good chronological resolution. Moreover, the diagrams were selected so that they encompassed most of the Holocene, and if possible, Late Pleistocene with a reasonably reliable chronological control.

Of those currently available in the EPD, the seven records included are the only ones that meet these requirements. Of course, we would have liked to include key records for the knowledge of the palaeoclimate of southern Iberian Peninsula, particularly the Padul record, but unfortunately these data are not currently available. It is true that some other records could have been included, in the case of Ayoó de Vidriales or Xan de Llamas, but we believe that the chosen ones represent the Iberian climatic and biogeographical variability amply. Our study includes records near the north coast (Monte Areo), located in internal valleys also in the north (Alto de la Espina), and in northern mountains (Zalama); also in northern Mediterranean mountains of the Iberian System (Quintanar de la Sierra) or in central Mediterranean mountains of the Iberian Central System (El Maíllo), in the Mediterranean region, in the peninsular east and not far from the influence of the Mediterranean sea (Navarrés), and finally in territories currently semi-desert in the southeast (San Rafael). We consider that the choice of these seven fossil records is adequate and represents adequately the climatic and biogeographical variability of the Iberian Peninsula

CHANGES: page 4 in "Data sources" we added "These records were selected as they represent different climatic regions of the Iberian Peninsula from the more humid northwestern parts to the dry regions in the south."

Mid-Holocene temperature trends

In our paper, we mention the ongoing discussion about the mid-Holocene temperature patterns in the Mediterranean region. All three reviewers comment on this question:

> **R 1: "**The paper sets out an aim of testing "contrasting interpretations" (p2, line 34) about Holocene climatic conditions, citing the works of Mauri et al., 2015 and Samartin et al., 2017. As far as I understand it, the discrepancy between these cited studies relates to the timing of maximum summer warmth during the Holocene and contrasts between previous pollen- and chironomid- reconstructions for the (western and central) Mediterranean region. I think this discrepancy should be spelled out more clearly in the introduction because some readers may not be familiar with that debate"

> **R 2: "**The Mediterranean is a big place. Samartin et al 2017 provide evidence of summer warming from 2 small adjacent lakes high in the northern Italian Apennines. This is not controversial, nor does it challenge previous work, nor should it necessarily provide support for climate models…"

> **R 3:** "I don't understand why the authors discuss the paper by Samartin et al, (2017) which is based on two chironomids records located at high elevation sites in northern Apennines; this paper focus on the reconstruction of the temperature of July while the aim of the paper of Ilvonen is to reconstruct precipitations. Moreover, the Tjuly reconstructed values are based on a modern chironomids dataset with only samples from Scandinavian and Alps; it's not comparable to Mediterranean taxa! So please avoid this discussion, or provide Tjuly reconstruction from pollen and discuss it."

RESPONSE: We note that here the reviewers' comment diverge, with reviewer 1 suggesting spelling out the question more clearly in the paper and reviewer 3 suggesting omitting it from the paper.

We write in our paper that "*We did not aim to use pollen data for summer temperature reconstructions for the reasons explained earlier, and our results do not contribute directly to this debate, but in general we agree with these authors in that the predominant driver of vegetation patterns in the Mediterranean region is water availability and not summer temperature, and this is a fact which must be borne in mind when assessing any feature in pollen-based temperature* *reconstructions in this region*." As this sentence indicates, we recognize that our data is not directly relevant for this debate, and we are certainly not trying to solve this question in our paper, mostly because we agree with R 2 who points out that the Mediterranean is a big place. Exploring this question would require a dataset that would cover all parts of the Mediterranean basin.

However, we also believe that information on temperature patterns in the Holocene are relevant when using pollen data for precipitation or lake-level data for humidity reconstructions. In response to R 3, we state that the Samartin et al. (2017) paper does not only show two chironomid-based summer temperature reconstructions from Italy, but also two model simulations for summer temperature based on two different models. Thus, the question about the mid-Holocene summer temperature conditions in the Mediterranean region is also relevant from the point of feasibility of palaeoclimate model simulations. For these reasons, we have retained our original text about the Samartin et al. (2017) paper in our revised version.

Earlier data

All reviewers point out that there are many earlier Late Pleistocene and Holocene climate reconstructions from the Iberian Peninsula and suggest many additional papers to be cited.

> **R 1**: "Regarding the point that "accurately dated high-resolution pollen records are needed" – the authors could make reference here to works by Combourieu Nebout et al. (2009) and Fletcher et al. (2010) which do identify vegetation changes in forest cover for SE Iberia around the 8.2 ka event and also give quantitative estimates for PANN anomalies associated with this events."

> **R 2**: "Recognition and comparison with earlier work. This is not the first pollen-based precipitation reconstruction for the region. The authors briefly mention some of these studies, but do not make a comparison despite the fact the data is publicly available."

> **R 3:** "A lot of references on past climate changes in the Mediterranean area are missing; they are needed to improve the discussion: Combourieu-Nebout et al., 2013; Bini et al., 2019; Peyron et al., 2013, Magny et al., 2013, Moreno et al., 2017…)."

RESPONSE: Indeed there are many earlier studies, and we have done our best to cite these papers. At the same time we have tried to keep the paper relatively short, and hence to we do aim to exhaustively cite papers from the other parts of the Mediterranean basin.

CHANGES: In response to this comment we have added references to the older papers (e.g. Combourieu-Nebout et al. 2009 on page 2). Peñalba et al. (1997) was already cited in our original paper, but we have added the following text to page 4. "The pollen data from Quintanar de la Sierra have been used earlier for quantitative climate reconstructions by Peñalba et al. (1997)".

Responses to comments by R 1

> "I'd also be interested to know whether the authors considered a drought severity index (e.g. scPDSI), aridity index (e.g. PANN/PET) or soil moisture index (alpha) (see e.g. Dai, 2011; Cramer and Prentice 1988). Ultimately, temperature and precipitation should interact to determine moisture stress for plant life, most notably during the drought season where the precipitation input is lowest and the evaporative demand is greatest. Conceptually at least, a moisture index might perform better than precipitation alone as a predictor for vegetation composition".

RESPONSE: We agree with R 1 that temperature and precipitation interact to determine the moisture stress for plant life and that these two climate variables are correlated, at least at low altitudes, so that the drought is most severe when the precipitation is low and temperature is high. However, our reconstruction extends to 15 ka, and we are hesitant to argue that this interaction and correlations extend to the Late Pleistocene period 15 ka to 12 ka. It is possible that during the Late Pleistocene the climate may have been both dry (low precipitation) and cold.

> "The methodology described for "averaging" across multiple moss polsters at each site is quite distinctive and I wonder whether the signal derived in this way has been evaluated in any particular previous work?"

RESPONSE: As the reviewer states, averaging across multiple samples is a common procedure when surface soil samples are used for modern pollen samples. We used the method with our moss polsters to derive a pollen signal which is not too much biased by extremely local features of one moss polster. We are not aware of any evaluation of this sampling stratigraphy with moss polsters.

> "My overall impression from the seven reconstructions is one of heterogeneity in the results – and I do not find all of the synthesis statements and descriptions of the findings entirely convincing. For example, the "synchronous rise of Pann values" around 11000 cal yr BP is not so clearly evident. I think that the paper could benefit from some further approaches/efforts to illustrate the common patterns (and site specific differences) better. The use of coloured bars indicating formal stratigraphical division of the Pleistocene, Early, Mid and Late Holocene in figures 4 and 5 doesn't help the reade to visualise where each record reaches maxima, minima, etc. It might be more helpful to colour code each record into above and below average sections, ±1/2 standard deviations around the mean, for example."

RESPONSE, CHANGES: To make the figures more informative, we have added vertical stippled lines to indicate the mean value of each reconstruction to Figs. 4 and 5.

In order to show the times with statistically significant decrease or increase in the Pann values with respect to both location and scale (meaning "level of smoothing" that is "bandwidth") we now provide a SiZer analysis by Chaudhuri and Marron (1999) for the WA-PLS reconstructions in the supplement. We have added a supplement figure (Fig. S3) which shows the SiZer maps and in supplement Table S2 we now explain the main findings from Figure S3. On page 7 we have now added the following text "To show the statistically significant features in the WA-PLS reconstructions, the SiZer analysis was carried out (Fig. S3 and Table S2) (Chaudhuri and Marron, 1999)."

"Going further, it might be valuable to support the written statements, for example about the declining general trend of Pann over the last 5000 years, with numerical summaries or boxplots for the different intervals to illustrate these patterns and help convince the reader that they are robustly expressed and significantly different from other intervals."

"Related to this previous point, it seems that the discussion is quite rigidly organized around chronostratigraphical subdivisions, even where there is limited relevant data, e.g. one reconstruction only pertaining to the Lateglacial (cf. section 3.3.1), no signatures of the 8.2 event (cf. section 3.3.3). The authors might seek to emphasise the new contribution resulting from the new reconstructions, focusing more on both commonalities and individual features with respect to the range of values, timing of maxima and minima, patterns of variability, etc."

RESPONSE: Results of the SiZer analysis (Fig. S3 and Table S2) show the declining trend over the last 5000 years in four of our records (Monte Areo, Alto de la Espina, Quintar de la Sierra and San Rafael). Furthermore, the SiZer maps also show values for maxima and minima (color changes from red to blue or from blue to red).

CHANGES: Added "Fig. S3 and Table S2" on page 11.

1. Page 1, line 19 "100% higher" – does this mean "double"?

RESPONSE: Yes

2. Page 1, line 21-24. "In general, our results suggest that. . ." – the manuscript does not really return to this overarching parallel between warm high latitude and humid Iberian conditions explicitly in the discussion or conclusions. It would be good to develop this further, and consider a possible climatological mechanism for the connection.

RESPONSE: Yes, but this would require using palaeoclimate modeling to understand the possible climatic mechanisms and atmospheric and oceanic processes that can explain the links between the Iberian Peninsula and the European high latitudes. In the current paper our main aim is to report the reconstructed precipitation trends, and more thorough analyses of these processes can be done in future papers in collaboration with modellers.

3. Page 2, line 1 – I'm not sure the Mediterranean can itself be the transition area from Atlantic to Mediterranean – needs some rewording

RESPONSE, CHANGES: Corrected to "The Iberian Peninsula is one of such regions…".

4. Page 2, line 29 – give select references for the type of climate variability or events implied here

RESPONSE, CHANGES: References added to Heiri et al. (2014) and Rasmussen et al. (2014)

5. Page 2, line 33 – expand on "contrasting interpretations" to clarify what this study is seeking to test

RESPONSE, CHANGES: We have changed "the mid-Holocene climatic conditions" to "the mid-Holocene temperature conditions". For more a thorough discussion, please see our response earlier in "Mid Holocene temperature trends".

6. Page 3, line 4 – can reconstructions be "fragmentary"? perhaps better "rare" or "sparse"?

RESPONSE, CHANGES: Changed to "sparse"

7. Page 3, line 12 – the paper drifts in usage between Iberian Peninsula and Spain – better to stick to one or the other, probably IP as the geographical entity. Here, for example, the surface area of Spain as a country seems irrelevant.

RESPONSE, CHANGES: Changed to "Iberian Peninsula" when we mean the whole region.

8. Page 3, line19 – "south and east"?

RESPONSE, CHANGES: Corrected

9. Page 4, Line 19 – in Figure 1 indicate where the Eurosiberian and Mediterranean regions are.

RESPONSE, CHANGES: The white line in Fig. 1 indicates the boundary between these two regions (added to the figure caption).

10. Page 5, Lines 14-15 “Given that our seven pollen records. . .” – the reads as though the decision to reconstruct precipitation was a function of the availability of records, but surely the scientific aim was to reconstruct precipitation and the sites were selected accordingly? Reword according to the intended meaning.

RESPONSE, CHANGES: Modified to “The seven pollen records were selected from altitude lower than 1500 m a.s.l.,…”

11. Page 6, Section 3.1 There are quite strong linear patterns in the residuals shown in Figure 3, which are not discussed in the paper – are these linked to temperature, site elevation, etc? The authors should comment on this and the implications for the reconstructions.

RESPONSE: We explored this to some extend by checking the modern geographical location, site elevation and modern precipitation of the sites in our calibration model. We observed that most sites with biggest residual values are located at the higher end of the precipitation gradient. However, there are also some outlier sites at lower precipitation. We do not observe any specific site elevation or geographical location that would explain the outliers. Thus we cannot provide a simple explanation for the residuals but we suspect that one factor is the difficulty to obtain accurate modern precipitation values for the sites. The other possible contributing factor is the well-documented edge effect typical to WAPLS, often leading to underestimated modern values at the higher end of the calibration models (see for example Juggins and Birks 2012).

12. Page 7, line 13. “summer temperature records” indicate from where (geographically).

RESPONSE, CHANGES: Changed to “…records from southwestern Europe”

13. Section 3.3.1. This section is rather long relative to the amount of new contribution from the one site – can it be made more concise? The relevance of the section on Fagus on Page 8 is not clear, for example.

RESPONSE, CHANGES: Shortened by deleting one sentence.

14. Page 8, lines 13 and 18 – what is the difference between “steppe vegetation” and “open vegetation” with respect to the implied contrast “By contrast. . .”?

RESPONSE, CHANGES: “By contrast” deleted

15. Page 9, lines 8-13. I don’t really follow how a “synchronous rise in Pann” is shown at Quintanar, San Rafael and Navarrés-3 at 11000 cal yr BP when the latter two records begin around that time and don’t show any rise as such – need to clarify the key finding here

RESPONSE, CHANGES: Changed to “the high Pann values in the early Holocene around…”

16. Section 3.3.3. It’s not entirely clear to me that this section is merited. The 8.2 ka event has not been introduced in the manuscript as a particular focus of interest, and it would require careful justification in any case with respect to the sampling resolution and age uncertainties of the selected records to demonstrate that this impact could really be tested or detected with the available records. In the end there is no substantial contribution of this study in relation to this event. Regarding the point that “accurately dated high-resolution pollen records are needed” – the authors could make reference here to works by Combourieu Nebout et al. (2009) and Fletcher et al. (2010) which do identify vegetation changes in forest cover for SE Iberia around the 8.2 ka event and also give quantitative estimates for PANN anomalies associated with this events.

RESPONSE: The 8.2 ka event is not a particular focus of interest in our paper, but we find it important to mention it briefly because it has been recently intensively discussed in the Mediterranean region and because some of our records indicate a slight reduction in Pann at 8400-7900 cal yr BP, possibly (but not firmly) suggesting this event in our results (e.g. Fig. 4). By stating that more high-resolution pollen records would be needed to investigate this event, we refer to studies that would particularly focus on the time period 8400-7900 cal yr BP, with sub-centennial time resolution.

17. Page 10, Line 27. Given that the main finding of the Renssen et al. (2009) work cited was spatial and temporal complexity and variability in the Holocene Thermal Maximum, I think the simple equivalence of the high Pann interval in Iberia and the high latitude HTM isn’t immediately comprehensible here and should be more precisely described and discussed.

RESPONSE: We agree that such a discussion would be relevant, but it would expand the paper substantially and require incorporating the palaeoclimate model simulations in the study to understand the atmospheric and oceanic processes that can drive the temperature and precipitation trends in N and S Europe. We consider that it is best to focus on pollen-based Pann results in the current paper.

18. Page 11, lines 22-28, the authors discuss human impact during the last 500 years, but then evidence agricultural activity since 7500 cal yr BP – it doesn't seem quite related in terms of the timescale or cultural setting; please clarify/prioritise whether this section is about the long record of human activity or the intensification of disturbance in recent centuries

RESPONSE: The evidence for the beginning of agriculture in general dates to roughly 7500 cal yr BP and the text about the intense human impact on vegetation refers to the local vegetation around the Monte Areo site (We write that "*The drop of reconstructed Pann from 1500 mm to under 600 mm during the last 500 years in the Monte Areo record is an extreme example of this pattern*")

19. Conclusions – the authors emphasise "strong spatial and latitudinal gradient during last 15 thousand years" – this gradient may be implicit but hasn't really been discussed or illustrated – this should be developed in the discussion to justify it as a conclusion.

RESPONSE: The spatial and latitudinal gradient is reflected in Pann differences between the sites located in the dry regions in the South and Southeast (max. Holocene Pann in Navarrés 3 and San Rafael under 600 mm) as compared to the sites in the Eurosiberian region in the North and Northwest, with Pann over 1000 mm during the most humid periods. These features can be seen in Figs. 4 and 5.

20. Conclusions – for the finding that the "Late Pleistocene is characterized by rapid shifts in Pann values" the authors should indicate that this is based on one site only

RESPONSE: Yes, there is only one new record in our paper, but we think that in general there exist a wealth of evidence for rapid Pann or humidity changes in the Late Pleistocene in the region.

21. Figure 1 – it would be helpful to indicate the site locations for other data presented in the paper, such as the lake records shown in Figures 6 and 7

RESPONSE, CHANGES: We have added the site locations for the lake records shown in Fig. 7.

Responses to the comments by R 2

1. Recognition and comparison with earlier work. This is not the first pollen-based precipitation reconstruction for the region.

RESPONSE: Please see our response to general comments "Earlier data" on page 7.

However, we also agree with reviewer 1 who argues that "*Also, in light of the strong environmental gradients and climatic diversity of the Iberian Peninsula, it is surprising that there are relatively few studies to date exploring climate reconstruction with this specific geographical focus*."

3. Human impact.

and

4. Data transparency.

RESPONSE: Will be answered below in detailed comments.

5. Evaluation. The authors compare their pollen-based precipitation reconstructions with lake level records, but the records are few, fragmentary, and much of it involves qualitative discussion. As it stands this study is relatively weak in the sense that there have already been previous pollen-based precipitation reconstructions for the region that are in many ways more comprehensive. A good way to strengthen the paper would be to provide a more comprehensive review of precipitation records in general, including lake level data. Morellon et al (2018) provide a good example of lake level synthesis which the authors partially reproduce in figure 70 p30. Morellon et al (2018) only look at the period 8-13k, but the authors here could extend this to encompass the entire Holocene. There are also plenty of lake level reconstructions that Morellon et al (2018) do not include such as Sanchez Goni, Las Pardillas (1999) (doi: 10.1191/095968399671230625, table 4), Davis et al, Los Monegros (doi:10.1016/j.quascirev.2007.04.007, figure 8) and Reed et al, Laguna Medina (doi:10.1191/09596830195735, figure 7).

RESPONSE: Fig. 7 in our paper also include a lake-level curve from Lake Estanya for the whole study period (15-0 ka) from Morellon et al. (2009). The lake-level reconstructions suggested by the reviewer do not encompass the whole Holocene; The reconstruction in Davis et al. (2007) period 10,500-5500 cal yr BP and Reed et al (2001) period 9000-0 cal yr BP. Sanchez-Goni & Hannon (1999) show a table indicating periods with high and low lake level from Las Pardillas Lake, but it would be difficult to convert such data to any form of a curve with a scale.

CHANGES: We note that the results of these three papers generally agree with our results, and we have added citations to them to the paper. We have modified the text (page 10 and 11) where we now write that "The more humid early-to Mid-Holocene conditions are also reported in the studies based on the two saline lakes in the Central Ebro desert (Davis & Stephenson, 2007)" and "In the southern Iberian Peninsula, the lake-level reconstruction from Laguna de Medina in SW Spain suggests humidity maximum at 7000-6000, followed by a steady decline (Reed et al. 2001), while in the multi-proxy dataset from the Padul wetland in Sierra Nevada the period with highest humidity has been dated to 9500-7600 cal yr BP (Ramos-Román et al. 2018a)"

Detailed comments:

> P2, line 5-6: Mediterranean climate is specifically characterized by wet winters and dry (growing season) summers, not 'dry and wet seasons'

RESPONSE, CHANGES: Corrected

> P2, line 21: what is a 'synthetic climate reconstruction'?

RESPONSE, CHANGES: Corrected (synthetic deleted)

> P2, line 22: there are lots of other studies you could mention..

RESPONSE: Please see our response to general comments part "Earlier data" on page 7.

> P3, line 30: Why only 236 samples?

RESPONSE: Please see our response to general comments part "Modern pollen samples and the training set (calibration model)" on pages 1-3.

> P3, line 31: Please provide as a minimum the condensed list of taxa that were used in the transfer function, and preferably also the full taxa list showing how all taxa were assigned to the condensed list used in the transfer function. In addition, please explain how you chose the particular taxa in the condensed taxa list used in the transferfunction.

RESPONSE: All data used in our reconstructions are freely available from the authors, including a full list of taxa and the pollen and spore values. We consider this a better alternative than the taxa list only. Note that we used all terrestrial pollen and spores types (taxa) in our reconstructions.

P4, line 12-13: Please provide a full list of the 236 modern pollen samples that were used, their location (lat, long and elevation) and the rainfall values assigned to these locations. A maximum of 1327mm/year seems quite low considering how wet the temperate parts of Iberia can get, and also considering the need for representative analogues for the temperate vegetation that dominated many Mediterranean areas in the early-mid Holocene.

RESPONSE, CHANGES: The full list of modern pollen samples (lat, long, rainfall values) is already available at http://dx.doi.org/10.17632/4pznttrd4h.1. We added the elevation information to that data. Please see also our response to general comments part "Modern pollen samples and the training set (calibration model)" on pages 1-3. Furthermore, all data used in our reconstructions are freely available from the authors.

P4, line 12-13: If samples were taken from the European Modern Pollen Database, or included in it, please include the full EMPD identity reference codes/numbers so that all of the samples can be identified. For any other samples it would be preferable if the pollen data was made available in the supplementary information or via submission toa public database or repository.

PESPONSE: Please see our response to general comments part "Modern pollen samples and the training set (calibration model)" on pages 1-3.

P4, line 15-19: Can you identify in the table of sites, or in the supplementary information, the exact entities (you need the EPD entity reference code) and chronologies (some sites have multiple chronologies or choice of control points) you used for the EPD sites so that the primary date can be identified. For the remaining sites please specify the exact source (author or Paleodiversitas) for each of the sites in the same table. Can you also specify whether any of this data has been made public, and where this data can be downloaded. For the data that is not public, it would be preferable if it was included in the supplementary information, as well as being submitted to the EPD.

RESPONSE: Please see our response to general comments part "Modern pollen samples and the training set (calibration model)" on pages 1-3 and "Selection of the seven fossil sites" on page 5. As we write *"The chronologies of all sites are based on radiocarbon dating. In order to produce chronology for each fossil pollen record we used Bayesian age-depth model called Bchron (Haslett and Parnell, 2008). Bchron first calibrates radiocarbon dates with a calibration curve (IntCal13) and then fits the age-depth model, which is consistent with the calibrated radiocarbon dates. Assumptions for the* *age-depth model are continuous, monotone and piecewise linear age-depth dependence. The age for the uppermost sediment of the core was assumed to be the year when the core was extracted. Fig. 2 shows the results of the seven Bchron runs."* This means that in order to get comparable chronologies we produced chronologies for all seven pollen records based on radiocarbon date data (can be found from Table 1 references). The (median) chronologies from the Bchron runs are already available at http://dx.doi.org/10.17632/4pznttrd4h.1.

> P4, line 25: 'To produce chronology' please correct the grammar

RESPONSE, CHANGES: Corrected

> P4, line 25- P5, line 5: It would be preferable if you provided the full chronological information for each of the sites, including all control points, depths of dates, the (uncalibrated) dates themselves and their uncertainties, material dated and reference codes. Also, please say if any corrections (eg for reservoir/hardwater effects) were applied. For the EPD sites, it would be a nice gesture if you also submitted your chronologies to the EPD since they are probably better than the existing chronologies.

RESPONSE, CHANGES: We updated the material already provided at http://dx.doi.org/10.17632/4pznttrd4h.1. The updated material includes now all depths for each of the seven pollen record. Please see Table 1 references in order to find the radiocarbon date data for each fossil pollen record. We did not apply any corrections (eg for reservoir/hardwater effects) since it is not possible to include them to Bchron model run.

> "P6, line 20-22: Be very careful about making broad unsubstantiated statements. Evidence of human impact does not mean the same as evidence of bias. There are many different methods for reconstructing climate from pollen data, some more susceptible than others. Li et al 2014 use WA-PLS, small calibration datasets and a single site example, all of which could be expected to perform poorly in areas of heavy human impact. The main conclusion of Li et al that human impact biases the pollen-based climate reconstruction is based almost entirely on correlation, or lack of, between the pollen-based temp/precip record and other records that can anyway be expected to be different because they represent different spatial scales, temporal resolutions, or represent entirely different sensors/proxies (speleothem isotopes are a combination of precipitation and temperature signals at the destination, as well as SST and isotopic ratio of the source). Li et al also don't mention the importance of the uncertainties of the pollen-climate reconstruction in making these comparisons (one of the main effects of human impact should be to increase the uncertainties if the transfer function works correctly). Again, no one is denying that human impact can be important in pollen climate reconstructions, but you need to be careful about your evidence and phrasing here.

and

> P11, line 29-33: Evidence of human impact on vegetation is not evidence that pollen-based climate reconstructions are 'strongly influenced by human impact. This is not to deny that the problem exists, but it is important to recognize that not all pollen-based climate reconstructions are the same, and that some have been designed specifically to limit this problem..."

RESPONSE: We agree that the most broad-scale biogeographical features in the vegetation of the Iberian Peninsula, from where our training set samples come from, are controlled by climate. We can see these main features in the presence of temperate broadleaves, such as *Fagus sylvatica*, in northern Spain, while the modern pollen samples from southern Spain are dominated by grasses and other more xerophytic plants. We therefore think that the main gradient in our training set reflects this climatic gradient, and this is why the performance statistics of our transfer function give reasonably high values. However, the human impact on vegetation in our study area is long-lasting, and can be locally very intensive, so that the original forest can been totally cleared for agriculture (e.g cereal or olive cultivation). The influences of such drastic human-induced vegetation changes on pollen-based climate reconstructions are inevitable. We note, for example, that in a recent overview about the pollen data and the relative importance of climate and human impact as factors causing vegetation change in the Holocene, Roberts et al. (2019) conclude that "*During the mid Holocene, most Mediterranean landscapes were transformed by a combination of climate and rural land use, but after ~3500 cal. yr BP, human actions became increasingly dominant in determining land cover*".

We do not argue that our transfer function is particularly good when evaluated statistically. On the contrary we write that "*When these performance statistics are compared with other validation tests with WA-PLS and Bayesian-based transfer functions, it can be seen that they are reasonably high, but still slightly lower than in other regional models*". As for the reasonably good statistical performance of our transfer function, we state that do not know what these performance statistic would be if there were no human impact on vegetation in the areas, but very likely they would be higher.

Later on in her/his comment, R 2 writes that "*Human impact adds noise, but it is not necessarily overwhelming noise*…" As a matter of fact, this is very much in line with our views – human impact has been intense and long-lasting in the Iberian Peninsula, and it cannot be ignored, but it does not necessarily mean that pollen records would not provide signals about the long-term climatic trends in the past.

> P7, line 17: There are many other sites from the EPD that cover this period.

RESPONSE: Please see our response to general comments part "Selection of the seven fossil sites" on page 5.

P7, line 17-28: Please read the work of Penalba et al 1997 (doi:10.1006/qres.1997.1922) at the site of Quintanar de la Sierra. The pollen-climate reconstruction in this paper looks very similar to your own.

RESPONSE, CHANGES: Peñalba et al. (1997) was already cited in our original paper, but we have added the following text to page 4. "The pollen data from Quintanar de la Sierra have been used earlier for quantitative climate reconstructions by Peñalba et al. (1997)".

P7, line 26-28: Be careful conflating different seasons in these comments. The Chronomid reconstruction is for summer temperatures, but your reconstruction is for annual precipitation. An increase in annual precipitation may be driven by wetter winters, unrelated to warmer summers shown by the chironomids.

RESPONSE: We agree with this comment. See our response to the point 5 by R 2 on pages 15-16.

P10, line 17: replace 'can be also' with 'can also be'

RESPONSE, CHANGES: Done

P10, line 23-24: This is misleading. The chironomid summer temperature record from Basa de la Mora lake by Tarrats et al 2018 indicates warmer temperatures in the early Holocene relative to the mid-late Holocene, but these temperatures were either similar or cooler than the present day. See figure 5a in Tarrats et al. The authors reconstruct a modern July air temperature of around 9.5C but they reconstruct early Holocene temperatures of around 9.1C. In fact the present July temperature for the site based on the New et al 2002 climatology adjusted for altitude is 13.2C. Tarrats et al 2018 suggest that the late Holocene samples are unreliable due to human impact, so the early Holocene summer temperatures in the chironomid reconstruction (9.1C) would in fact appear to be 4C cooler than the present day climate (13.2C).

RESPONSE, CHANGES: We agree with R 2 that in the Tarrats et al. (2018) record the reconstructed modern summer temperature is higher than during the early- to- mid-Holocene temperature maximum. We have modified the text on page 11 where we now write that "*In addition, palaeoclimate reconstructions from central Pyrenees, based on chironomids, and thus independent of pollen data, indicate that the summer temperature was high from 8800 to 6200 cal yr BP, although stilll lower than the modern summer temperature at the site (Tarrats et al., 2018)*"

We have deleted the Tarrats et al. (2018) curve from Fig. 7.

P12, line 18-19: Please be precise in your terminology. When you say 'high' do you mean higher than present during the period 8-4k? This is probably true for lake levels, but where is the evidence for higher summer temperatures? In the rest of the paper you appear to dismiss the pollen based reconstructions, so you are only left with the Pyrenees chironomid reconstruction by Tarrats et al (2018) which shows either comparable to present or most likely cooler summer temperatures. Are there other published quantitative summer temperature reconstructions from Iberia that support your conclusion?

RESPONSE: See our response to the point 5 by R 2 on pages 15-16.

P13, line 9-12. Please acknowledge the EPD and EMPD according to the requirements of the protocol for data use (http://europeanpollendatabase.net/datapolicy/).

RESPONSE, CHANGES: Acknowledgements were added to the paper.

P24, Figure 1: I would recommend avoiding graded scaling, and especially multiple colours for a simple graduated scale. Contour scaling using simple 1 or 2 colour shading is a much clearer way to show this kind of information on a map. Look in any climate text book.

RESPONSE, CHANGES: Done

P27 figure 4, P28 Figure 5: I cannot understand the scaling. Along the top is every 400mm and the bottom is every 500mm. Please use the same scale, and also make the tick marks clearer. Also include a vertical line to see the anomaly from the present, not just a dot for the present precipitation What are the 'formal sub-divisions of the Holocene'? please provide a citation.

RESPONSE, CHANGES: We have modified the scaling. The Pann scale is now indicated clearly for each panel in the figure. We have enlarged the tick marks.

The vertical line has been added. It shows the anomaly from the mean (not the present precipitation). The dot indicates the modern measured precipitation value in each reconstruction location.

The formal subdivisions of the Holocene, ratified by the International Commission on Stratigraphy (ICS) in 2018, are Greenlandian, Northgrippian and Megalayan. These subdivision and their age limits can be checked for the homepage of the ICS. We have added this explanation to the figure caption and added a citation to Walker et al. (2018).

> "P30, figure 7: Can you not provide a more comprehensive review of lake levels and other precipitation proxies for comparison with the pollen based reconstructions? Many are described in the text but not shown here. See #5 of my opening comments. I would also mention Harrison & Digerfeldt 1993 'European lakes as palaeohydrological and palaeoclimatic indicators' (see figure 10), which is old but still appears to be relevant today."

RESPONSE: Please see the response to opening comment 5 above on pages 15-16.

Responses to the comments by R 3

"I first suggest to better highlight the innovative side of this study. In particular if we compare the objective of this work with those of the paper of Tarroso et al (2016) which focus on the reconstruction of the climate (Temperature and precipitation) in Iberian peninsula during the last 15000 years from pollen data. This study has several positive points that should be further highlighted in the text: a new modern pollen dataset, a multi-method approach… "

RESPONSE: We agree that our precipitation reconstructions partly differ from those in Tarroso et al. (2016). It is more difficult for us to assess the reasons of these differences. In essence, it would be necessary to re-run the reconstructions of Tarroso et al. (2016) to find out what are the factors mostly contributing to the differences. We consider such an assessment outside the focus on our paper.

"However, the description of the modern pollen dataset is too short and the discussion on the multi –method approach needs to be improved. The discussion is essentially based on the results of the WAPLS: why? This point must be justified. If the results of the Bayesien method are not robust, then yes, you can only discuss the WAPLS, otherwise you have to discuss both."

and

"The WAPLS is a classic method, often used in paleoclimate studies. In contrast, the Bayesien reconstruction method is newer: could you better explain and justify the choice of this method instead or other more classical methods (PDF, MAT, PSL…). More references on the Bayesien reconstruction method are required: where this method has been tested and applied? For which time periods?"

RESPONSE, CHANGES: We agree with the reviewer that it is good to use more than one reconstruction technique in a paper such as this. In response to this comment, we now write on page 6 that "*The Bayesian modelling provides some potential advantages, such as joint inference and a clearer modelling of uncertainty, in climate reconstructions (Parnell et al. 2016)*".

As R 3 mentions WA-PLS method is often used in paleoclimate studies. However, in recent years, the popularity of Bayesian modelling in paleoclimate reconstructions has increased and there are also user-friendly Bayesian models available like R package Bclim (Bayesian Palaeoclimate Reconstruction from Pollen Data, Parnell et al., 2015) and BUMBER (Bayesian user-friendly model for palaeo-environmental reconstruction, Holden et al., 2017). For more discussion about Bayesian models and comparison between Bayesian methods and other methods see for example Birks et al., 2010; Holden et al., 2017; Li et al., 2016 and Parnell et al. 2016.

In order to see the compatibility of the results based on the two reconstruction techniques we performed correlation analysis using scale space multiresolution correlation analysis (Pasanen and Holmström, 2016). As we now write in the Supplement "*Scale space multiresolution correlation analysis takes into consideration the possibility that the correlation between two time series may change over time and can have different features when inspected at different time scales. The method has two steps. In the first step the time series are decomposed into a number of scale-dependent components and in the second step the local temporal changes in correlation between pairs of such components are explored by using weighted correlation within a sliding time window of varying length.*" As a result method identifies the time intervals and the time scales for which correlation is credibly positive or negative. We have added a supplement figure (Fig. S4) which shows the results from the scale space multiresolution correlation analysis. These results suggest that we obtain similar reconstructed features with multiple timescales for Monte Areo, Quintanar de la Sierra, San Rafael and El Maíllo with both methods. The features for Zalama and Navarrés-3 are similar in long timescales and for Alto de la Espina the reconstructed features seem to differ.

As regards the compatibility of the results based on the two reconstruction techniques, we have added the following text on page 7: "*According to the results of the scale space multiresolution correlation analysis (Pasanen and Holmström, 2016), Alto de la Espina is the only one where the main features of the two reconstruction techniques are different (Fig. S4).*"

In the figures we have chosen to show only the WA-PLS reconstructions in order to keep the figures clear and simple. The WA-PLS reconstructions were chosen based on the slightly higher performance statistics for the modern pollen-climate training set.

> "My second point concerns the lack of comparison of your results with the precipitation curves available in the Mediterranean area: the study of Tarroso et al (2016) for Spain, Dormoy et al (2009) for south Spain; studies of Peyron et al. (2011; 2013), Combourieu-Nebout et al., 2013 and Magny et al (2013) for Italy. It's important to add these curves in the figures (6 or 7?) to discuss the regional climate pattern. Particularly the curves of Tarroso et al., (2016) which are based on another climate reconstruction method, the PDF, show clearly a different pattern than the precipitation reconstructed here; the differences have to be discussed more in depth."

RESPONSE, CHANGES: This is a justified argument. It would indeed be interesting to compare more extensively our results with various types of precipitation and water availability related proxy records from the Iberian Peninsula and the western and central Mediterranean regions. The reason we have not done so, is, understandably, that such comparisons would make the paper much longer and figures much larger. For this reason, we have, for example, shown lake-level curves only from the Iberian Peninsula, and not from Italy or other regions, in our Fig. 7.

We agree that our precipitation reconstructions partly differ from those in Tarroso et al. (2016). It is more difficult for us to assess the reasons of these differences. In essence, it would be necessary to re-run the reconstructions of Tarroso et al. (2016) to find out what are the factors mostly contributing to the differences. We consider such an assessment outside the focus on our paper.

In response to this comment we have added references to the older papers (e.g. Combourieu-Nebout et al. 2009 on page 2).

> "Much of the discussion and figures are based on chironomidss temperature curves (figures 6, and7), so either the authors remove the temperature curves to base the discussion only on precipitation (and compate it with more regional precipitation patterns), or the authors apply their methods to produce temperature curves, or the authors include the temperature curves of Tarroso et al for Spain."

RESPONSE, CHANGES: Chironomid-based temperature reconstruction is now deleted from Fig. 7. See our response to R 2 on page 20.

> "Last point: Authors don't investigate the links of these reconstructed climate changes with the different climate forcings. It's an important missing point."

RESPONSE: To explore and understand the influence of different forcings on Pann trends in the Iberian Peninsula would require the use of palaeoclimate models. The aim of our paper is to report and discuss the pollen-based reconstructions results. The study involving model simulations and discussing the role of different forcing factors can be done as a next step in the future.

Other points

Data sources

> "The paragraph on the modern pollen dataset is too short given that the quality and accuracy of the modern pollen dataset is very important in transfer functions. The modern pollen dataset used here has never been published, so more details are needed: could you add a table or a map with the biome corresponding to each modern sample? We need it to be sure that all the vegetation type occurring in the past are included in your dataset. I particularly think about the more herbaceous during the Younger Dryas and the taxa of the Bolling/Allerod. Another important point to discuss is the human impact: how do you deal with that in the modern dataset? Do you exclude anthropic taxa?"

RESPONSE, CHANGES: We have now added more information about the modern pollen dataset, see our response to general comments on page 1-3. We also discuss the role of human impact, see our response to R 2 on page 18-19. We did not exclude any terrestrial pollen or spore taxa from our dataset, because defining the anthropogenic taxa would be more or less subjective and thus would add a source of subjectivity to our transfer function.

Reconstruction of past variables

> "Line 26: you test the performance of the calibration of the transfer function, you don't test the performance of the modern training set: please correct."

RESPONSE, CHANGES: Corrected by deleting "to test the performance of our modern pollen-climate training set and"

> "Line 28: reformulate: for constructing the transfer functions for annual precipitation"

RESPONSE, CHANGES: We changed "for constructing" to "to calculate".

Results and Discussion, Transfer function performance

> "The fig 3 (observed/reconstructed) is not discussed at all in the text. More sentences are needed to comment the performance of each method, for example: some high precipitation values are clearly underestimated with the WAPLS: why? May be these samples are biased by human impact and could be considered as outliers and then removed from the dataset."

RESPONSE: We explored the residuals in Fig 3 to some extend by checking the modern geographical location, site elevation and modern precipitation of the sites in our calibration model. We observed that most sites with biggest residual values are located at the higher end of the precipitation gradient. However, there are also some outlier sites at lower precipitation. We do not observe any specific site elevation or geographical location that would explain the outliers. Thus we cannot provide a simple explanation for the residuals but we suspect that one factor is the difficulty to obtain accurate modern precipitation values for the sites. The other possible contributing factor is the well-documented edge effect typical to WAPLS, often leading to underestimated modern values at the higher end of the calibration models (see for example Juggins and Birks 2012). There is no clear evidence that sites with biggest residuals should be considered as outliers (for example due to human impact) and therefore removed.

"Line 20-23: The R2 for PANN is always lower than the R2 for temperature; I don't understand why the authors compare their R2 with R2 in China; more European or Mediterranean calibrations are available (check the bibliography: Bordon et al., 2009…). It will also be important to test the spatial autocorrelation see the papers by Telford and Birks, 2009 and others), to evaluate the performance of the models, did you do it? "

RESPONSE: Yes, we actually did this, but we did not include the h-block tests in the original paper because of lack of space. The result of this test indicates some spatial autocorrelation in the calibration set. For example, when we set h value as 20 km RMSEP increases to 170.7595 mm and R2 decreases to 0.4803. With this 20 km radius an average of 5.5 sites (min=1, max=20) were omitted in the h-block runs.

CHANGES: In the revised version of the paper, we have added the following text "*We also tested our WA-PLS calibration model for the possible spatial autocorrelation using the h-block test (Telford and Birks 2009). When the h value is set at 20 km, RMSEP increases to 170 mm and R2 decreases to 0.48. With this 20 km radius an average of 5.5 sites (min=1, max=20) were omitted in the h-block runs. This indicates some spatial autocorrelation in our calibration model. This is probably inevitable in a dataset such as ours, which is based on moss polster samples often collected from sites near each other.*"

Results and Discussion, Evaluation of the reconstructions

"Line 5: please reformulate: some differences in the levels of reconstructed Pann values"

RESPONSE, CHANGES: Changed to " the actual levels of reconstructed Pann values may differ to some extend".

Precipitation trends

"Replace Late Pleistocene by Lateglacial"

RESPONSE: We have retained the term "Late Pleistocene" because it is an ICS ratified term and in line with the terminology we use for the subdivision of Holocene in our paper.

"Line 19, 21: Pann is not a record, it's a reconstructed value, clarify"

RESPONSE, CHANGES: Done

"It's hard to see on the figures 4, 5 the climate patterns discussed in the text. For example: line 21 " show an increasing trend between 14500 and 14250 cal BP". The scale of the figure is not adapted to follow the discussion. Please correct."

RESPONSE, CHANGES: To make the figures more informative, we have added vertical stippled lines to indicate the mean value of each reconstruction to Figs. 4 and 5. We have modified the scaling. The Pann scale is now indicated clearly for each panel in the figure. We have enlarged the tick marks.

"P. 8, line 3: I don't agree with the author's interpretation: the pattern at Q de la Sierra is not stable and is not in agreement with a relatively stable rainfall pattern in northern Iberian Peninsula during the younger dryas."

RESPONSE: We use the expression "*a relatively stable rainfall pattern*" which we think is justified. There is less variability in the GS-1 stadial sequence than in the early Holocene in the Quintanar de la Sierra record.

"Line 24: The comparison with the lake levels is hard to follow; Estanya lake DOESN'T reflect large climate changes during Younger Dryas (fig 7): correct it."

RESPONSE, CHANGES: Corrected. We now write that "In the Estanya Lake record, at lower altitude in the Pyrenees, the reconstructed lake level is low during the GS-1, but drops even lower at the GS-1-Holocene transition (Fig. 7)"

"P.9, line 2 "… lower during the period 12.900 to 11.700 cal BP": to be nuanced; it depends where in Spain: in Villarquemado, Fuentillo and Padul, the lake levels were high during the Younger Dryas."

RESPONSE: OK, we mean the lake levels in N Spain, cited in our paper

"P9, lines24-26, need to better explain the reasons of differences between proxies reconstructions: precipitation seasonality…, check the papers by Magny et al 2013 and others"

and

"8.2 ka event: discussion on this major event is too short, check the references on the 8.2 ka event (Magny et al 2003, 2013…) to improve the discussion"

RESPONSE: As already answered to R 1 the 8.2 ka event is not a particular focus of interest in our paper, but we find it important to mention it briefly because it has been recently intensively discussed in the Mediterranean region and because some of our records indicate a slight reduction in Pann at 8400-7900 cal yr BP, possibly (but not firmly) suggesting this event in our results (e.g. Fig. 4). By stating that more high-resolution pollen records would be needed to investigate this event, we refer to studies that would particularly focus on the time period 8400-7900 cal yr BP, with sub-centennial time resolution.

> "P11, line 4: I don't see where are the "reasons explained earlier"

RESPONSE: On page 2 we say that our study was designed to test and validate humidity records with pollen-based precipitation reconstructions "*Given the steep gradients and the coupling between vegetation and water availability, past vegetation changes in the Iberian Peninsula provide a means to investigate past water availability and precipitation changes. In the last decades, a number of studies based on lake level, pollen, and speleothem data have dealt with synthetic climate reconstructions in the Iberian Peninsula (Tarroso et al., 2016; Morellón et al., 2018). Here, we report pollen-based quantitative precipitation reconstruction results based on a transfer function approach from seven pollen records from different parts of the Iberian Peninsula following a North-South transect from the Atlantic to the Mediterranean climatic domain. To provide a regional synthesis of the precipitation and humidity changes, we compare our pollen-based precipitation reconstructions with independent records of humidity, such as lake-level data from the Iberian Peninsula, from ~15,000 calibrated years before present (cal yr BP) to the present.*"

> "P11, line 14: do you take into account Pteridium in our dataset? I don't think so, so may be exclude these samples."

RESPONSE: *Pteridium* is included in our calibration model and in the reconstructions because the purpose of our study was to include all terrestrial pollen and spore types in the reconstructions.

Figures

> "figure1: the two regions Eurosiberian and Mediterranean must be indicated on the map"

RESPONSE, CHANGE: The white line in Fig. 1 indicates the boundary between these two regions. Added to the figure caption.

> "fig2: may be better in supplementary material"

RESPONSE: We decided to keep the Fig. 2 in its original place in order to emphasize that we produced comparable chronologies for all seven cores based on radiocarbon date data.

"fig 3: not discussed in the text, to be done; check the outliers and remove it if they are linked to human impact"

RESPONSE: Already answered above. Please see the answer on page 26.

"fig 4 and 5: to discuss the climate trends, you have to you trace the figures in anomalies (differences between past and 0k value) to avoid altitude bias."

RESPONSE: Already answered above. Please see the answer on page 28.

"For clarity, I strongly recommend to the authors to merge the figures 4 and 5, and to put on the same graphs the curves obtained with both methods (all in anomalies)."

RESPONSE: We considered this but found it more informative to show these two reconstruction outputs separately.

"The different chronozons must appeared on the figures: GS1(or Y Dryas), Holocene to help to follow the discussion."

RESPONSE, CHANGES: Added to Figs. 6 and 7.

"fig 7: The different chronozons must appeared on the figures: GS1(or Y Dryas),in dot…"

RESPONSE, CHANGES: Added

References used only in the responses to reviewers

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Quantitative reconstruction of precipitation changes in the Iberian Peninsula during the Late Pleistocene and the Holocene

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Abstract. Precipitation is a key climate driver of vegetation and ecosystems of the Iberian Peninsula. Here, we use a regional pollen-climate calibration model and fossil pollen data from seven sites to provide quantitative reconstructions of annual precipitation values for the last 15,000 years. Our records show that in the Late Pleistocene (~15,000 to 11,600 cal yr BP) precipitation changes in the Iberian Peninsula took place markedly in tune with the temperature trends in northern Europe, with higher precipitation during the Greenland interstadial 1 (Bølling-Allerød) and lower precipitation during the Greenland stadial 1 (Younger Dryas). The early Holocene was characterized by a rapid precipitation increase after 11,600 cal yr BP, followed by a slowly declining trend until roughly 8000 cal yr BP. From 8000 to 4000 cal yr BP the reconstructed precipitation values are the highest in most records, with maximum values nearly 100 % higher that the modern reconstructed values. The results suggest a gradually declining precipitation over the last four millennia, although the late-Holocene reconstructions are biased by intensifying human impact on vegetation. In general, our results suggest that the main changes in precipitation in the Iberian Peninsula have occurred in pace with the main temperature changes in the North European-Atlantic region, with warm (cold) periods in the North corresponding with humid (dry) periods in the Iberian Peninsula.

1 Introduction

Successful use of quantitative transfer functions for climate reconstructions from pollen and other biological proxy data have many requirements. Of particular importance is that the reconstructions must be focused on regions where the palaeorecords are climatologically sensitive to the climate variable of interest and where it is possible to construct high-quality modern calibration sets (Birks, 1995). Within the scope of pollen-based climate reconstructions, such regions are where there exists a simple zonal climatic gradient, determined, or strongly influenced, by one or few dominant climatic variables, and where there exists equally clear vegetation zonation determined by these dominant climatic variables (Seppä et al., 2004). ~~The Mediterranean region~~The Iberian Peninsula is one of such regions, as it is a climatic transition area between the Atlantic to

Mediterranean and subtropical to middle latitude climate gradients, and displays wide regional climate variability and large gradients, especially following a North-South transect (Karagiannidis et al., 2008), constituting thus a small-scale coupled sea-atmosphere system with a short time response to climatic forcing (Xoplaki et al., 2004). The Mediterranean climate is also influenced by weather conditions over the Atlantic and sometimes by polar outbreaks. However, the key factor of the Mediterranean climate is its seasonality, marked by a strong annual precipitation cycle between dry summer and wet winters ~~seasons~~ (Dünkeloh and Jacobeit, 2003; Lionello et al., 2006).

Since the majority of Mediterranean ecosystems are water limited and depend on the seasonal and temporal dynamics of precipitation (Blondel et al., 2010), the Mediterranean forests are highly vulnerable to future climate changes. It is expected that that by 2100 the annual rainfall will drop by up to 20 % (up to 50 % less in summer), and the mean temperatures will increase by 3-4 °C (Solomon et al., 2007; Giorgi and Lionello, 2008). During the last decades, the intensity and frequency of drought and fire events have increased in the Mediterranean region (Solomon et al., 2007). Even more extreme droughts and warmings have been reported in the palaeoclimatological data (Carrión et al., 2010; Tarroso et al., 2016). Precipitation has been a key climatic variable both in the history of vegetation and in the demographic and cultural dynamics of the Mediterranean Basin, and particularly in the Iberian Peninsula (Ninyerola et al., 2007; Benito-Garzón et al., 2008; Pontevedra et al., 2017), where the combination of archaeological and palaeoenvironmental studies has shown the influence of abrupt climatic events on settlement patterns and selective ways of anthropogenic exploitation of ecosystems (Carrión et al., 2010; Lillios et al., 2016; Blanco-González et al., 2018).

Given the steep gradients and the coupling between vegetation and water availability, past vegetation changes in the Iberian Peninsula provide a means to investigate past water availability and precipitation changes. In the last decades, a number of studies based on lake level, pollen, and speleothem data have dealt with ~~synthetic~~ climate reconstructions in the Iberian Peninsula and adjacent seas (Combourieu Nebout et al. 2009; Fletcher et al. 2010; Tarroso et al., 2016; Morellón et al., 2018). Here, we report pollen-based quantitative precipitation reconstruction results based on a transfer function approach from seven pollen records from different parts of the Iberian Peninsula following a North-South transect from the Atlantic to the Mediterranean climatic domain. To provide a regional synthesis of the precipitation and humidity changes, we compare our pollen-based precipitation reconstructions with independent records of humidity, such as lake-level data from the Iberian Peninsula, from ~15,000 calibrated years before present (cal yr BP) to the present. This time period is interesting because it encompasses the Pleistocene-Holocene transition, a major transition in climate and vegetation history, and the rapid Late Pleistocene climatic changes documented in the ice core records and in the records from the European continent (Heiri et al. 2014; Rasmussen et al. 2014) .

Orbitally-induced differences in seasonal insolation have mainly determined the long-term Holocene climatic evolution in Europe, involving a fairly distinct thermal maximum during the early and mid-Holocene in the high latitudes, followed by a transition to colder conditions around 5000 cal yr BP (Renssen et al. 2009; Marcott et al. 2013). For southern Europe, contrasting interpretations especially about the mid-Holocene ~~climatic~~ temperature conditions have been presented on the basis of biotic proxy data (Mauri et al. 2015; Samartin et al. 2017). Attempts to unravel climate variability in the Holocene in the

Mediterranean region are complicated by interactions between human activity and natural environmental changes, especially those that have occurred from the mid-Holocene to the present day (Carrión et al., 2000). Therefore, multiproxy studies and detailed high-resolution palaeoclimatic reconstructions are required to disentangle the various climatic signals merged in palaeorecords. Pollen based climatic reconstructions in the Iberian Peninsula are still sparse~~fragmentary~~, but they are important and interesting because they provide a range of quantitative precipitation estimates that are understandable in comparison with present climate, allow the testing of predicted climate changes under scenarios of future climate change, and help understand their effects on flora and fauna (Pérez-Díaz et al., 2017). Moreover, they are directly associated with archaeological and cultural trends and events, and they contribute to the prehistoric development of human societies under changing climatic and environmental conditions in the Mediterranean basin.

2. Material and methods

2.1. Study area

Our study area is in Iberian Peninsula following a North-South transect from latitude 43° 47´N to 36° 01´ N and longitude 9° 30´ W to 3° 19´E, encompassing several mountain ranges. The mean elevation of the Iberian Peninsula is around 660 m.

The climate of the peninsula is divided into two major climate zones: (i) the Atlantic climate characterized by mild summers and cold, rainy winters; and (ii) the Mediterranean climate with mild winters and hot, dry summers (Capel, 2000). The Atlantic Ocean influences the northern and western parts of the peninsula, and the Mediterranean Sea influences the South (Fig. 1). The coastline is under the influence of the Atlantic Ocean in the North and the West, and the Mediterranean Sea in the South and East. The lowest temperatures are measured in the regions influenced by the Atlantic Ocean and the highest in the regions adjacent to the Mediterranean Sea and the Sahara desert. In addition to a general North-South climatic gradient, seasonal and diurnal thermal gradients stretch from the coast to the centre of the peninsula (Dasari et al., 2014). From a biogeographical point of view, the Eurosiberian bioregion extends from Galicia, northern Portugal, Asturias, Cantabria, the Basque Country and the western and central Pyrenees. It is characterized by a wet climate, moderated by the oceanic influence, with temperate-cold winters and no clearly defined dry season. The Mediterranean bioregion incorporates all inland plateaus and mountains as well as the Mediterranean basin zones (Rivas-Martínez, 2007). The main vegetation types vary from semi-desertic flora, Mediterranean oak forests, steppeland areas and evergreen pine forests, to deciduous and high-mountain pine forests, and subalpine and alpine vegetation (Blanco-Castro et al., 1997).

2.2. Data sources

The use of transfer functions for quantitative climate reconstructions requires a collection of modern pollen samples that can be used as a training set in the reconstruction. Our modern pollen-climate training set includes 236 modern pollen samples with known modern annual precipitation (Pann) values analysed for relative abundances of 136 pollen taxa (Fig. 1). Modern pollen surface samples (moss polsters) were collected with positional and altitudinal data recorded using a portable GPS device, following North-South and East-West transects in Spain (Fig. 1). Several moss samples were randomly collected on the ground at each site within an area of 100 m^2 and homogenized into one sample. The collection approach ensured a representative sampling of flora with either long-range or short-range pollen dispersal and also minimized local overrepresentation of single species. Sites were chosen using the Vegetation Map of Spain (Rivas-Martínez, 2007) to properly characterize the major vegetation communities. The samples were treated with the standard techniques (Moore et al., 1991). All pollen samples in the training set were treated in the laboratory and analyzed under the microscope by the same person (JALS), to ensure the taxonomical harmonization of these 236 selected pollen samples. The identification of critical pollen morphotypes, for example those in the *Quercus* genus, was been carried out in a consistent manner (López-Sáez et al. (2010; 2015)).

A minimum of 500 pollen of taxa belonging to pollen sum taxa were counted while aquatic taxa were excluded from the pollen sum. To establish criteria of standardization and consistency in the data and to reduce bias, only taxa with percentages > 1 % and present in at least 5 % of the samples were included. Following this procedure, 136 pollen taxa were selected and the percentages were recalculated accordingly. Modern annual precipitation values were obtained from the WorldClim database (Fick and Hijmans, 2017) in a 30-sec resolution (approximately 1 km^2). Annual precipitation values for the surface sites range from 231 mm to 1327 mm with gradient 1096 mm. For more details on the modern pollen samples see López-Sáez et al. (2010, 2013, 2015) and Davis et al. (2013).

The pollen records on which the past precipitation reconstructions are based are peat cores from seven bogs: Alto de la Espina (or La Molina), El Maíllo, Monte Areo, Navarrés-3, Quintanar de la Sierra, San Rafael and Zalama (Fig 1). These records were selected as they represent different climatic regions of the Iberian Peninsula from the more humid northwestern parts to the dry regions in the south. They were gathered from the European Pollen Database (http://www.europeanpollendatabase.net), the Spanish research project Paleodiversitas (Carrión, 2015), or directly provided by researchers (Table 1). The pollen data from Quintanar de la Sierra have been used earlier for quantitative climate reconstructions by Peñalba et al. (1997). Pollen percentages (Fig. S1) were calculated from terrestrial pollen sums, excluding ferns and aquatic plants. Sites Alto de la Espina, Monte Areo and Zalama are located in the Eurosiberian region, while El Maíllo, Navarrés-3, Quintanar de la Sierra and San Rafael are located in the Mediterranean region (Fig. 1). In the Eurosiberian region, Zalama is located at the highest altitude, followed by Alto de la Espina and Monte Areo. Quintanar de la Sierra belongs biogeographically to the Mediterranean region, but is located in the heart of the northern Iberian Range that can be considered as an “island of Eurosiberian vegetation”. El Maíllo is located in valley area of the peninsular centre and Navarrés-3 is in an area close to the coast of the Mediterranean Sea. San Rafael is in the most southeastern zone.

The chronologies of all sites are based on radiocarbon dating. In order t~~T~~o produce chronology for each fossil pollen record we used Bayesian age-depth model called Bchron (Haslett and Parnell, 2008). Bchron first calibrates radiocarbon dates with a calibration curve (IntCal13) and then fits the age-depth model, which is consistent with the calibrated radiocarbon dates. Assumptions for the age-depth model are continuous, monotone and piecewise linear age-depth dependence. The age for the uppermost sediment of the core was assumed to be the year when the core was extracted. Fig. 2 shows the results of the seven Bchron runs. The figure shows the posterior distributions of the calibrated radiocarbon dates, the posterior mean chronology, and the 95 % credible intervals for the possible chronologies. For Alto de la Espina, Monte Areo, El Maíllo and Zalama the Bchron chronologies seem to be reliable for the whole core. For Quintanar de la Sierra we include only the last 14,500 years in the reconstruction since before this date the chronology becomes too uncertain because the radiocarbon dates are remarkably inconsistent. For San Rafael five AMS dates suggest a fairly stable and reliable Holocene sedimentation rate. However, the Late Pleistocene sequence is based only on one date, and we consider therefore the Late Pleistocene sequence's chronology poorly constrained, and exclude it from the palaeoclimate reconstructions. The record from Navarrés-3 begins 12,000 cal yr BP because before that time the chronology becomes unreliable in the lower parts of the core. The core, however, ends about 3000 cal yr BP, thus missing the late Holocene part, making the Navarrés-3 a chronologically floating sequence (Fig. 2). All ages in the text are expressed as cal yr BP.

2.3. Reconstruction of past climate variables

The selection of the climate variable of interest is a critical step in quantitative climate reconstructions (Li et al., 2015). In the Iberian Peninsula, and in larger context in the whole Mediterranean region, where summers are hot and dry, water availability is generally considered the critically important climatic variable for plant populations and communities, and its regional and temporal changes greatly influence the vegetation structure and composition (Vicente-Serrano et al., 2014; Samartin et al., 2017; Vidal-Macua et al., 2017). However, the summer temperature may also be an important factor especially at more mesic sites and at the high altitudes (Pasho et al., 2011; Vidal-Macua et al., 2017). It is realistic to accept that no single climatic variable can account for the complete influence of climate on vegetation and that no single or few reconstructed climate variables can capture the full spectrum climate patterns and changes in the past. ~~Given that our~~ The seven pollen records were selected ~~are from sites located at~~ from altitude lower than 1500 m a.s.l., and the climate variable we have reconstructed is annual mean precipitation (Pann). In our study region, Pann is an ecologically important and conceptually simple variable, which can be used in comparisons with other palaeoclimate records and model simulations. Precipitation has a clear zonal pattern in the Iberian Peninsula, and its importance for vegetation patterns is reflected by the comparable zonality of vegetation. In the leave-one-out cross-validation test, Pann has high r^2 and low RMSEP (Table 2), demonstrating that it accounts for a large proportion of variance in the precipitation-related climatic patterns in the region.

We use two different, complementary quantitative techniques, weighted-averaging partial least squares regression technique (WA-PLS) and Bayesian modelling~~, to test the performance of our modern pollen-climate training set and~~ to produce the past precipitation reconstructions from the seven pollen records. With both techniques, all 236 modern pollen samples were used ~~for constructing~~ to calculate the transfer functions for modern annual precipitation (Pann). WA-PLS is a non-linear, unimodal regression and calibration technique commonly used in quantitative environmental reconstructions (Juggins and Birks, 2012). In all cases, we used a two-component WA-PLS model by ter Braak and Juggins (1993). Training set pollen data values (as percentages) were square root transformed for WA-PLS regression in order to reduce noise in the data. Calculation of WA-PLS transfer functions was performed in the C2 programme (Juggins, 2007).

The Bayesian modelling provides some potential advantages, such as joint inference and a clearer modelling of uncertainty, in climate reconstructions (Parnell et al. 2016). The Bayesian reconstruction method used is based on Bummer, a Bayesian hierarchical multinomial regression model introduced in Vasko et al. (2002). In the basic Bummer model, the observed pollen taxon relative abundances are modelled by a multinomial distribution, where the taxon occurrence probabilities are treated as Dirichlet-distributed random variables whose distribution is determined by the pollen environmental response parameters as well as the mean annual precipitation. The taxon environmental response is modelled by a unimodal Gaussian function, with shape and mean determined by the response parameters alpha (scale), beta (optimal precipitation) and gamma (tolerance); See Figure S2. The prior distributions of the model parameters are listed in Table S1.

The performance of both transfer functions was evaluated by leave-one-out cross-validation (Birks et al. 1990). Based on the leave-one-out cross-validation results we calculated the coefficient of determination (r^2), root-mean-square error of prediction (RMSEP) and maximum bias as performance statistics.

3. Results and Discussion

3.1. Transfer function performance

Leave-one-out cross-validation performance statistics (r^2, RMSEP and maximum bias) for the two-component WA-PLS and Bayesian transfer functions are shown in Fig. 3 and Table 2. The r^2 between the observed modern values and those predicted by WA-PLS in cross-correlation test is 0.61 and in the Bayesian model 0.55 and the RMSEP is 145 mm with WA-PLS and 170 mm with Bayesian model. Thus WA-PLS slightly outperforms the Bayesian model as measured with RMSEP, r^2 and maximum bias. One potential reason for this is that in the Bayesian model we used a wide priori for the predicted precipitation in order not to restrict the precipitation values too much a priori. When these performance statistics are compared with other validation tests with WA-PLS and Bayesian-based transfer functions, it can be seen that they are reasonably high, but still slightly lower than in other regional models. For example, in northern Europe, r^2 values between the predicted and observed summer or annual mean temperature values are generally 0.7 to 0.85 (Seppä and Bennett, 2003; Birks and Seppä, 2004), in China for Pann 0.8 (Li et al., 2016) and in training set from the Swiss Alps as high as 0.9 for mean summer temperature (Lotter et al., 2000).

There are a number of reasons, which can explain the slightly lower performance statistics of the pollen-climate calibration set in the Iberian Peninsula as compared to northern Europe. One undeniable factor is the long-lasting and intense human impact that causes bias in the climate-vegetation relationships (Carrión et al., 2000; López-Sáez et al., 2016) and blurs the performance of the pollen-climate transfer functions (Li et al. 2015). Another likely source is that the fossil pollen samples and modern samples in the training set represent different sedimentary environments. Besides having consistent taxonomy and nomenclature and being of comparable quality, the modern pollen data should be from the same sedimentary environment (e.g., lakes of similar size) as the fossil data-sets used for reconstruction purposes (Seppä et al., 2004; Birks et al., 2010). Unfortunately it is not possible to use pollen samples from the same sedimentary environment for the training set and fossil data in the Iberian Peninsula. The fossil assemblages are from mires, but the modern samples in the training set represent locally integrated moss samples. This is a common problem when constructing pollen-climate transfer functions in dry and semidry regions, with a limited number of lakes and peat bogs (Pontevedra et al., 2017). We also tested our WA-PLS calibration model for the possible spatial autocorrelation using the h-block test (Telford and Birks, 2009). When the h value is set at 20 km, RMSEP increases to 170 mm and R2 decreases to 0.48. With this 20 km radius an average of 5.5 sites (min=1, max=20) were omitted in the h-block runs. This indicates some spatial autocorrelation in our calibration model. This is probably inevitable in a dataset such as ours, which is based on moss polster samples often collected from sites near each other.

3.2. Evaluation of the reconstructions

The results of the Pann reconstructions are shown in Figs. 4 and 5. The shapes of the reconstructions based on WA-PLS and Bayesian modelling are comparable but the actual levels of reconstructed Pann values may differ to some extend.~~there are some differences in the levels of reconstructed Pann values~~. In general, the variability is higher in the WA-PLS-based reconstructions, as can be seen especially in the records from Monte Areo, San Rafael and El Maíllo, while the absolute reconstructed Pann values are similar in both reconstruction approaches. According to the results of the scale space multiresolution correlation analysis (Pasanen and Holmström, 2016), Alto de la Espina is the only one where the main features of the two reconstruction techniques are different (Fig. S4). It is important to keep in mind that with the Bayesian reconstructions we show only the posterior mean value, which is just one possibility to summarize the Bayesian reconstruction, and therefore comparison to WA-PLS reconstructions is not straightforward. Furthermore, the individual Bayesian precipitation reconstructions have higher variability compared to the posterior mean. When the seven Pann reconstructions are compared, they indicate relatively consistently the main trends (Figs. 4-5). For exploring the generality of our results, we compare them with selected Late Pleistocene and Holocene lake-level that reflect general humidity in the Iberian Peninsula. Additionally, to gain insights to the underlying climatic mechanisms and climatic teleconnections that can explain the reconstructed features, we compare the results with chironomid-based summer temperature records from southwestern Europe and temperature-related proxy records from the Greenland ice cores (Figs. 6-7), which represent the general Late Pleistocene and Holocene climatic conditions in the northern Atlantic region. To show the statistically significant features in the WA-PLS reconstructions, the SiZer analysis was carried out (Fig. S3 and Table S2) (Chaudhuri and Marron, 1999).

3.3 Precipitation trends

3.3.1. Late Pleistocene (~14,500-11,600 cal yr BP)

In our dataset, the Late Pleistocene Pann record is only available from the Quintanar de la Sierra pollen sequence, as it reaches back to 14,500 cal yr BP, with a reasonably high resolution (Figs. 4-5). The reconstructed Pann values in the WA-PLS-based reconstructions~~ord~~ show an increasing trend between 14,500 and 14,250 cal yr BP, rising from 700 to 900 mm; a prolonged decrease until 13,900 cal yr BP (< 800 mm), and, finally, an oscillating curve with relatively constant values of about 800-850 mm until 12,900 cal yr BP (Fig. 4). A similar tendency is observed in the Bayesian reconstructions although with slightly higher values, reaching a maximum higher than 1000 mm ~14,250 cal yr BP (Fig. 5). These features are generally consistent with the main climatic trends in Europe during the Late Pleistocene. The period with higher Pann from 14,500 to 12,900 cal yr BP corresponds with the Greenland interstadial 1 (GI-1), or Bølling-Allerød interstadial, with higher temperatures in northern Europe, and the subsequent period 12,900-11,700 cal yr BP corresponds with the Greenland stadial 1 (GS-1), or Younger Dryas stadial, clearly reflected in the Greenland ice core data (Fig. 6). The correspondence between the higher precipitation with higher temperatures and lower precipitation with lower temperatures in Europe can been also seen in the comparison with chironomid-based summary temperature curve for the Late Pleistocene (Fig. 6).

In a more precise comparison with Late Pleistocene records from the Iberian Peninsula, our results are in agreement with those presented by Naughton et al. (2016) and Tarroso et al. (2016), who also describe the GI-1interstadial as a period of increase in humidity with a relatively stable rainfall pattern in northern Iberian Peninsula, which in the case of Quintanar de la Sierra is evident only from 13,900 cal yr BP. These climatic conditions of greater humidity allowed the survival of the beech (*Fagus sylvatica*) in late-glacial refugia of the northern Iberian System, particularly during the first half of the Bølling-Allerød interstadial (López-Merino et al., 2008). Although the presence of beech has not been confirmed in this period in Quintanar de la Sierra (Peñalba, 1994; Fig. S1), it is documented in other neighbouring pollen records such as Grande Lake (Ruiz-Zapata et al., 2003). Beech forests are considered typical elements of the Eurosiberian region (Rivas-Martínez, 2007), but some Mediterranean areas of the Iberian Peninsula, i.e. the northern Iberian Range, can be considered as islands of Eurosiberian vegetation. Today, beech forests are only residual in these mountains (López-Merino et al., 2008). Our reconstructed Pann values are also in agreement with other Iberian pollen records showing a clear expansion of deciduous oak forests during the GI-1 interstadial indicating wetter and warmer conditions, summarized by Carrión et al. (2010) and González-Sampériz et al. (2010).

The GS-1 stadial can be seen in the Quintanar de la Sierra reconstruction by a decline of precipitation to 750-650 mm from 12,900 to 11,700 cal yr BP (Figs. 4-5). The Iberian pollen records show usually an increase of *Betula*, heliophilous herbs, *Poaceae*, and shrubland and semi-arid pollen taxa such as *Artemisia*, *Chenopodiaceae*, *Ephedra* during the GS-1, as well as *Pinus* in mountain environments, confirming the aridity during this period. Steppe vegetation has been described during the GS-1 in most Iberian territories (e.g., Allen et al., 1996; Peñalba et al., 1997; van der Knaap and van Leewen, 1997; Ruiz-Zapata et al., 2003; González-Sampériz et al., 2006, 2010, 2017; Carrión et al., 2010; Fletcher et al., 2010b; Moreno et al., 2011; López-Merino et al., 2012; Muñoz-Sobrino et al., 2013; Iriarte-Chiapusso et al., 2016). By contrast, r Records from the inland Mediterranean environments and southeastern region reveal little changes in vegetation and suggest the persistence of conifers and open landscapes during the GS-1 (Carrión and van Geel, 1999; Vegas et al., 2010; Aranbarri et al., 2014).

The Quintanar de la Sierra record also concurs with the lake-level reconstructions for the GS-1 (Morellón et al., 2018; Fig. 7). In particular, Estanya Lake, at lower altitude in the Pyrenees, reflects large climatic change during the GS-1, with the onset of a marked decrease in the lake level, increased salinity, and a sudden decline in organic productivity with the absence of diatoms (Morellón et al., 2009). T The Enol Lake record also shows very low productivity and low carbonate content during the GS-

1, which can be interpreted as an indication of lower temperatures and a decline in precipitation (Moreno et al., 2011). A similar scenario was reconstructed in Roya lagoon in northwestern Iberia, where a decrease in organic productivity has been interpreted as an indication of colder and drier conditions between 12,700 and 11,700 cal yr BP (Muñoz-Sobrino, et al., 2013). The Grande Lake also shows a marked dry period from 12,600 cal yr BP until a rise at 11,700 cal yr BP, as reflected by the deposition of rhythmites and a shift in diatom and pollen assemblages (Ruiz-Zapata et al., 2003; Vegas et al., 2003). In the Estanya Lake record, at lower altitude in the Pyrenees, ~~reflects large climatic change~~ the reconstructed lake level is low during the GS-1, but drops even lower at the GS-1-Holocene transition (Fig. 7). ~~with the onset of a marked decrease in the lake level, increased salinity, and a sudden decline in organic productivity with the absence of diatoms~~ (Morellón et al., 2009). ~~Similar to this, r~~Records from the easternmost sites located near to the Mediterranean coastal areas recorded markedly arid conditions during most of the GS-1 either in two phases or in a more continuous pattern (Morellón et al., 2018). There is thus substantial multi-proxy evidence suggesting that the Pann was relatively high during the period 14,500 to 12,900 cal yr BP (GI-1), and lower during the period 12,900 to 11,700 cal yr BP (GS-1).

3.3.2. Early Holocene (~11,600-8200 cal yr BP)

The early Holocene in the Quintanar de la Sierra record is characterized by a marked peak in the Pann values, up to over 1000 mm at 11,600 cal yr BP, followed by a progressive decline to under 800 mm until 8200 cal yr BP (Fig. 4). The other records covering the early Holocene show similar features with a period of maximum Pann values at ~11,600-11,000 cal yr BP and a later period with progressively decreasing values until 8200 cal yr BP (Figs. 4-5). These patterns are especially evident in the records from the Eurosiberian biogeographic region (e.g., Monte Areo, Alto de la Espina), while those in the Mediterranean region show more gradual and irregular trends (San Rafael, Navarrés-3, El Maíllo).

It is notable that in our reconstructions, the ~~rise~~ high ~~of the~~ Pann values in the early Holocene around 11,000 cal yr BP appears synchronous between the Eurosiberian and Mediterranean regions, as can be seen in the reconstructed values in the Quintanar de la Sierra, San Rafael, and Navarrés-3 records (Figs. 4-5, 7). This contrasts the earlier interpretations that the development of the vegetation in the Iberian Mediterranean region was quite different than in the Eurosiberian region, as the persistence of conifer populations continued during the early Holocene, showing only minor oscillations in the mesophilous pollen frequencies in respect to the preceding GS-1 (Carrión et al., 2010). However, it is also important to note that the Pann trend suggested by our data, with a higher Pann values in the early Holocene, with Quintanar de la Sierra, Monte Areo and San Rafael records reaching the maximum Holocene Pann values as early as about 11,600 cal yr BP, followed by a progressively lower values until 8200 cal yr BP is not fully compatible with the lake-level reconstruction data. For example, in the reconstruction from Estanya Lake, located in the transitional area between the humid Pyrenees and the semi-arid Central Ebro Basin in northeastern Spain, the onset of the Holocene (~11,600-9400 cal yr BP) is characterized by low lake levels (Fig. 7), with a shallow, ephemeral, saline lake-mud flat complex with carbonate-dominated sedimentation during the flooding episodes, and gypsum precipitation during desiccation phases (Morellón et al., 2009), which also affected the development and preservation of diatom communities. These differences between different types of proxy records show that the Early-

Holocene precipitation and moisture conditions in the Iberian Peninsula are still poorly understood and that more high-resolution reconstructions are needed to solve the inconsistencies between different types of data and the outstanding questions.

3.3.3. 8.2 ka event

The clearest short-lived abrupt event in the Holocene records in the North Atlantic-North European region is the 8200 cal yr BP (8.2 ka) cold event (Alley et al., 1997). This event has been detected in many pollen records from the Iberian Peninsula (López-Sáez et al., 2008). On the Mediterranean coast and in the middle Ebro valley, it is characterized by the progression of Mediterranean pine and evegreen oak forests and the decline of deciduous oak (Davis and Stevenson, 2007, while in the eastern territories (e.g., Les Alcusses and Navarrés; Fig. S1) the high-mountain pine forests more adapted to a cold continental climate expanded, while the Mediterranean vegetation in lower and inner areas was reduced (Carrión and van Geel, 1999; Tallón et al., 2014). In the semi-arid region in the southeast, the San Rafael pollen record points out the development of grasslands and xerophytic vegetation (Pantaleón-Cano et al., 2003; Fig. S1). Changes in lake level also indicate increased aridity, with desiccation during this period at Medina Lake in the southwest (Reed et al., 2001) and at Villafáfila lakes in inland Iberia (López-Sáez et al., 2017). In our results, in the Alto de la Espina record, the reconstructed Pann drops to under 800 mm, but this takes place 8000-7900 cal yr BP, and in the Quintanar de la Sierra and San Rafael records there is a dip between 8300-8100 cal yr BP, but it is indicated only by one data point (Figs. 4-5). Thus there is no unequivocal evidence for this event in our data in the Mediterranean or Eurosiberian regions, but we cannot exclude its possibility either, and conclude that accurately dated high-resolution pollen records are needed to firmly detect the nature of the 8.2 ka event in quantitative Pann reconstructions.

3.3.4. Mid Holocene (~8200-4200 cal yr BP)

The Mid Holocene from 8200 to 4200 cal yr BP is characterized by higher Pann values in most of the reconstructions (Figs. 4-5), exceeding 1000 mm in Alto de la Espina and Monte Areo within the Eurosiberian region, and 900 mm in Quintanar de la Sierra. San Rafael and Navarrés-3, the two records located in the Mediterranean region, show clearly higher Pann values throughout the study period, with mean values between 400-600 mm. The Zalama and El Maíllo records are clear exceptions from this general trend, as in these records the Pann values remain constant around 900 mm. However, in most cases, in the reconstructed Pann values are above the Holocene means and the mid-Holocene is thus the longest and most prominent humid period reflected in our records.

The Mid-Holocene humid period can ~~be also~~ also be generally observed in other records from the Iberian Peninsula. The reconstructions from Basa de la Mora Lake in northeastern Spain shows a period of highest Holocene lake levels from 8100 to 5700 cal yr BP (Pérez-Sanz et al., 2013; González-Sampériz et al., 2017) and the Estanya lake-level reconstruction based on sedimentary facies analysis suggest a period of high lake levels from 8200 to 4200 cal yr BP, supported by a period of low but variable water salinity (Fig. 7) (Morellón et al., 2009, 2018). The more humid early-to Mid-Holocene conditions are also reported in the studies based on the two saline lakes in the Central Ebro desert (Davis & Stephenson, 2007).

In the southern Iberian Peninsula, the lake-level reconstruction from Laguna de Medina in SW Spain suggests humidity maximum at 7000-6000, followed by a steady decline (Reed et al. 2001), while in the multi-proxy dataset from the Padul wetland in Sierra Nevada the period with highest humidity has been dated to 9500-7600 cal yr BP (Ramos-Román et al. 2018a). In addition, palaeoclimate reconstructions from central Pyrenees, based on chironomids, and thus independent of pollen data, indicate that the summer ~~temperatur~~temperature was ~~es were~~ high from 8800 to 6200 cal yr BP, although still lower than the modern summer temperature at the site (Tarrats et al., 2018). Thus the period from roughly 8000 to 5000 cal yr BP was characterized by high summer temperatures and higher than present precipitation in our study region.

In larger regional context this mid-Holocene period with high Pann corresponds with the Holocene thermal maximum (HTM) in the high latitudes (Renssen et al., 2009). In the Mediterranean region, including the Iberian Peninsula, the climate of this period has been long debated. In many pollen-based climate reconstructions the period from 8000 to 5000 cal yr BP has been seen as a period of cool summers (Davis et al., 2003; Mauri et al., 2015), which contradicts with the output of climate models for the period. Samartin et al. (2017) used chironomid-based summer temperature reconstructions from Italy to argue that the summer temperature during the period has been higher than at present, in line with the models, and postulated that the pollen-based reconstructions of Mid-Holocene temperatures in the Mediterranean region are biased by the human influence. The inferred warm summers in the chironomid-based reconstruction from Basa de la Mora Lake in the Pyrenees support this argument (Tarrats et al. 2018). We did not aim to use pollen data for summer temperature reconstructions for the reasons explained earlier, and our results do not contribute directly to this debate, but in general we agree with these authors in that the predominant driver of vegetation patterns in the Mediterranean region is water availability and not summer temperature, and this is a fact which must be borne in mind when assessing any feature in pollen-based temperature reconstructions in this region.

3.3.5. Late Holocene (~4200 cal yr BP-present)

Our records suggest a declining general trend of Pann over the last 5000 years (Figs. 4-5, Fig. S3, Table S2). This is clearest in the records from Quintanar de la Sierra, Alto de la Espina and San Rafael, where the Pann values decline to about 500-200 mm from the mid-Holocene Pann maximum. When the modern Pann values are compared with the maximum values at 8000-5000 cal yr BP, a 50 % reduction of Pann in Spain is indicated. The record from Zalama differs from this trend, as it shows a fairly stable Pann trend over this period. In the Alto de la Espina record, a short-lived peak of anomalously high Pann values is indicated at 1500 cal yr BP. As shown in the pollen diagram, these values are caused by the exceptionally high *Pteridium* spore values, reaching a maximum up to 83 % at 1500 cal yr BP (Fig. S1). Such a peak of *Pteridium* is clearly an anomaly, probably caused by a local over-representation of *Pteridium* population at the coring site on the Alto de la Espina bog.

The increasing dryness over the last 5000 years evident in our Pann records (Figs. 4-5) has been observed in many records from the Iberian Peninsula. In the Basa de la Mora record, the lake level falls from 6000 cal yr BP to 4000 cal yr BP, with the period of lowest Holocene level from 3500-2300 cal yr BP, followed by a slight rise over the last two millennia (González-

Sampériz et al., 2017). In Estanya Lake record, the more saline and shallower conditions are seen between 4800 and 1200 cal yr BP, as indicated by the deposition of gypsum-rich sediment and massive sapropels facies (Morellón et al., 2009). Similarly, the multiproxy data from the Padul record in Sierra Nevada in southern Spain show clear evidence for aridification over the last 4000 years (Ramos-Román et al. 2018b).

A characteristic feature in our Pann reconstructions is a high variability in the records and between the records during the last 2000 years. The drop of reconstructed Pann from 1500 mm to under 600 mm during the last 500 years in the Monte Areo record is an extreme example of this pattern, suggesting that these wiggles do not represent realistic changes in the Pann values, but reflect more likely noise in the data. One reason for such variability may be the increasing human impact on vegetation in the Iberian Peninsula. The earliest evidence of agriculture in the Iberian Peninsula is documented in the eastern territories ~7500 cal yr BP during the Early Neolithic. Between ~7500-7000 cal yr BP, agriculture spread across the peninsula (Peña-Chocarro et al., 2018).

In general, the pollen-based climate reconstructions in the Eurosiberian and Mediterranean regions are in most cases strongly influenced by the human impact on vegetation, including cultivation, forestry, husbandry, burning and clear cutting (Carrión et al., 2010; López-Merino et al., 2014; Lillios et al., 2016). Over the centuries, the human influence has caused the original natural vegetation to shift towards semi-anthropogenic ecosystems, creating novel plant communities such as olive, chestnut, walnut and cork-oak woodlands, or promoted disturbance-adapted sclerophyllous vegetation types. The problem of human influence in the Mediterranean region has been observed in many pollen-based climate reconstructions. For example, in a reconstruction from Accesa Lake in central Italy, the last 2000 years were excluded from the reconstruction because the pollen signal is strongly dominated by human impact (Peyron et al., 2011) and in a record from Lago di Pergusa in southern Italy, the climate reconstructions based on the pollen data were shown to be biased by the decline of Mediterranean tree pollen and the increase of herb pollen and other anthropogenic indicators over the last 3000 years (Sadori et al., 2013). Such a long-lasting and intense human impact adds another factor changing the vegetation composition, blurring the detection of the climatic signals, and is reflected as high local variability in pollen-based climate reconstructions (Li et al., 2015).

4. Conclusions

Precipitation is a key driver for the ecosystems in the Iberian Peninsula and changes in its amount and spatial and temporal distributions have an impact on vegetation history, human activities, and natural hazards. It is thus an important variable in climate and palaeoclimate studies. Thus far most of the reconstructions of changes in past precipitation in the Iberian Peninsula have been based on qualitative and indirect data, such as inferred vegetation changes or changes in lake levels. We have constructed a modern pollen-climate calibration set specifically for the Iberian Peninsula and used it to provide quantitative precipitation reconstructions from fossil pollen cores from different climatic regions. The results show that precipitation in the Iberian Peninsula has had a strong spatial and latitudinal gradient during the last 15 thousand years. The reconstructed Pann values are clearly higher in northern Spain than at the two sites in the Mediterranean region. The Late Pleistocene is characterized by rapid shifts in Pann values, with the dry period during the GS-1 corresponding the low temperatures in northern Europe. The most pronounced period with high Pann values dates to 8000-4000 cal yr BP, and corresponds roughly with high lake levels and high summer temperatures in the Iberian Peninsula. We thus conclude that this period is comparable with the Holocene thermal maximum in northern Europe. During the Late Holocene the reconstructions are less consistent. One factor explaining this is probably the substantial human impact on vegetation, such as the clearance of forests and the development of cultivated fields, pastures, meadows and heathlands. The pollen-based Late-Holocene climate reconstructions from the Iberian Peninsula are thus substantially biased by the human impact.

Code and data availability

Code used to conduct the analysis for the Bayesian model is already published in the journal The Annals of Applied Statistics as Holmström et al. (2015): doi:10.1214/15-AOAS832SUPPC. In order to run the model used in this manuscript the prior distributions need to be set according to Table S1. Data used to create Figures 1, 3, 4 and 5 and Table 2 are available at http://dx.doi.org/10.17632/4pznttrd4h.1 (Ilvonen et al., 2019). Other data are available from the authors upon request.

Supplement link (will be included by Copernicus)

Author contributions

LI, JALS and HS designed the study. LI performed the simulations and computations required for the Bayesian model and WA-PLS method. JALS, FAS, SPD and JSC provided the data. LI, JALS and HS were mainly responsible for preparing the manuscript, while all authors commented and contributed to the discussion and interpretations

Competing interests

The authors declare that they have no conflict of interest.

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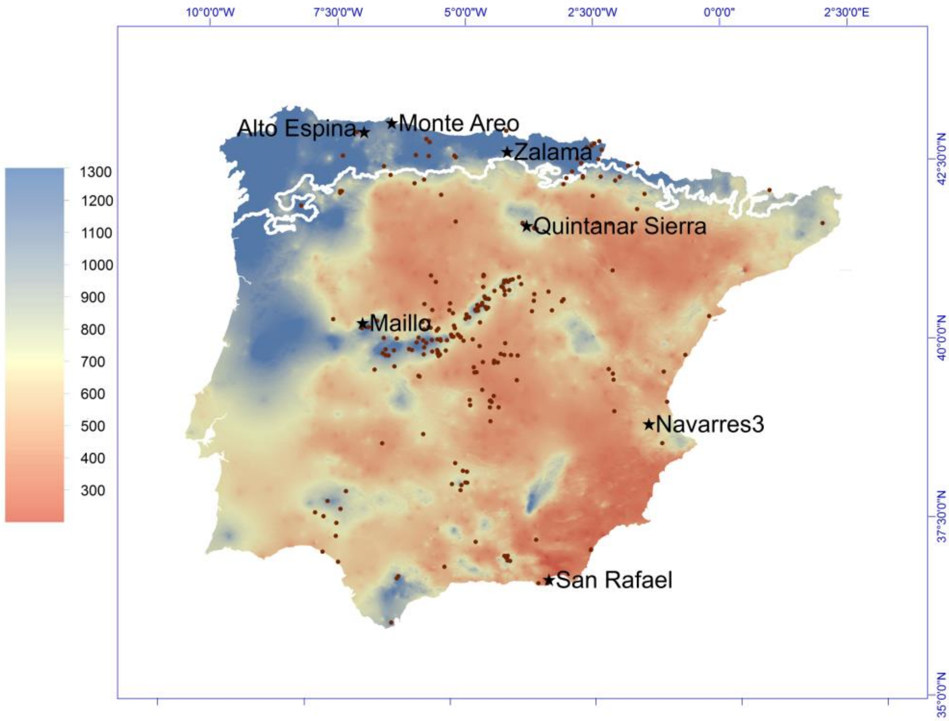
Table 1: Information on the seven fossil pollen records.

Site	Latitude N	Longitude W	Altitude (m a.s.l.)	Pann (mm)	References
Alto de la Espina	43º 22’ 52’’	6 º 19’ 38’’	650	930	López-Merino et al. (2011, 2014)
El Maíllo	40 º 32’ 48’’	6 º 12’ 35’’	1100	715	Morales-Molino et al. (2013)
Monte Areo	43 º 31’ 44’’	5 º 46’ 08’’	200	881	López-Merino et al. (2010)
Navarrés-3	39 º 05’36’’	0 º 41’00’’	225	429	Carrión and van Geel (1999)
Quintanar de la Sierra	42 º 01’31’’	3 º 01’ 34’’	1470	743	Peñalba (1994)
San Rafael	36 º 46’ 25’’	2 º 36’ 05’’	0	231	Pantaleón-Cano et al. (2003)
Zalama	43 º 08’06’’	3 º 24’ 35’’	1330	1059	Pérez-Díaz et al. (2016)

Table 2: Information and performance statistics of the modern pollen-climate training set. Reported statistics based on leave-one-out cross-validation are root mean square error of prediction (RMSEP), coefficient of determination (r^2) and maximum bias. The WA-PLS statistics are based on a two-component model.

Number of sites	236
Precipitation gradient	231 to 1327 mm
Precipitation range	1096 mm
Number of taxa	136
WA-PLS RMSEP	144.71 mm
WA-PLS r^2	0.61
WA-PLS maximum bias	328.08 mm
Bayesian model RMSEP	170.82 mm
Bayesian model r^2	0.55
Bayesian model maximum bias	239.53 mm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37°30'0"N
35°0'0"N
1300
1200
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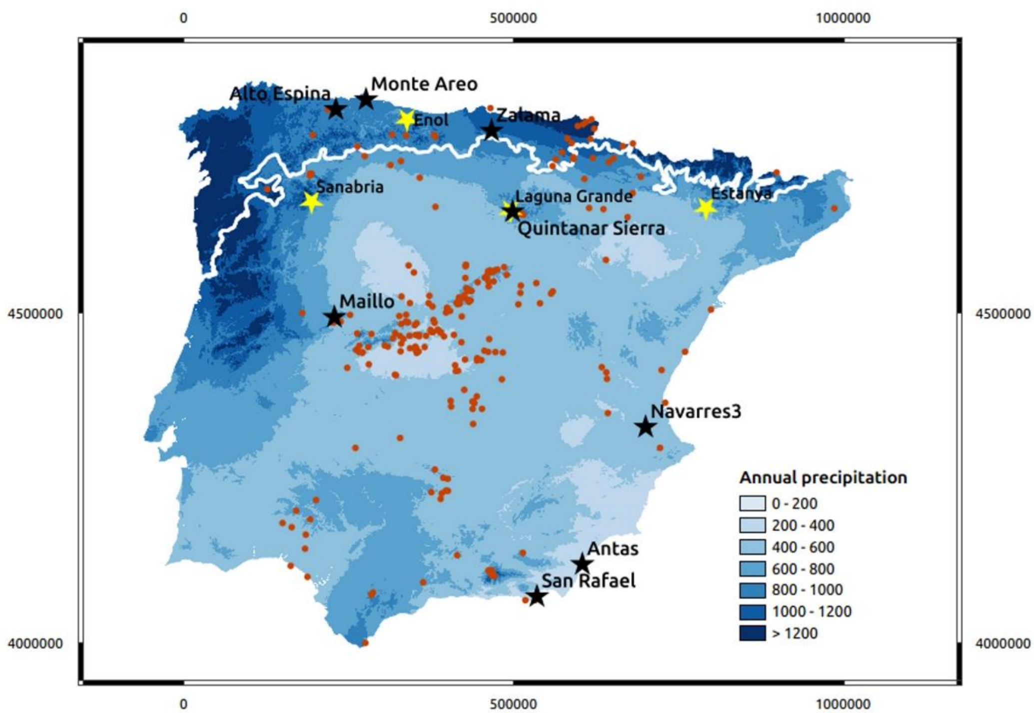
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San Rafael
Annual precipitation
0 - 200
200 - 400
400 - 600
600 - 800
800 - 1000
1000 - 1200
> 1200

Figure 1. Locations of training sites and cores. Training sites are denoted with dots and cores are denoted with black stars. The colours in the map indicate the modern Pann (annual precipitation) values in mm yr^{-1}. The white line indicates the boundary between the Eurosiberian and Mediterranean biogeographical regions. The yellow stars denote the lake record locations from Fig. 7.

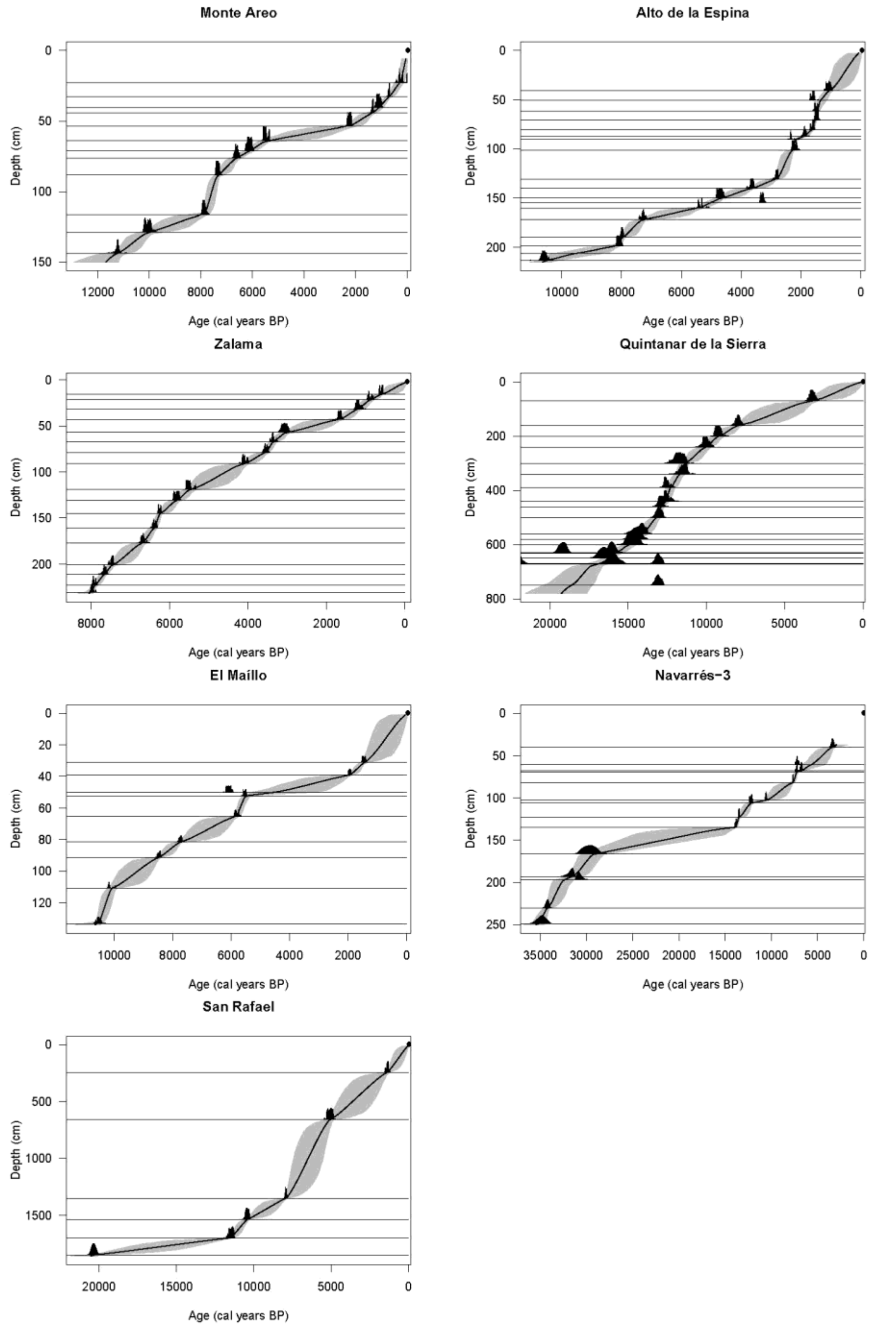


Figure 2: Outputs of Bchron chronology model run for the seven cores used in precipitation reconstructions. The posterior distributions of the calibrated radiocarbon date are shown in black, the gray lines indicate the radiocarbon dated depths and the 95 % credible intervals for the chronologies are in grey bands. The black line is the posterior mean chronology and the dot marks the top of the core. In the reconstructions we use posterior mean chronologies.

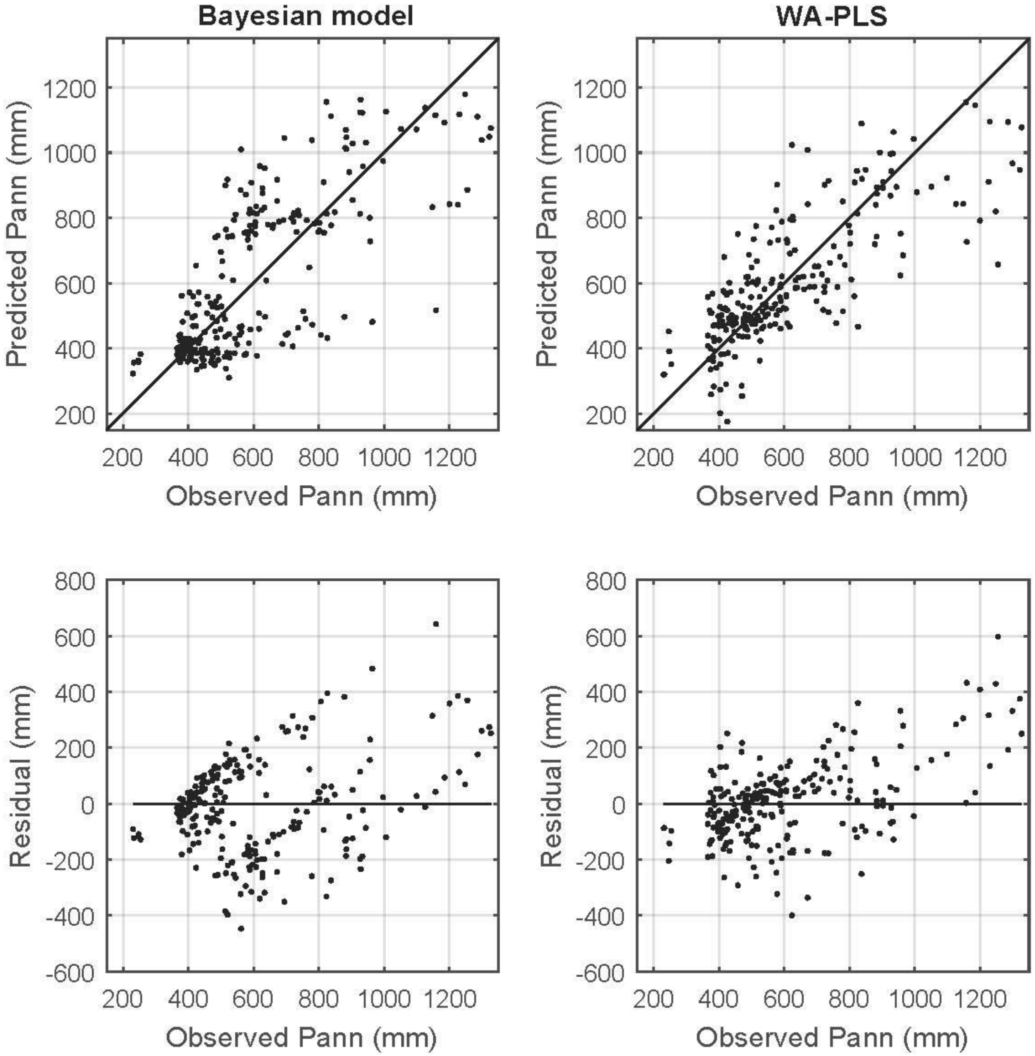


Figure 3: Plots of predicted versus observed modern Pann and residuals of predicted versus observed modern Pann for Bayesian model and two-component WA-PLS in leave-one-out cross-validation.

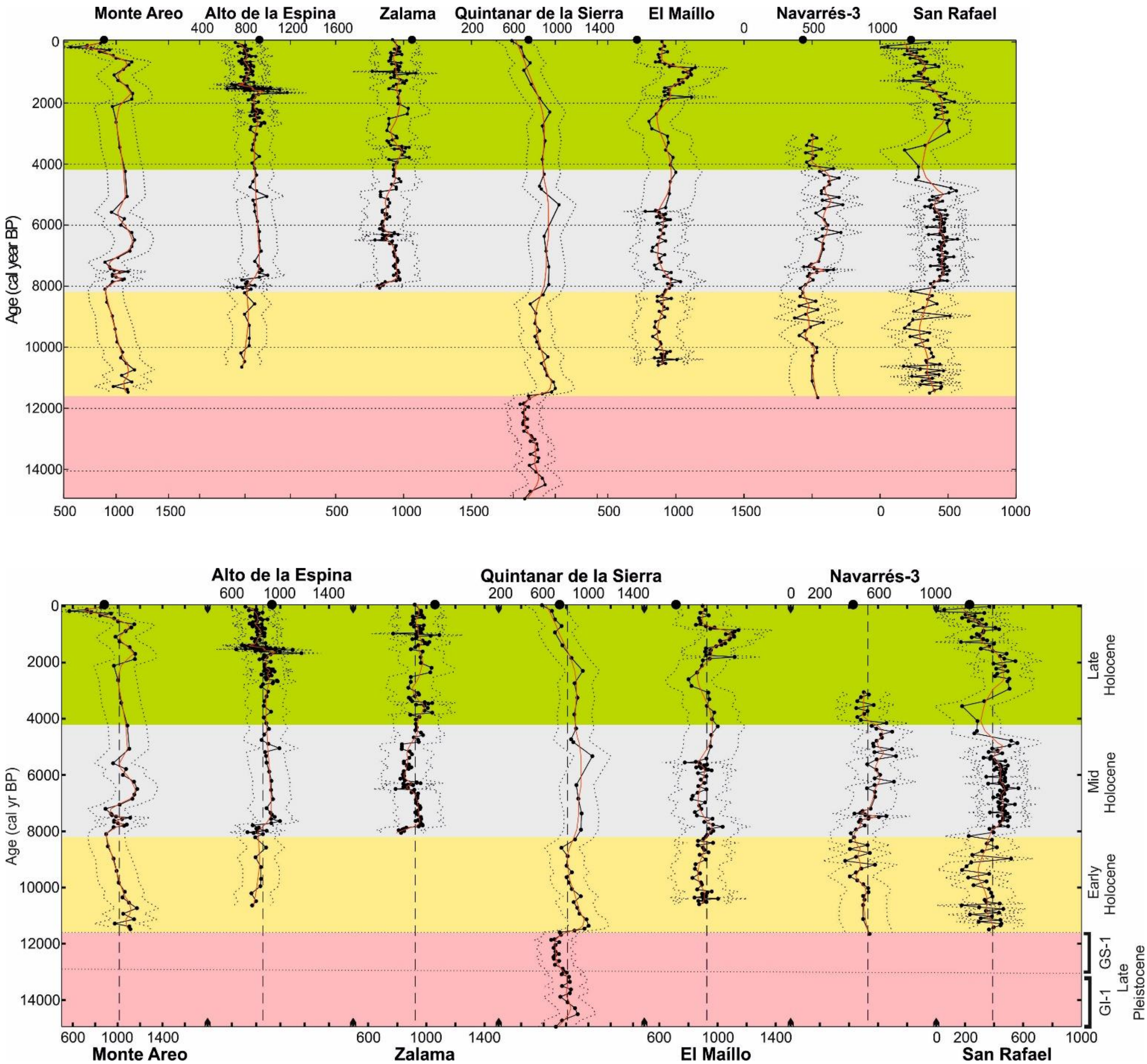


Figure 4: Pann (mm yr^{-1}) reconstructions for seven pollen records using WA-PLS. The black dots connected with the solid black line are the reconstructed values for Pann, the solid red line is a LOWESS smoother added to the reconstructions (span 0.1) and the black dotted lines denote bootstrap estimated standard errors. The vertical stippled line indicates the mean value of each reconstruction. The big black dot is the modern measured value for Pann. X-axis is Pann and y-axis is time in years before present. The little arrowheads separate the x-axis of different reconstructions. The colors indicate the formal stratigraphical subdivision of the Holocene and Late Pleistocene (Walker et al., 2018).

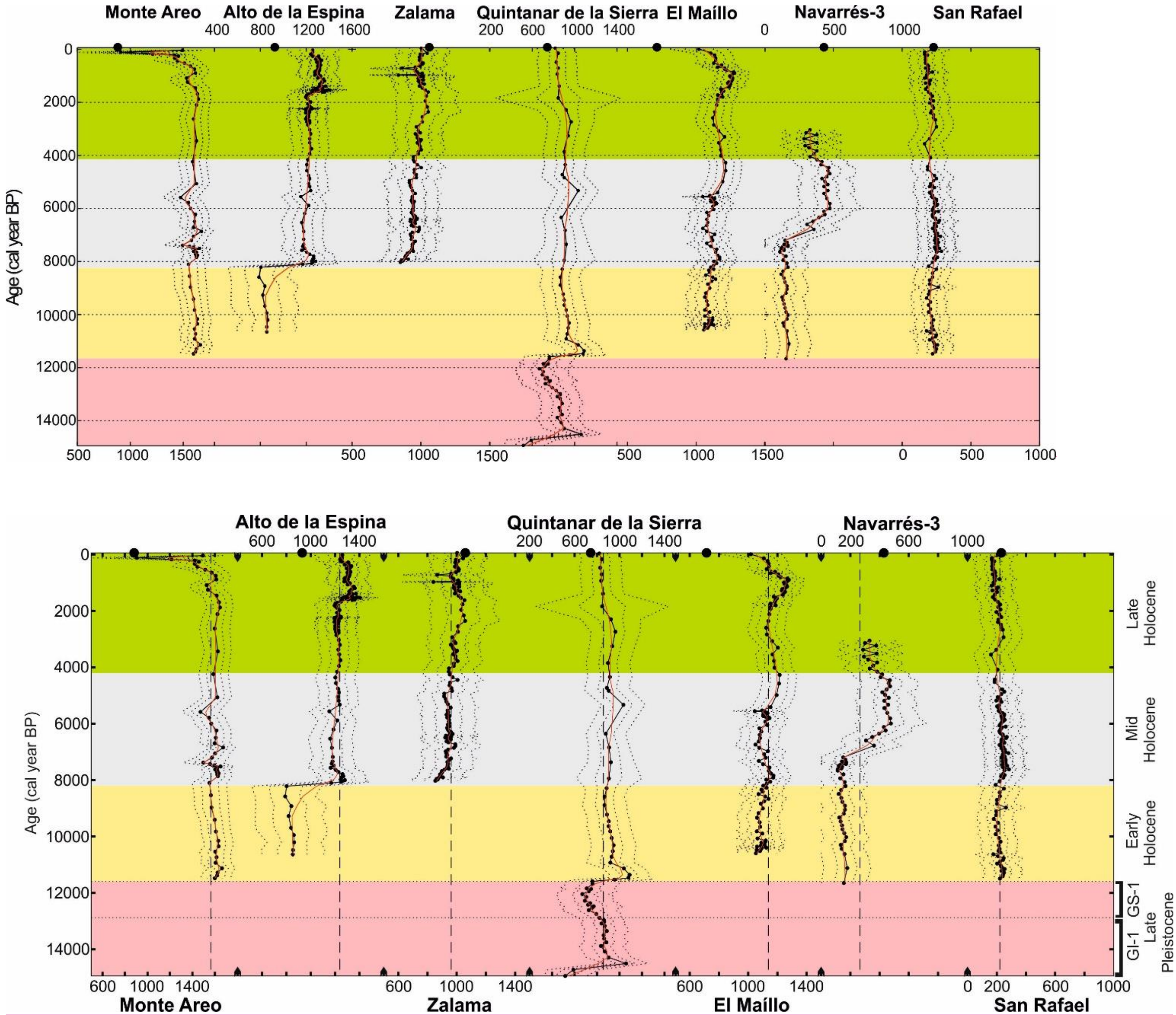
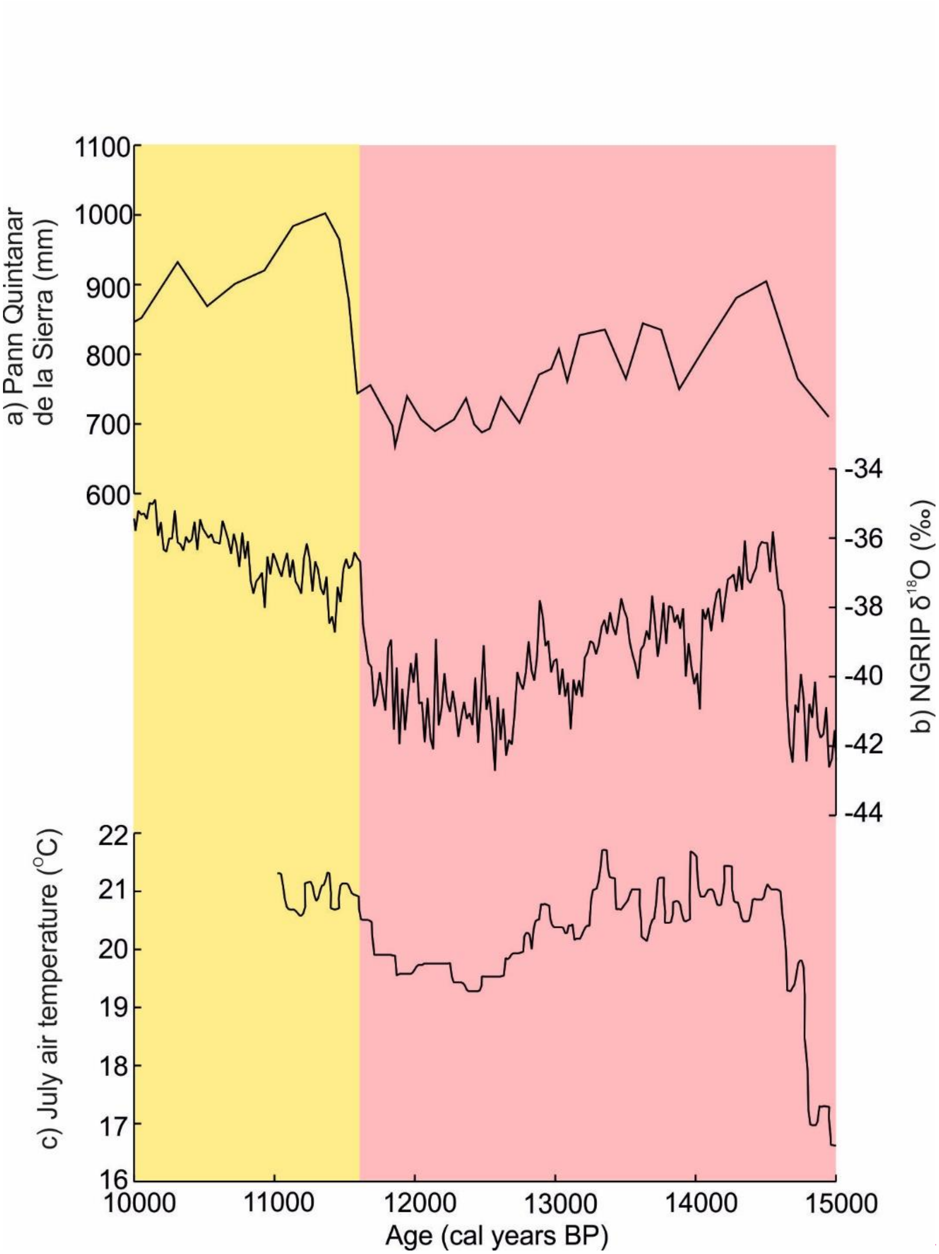


Figure 5: Pann (mm yr^{-1}) reconstructions for seven pollen records using Bayesian model. The black dots connected with the solid black line are the posterior mean values for Pann, the solid red line is a LOWESS smoother added to the reconstructions (span 0.1). The inner and outer black dotted lines show the point-wise and simultaneous 95 % credible bands, respectively. The vertical stippled line indicates the mean value of each reconstruction. The big black dot is the modern measured value for Pann. X-axis is Pann and y-axis is time in years before present. The little arrowheads separate the x-axis of different reconstructions. The colors indicate the formal stratigraphical subdivision of the Holocene and Late Pleistocene (Walker et al. 2018).



a) Pann Quintanar
de la Sierra (mm)
1100
1000
900
800
700
600
-34
-36
-38
-40
-42
-44
b) NGRIP δ18O (‰)
c) July air temperature (°C)
22
21
20
19
18
17
16
10000
11000
12000
13000
14000
15000
Age (cal years BP)

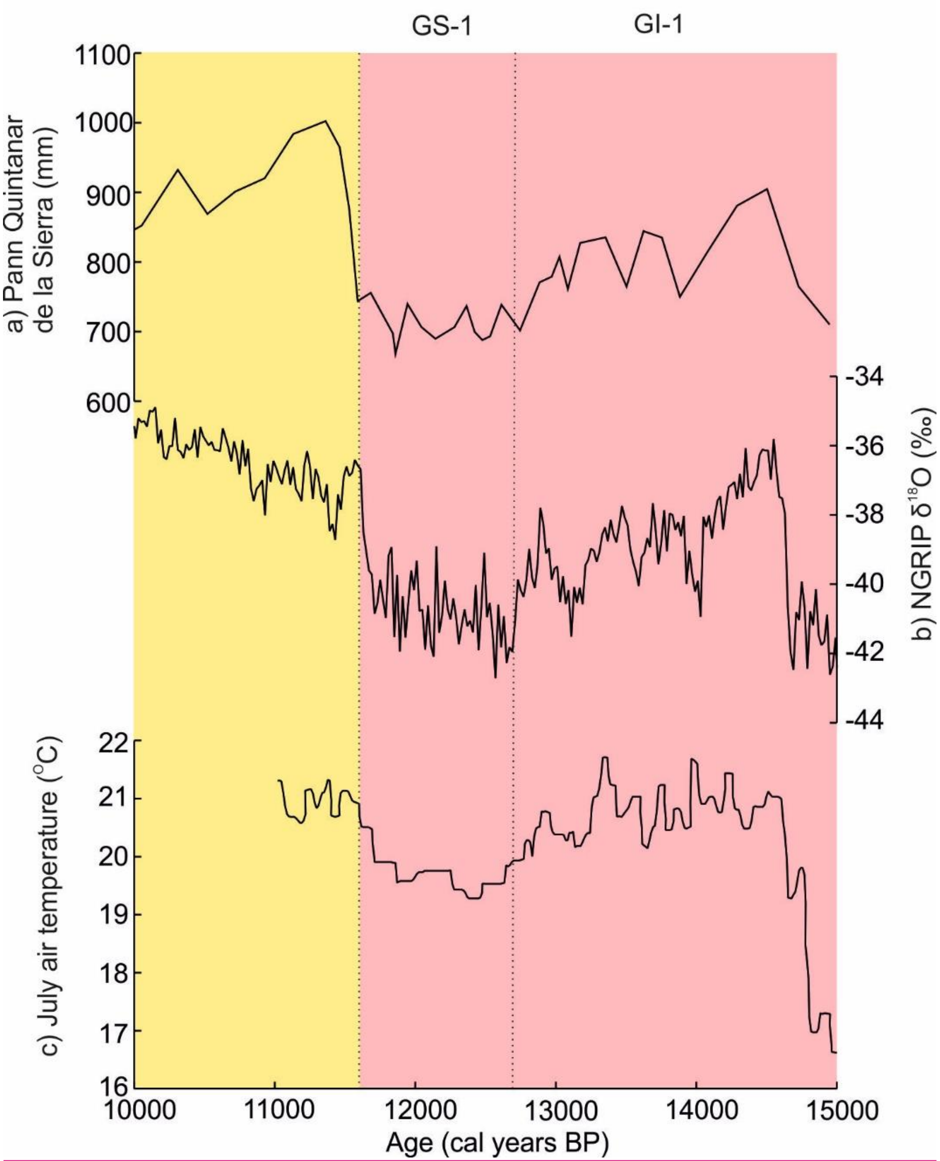
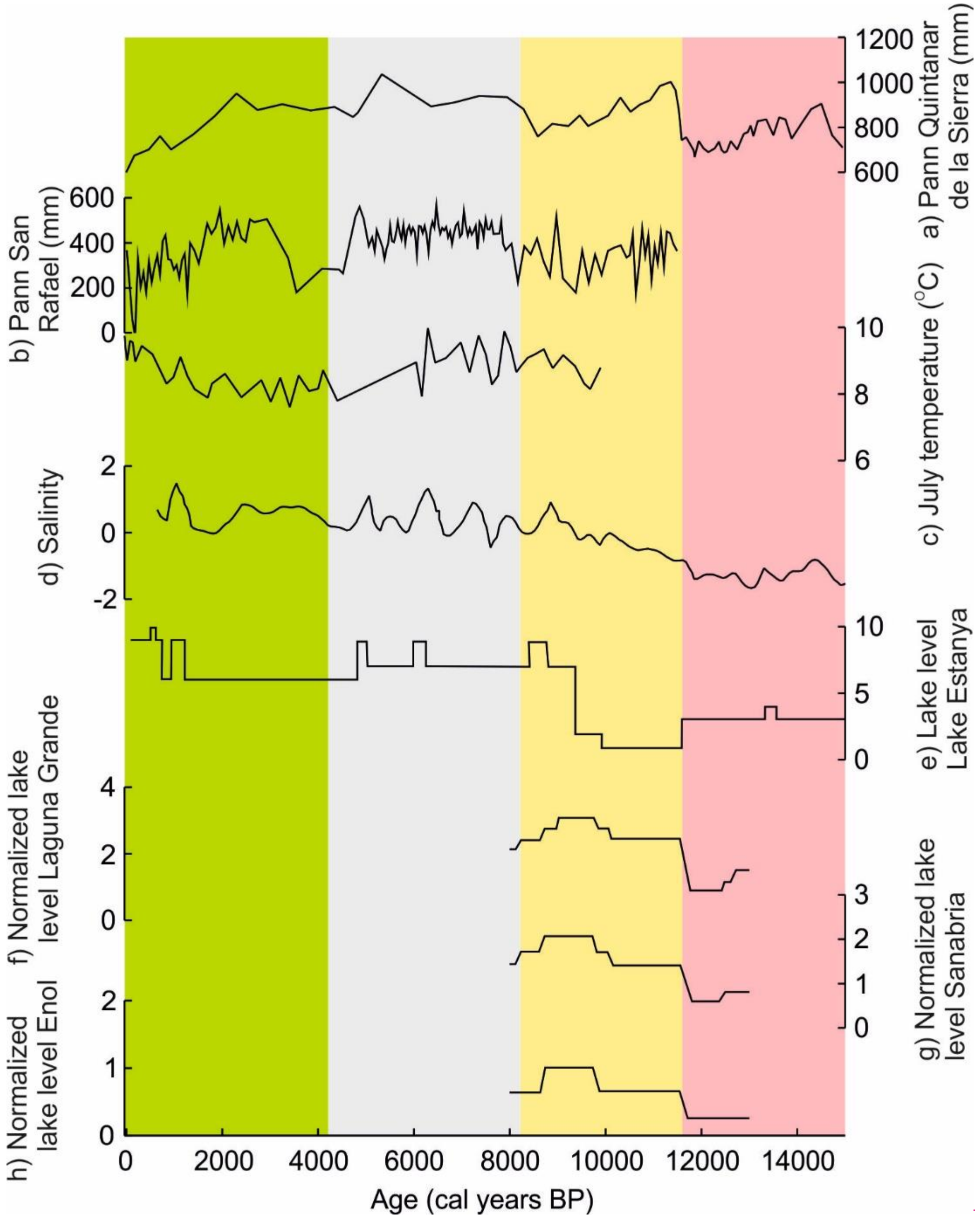


Figure 6: The Late-Pleistocene precipitation reconstruction from a) Quintanar de la Sierra compared with b) $\delta^{18}O$ record from the NorthGRIP ice core from Greenland (Rasmu~~n~~ssen et al., 2014) and c) chironomid-based July mean temperature reconstruction for SW Europe (Heiri et al., 2014). The colors indicate the formal stratigraphical subdivision of the Holocene and Late Pleistocene (Walker et al. 2018).


a) Pann Quintanar de la Sierra (mm)
b) Pann San Rafael (mm)
c) July temperature (°C)
d) Salinity
e) Lake level Lake Estanya
f) Normalized lake level Laguna Grande
g) Normalized lake level Sanabria
h) Normalized lake level Enol
Age (cal years BP)

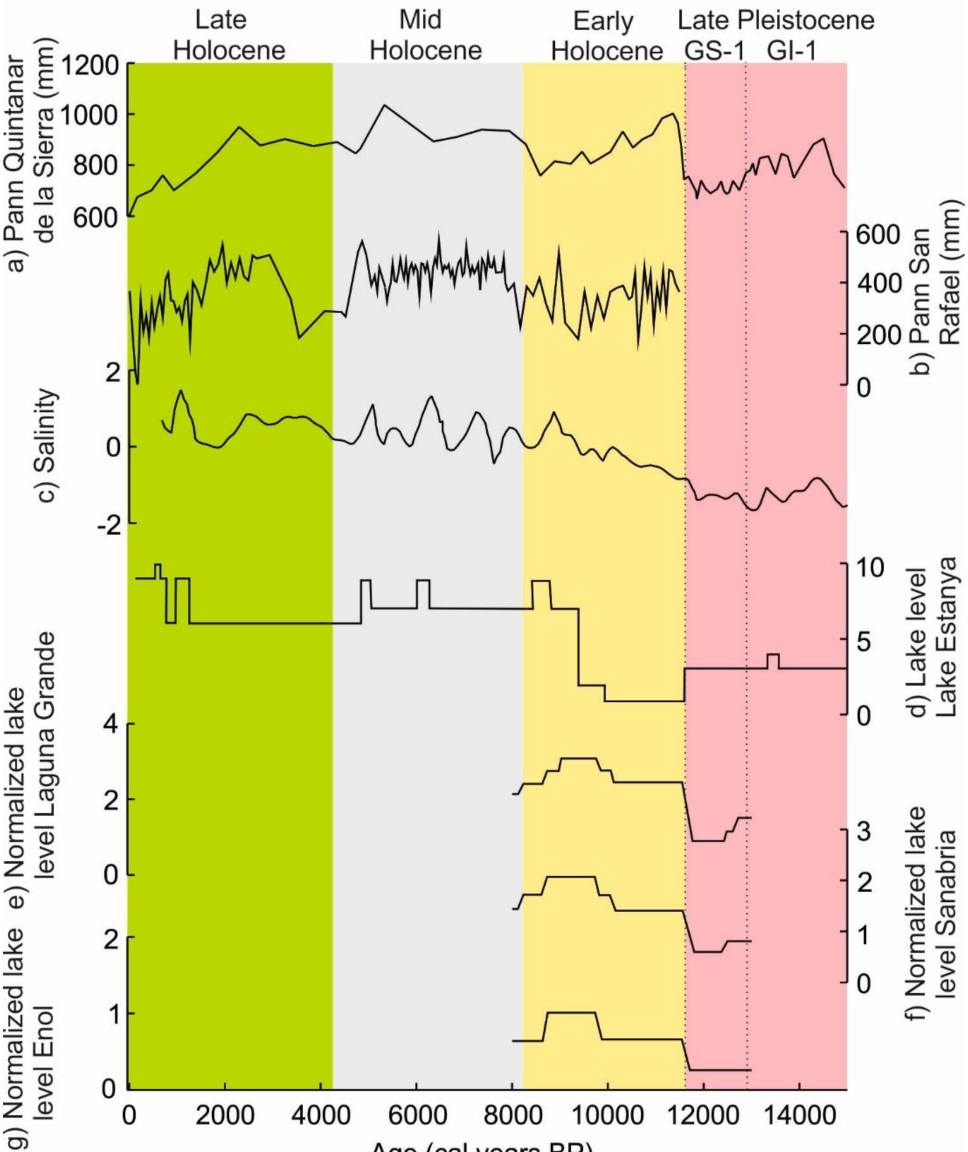
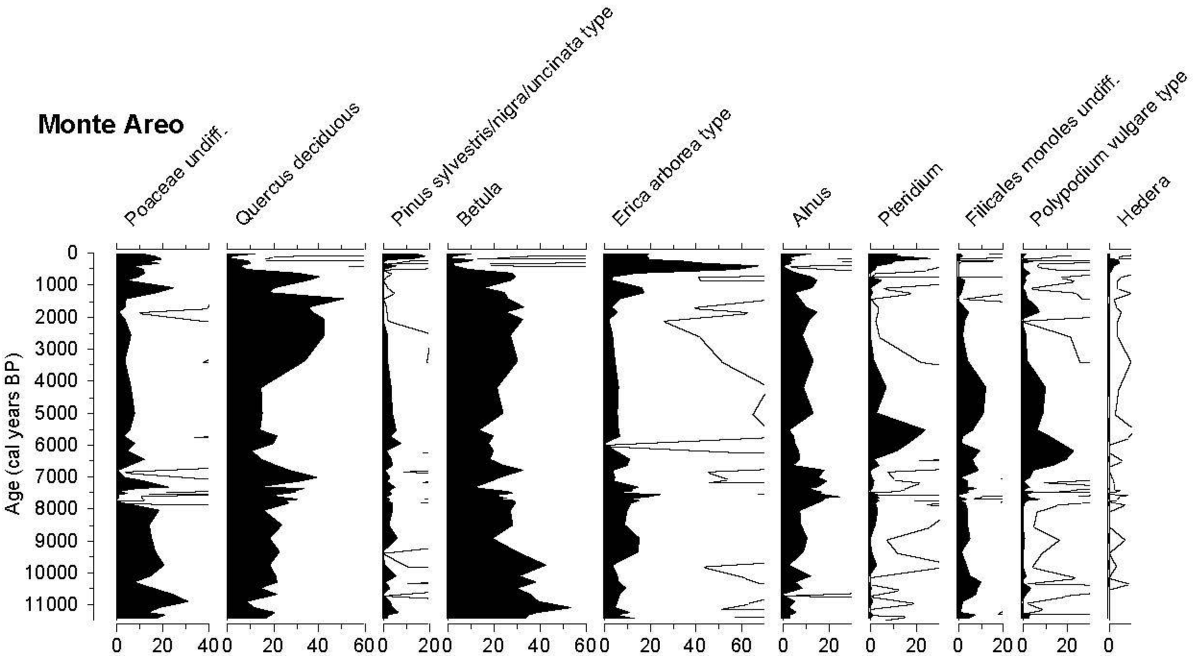
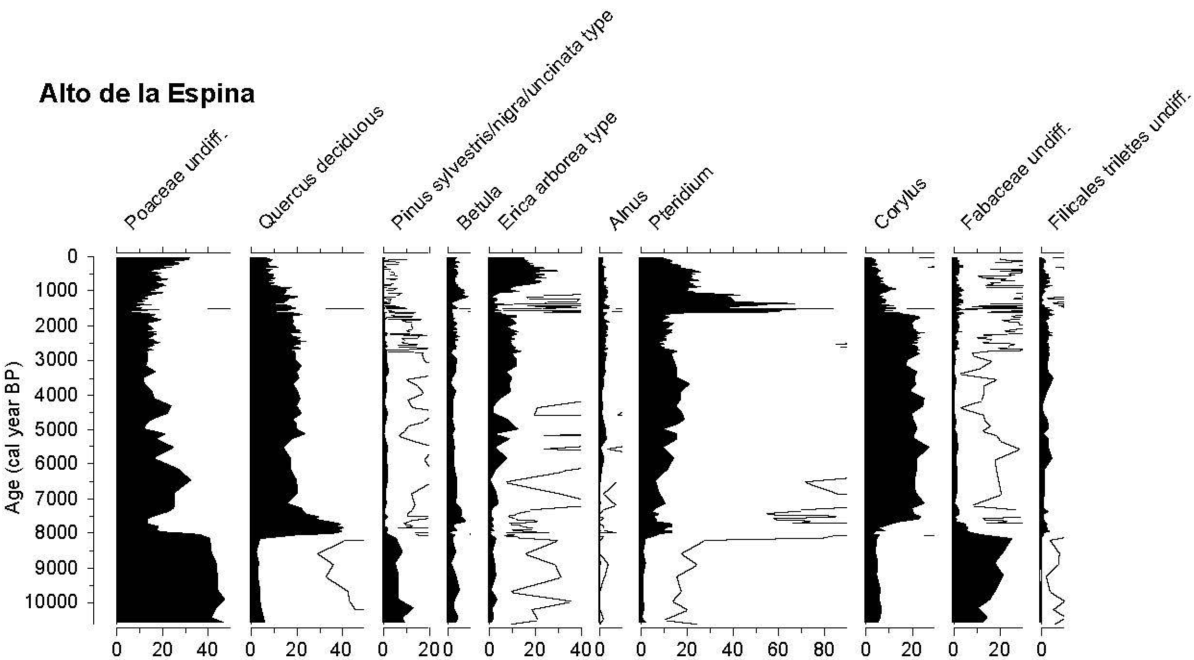


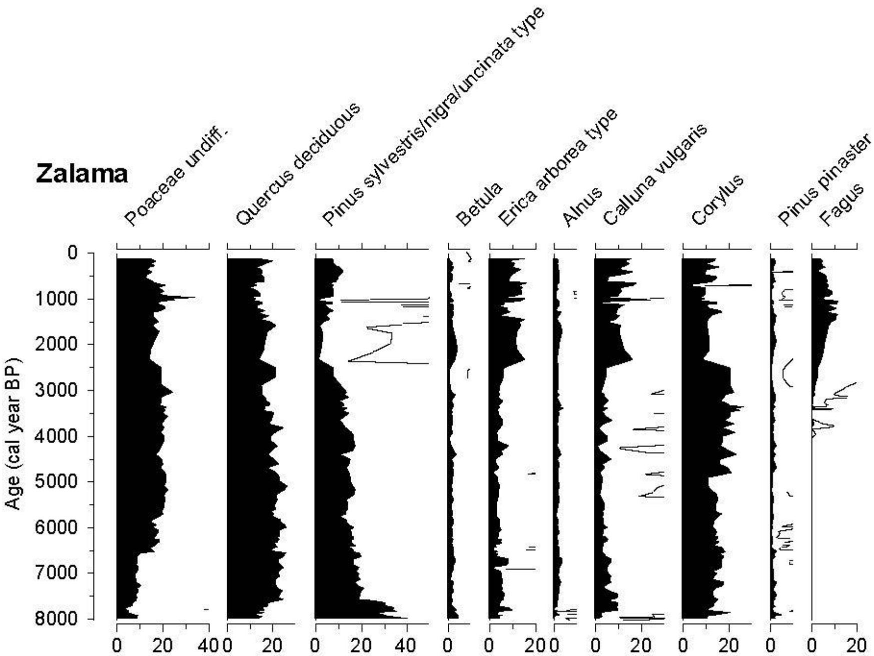
Figure 7: Reconstructed precipitation trend from a) northern Spain (Quintanar de la Sierra) and b) southern Spain (San Rafael) compared with ~~c) chironomid-based July temperature reconstruction for Basa de la Mora Lake in Central Pyrenees, Spain (Tarrats et al., 2018), d~~ c) salinity from lake Estanya. The salinity values (-2, 2) are PCA axis 2 values, with negative values indicating higher salinity (Morellón et al., 2009), ~~e~~d) lake level reconstruction of lake Estanya (Morellón et al., 2009), ~~f~~e) normalized lake level for Laguna Grande (Morellón et al., 2018), ~~g~~f) normalized lake level for Sanabria (Morellón et al., 2018) and ~~h~~g) normalized lake level

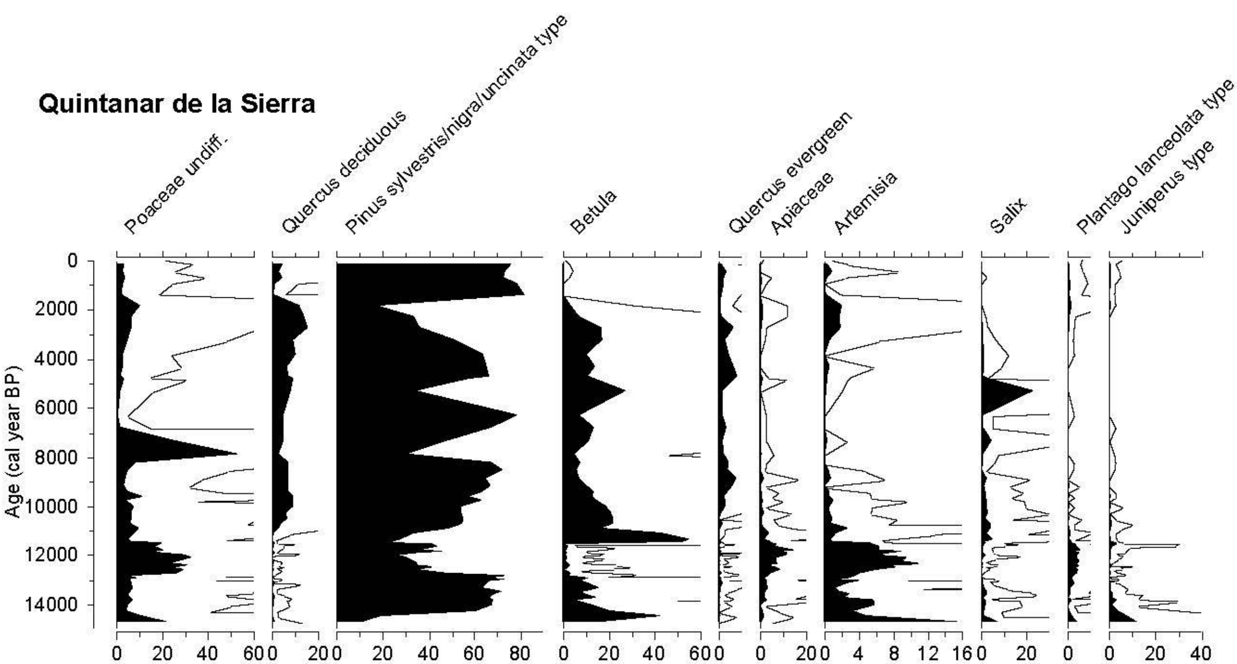
for Enol (Morellón et al., 2018). The colors indicate the formal stratigraphical subdivision of the Holocene and Late Pleistocene (Walker et al. 2018).

Figure S1. Simplified pollen percentage diagrams for seven pollen records used in precipitation reconstructions. Only the ten most common and important pollen taxa are shown. Black silhouettes indicate the percentage values and the unshaded silhouettes 10 x exaggerations.

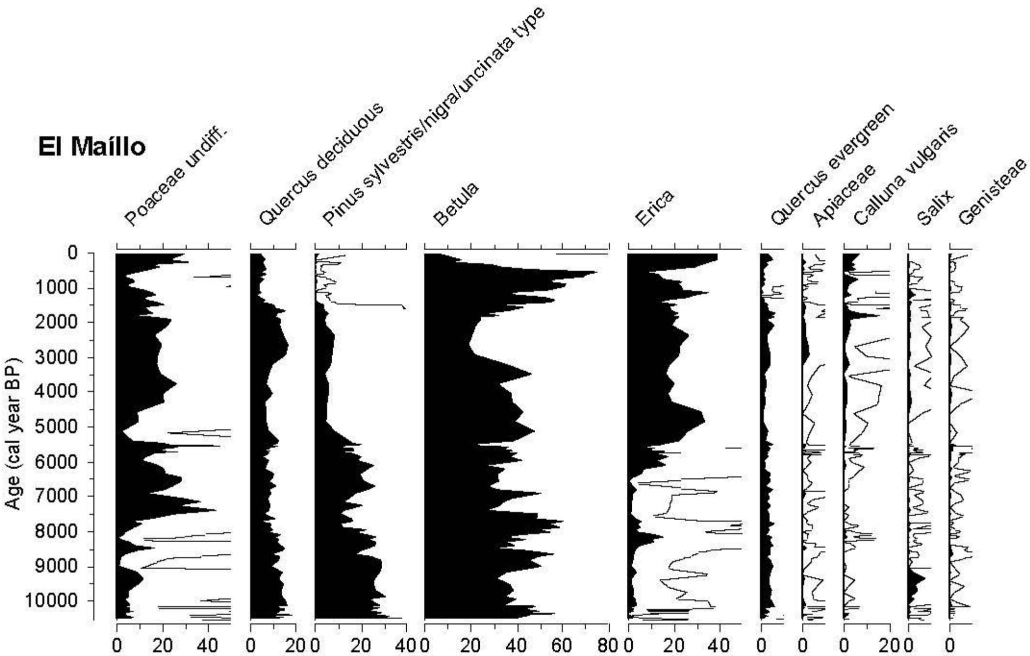




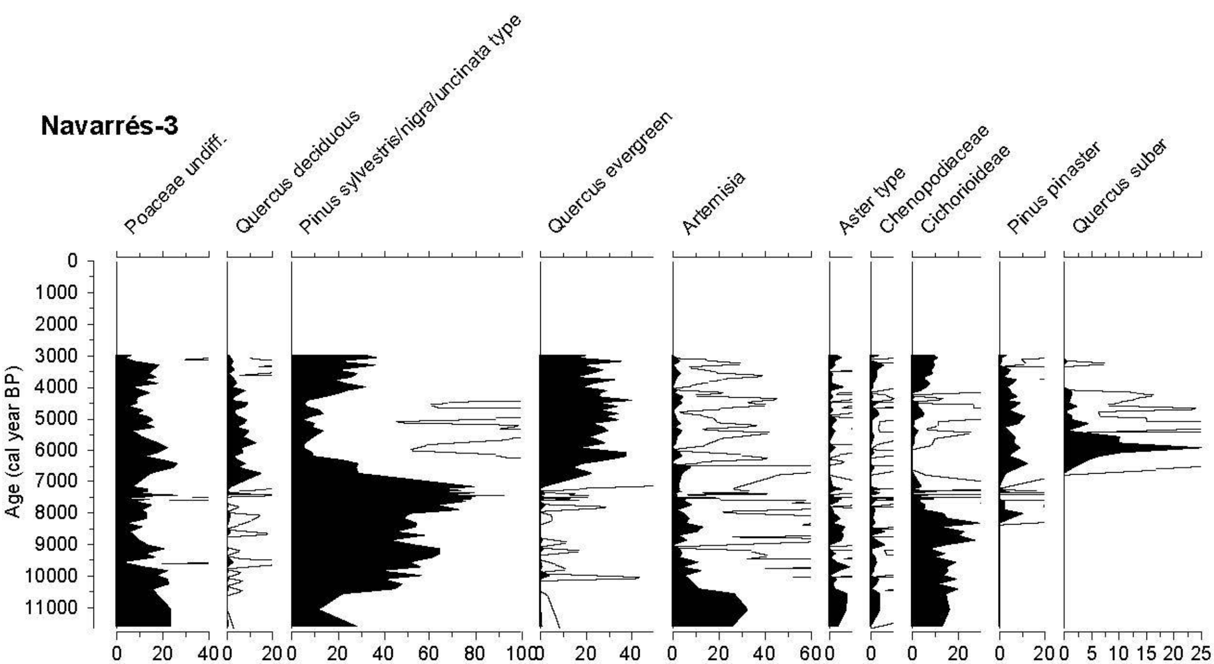

Zalama
Poaceae undiff.
Quercus deciduous
Pinus sylvestris/nigra/uncinata type
Betula
Erica arborea type
Alnus
Calluna vulgaris
Corylus
Pinus pinaster
Fagus
Age (cal year BP)
0
1000
2000
3000
4000
5000
6000
7000
8000
0 20 40
0 20
0 20 40
0
0 20
0
0 20
0 20
0
0 20


Quintanar de la Sierra
Poaceae undiff.
Quercus deciduous
Pinus sylvestris/nigra/uncinata type
Betula
Quercus evergreen
Apiaceae
Artemisia
Salix
Plantago lanceolata type
Juniperus type
Age (cal year BP)
0
2000
4000
6000
8000
10000
12000
14000
0 20 40 60
0 20
0 20 40 60 80
0 20 40 60
0
0 20
0 4 8 12 16
0 20
0
0 20 40

El Maíllo



Navarrés-3



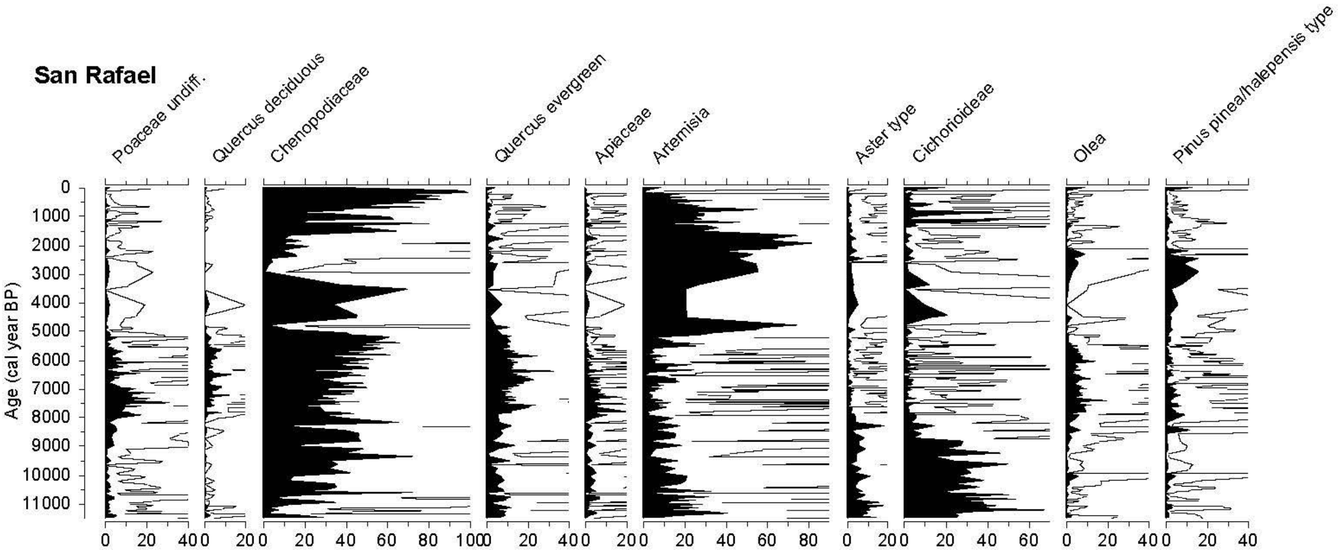

San Rafael
Poaceae undiff.
Quercus deciduous
Chenopodiaceae
Quercus evergreen
Apiaceae
Artemisia
Aster type
Cichorioideae
Olea
Pinus pinea/halepensis type
Age (cal year BP)
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000

Figure S2: Gaussian response curve for a taxon *j* determined by α_j (scaling factor), β_j (optimum precipitation), and γ_j (tolerance to precipitation).

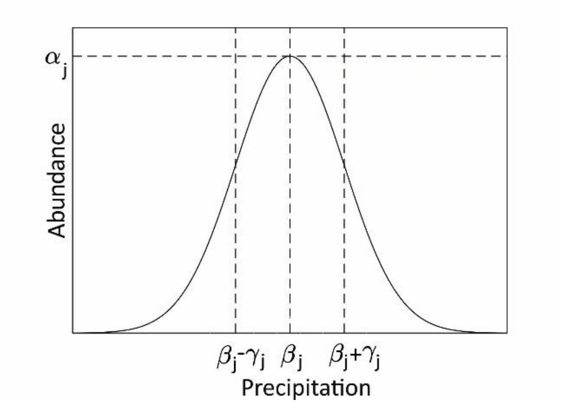
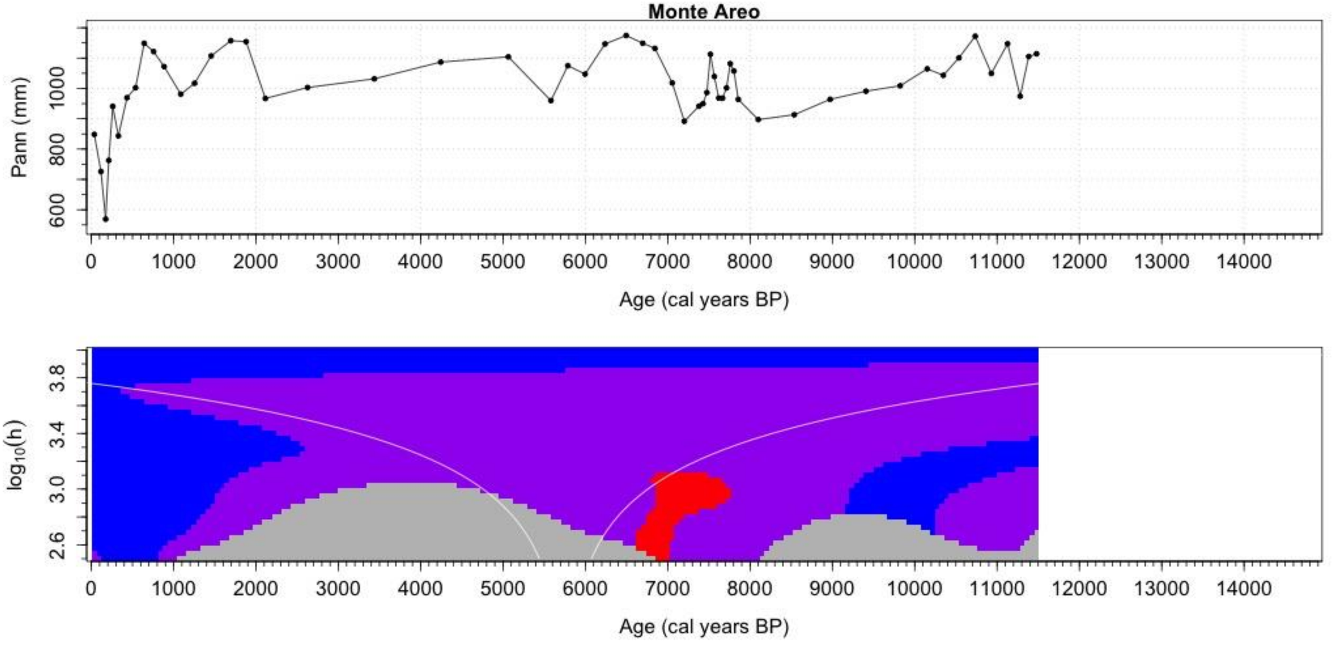
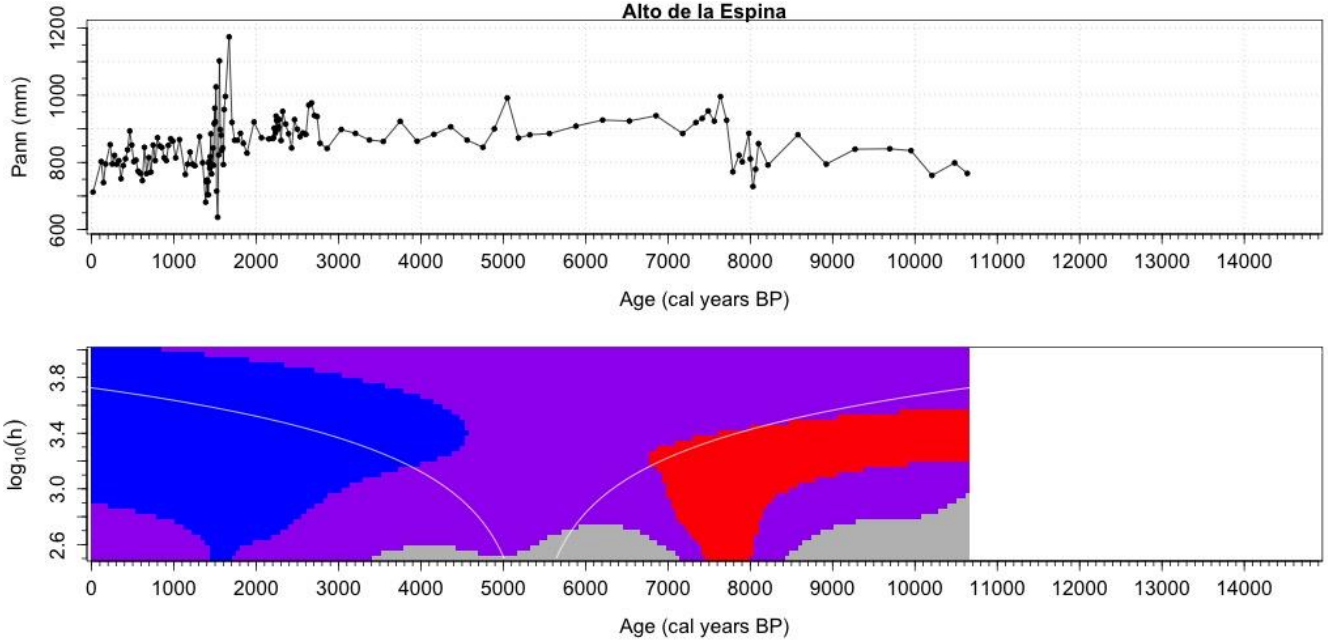
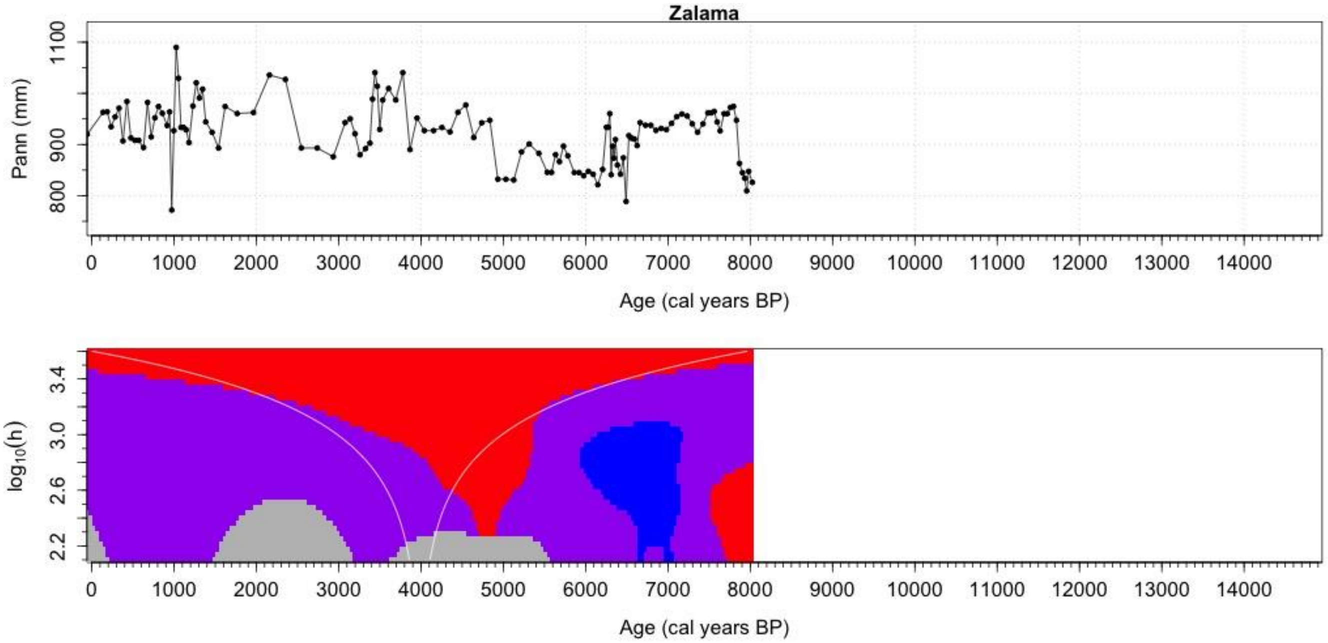
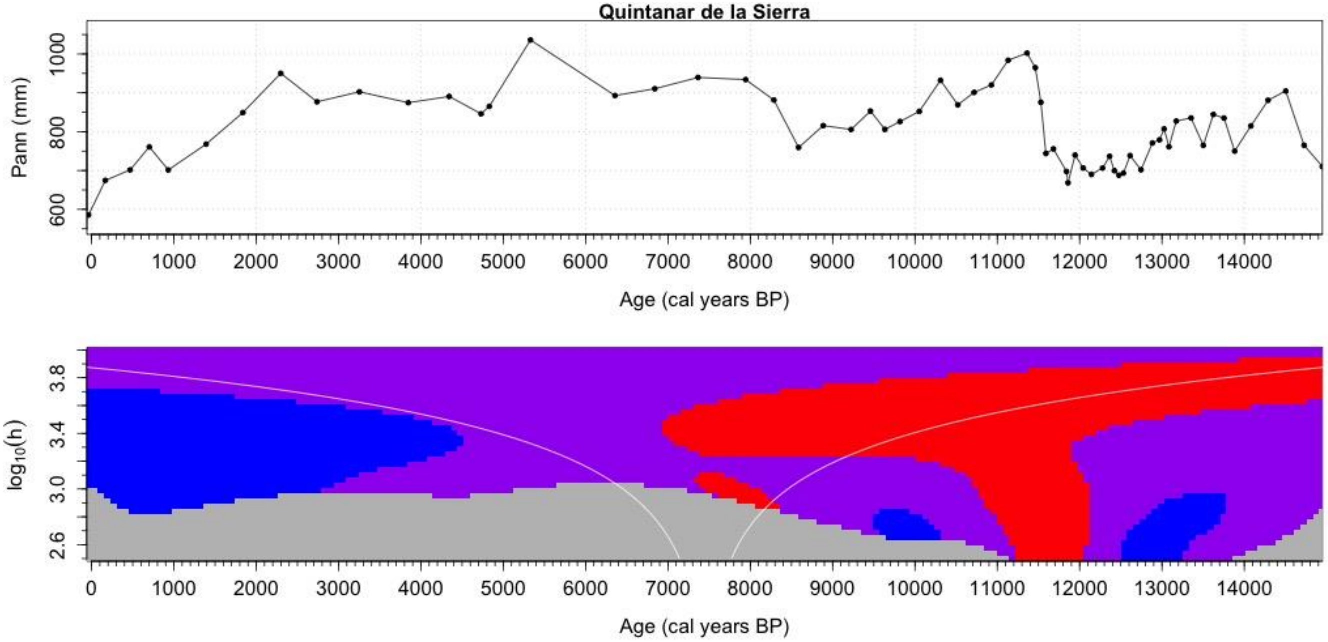


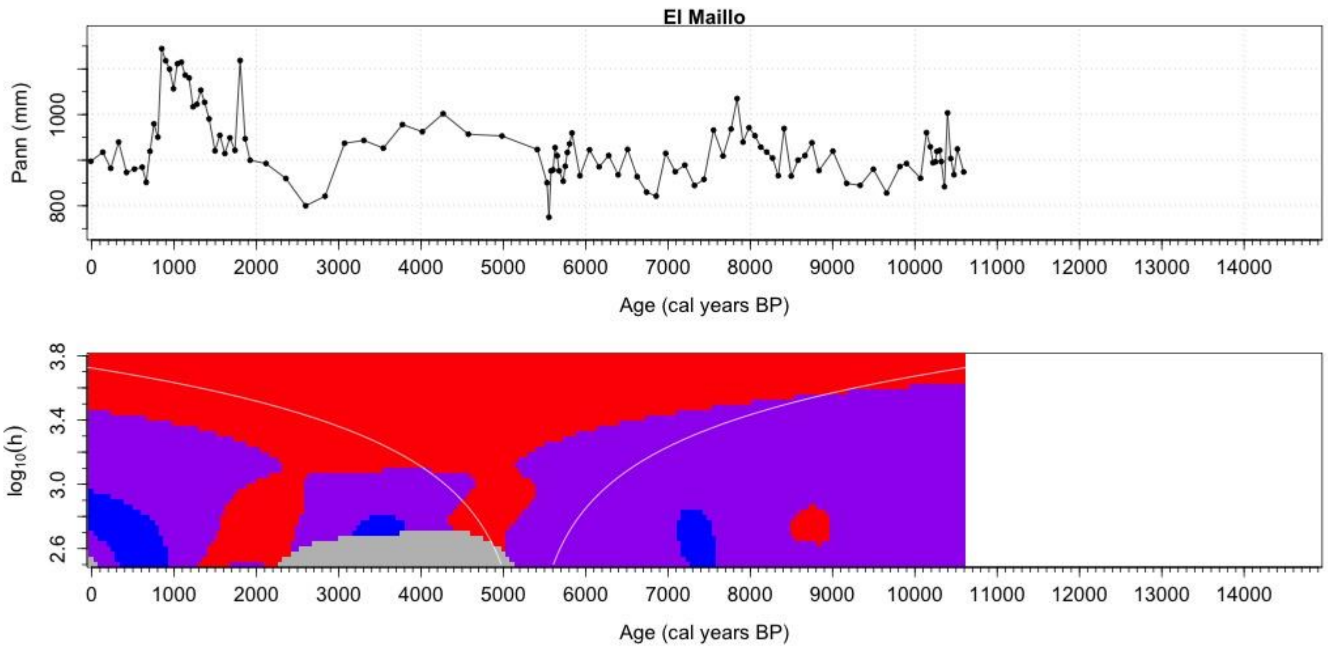
Figure S3: SiZer analysis (Chaundhuri and Marron, 1999) of the seven pollen records used in precipitation reconstructions based on WA-PLS reconstructions. Upper panel: WA-PLS reconstructions. Lower panel: the SiZer map which summarises the statistical significance of the sign of the derivative of the smooths of the density underlying the data. Blue color indicates decreasing values and red color indicates increasing values as we read the data from past to present. Purple indicates a non-significant slope and gray indicates that data is insufficient for the inference. Verical axis: logarithm of the bandwidth h. The white lines give a graphical representation of the bandwidth as intervals representing ±2h. With small values for $\log_{10}$(h) we obtain the features with little smoothing and the higher the value for $\log_{10}$(h) the more smoothing is done and we obtain the coarser level features. SiZer map also shows values for maxima and minima as color changes from red to blue or from blue to red. The analysis was produced by the R package Sizer at https://github.com/dereksonderegger/SiZer.

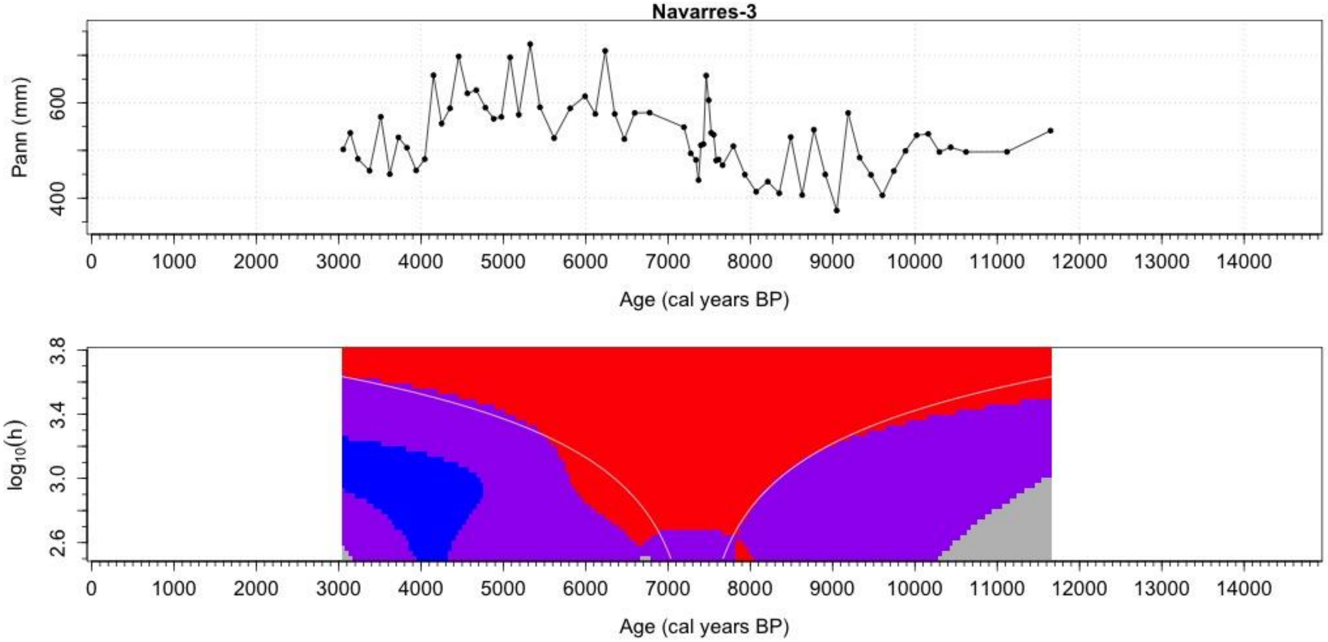



Alto de la Espina
Pann (mm)
600
800
1000
1200
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
Age (cal years BP)
$\log_{10}(h)$
2.6
3.0
3.4
3.8
Age (cal years BP)


Zalama
Pann (mm)
800
900
1100
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
Age (cal years BP)
$\log_{10}(h)$
2.2
2.6
3.0
3.4
Age (cal years BP)


Quintanar de la Sierra
Pann (mm)
Age (cal years BP)
log10(h)
Age (cal years BP)


El Maillo
Pann (mm)
Age (cal years BP)
log10(h)
Age (cal years BP)


Navarres-3
Pann (mm)
Age (cal years BP)
log10(h)
Age (cal years BP)

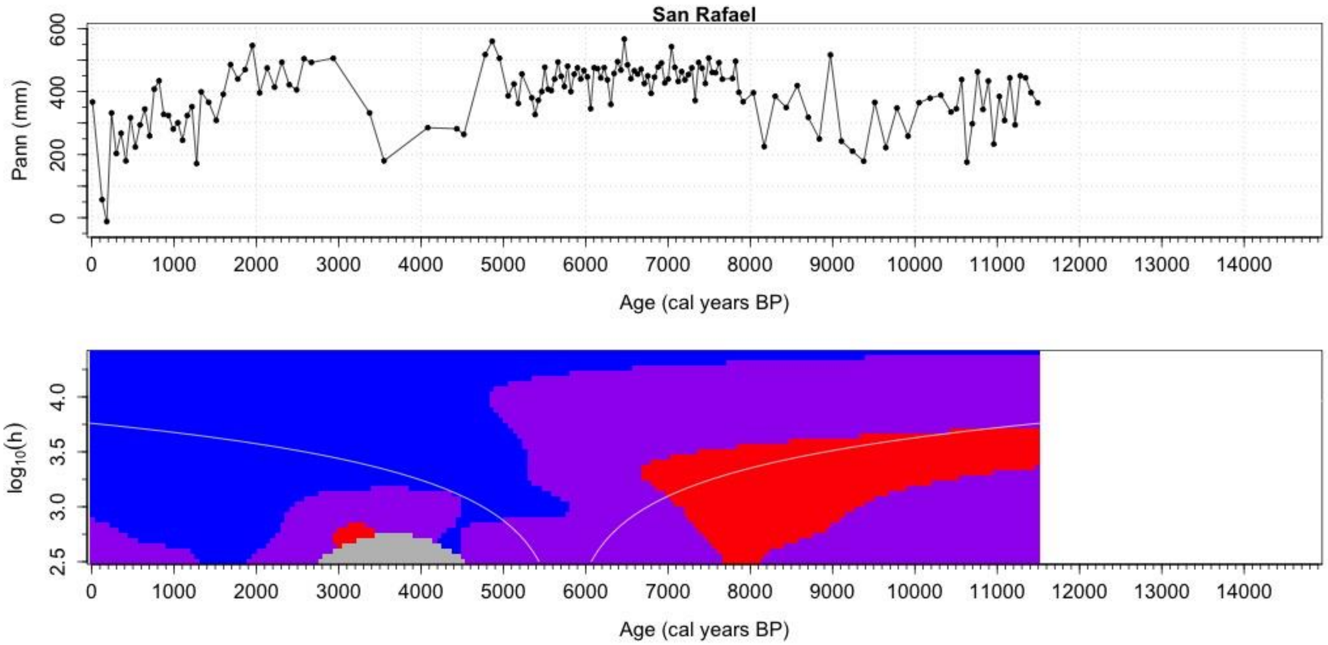
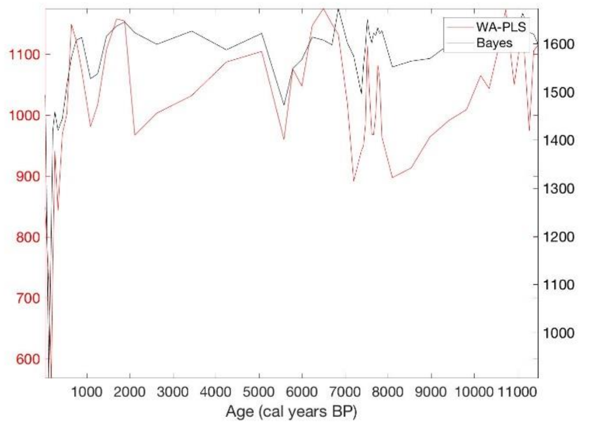

San Rafael
Pann (mm)
Age (cal years BP)
log10(h)
Age (cal years BP)

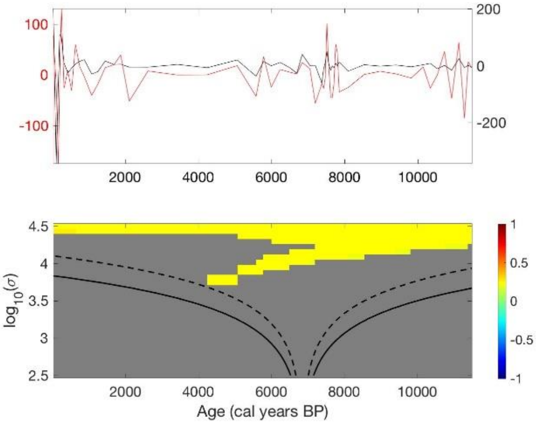
Figure S4: Scale space multiresolution correlation analysis (Pasanen and Holmström, 2016) of similarity between WA-PLS and Bayesian model Pann reconstructions for the seven pollen records. Scale space multiresolution correlation analysis takes into consideration the possibility that the correlation between two time series may change over time and can have different features when inspected at different time scales. The method has two steps. In the first step the time series are decomposed into a number of scale-dependent components and in the second step the local temporal changes in correlation between pairs of such components are explored by using weighted correlation within a sliding time window of varying length. As a result method identifies the time intervals and the time scales for which correlation is credibly positive or negative. Panel a) original reconstructions. Panels b, c, d, e, f) extracted short and long timescale components, and analysis of the statistically significant features with their correlation patterns shown in credibility maps. In other panels than a) the horizontal distance between the solid black lines represents the width of the kernel that indicates the time range used in calculating the correlation and the dashed lines indicate the width of the interval where the kernel height has decreased to 50% of its maximum. Red shades indicate statistically significant positive correlation and blue shades indicate statistically significant negative correlation. Gray color indicates non-significance with posterior probability less than 0.95. In order to produce the correlation credibility maps we need to obtain posterior samples also for the WA-PLS reconstructions. We use the idea introduced in Fang et al. 2018 but in our case we obtain the noise variance for the Pann directly from the WA-PLS results.

Monte Areo

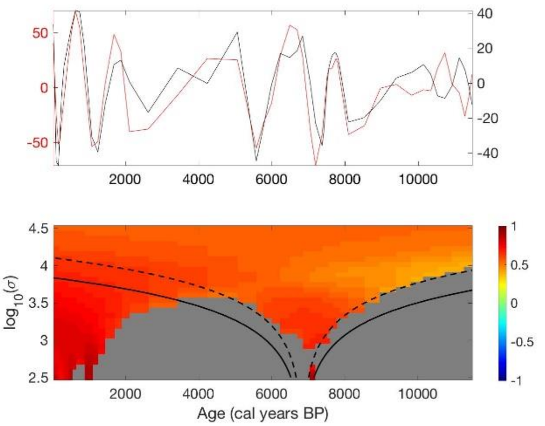
a)



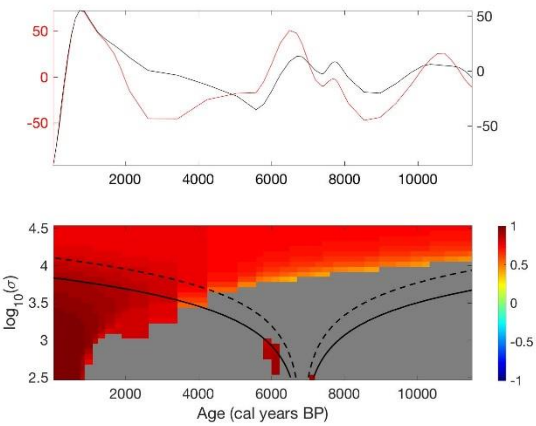
b)



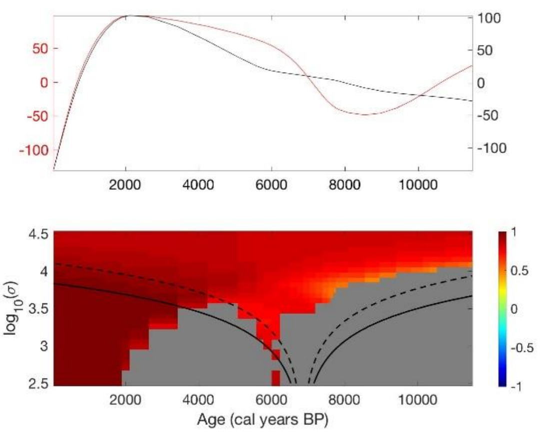
c)



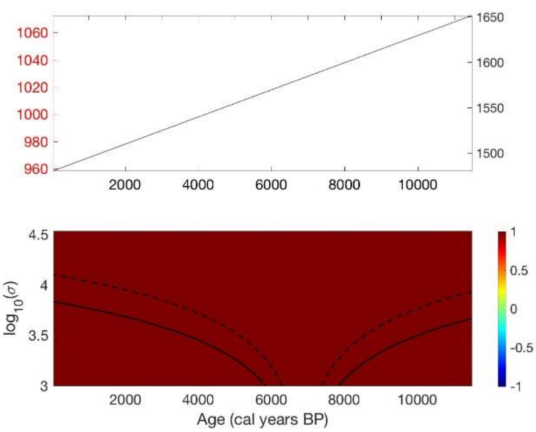
d)



e)

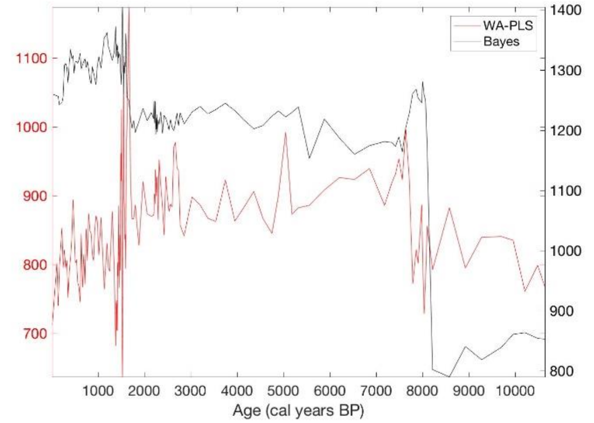


f)

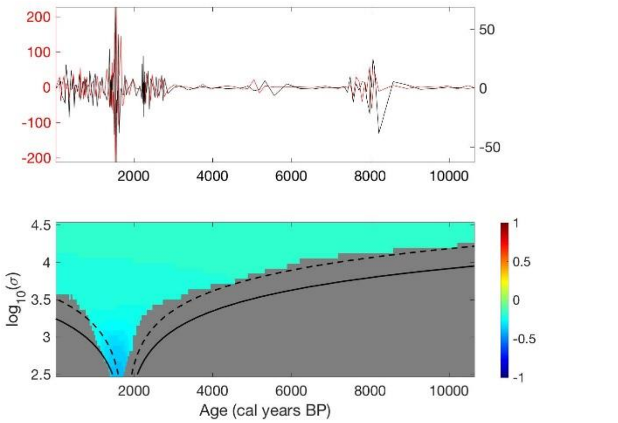


Alto de la Espina

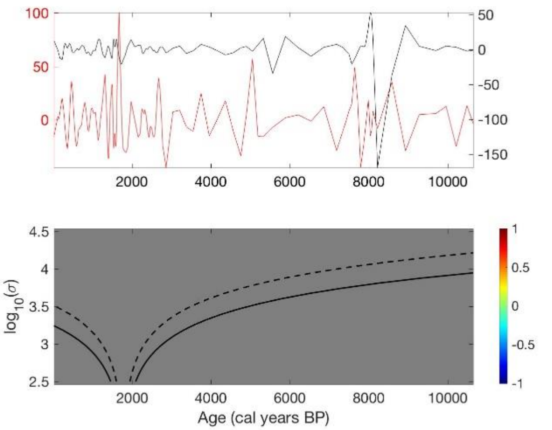
a)



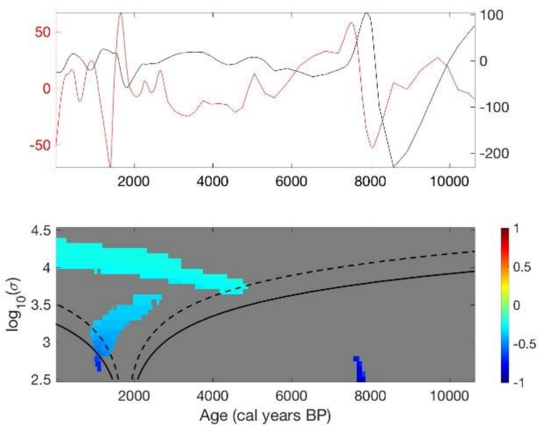
b)



c)



d)



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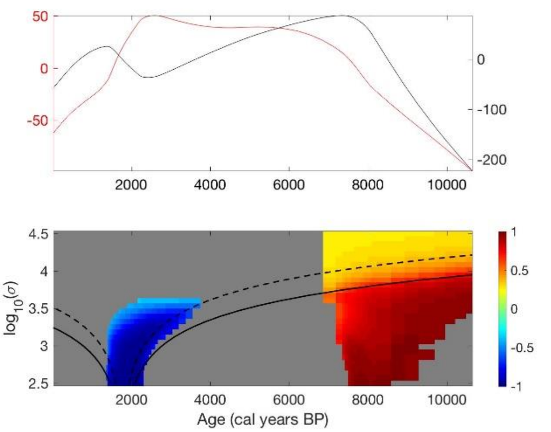
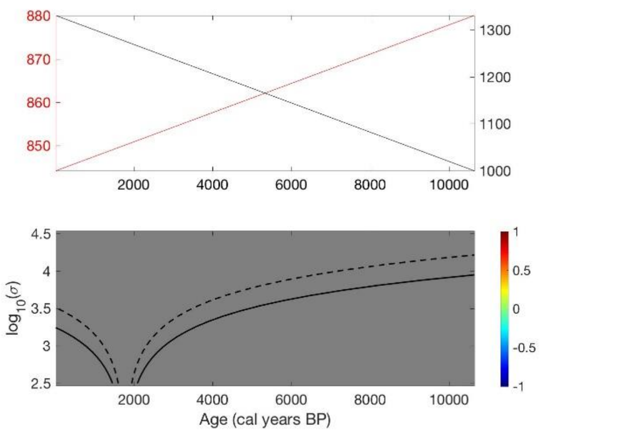
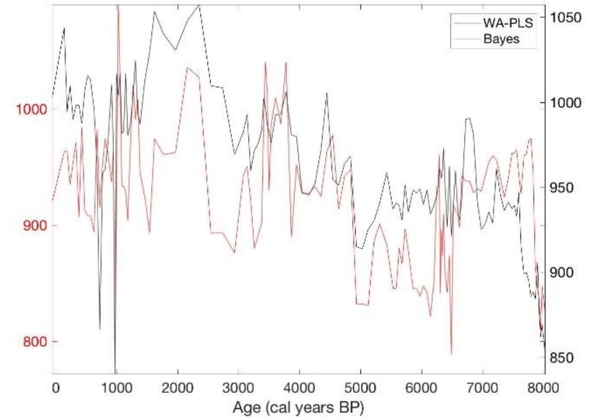


f)

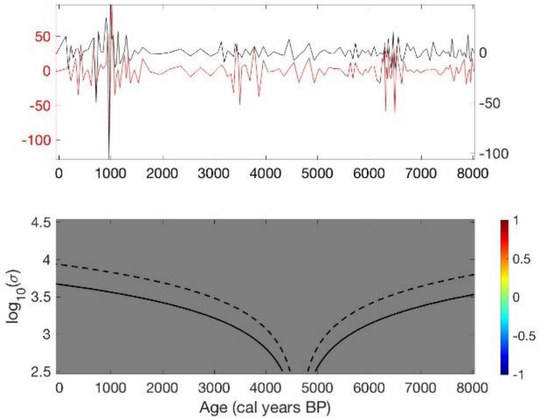


Zalama

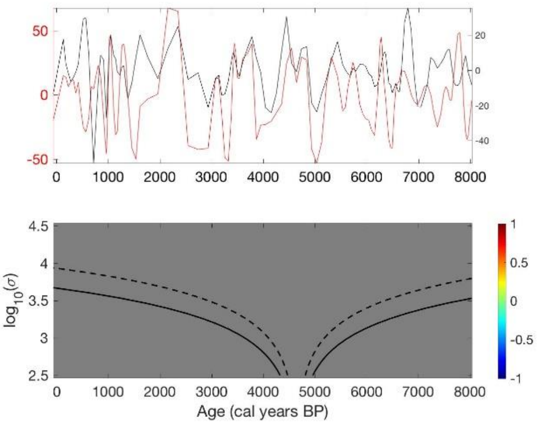
a)



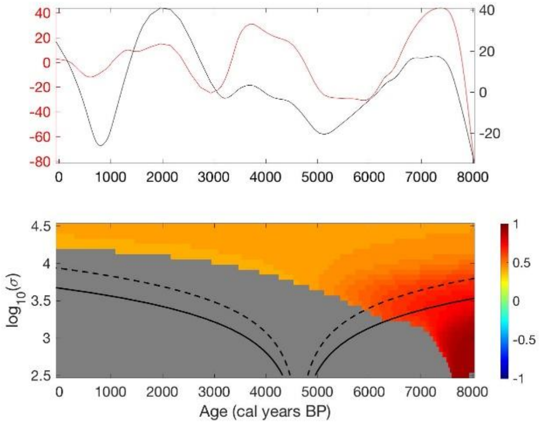
b)



c)



d)



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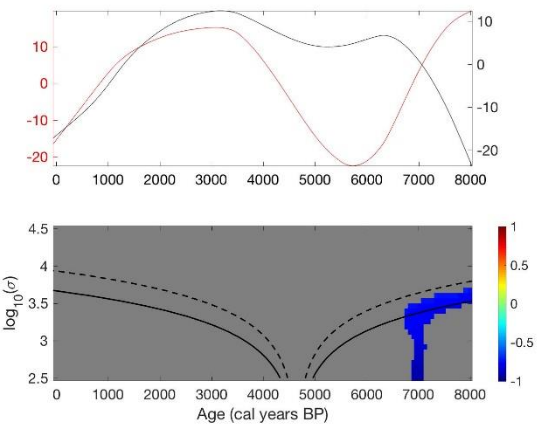
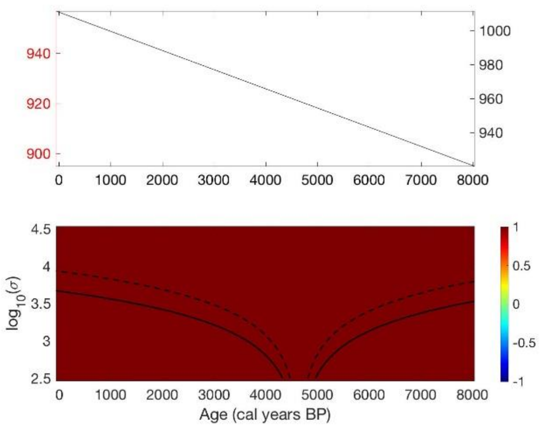
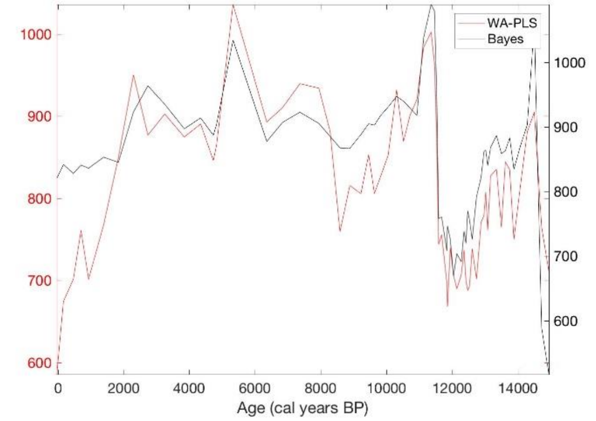


f)



Quintanar de la Sierra

a)



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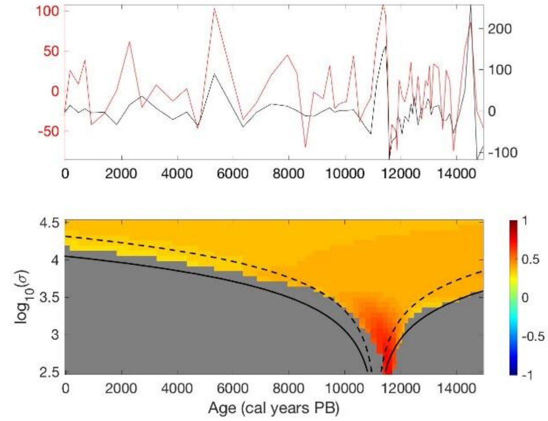
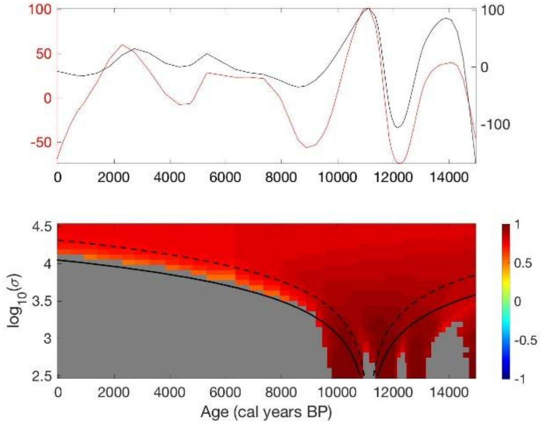


c)



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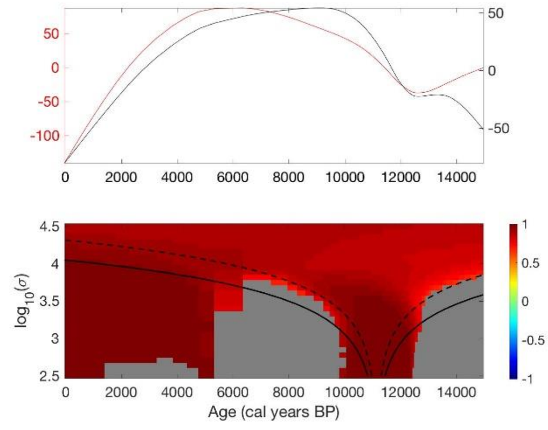
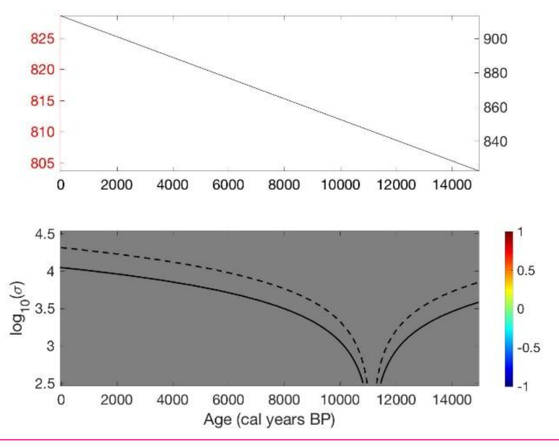
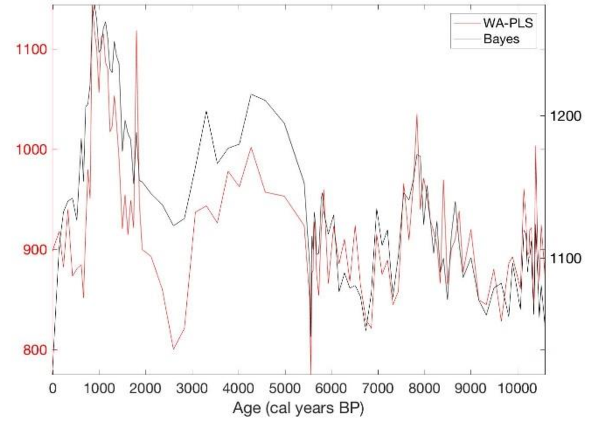


e)

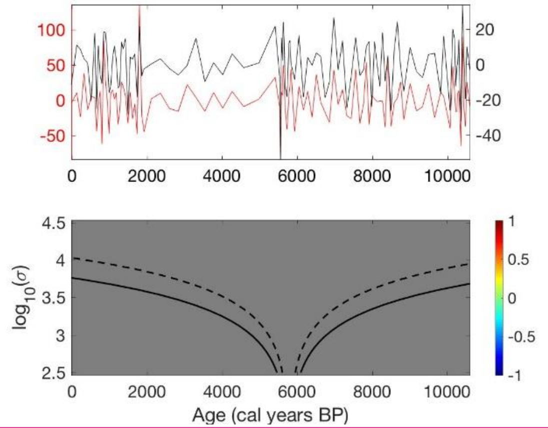


El Maíllo

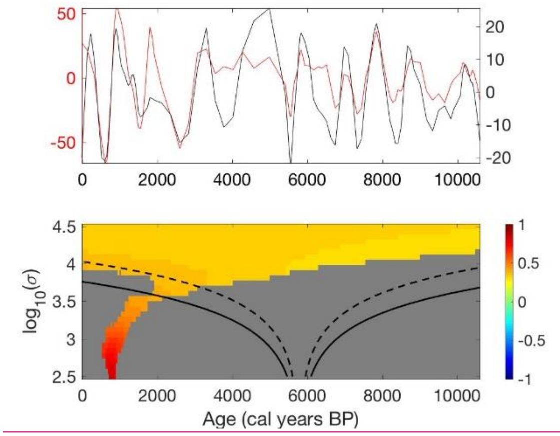
a)



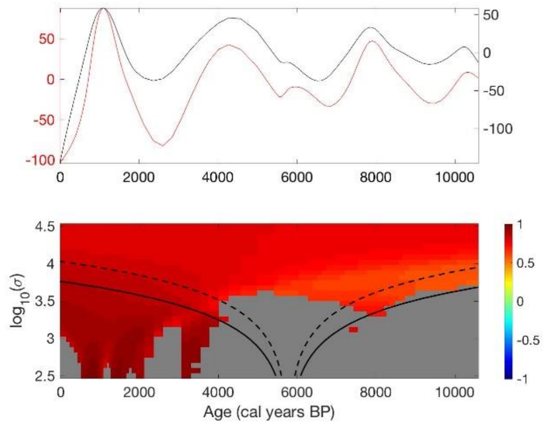
b)



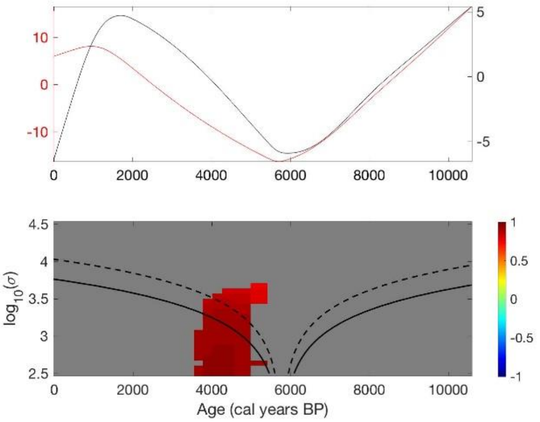
c)



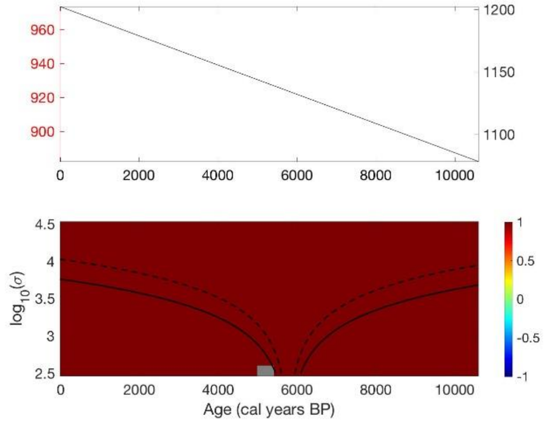
d)



e)

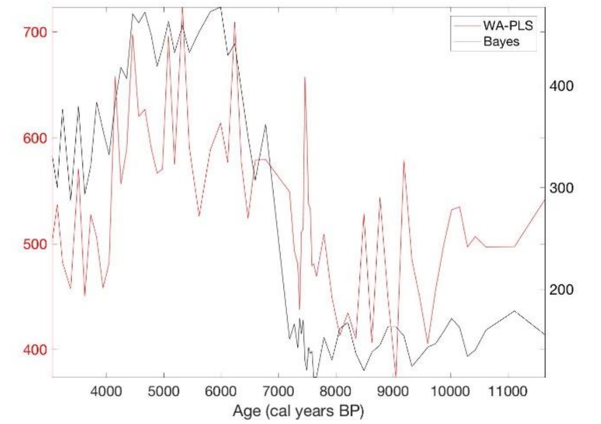


f)

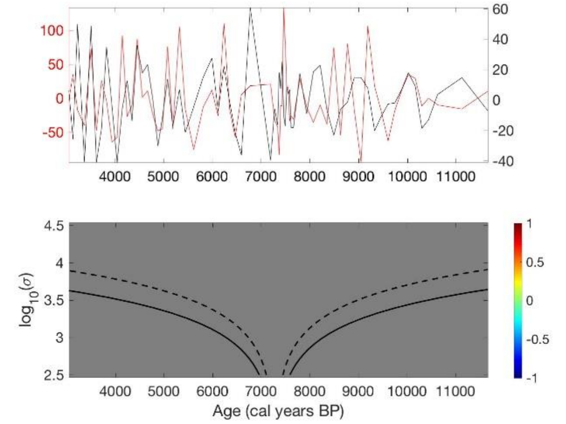


Navarrés-3

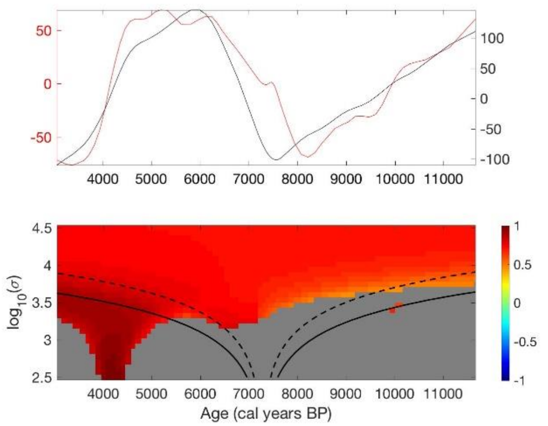
a)



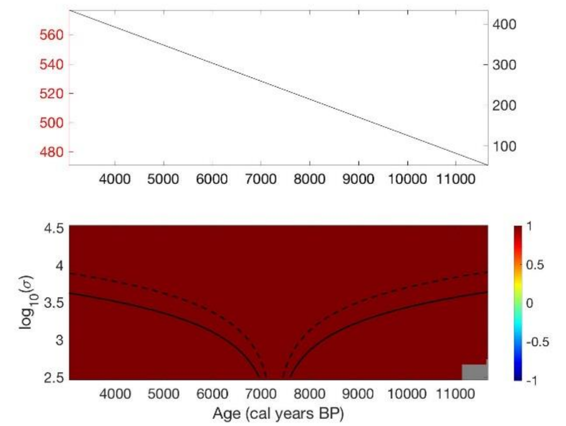
b)



c)

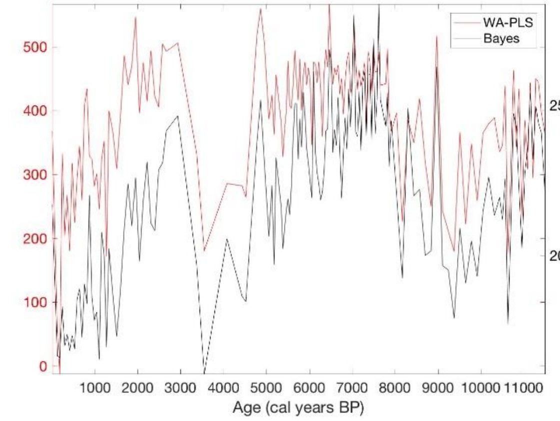


d)

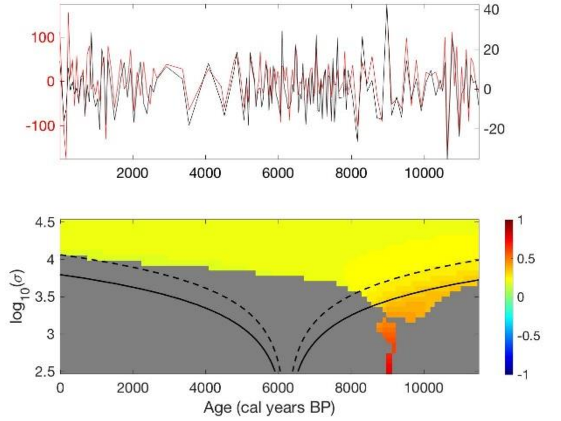


San Rafael

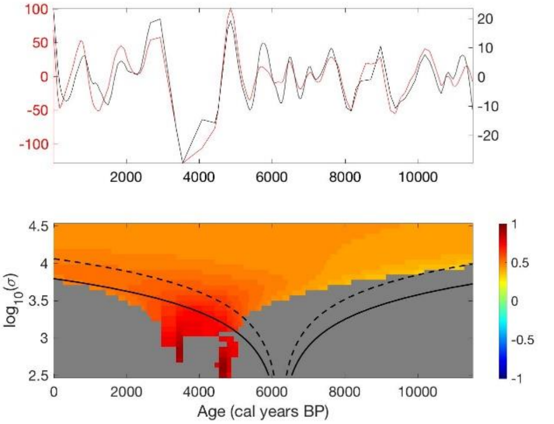
a)



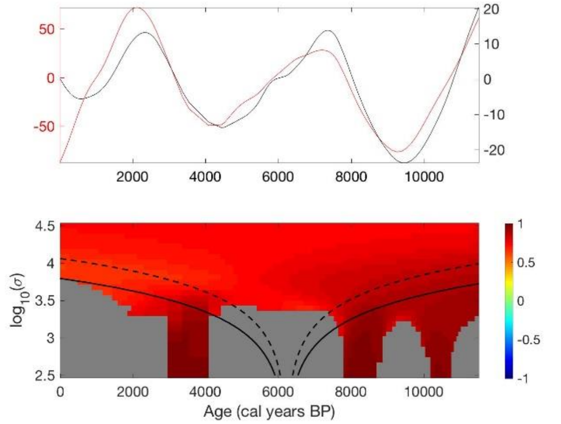
b)



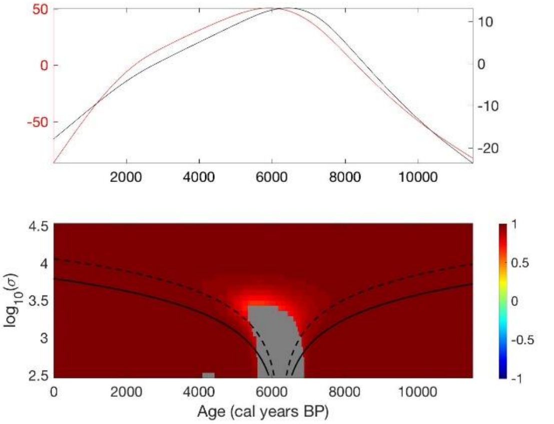
c)



d)



e)



f)

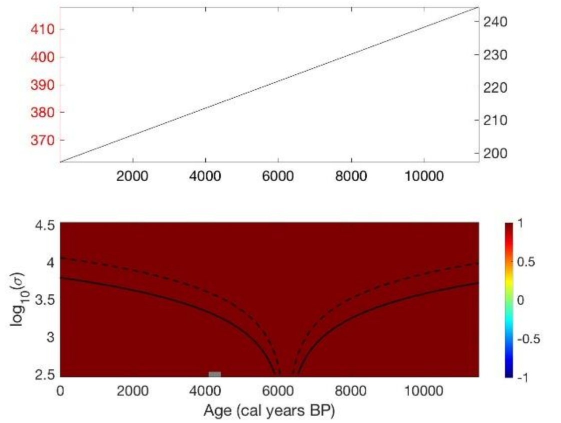


Table S1: The prior distributions of the Bayesian model parameters. We denote by *n* and *k* the number of sites and the number of taxa in our modern calibration set. The number of slices in studied pollen record c, c=1,…,7, is denoted as n_c. Pann(*i*) is the observed modern Pann at site *i* and Pann(*c*) is the observed modern Pann at the location of pollen record *c*.

Parameter	Prior distribution
α_j scaling factor for taxon *j*, *j*=1,…,*k*	$Uniform(0{,}90)$
β_j optimum precipitation for taxon *j*, *j*=1,…,*k*	$Normal(\widehat{\beta_j}, 250^2)$, see Salonen et al. (2012) for $\widehat{\beta_j}$
γ_j tolerance to precipitation for taxon *j*, *j*=1,…,*k*	$Gamma(9, 33)$
x_i^m modern Pann for site *i*, *i*=1,…,*n*	$Normal(Pann(i), [1/4 \cdot Pann(i)]^2)$ for leave-one-out cross-validation
x_{ci}^f past Pann for slice *i*, *i*=1,…,n_c in pollen record c, *c*=1,…,7	$Normal(Pann(c), [1/4 \cdot Pann(c)]^2)$ for pollen record reconstructions

Table S2: Main features of the SiZer maps for the seven pollen records used in precipitation reconstructions based on Fig. S3. The SiZer maps are shown for the WA-PLS reconstructions.

Site	Main features of the SiZer map based on Fig. S3
Alto de la Espina	Pann values are increasing until 7000 cal yr BP, from 7000 cal yr BP to 4500 cal yr BP the slope is non-significant and from 4500 cal yr BP until present the Pann values are decreasing.
El Maíllo	The general trend for the whole reconstruction is increasing. With small smoothing levels we find a local maximum around 8000, 4000 and 1000 cal yr BP and a local minimum around 2500 cal yr BP.
Monte Areo	The general trend for the whole reconstruction is decreasing. With smaller smoothing levels the Pann values are decresing until 9000 cal yr BP with a local minimum around 8000 cal yr BP. The Pann values are increasing around 7000 cal yr BP, from 7000 cal yr BP to 2000 cal yr BP the slope is non-significant and from 2000 cal yr BP until present the Pann values are decreasing.
Navarrés-3	The general trend for the whole reconstruction is increasing. With smaller smoothing levels the Pann values are increasing from 8300 cal yr BP to 5700 cal yr BP and from 4700 cal yr BP to 3000 cal yr BP the Pann values are decreasing.
Quintanar de la Sierra	There is local minimum around 12300 cal yr BP followed by and local maximum around 11000 cal yr BP. Until 7000 cal yr BP the Pann values are increasing, from 7000 cal yr BP to 4500 cal yr BP the slope is non-significant and from 4500 cal yr BP until present the Pann values are decreasing.
San Rafael	The general trend for the whole reconstruction is decreasing. With smaller smoothing levels the Pann values are increasing until 7000 cal yr BP and the slope is non-significant from 7000 cal yr BP to 5800 cal yr BP. From 5800 cal yr BP until present the Pann values are decreasing with a local minimum around 3700 cal yr BP.
Zalama	The general trend for the whole reconstruction is increasing. With smaller smoothing levels the Pann values are decreasing from 7200 cal yr BP to 6000 cal yr BP and increasing from 5400 cal yr BP to 4200 cal yr BP.