**Editor**

We would like to sincerely thank the editor and the anonymous referees for considering this manuscript for publication.

In this document, we answer to specific and technical comments in detail, with especial emphasis on some of them. *Editor's and referee's comments are written in italics*, and point-by-point responses are written in purple.

*Modern vegetation context: Addition of Abies/Fagus distribution and timberline/treeline elevations is welcomed, though you supplied differing figures (2200–2300 m vs. 1700–1800 m) — please verify and reconcile these values before submission.*

Thank you for the clarification. We have verified the values and unified them in the manuscript.

*Radiocarbon table: Beyond the agreed CI/median additions, explicitly include the dated material type for each sample in Table 1.*

We have included all requested information in Table 1, so it is more informative.

*Core naming consistency: Standardize core/section naming (e.g., 1U–5U, TRAM20-1A, TRAM21-1A) consistently across text, tables, and figures; the master-core approach should be removed as agreed.*

Thank you for pointing that out. We have revised all the manuscript and ensure that all core and section naming are correct. TRAM20-1A, TRAM20-1B, TRAM21-1A and TRAM21-1B are the names of all the cores extracted at Tramacastilla lake. Sections 1U-5U refer to the sections recovered in each extraction operations using the UWITEC platform. However, in this manuscript we focus on core TRAM20-1B due to its excellent continuity, so all biological and non-biological analyses included in this study have been applied to it. When the core is missing, and only sections 1U-5U are named, it is core TRAM20-1B we are referring to.

*Age-model coherence: Resolve the contradiction between the "hiatus" and "low sedimentation rate" interpretations for the lower core section, and align all figures (main and supplementary) with the single adopted interpretation.*

We would like to express our sincere gratitude for this important question. We have revised all the manuscript and adapted the figures according to the "hiatus" interpretation.

*Charcoal fuel-source analysis: incorporating charcoal morphological analysis to infer fuel source (e.g., following Florescu et al., 2024), would strengthen the fire-regime interpretation and directly complements the existing peak-detection approach. Do you have such data or is it easy to obtain/add those?*

We would like to thank you for the analysis provided. We agree that the approach considered in the study would strengthen the fire-regime interpretation, and would shed light in the fire regime reconstruction at Tramacastilla. However, we do not have the data required to perform that analysis. We will consider to obtain that kind of information in future research, so a more complete reconstruction can be achieved.

**Referee #1**

We are extremely grateful for the comments provided, which have led to a considerable improvement of the current manuscript, and have contributed to enhancing its clarity, scientific rigor and scope.

Overall, we will include the references mentioned in various parts of the manuscript, as well as the suggestions made by the reviewer regarding typographical and grammatical errors in the text.

- General comment:

*This manuscript presents a novel multiproxy palaeoecological record from a high-elevation lake located on the southern slope of the Pyrenees, which combines pollen, charcoal and sedaDNA to reconstruct vegetation changes and their drivers during the Lateglacial and the Holocene. The main novelty is the integration of the previously published sedaDNA dataset with the more "classic" palynological record. The fire regime reconstruction of the local fire regime based on the peak detection analysis adds further value to this study. The combination of datasets allows a novel interpretation of the landscape transformation at high elevation in the Pyrenees during the second half of the Holocene that proposes that human intervention was a major driver but was strongly supported by changing climatic conditions associated with the Neoglacial. I consider that the manuscript is overall well prepared, the data are complete and valuable and the discussion of the results is comprehensive and interesting to a broad audience. However, I also have some comments, suggestions, questions and concerns that the authors may consider before their manuscript is published. I provide them in an annotated pdf version of the manuscript that I attach.*

We would like to express our sincere gratitude to the referee for your insightful and encouraging comments on our manuscript. We believe that the modifications derived from the comments will help to improve the quality of the work.

- Line 11:

*Do you mean short- and long-range trashumance and other forms of livestock management? Some of them have been very important but have been declining for the past few decades.*

It is true that, over the last century, the Pyrenees have seen a significant decline in traditional practices. We have included this detail in the abstract.

- Line 16:

*Check the timing, because I would say that the Neoglacial mostly extends over the Late Holocene.*

We have specified we refer to the initial phase of the Neoglacial period, that started ca. 6 ka BP, according to García-Ruiz et al. (2020a), as it is true that the Neoglacial extends over the Late Holocene.

- Line 46, comment in the word “transterminance”:

*This is a loan from Spanish, in English "short-distance thanshumance" or "short-range transhumance" are commoner.*

We coincide that others terms such as “short-distance transhumance” or “short-range transhumance” are commoner. However, we would like to keep the original, as we feel it is more adequate to what we are referring to, and follows the same criteria as García-Ruiz et al. (2020b), where they use the term “transterminance”.

- Line 82:

*What about Abies and Fagus forests? These taxa are abundant in some sections of the palaeobotanical record and it would be good to mention which role they play in present-day vegetation.*

We have included a sentence talking about current distribution of *Abies* and *Fagus* forests, that are of great importance in the palaeoecological record.

- Line 84:

*I was wondering whether the authors could provide an indication of the elevations of the current timberline (or forest line) and treeline ecotone so the readers have a better idea of the local vegetation.*

The timberline ecotone in the Upper Gállego Valley is situated at 1700-1800 m, and the treeline reaches 2000-2200 m. We have included this information in the manuscript.

- Line 102:

*Please, specify which are the mentioned sedimentary features. Do the authors have an explanation for this?*

Uppermost sections (1U and 2U) from selected cores displayed sediments that are a product of high-energy depositional processes without in-lake organic production that may include reworked organic material into the sediment, resulting in a non-coherent chronology. We have included this information in the manuscript.

- Lines 107 and 336:

Line 107: *Did the authors search for terrestrial plant macrofossils? Bulk can be problematic even if the bedrock is not calcareous.*

Line 336: *plant macrofossil analysis and/or the identification and quantification of conifer stomata would have added great value to the palaeoecological record discussed here. These proxies would have enabled assessing the local presence of tree taxa in the catchment, allowing inferring shifts in the treeline and timberline position, for instance.*

In this regard, we appreciate the suggestion, as it would have been interesting to analyse plant macrofossils and/or conifer stomata. However, the absence of any of these remains prevented us from carrying out these analyses. Consequently, we based radiocarbon dates on bulk samples.

- Comments on table 1:

*The authors may consider following Stuiver and Polach (1977) to round the radiocarbon dates […]*

*Probability distributions of calibrated radiocarbon dates do not follow a normal distribution. Therefore, I recommend to indicate the 95% confidence interval and the median or the mean of such distribution. That would mean adding another column to the table […]*

*Additionally, the authors may add another column showing the "Age in the figures", which would be that assigned to the corresponding depth from the age-depth model.*

We are grateful for these relevant comments regarding dating information. We have included everything in Table 1.

- Line 123:

*Did the authors try to identify and quantify spores of coprophilous fungi as indicators of grazing (by wild or domestic ungulates)?*

We agree that this is an important question. Regrettably, this analysis falls outside the scope of the present manuscript, but we will consider it for future research.

- Line 143:

*Asteraceae is a huge family and each of the listed pollen taxa includes species living in very different habitats, not just in steppe-like grasslands […] Same with Caryophyllaceae.*

We agree that both are big and complex families. However, we would like to keep that classification, as we followed pollen classification from González-Sampériz et al. (2006), that is focused on El Portalet record, and is the nearest sequence from Tramacastilla.

- Comment on Figure 2:

*Here and elsewhere: Perhaps it enhances visualisation and is more correct (please, see my comment in the radiocarbon dates table) to add a secondary Y axis showing the age (obtained from the age-depth model).*

Thanks for the valuable insight. We have included an age scale in both Figures 2 and 4.

- Comment on Figure 5:

*I would suggest the authors to add the most relevant information got from sedaDNA concerning livestock, as it is an important topic in the Discussion section.*

Indeed, animal *sed*aDNA information is widely referred to in the text. We have included that information in Figure 5, as long as this addition does not reduce its clarity or makes it more complex.

- Line 349:

*Precisely Plantago is not the best example, because several well characterised pollen types have been described within this genus (check for instance The Northwest European Pollen Flora or Beug).*

Thank you for the meaningful comment. We have replaced that example with *Trifolium* type.

- Line 359:

*Well, Poaceae pollen is produced in high loads and transported by the wind, that is why it is one of the most abundant herbaceous pollen types in most European records.*

Indeed, what we wanted to point out in that sections is that we would have expected the representation of Poaceae pollen and *sed*aDNA to be more equivalent, as animal excrements would result in an over-representation of palatable plants in the *sed*aDNA record. The little difference between both analysis discards this idea.

- Line 411, on “Pllan d’Estan”:

*Typo, revise.*

We appreciate the detail, although we confirm it is not a mistake, as that is the local name to refer to the area.

- Line 413:

*Two of the records referred are from the Cantabrian Range, where the influence of the Mediterranean Sea must have been quite limited compared to the North Atlantic. I would rather look in this direction.*

We thank you for the meaningful comment, and have looked for more cites that support our results.

- Line 461 (in “continuous though not frequent fires”):

*I am not sure that I understand what the authors mean; please check.*

Thanks for the appreciation. We have changed this part in the manuscript, with: “regular low intensity fires”.

- Line 469:

*The connection between these two processes I am afraid is not clearly made here. Forest expansion during the Early Holocene also happened in other areas of Central Europe where glacial refugia were not particularly close. I am not questioning that glacial refugia were located nearby, but the evidence presented here is not conclusive in that regard.*

We thank the reviewer for this perceptive observation. We agree that rapid forest expansion during the Early Holocene is not in itself conclusive evidence for the proximity of glacial refugia, as similar patterns are observed in regions of Central Europe that lack nearby refugial areas. Our intention was not to present the forest expansion as proof of refugia, but rather to note that the observed pattern is consistent with the hypothesis of regional refugia previously proposed for this area. We have revised the text to make this distinction clearer and to avoid any over-interpretation of our data.

- Line 547:

*This explanation seems plausible, and similar to what apparently happened with agricultural practices at the beginning of the Neolithic on the Eastern Mediterranean (please, see van Vugt et al.'s publications). However, I would recommend the authors to avoid overstatements given the evidence presented. Actually, I miss a summary pollen diagram in both percentages and accumulation where one can get a better idea of the shifts in the abundances of trees, shrubs and upland herbs. In the figures shown in the manuscript, I am not fully able to assess such changes adequately.*

Thank you for your thoughtful comments and for the suggestion to consider the parallels with the Eastern Mediterranean Neolithic. We also appreciate your caution regarding overstatements. We will carefully re-read the final paragraph of our discussion and take you point that some phrasing could be perceived as too assertive. We have therefore revised the text throughout to ensure that our interpretation is presented with the appropriate degree of caution, avoiding any suggestion of definitive causal links and making it clear that our data are consistent with, rather than conclusive proof of, the proposed scenario. We trust that these adjustments adequately address your concern.

Regarding your request for a summary pollen diagram showing trees, shrubs, and herbs, we fully understand its potential usefulness. We have included that summary in Figure 4.

- Line 560:

*Well, Abies was actually disfavoured by human activities in many areas of Europe, you may look at Tinner et al. (2013) Ecol. Monogr., Henne et al. (2013) Landscape Ecol. or Morales-Molino et al. (2021) Ecosystems.*

We thank you for pointing out this important nuance regarding the effects of human activities on *Abies*. We were aware that the evidence is not unanimous, and we agree that in many regions of Europe *Abies* was indeed disadvantaged by anthropogenic disturbances. We have therefore incorporated the references you suggested into the revised manuscript, and we have nuanced our phrasing to better reflect this complexity.

**Referee #2**

We sincerely thank you for the constructive assessment of our work. We also thank you for the feedback provided, especially for highlighting areas where the manuscript can be more informative.

We will include specific suggestions from Referee #2 in the text, though in this document we address some specific and technical comments in detail (note that missing comments will be directly corrected in the manuscript).

- General comment

*This manuscript presents a multi-proxy palaeoecological record from a subalpine lake in the Pyrenean mountains. The authors combine pollen and charcoal analysis with a previously published sedaDNA record to reconstruct vegetation and fire dynamics for the last 12000 years, however their pollen analysis reaches back further. The combination of different proxies and the comparison with existing climate records allows the authors to discuss the different drivers of vegetation change and disentangle the impacts of climate and land use on the vegetation. They propose that cooling during the Neoglacial led to an opening of the vegetation, which was exacerbated by anthropogenic activities. Overall, the data is of high quality, the analyses support their statements, and the manuscript is well prepared. However, I do have some comments, suggestions and questions I would like the authors to address before publication.*

We are grateful for the relevant comments that Referee #2 has made to our work. It has expanded our scope and helped us to produce a clearer version. We answer each suggestion in depth in the following lines.

- Geographical setting:

*It would be interesting to expand the information regarding the geographical setting with information on today's temperatures (summer, winter, mean) and the altitude of the tree- and timberline. This would allow readers to better assess some of the discussed changes.*

The timberline ecotone in the Upper Gállego Valley is situated at 1700-1800 m, and the treeline reaches 2000-2200 m. We agree with adding information about today's temperatures and the treeline and timberline.

- Methods comment 1:

*It is unclear from the methods how the 5 sections (1U-5U) were assigned. It this purely based on changes in the lithofacies or was a statistical method used?*

Sections 1U-5U were assigned according to the extraction operations using the UWITEC platform. This approach allows several sections to be extracted, penetrating the sediment 1.8 m at a time. In Tramacastilla, we could perform 5 extraction operations, obtaining 5 sections (1U-5U) that reached 9 m depth. We have included this information in the manuscript in order to enhance clarity.

- Methods comment 2:

*Do you think that the sections 1U and 2U are the result of the damming of the lake?*

Actually, we do not believe that sections 1U and 2U are the result of the damming of the lake, as the damming happened in 1956, and both sections reach about 800 m. However,

the damming could have caused the sediment of those sections to mix, and so would be the cause of the absence of an accurate chronology.

- Methods comment 3:

*You describe the creation of a master core, but based on the rest of the results it seems you stayed on one core drive for the pollen and charcoal analysis and used the other core drive for the sedaDNA analysis. Did you use the parallel drives (TRAM21-1A and TRAM20-1A) at all for core correlation and master core building?*

Due to the lack of some parts of the sediment in the parallel drives (TRAM20-1A and TRAM21-1A), we finally did not create a master core. We have deleted that part from the manuscript.

- Methods comment 4 (line 383) and line 215:

*In Line 383 you mention a hiatus in the lower section of your cores, but this hiatus is not clear in any of the figures, nor modelled in your age-depth model. I would recommend including the hiatus in your bacon model, if you are sure, it is there. As that would create a better agedepth model. Furthermore, in some of the figures in the supplemental material, the hiatus is included in the age/depth axis, but in the manuscript it is never. […]*

*Do you think the lake wasn't frozen for most of the time before the period 22-15 ka BP? Also, this interpretation is in stark contrast with the later mentioning/interpretation of a hiatus for this section of your core. Please stick to one interpretation, either a hiatus or low sedimentation rates. Then all the figures, discussion, but also supplemental figures should reflect the final interpretation.*

Thank you for the meaningful comments. We agree that both interpretations are contradictory, so we have stuck to one of them, giving coherence to the data.

- Methods comment 5:

*Could you clearly specify for which section of the core (xxx cm- xxx cm) you constructed the age-depth model?*

We conducted the age-depth model for the sediment between 390 and 880 cm. We have included this information in the manuscript to enhance clarity.

- Methods comment 6 and comment in results:

*Why did you choose to date bulk samples? Where there no terrestrial plant macrofossils available? […]*

*Did you also consider using proxies such as conifer stomata or macrofossil analysis? Especially conifer stomata could have been analysed on the same slides as the pollen analysis and could confirm the local presence of conifer trees.*

We dated bulk samples as the sediment lack of any terrestrial plant macrofossils. We have included this specification in the manuscript.

In fact, no conifer stomata nor plant macrofossils were found in Tramacastilla lacustrine sediment, though it would have been interesting to be able to study them.

- Methods comment 7:

*Table 1: I would add some additional info to the table including the calibrated age range of the 95% confidence interval, plus the mean or median calibrated age.*

We are grateful for this relevant comment regarding dating information. We have included everything in Table 1, as it enhances the clarity of the table.

- Methods comment 10:

*Is the charcoal analysis contiguous? Would be nice to mention.*

Yes, charcoal analyses were performed in 202 continuous samples. We have included that for clarification in the text.

- Line 191:

*It is interesting you have indications for low lake levels, as I would expect the lake levels to be much higher due to the damming of the lake. Do you have an explanation for this?*

It is true that after the damming, the depth of the lake increased from 4 to 13.5 meters. Indeed, low lake levels do not correspond to the period after damming, but for the period between 800 BP and the damming.

- Comment on Figure 4:

*Why is this figure not plotted on age, it would make it much easier for the readers to see when things are happening? If you would prefer to plot on depth, could you at least add an age axis.*

*It would also be nice to add a summary diagram, so changes in trees, shrub and herb vegetation are easier to see.*

We would prefer to keep the results' figures in depth rather than age, as it retains the core reference as a geological sediment. We will add an age axis on Figures 2 and 4.

Regarding the summary diagram, we fully understand its potential usefulness. We have included that summary diagram in Figure 4.

- Comment on Figure 5:

*Maybe you could add some more labels to this graph. For example, that e and f are coniferous trees, g and h deciduous species. I would also show the results for domesticated animals from the sedaDNA here. It would enhance your discussion. In the text a chironomid temperature reconstruction is mentioned. Maybe this could be shown as well?*

We believe that adding labels would not enhance the clarity of the figure. Indeed, note that e and f are not only coniferous trees, but include *Fagus*. Regarding animal *sed*aDNA, we thank you for that valuable insight. We will include it, as long as this addition does not reduce its clarity or makes the figure more complex. Note that the chironomid temperature reconstruction does not correspond to Tramacastilla lake, but to Basa de la Mora. Besides, some data are missing in that record, so we believe Mendukilo temperature reconstruction is more useful in Figure 5, and widely refer to in the text.

- Line 349:

*You mentioned that the low taxonomic resolution of pollen analysis could lead to an overestimation of human impact on the landscape, and you use the example of Plantago,*

*which I don't think is a good example. It is possible to distinguish several Plantago pollen types including Plantago lanceolata type, which is a strong indicator of anthropogenic impact (see Beug 2004, Behre et al. 2023).*

Thank you for your meaningful comment. We have replaced that *Plantago* example with *Trifolium* type.

- Lines 359-363:

*They hypothesis that excrement from animals could bring DNA into the lake is interesting, but I can't imagine this to be a large contributor to the sedaDNA signal. Are there any studies that have shown a contribution of excrement to the sedaDNA signal in a lake? To further study this hypothesis the inclusion of dung fungal spores in the palynological analysis would be very valuable. Increases in dung fungal spores such as Sporormiella would show if there was an increase in herbivory around the lake, and if this is related to change in herbs/grasses. Furthermore, it is not surprising there is a difference between Poaceae pollen and Poaceae sedaDNA representation. Poaceae pollen are wind-pollinated, very abundant and always well represented in pollen records, whereas grass biomass is usually not very high and Poaceae do not seem to work so well with sedaDNA metabarcoding.*

We acknowledge that excrements from animals are unlikely to be a major source of the *sed*aDNA signal. We are not aware of studies that directly quantify this contribution, and we have therefore reframed this point more cautiously, presenting it only as a secondary possibility.

We also agree that coprophilous fungal spores (e.g., Sporormiella) would be highly valuable for assessing herbivory. Regrettably, this analysis falls outside the scope of the present revision, but we have explicitly noted it as a promising avenue for future research.

Regarding the Poaceae discrepancy, we fully agree with the reviewer's explanation and have clarified this point in the revised text.

- Lines 366-375:

*Did you also look at the modern surface sample (pollen and sedaDNA) to better understand the connection between the pollen, sedaDNA and vegetation? This could help with understanding the results.*

We agree that it would be very interesting to look at the modern surface sample. However, we were not able to carry out that analysis. We will consider to do it in the future.

- Line 403:

*You mention the plant communities were not very diverse during the Late Glacial. Did you think about calculating richness for the sedaDNA and the pollen, that could have been a nice addition to the discussion about plant diversity. Do you think it is possible for the Late Glacial vegetation to also have a rich herbaceous vegetation composition? Some sites in the Alps do suggest this (e.g. van Vugt et al. 2022).*

Thank you for your meaningful comment. While plant diversity analysis would add valuable insight to our data, we believe it is beyond the scope of this manuscript. However, we will consider it for further research. Regarding Late Glacial richness, we do

not believe that herbaceous vegetation was richer during the Late Glacial compared to the Late Holocene (ca. 4 ka BP). However, it could be greater during that period compared to the Early Holocene, when dense forests were dominant.

- Lines 454-460:

*Could continentality have played a role in the Betula and Corylus dynamics? In the Alps the dominance of Corylus during the Early Holocene is often related to high summer insolation and continentality (e.g. Aregger et al. 2025).*

Actually, we had previously consider that explanation. However, similar vegetation dynamics of *Betula* and *Corylus* were found in Basa de la Mora (Pérez-Sanz et al., 2013), a place with higher continental influence. Besides, a different situation was found in nearby Portalet (González-Sampériz et al., 2006), which is located in the same valley than Tramacastilla and thus has similar climate. This evidence led us hypothesise that local environmental features were responsible for those differences in *Betula* and *Corylus* dynamics.

- Lines 473-476:

*Couldn't differences in dispersal also lead to this pattern. The winged fruits of Betula are more easily dispersed than the heavy hazel nuts of Corylus.*

We are grateful for the meaningful comment. Indeed, dispersal differences could explain the different patterns between *Betula* and *Corylus*. We have included it in the text.

- Line 483-484:

*So ground fires instead of crown fires?*

Thank you for the detailed term. We have included this specification in the text.

- Lines 518-521:

*Could the pollen or sedaDNA data even record hunting activities. The anthropogenic taxa are not related to hunting activities, but show arable and pastoral farming.*

Actually, we do not know whether there are ways of discerning hunting from other human-related activities through pollen or *sed*aDNA data. However, hunting practices at that time would not have a considerable impact on ecosystems, as archaeological evidence point to a low impact of hunter-gatherers groups.

- Lines 549-552:

*Where is the treeline today? Do you see any indications for a lowering of the treeline? Or are there any records from region that looked at treeline ecotone dynamics?*

The treeline currently reaches 2000-2200 m asl. The absence of plant macrofossils prevents us from reconstructing treeline ecotone dynamics, and no studies from the valley have focused on that question. However, it would be interesting to explore it through different approaches, and we will consider it for future research.

- Line 568-571:

*People could also have opened the niche for Abies and Fagus?*

As we mentioned in the manuscript, we believe that natural climatic conditions (supported by the known biogeography of both taxa) initially triggered the expansion of

both *Abies* and *Fagus*. After it, anthropogenic activities may have subsequently facilitated their spread, providing a competitive advantage over previously dominant taxa. No evidence was found that pointed to human activities initially triggering *Abies* and *Fagus* expansion, and other Pyrenean sequences record similar chronologies for their expansion, supporting the idea of climate as the main responsible of it.

- Comment on Figure 7:

*Would it be possible to also plot the charcoal records for the records? So it's nicer to see the vegetation-fire dynamics?*

Thank you for pointing that out. We have included charcoal records from all the records plotted in Figure 7, provided the data is available, so a better idea of regional vegetation and fire dynamics.

- Comment on discussion sections:

*The subchapters of the discussion are called greelandian, northgrippian etc. but in the text Early Holocene, Mid Holocene etc. is used. Is there a particular reason to switch between these different names?*

There is no particular reason for using different names. We have unified the terms so as not to cause confusion.

- Line 45:

*I have never heard of transterminance, is this the same as transhumance?*

Transterminance is defined as the pastoral mobility only in altitude, while trashumance is long-distance pastoral mobility. This is a strategy used in mountain ecosystems in order to take advantage of subalpine and alpine pasturelands during summer (Carrer and Migliavacca, 2019; García-Ruiz et al., 2020b).

- Line 341:

*Pollen can be extra-local to regional, depending on catchment size. What do you think is the pollen catchment for Tramacastilla?*

Considering the catchment area of Tramacastilla lake, we think the pollen reconstruction corresponds to local rather than regional scale. However, it will always have a more regional scale compared to *sed*aDNA vegetation reconstruction.

## References


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