Dear referee

Many thanks for your valuable comments on our manuscript. We have carefully considered your suggestions and made corresponding revisions. We hope that we can upload the revised manuscript for your further review. The reply are as follows:

General Comments

1. This manuscript presents field data of soil aggregate pore structure and carbon content through an annual freeze-thaw cycle. The measurements appear to have been carefully executed, and demonstrate some trends throughout the year for both pore structure and carbon content. The work also demonstrates strong correlations between some pore structure observations and carbon cycling through the year. Most strikingly, POC and MAOC pools strongly are associated with different pore characteristics during the freezing and thawing seasons. The review of soil aggregate FT mechanics is quite extensive.

   Many thanks for acknowledging our work.

2. Despite extensive literature review, the manuscript struggles to contextualize its findings. Most importantly, the relationships presented are purely correlational, and are difficult to assume as causal. Protection is postulated as the driving mechanism for carbon protection, but the seasonal inputs and outputs are hardly mentioned. Additional drivers like mineralogy, hydrology, and FT intensity are also not discussed. The influence of these factors has already been described in another manuscript by the same authors, where soil water content was found to be a critical factor (https://doi.org/10.1016/j.catena.2023.107359). This highly related study should be more carefully introduced and discussed in the present work. Moreover, the broader significance of carbon protection in aggregate pores is not strongly established by the manuscript. For example, the study region is generously introduced in the introduction, but does not return in any of the results, discussion, or conclusions. The manuscript could also be improved by a smaller number of better integrated citations. Grammar and paragraph structure could be improved and streamlined throughout.

We highly appreciate your comprehensive and meaningful comments on the manuscript. Based on the results on RDA and correlation analysis, we referred to previous studies to ensure that our findings were not out of casualty, which can be seen in the Discussion section, e.g. "In the freezing period, pores of < 15 μm served as preferential spots for POC stabilization. As the period is featured by SOC accumulation, < 15 μm pores reduced SOC decomposition via limiting microbial access, gas diffusion and water availability, shifting microbial metabolism to less efficient anaerobic respiration (Strong et al., 2004; Keiluweit et al., 2017; Wang and Hu, 2023)."

We realized the significant impact of other soil factors, especially moisture content, on organic carbon. In other studies, we attempted to compare the impact of soil structure and other factors on SOC. But in this manuscript, we focus on comparing the contributions of different soil structural parameters to carbon fractions.

In our discussion part, we have linked our findings with our previous work, as well as the features of the QTP. For example, in Line 376-382: In the thawing period, pores of <15 μm inhibited the POC loss. Previous studies proved that these pores reduced SOC decomposition via limiting microbial access and shifting microbial metabolism to less efficient anaerobic respiration (Strong et al., 2004; Keiluweit et al., 2017). On the QTP, the positive impact of soil moisture on SOC protection has been revealed in both aggregate scale and landscape scale (Ma et al., 2022; Wang and Hu, 2023). The thawing process is accompanied by an increase in microbial activity and moisture availability, pores of <15 μm are able to hold water surrounding the soil particles (Kim et al., 2021).

To avoid grammatic mistakes and bad organized components, we have thoroughly modified our manuscript. We wish to submit the revised manuscript.

3. I would be interested to see a closer look at the data, with increased focus on the seasonal cycle, causality, and other driving factors. I think the value of the annual time series was not fully explored, and suggest that the analysis could look more carefully at the changes in each layer of each ecosystem over time, rather than aggregating all the soil layers and both ecosystems into the same statistical analysis. For the interesting data and contribution to understanding challenging soil processes, I recommend this manuscript to be reconsidered with revisions to the analysis, discussion, and contextualization of the findings.

We highly appreciate your insightful suggestions. Analyzing in each layers/ecosystems can indeed yield some interesting results, but in this study, as we focus on the relationship between pores and SOC, more analysis can lead to inconsistent results, which is not conducive to revealing the relationship. In the future research, we would include more indicators to comprehensively reveal the organic carbon protection mechanisms of different soil layers.

Specific Comments

1. The author's previous work in the region should be more thoroughly described and integrated into the manuscript. Discussion of mineralogy, soil water content, and inter-aggregate porosity would all aid in the interpretation of your novel findings here.

Thanks very much for the comments. The related findings have been described and analyzed in the Introduction and Discussion sections. For example, in Line 85-89 (in Introduction): Our previous studies have showed that, alpine meadow soil aggregates of the QTP had dense pore networks with many elongated pores in them due to frequent FT cycles (Zhao et al., 2020). For typical ecosystems on the QTP, the aggregate protection of SOC was promoted by pores of <15 μm by limiting microbial access and the process was most closely associated with soil moisture content (Wang and Hu, 2023).

2. The introduction and conclusion could be strengthened by removing extraneous detail, while focusing more on the implications of the work. Climate change and the QTP is a very interesting topic, and the reader would be interested in the implications of your work to understanding the future of the region.

Many thanks for the insightful comment. We have added some background and implications in our manuscript. For example, in Line 89-91: "Aggregate stability has been proved to impact SOC protection on the QTP and thawing-induced SOC loss of aggregates will translate into carbon emissions from the meadow to the atmosphere and exacerbate global warming (Ozlu and Arriga, 2021). Also in Line 399-401: Future research needs to further quantify the impact of soil structure on organic carbon, which will enable us to apply the mechanisms we have discovered to landscape scales to improve existing global carbon cycle predictions.

3. The data on vertical structure (eg Table 1) has potential to be interesting, but is largely

unsupported by the manuscript. I suggest it should either be presented with supporting discussion, or trimmed from the manuscript.

Thanks very much for the valuable comment. We have added the related discussion: Freezing also resulted in a more uniform distribution of SOC across different soil layers. This finding is consistent with the findings of Zhao and Hu (2023), which proposed the buffered difference in microbial biomass between soil horizons in the frozen period. These indicated the positive effect of freezing on vertical nutrient transport, which lacks investigations so far.

4. Table 2 and Figure 7 present some interesting correlations, but I would be interested to see a scatter plot (perhaps color-coded by ecosystem) for some of the key relationships. I'm worried that the seasonal differences reflect different ecosystem behaviors, rather than mechanistic causality.

Many thanks for your valuable suggestions. We have added the scatter plots of some crucial correlations as is shown in Fig. 7 and Fig. 8 and checked whether they reflected ecosystem behaviors. All data were presented as the mean value of each ecosystem in each FT period to avoid error caused by extreme values.

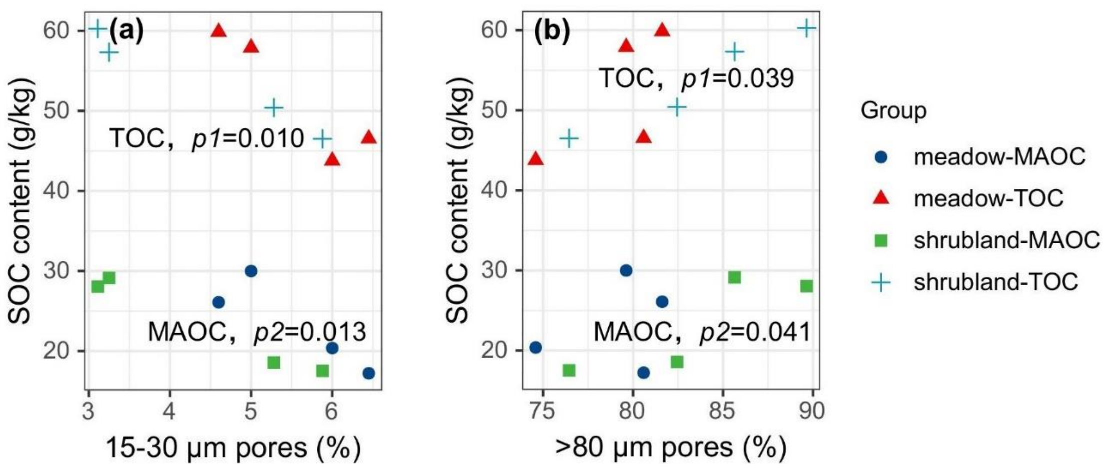

Fig. 7. Scatter plots of relationships between (a) SOC content and 15-30 μm pores and (b) SOC content and > 80 μm pores in the freezing process.

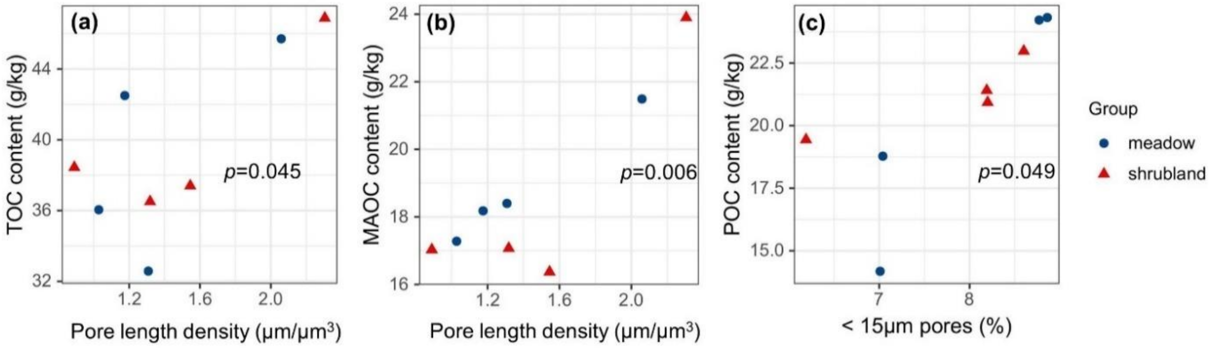

Fig. 8. Scatter plots of relationships between (a) TOC content and pore length density, (b) MAOC content and pore length density and (c) POC content and < 15 μm pores in the thawing process.

5. The results throughout the paper are presented without much discussion of the physical mechanisms. I think the results in changing pore structure would be much more compelling with thoughtful discussion of the physical mechanisms. The same goes for the mechanisms of carbon protection, considering the sources and sinks of carbon.

We highly appreciate your insightful comments. We have added the discussion of the physical mechanisms, which can be seen in Line 367-389: In the freezing period, pores of 15-30 μm had negative impact on SOC protection, this was consistent with our previous results (Wang and Hu, 2023). Pores of 15–30 μm are probably suitable habitat for soil microbes and support their activity, where greater SOC decomposition takes place (Kravchenko & Guber, 2017; Liang et al., 2019). Pores of >80 μm favoured SOC protection of aggregates. As the period was featured by SOC accumulation (especially residue entry), Pores of > 80 μm serve as primary sites for residue entry and are promoted by microbial materials and SOC, which enhance soil aggregation and thus drive more SOC to be protected (Ananyeva et al., 2013; Dal Ferro et al., 2014; Zhang et al., 2023). Freezing promoted the formation of these pores which were conducive to organic matter entry into aggregates. In the thawing period, pores of <15 μm inhibited the POC loss. Previous studies proved that these pores reduced SOC decomposition via limiting microbial access and shifting microbial metabolism to less efficient anaerobic respiration (Strong et al., 2004; Keiluweit et al., 2017). On the QTP, the positive impact of soil moisture on SOC protection has been revealed in both aggregate scale and landscape scale (Ma et al., 2022; Wang and Hu, 2023). The thawing process is accompanied by an increase in microbial activity and moisture availability, pores of <15 μm are able to hold water surrounding the soil particles (Kim et al., 2021). Therefore, POC associated with these pores was less vulnerable to microbial processing and desorption due to equilibration with the more frequently exchanged soil solution (Schluter et al., 2022). The protection promotes the consequent transport of POC towards mineral sorption and thus contributes to the long-term SOC storage (Vedere et al., 2020). Overall, the FT-induced pore structure posed a positive impact on SOC protection in that: pores of > 80 μm promoted by freezing serve as primary sites for organic matter entry, while pores of <15 μm promoted by thawing inhibited POC decomposition through holding moisture.

6. Better paragraph structure and organization will improve the overall clarity and readability tremendously. I would be happy to provide more detailed comments on a revised manuscript.

Thanks very much for your insightful opinions. We have improved the organization especially for the Introduction and Discussion sections in the revised manuscript, which will present a better link between our findings and backgrounds of the study.

Overall, thanks again for all your valuable comments.