Author's response to reviewers:

We wish to sincerely thank both reviewers for taking the time taken to examine our manuscript, their insightful and kind suggestions for improving the manuscript, and for recognising the value of our work. We provide detailed responses to all remarks and suggestions included by both reviewers. Line numbers in our changes are based upon the tracked change version of the manuscript, except for the original text of the comments by the reviewers.

Additional minor changes not requested by reviewers: -

At the request of co-author N. Stivrins, I have added two additional affiliations to his name (L18-21).

In response to an email request from the editorial support team dated 27/03/25: "Please note that your reference list has not been compiled according to our standards. Please consider adjusting your reference list with the next revision of your manuscript"- The references have been changed in accordance with author guidelines in the tracked changes version of the manuscript.

Italics added to "polifolia" in Figure 9.

Minor spelling errors in Figure 10: "Euglypha l**ae**vis, Nebela co**ll**aris" amended.

Poeceae sp. changed to "Poaceae undiff." In Figure 11.

Italics and additional letters removed from letters on some taxa in Figure 12: "*Sphagnum* **s**pores and Filicales monolet**e"**

Incidences of spp. for taxa changed to sp. to match diagrams: L184, L521, 547, L565, L589 and L704.

Unclosed parentheses fixed L381 - 382.

Anonymous Reviewer #1.

- *L83: 'in the UK'*

Author's response: *Change made as requested.*

- *L85-90: rather than use the term 'alkaline pollution', I recommend 'increased alkalinity'*

Author's response: *We agree, change made as requested.*

- *L143: alkaline generating industries?*

Author's response: *Change made as requested.*

- *L389: While the age-depth model appears to be robust, does the limestone bedrock at the site and the input of calcareous material on to the bog affect the radiocarbon dates by adding old carbon?*

Author's response: We thank the Reviewer for this comment; it is something we hadn't really considered. Obviously, all radiocarbon samples were prepared carefully prior to analysis at the radiocarbon facility in Poznan to remove carbonates, we cannot account for the possibility of other sources of old carbon, such as uptake by vegetation (possibly derived from the cement dust) towards the surface. This is a valid interpretation for the radiocarbon reservoir effect that we found improved our model fit.

In response to this comment, we have added some sentences to this section (L421 – 423): "A more likely explanation could be the uptake of old carbon by vegetation of dissolved carbonates, particularly in the more recent samples (Madeja and Lafowski, 2008) where old carbon may derive from the buried cement dust".

- *L411-12: I would delete 'where lithogenic element activities increase' or at least replace 'activities' with 'counts'*

Author's response: We opted to make both changes as suggested.

- *L541: remove 'low levels of'? There could be a filtering effect.*

Author's response: Agreed, change made as suggested.

- *L583: Principal; in Fig 13 Principal – which is it?*

Author's response: It is principal, not principle, we thank the reviewer for noticing. Changes made to figure caption on Figure 13 and the manuscript was searched for any other incidents, none found.

- *L624: Was palynological richness measured (cf Birks & Line) or by some other method?*

Author's response: I did do a quick assessment to check this was true at the time of writing, but the data is not included on any figures as it doesn't add much, and the palynological figures are already relatively dense. A quick plot of the richness is shown below (Fig 5). If readers wish to check this, they are welcome to access the supplementary materials, no changes made.

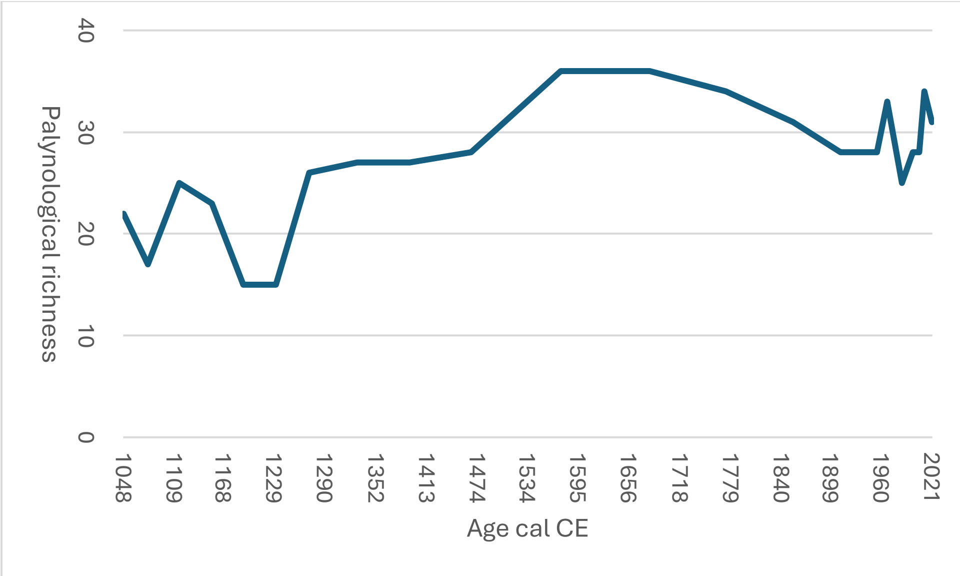

Fig. 5. Palynological richness through time at Varudi, based upon the number of terrestrial pollen taxa identified.

- *L764: most likely increased. A lot of uncertainty in the amount measured.*

Author's response: Suggestion noted, and change made as requested.

- *L790: you appear confident: 'our study is the first to define thresholds for tipping points in peatland ecosystems in response to changes in alkalinity'. Lines 804 onwards you step back pointing out all the uncertainties. So how confident are you? Perhaps yours is the first step to define thresholds…*

Author's response: We agree with the reviewer that the results of this study regarding the threshold values are likely uncertain, owing to the uncertainties and methodological limitations highlighted in this section. We do not want to over-state our results. In response, we have changed some sections of the text to reflect our confidence in our results better, in both the suggested section of text (L838) and in the later conclusion (L900).

Line 855-857 Original text: "To our knowledge, our study is the first to define thresholds for tipping points in peatland ecosystems in response to changes in alkalinity".

Changed text: "To our knowledge, our study represents the first step towards defining thresholds for tipping points in peatland ecosystems in response to changes in alkalinity".

Lines 921-922- Original text: "It establishes the first threshold indicator values for ecosystem tipping points in response to alkalinisation".

Changed text: "It establishes the first attempt to define threshold indicator values for ecosystem tipping points in response to alkalinisation".

Anonymous Reviewer #2.

- *When did drainage and peat harvesting start at the site? This information is missing.*

Author's response: I am not sure whether an exact date for when drainage works began at Varudi is known. Documentary evidence is not available to our knowledge for drainage or peat extraction histories online. However, historic maps show that most of the extensive drainage and harvesting took place before 1977 (Fig. 1) and after 1944 (Fig 2), with the areal extent of peat extraction matching that of the present day by 1988 (Fig 3). A map in use between 1866 – 1911 shows some evidence of drainage near the northern margins of the bog (Fig. 4), likely related to the developing forestry works visible on the western site of the mire.

In response to this comment, we include the following sentence to the introduction section relating to the site history, L156 -164: "There is limited documentary information available related to the timing of drainage and peat cutting at Varudi, although historic maps (ETOMESTO, 2025; MAA-JA RUUMIAMET, 2025) indicate that most of the extensive drainage took place before 1977 and after 1944, probably relating to the large-scale drainage projects undertaken in Estonia in the 1960s under Soviet rule (Paavilainen and Päivänen, 1995). Peat extraction matching the areal extent of present-day works at the site were in-place by 1988. Prior to this, there is documentary evidence for drainage in the northern, eastern and western margins of the site having taken place around before 1866 – 1911, likely indicative of the systematic forest drainage that took place in Estonia around this time (Paavilainen and Päivänen, 1995)."

References have been added to reference list.

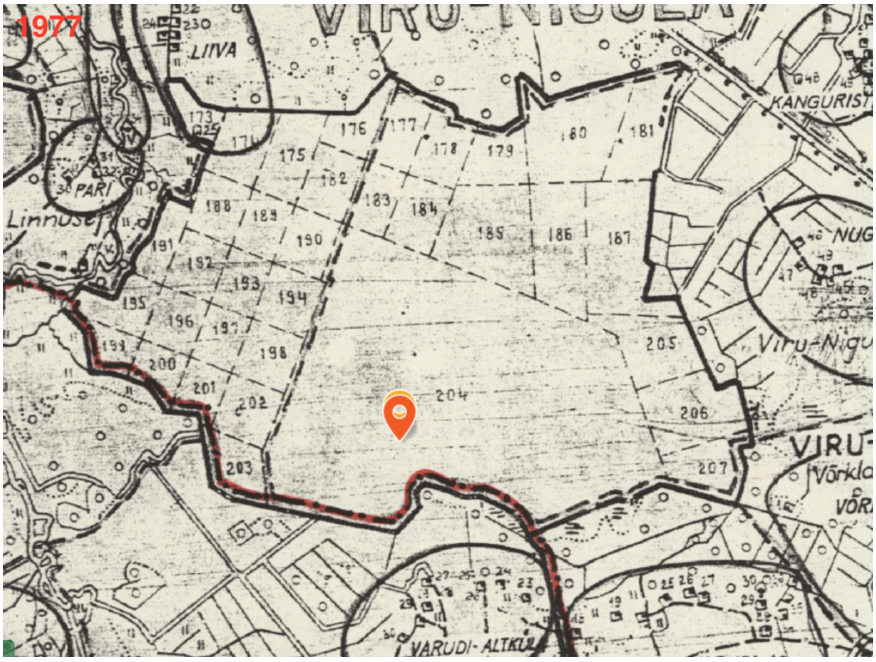

Fig.1 Varudi map, 1977

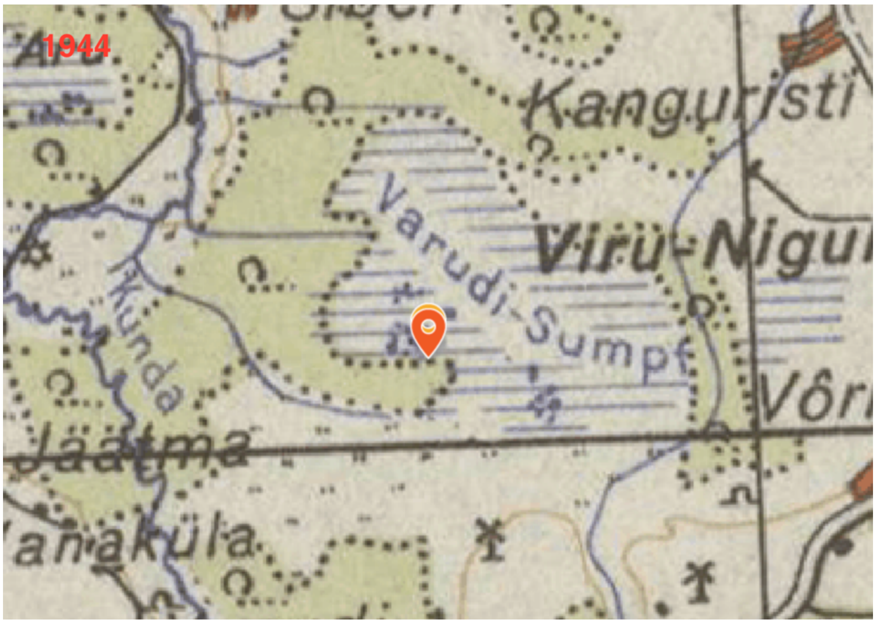

Fig. 2 Varudi map, 1944.

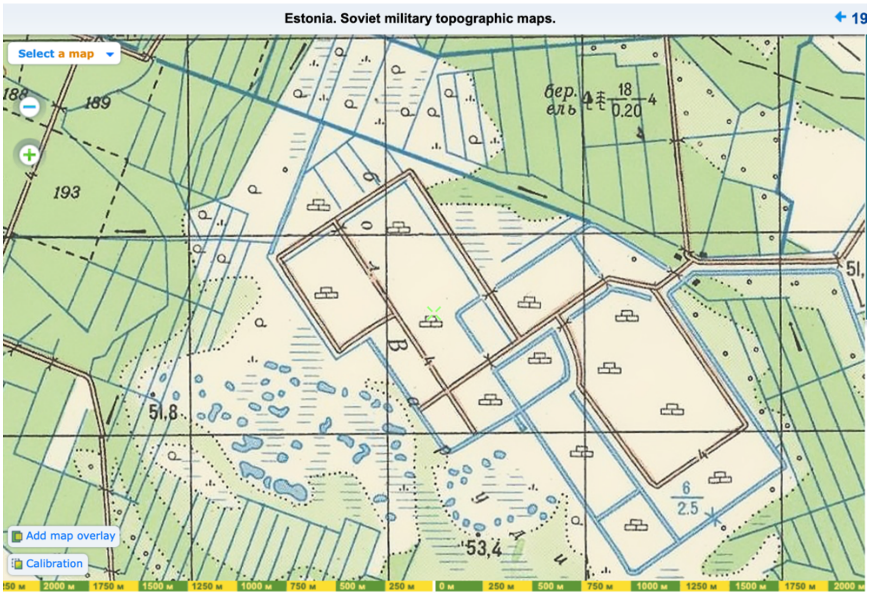

Fig 3. Varudi map, 1988.

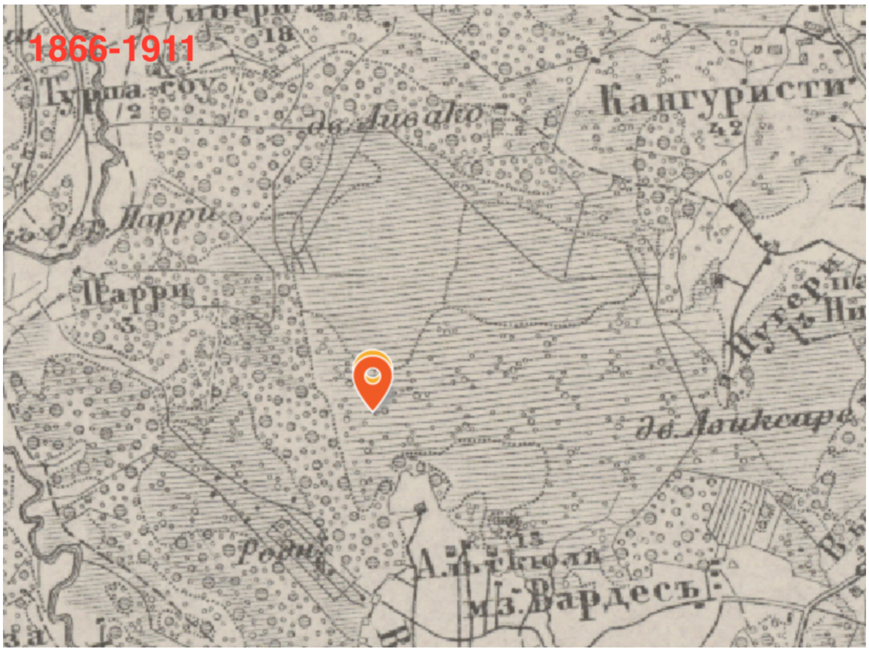

Fig 4. Varudi map, 1866 – 1911

- *The data were square root transformed… (capital letter)*

Author's response: *Change made as requested.*

- *PrC (abbreviation is not explained)*

Author's response: *Abbreviation explained as requested by reviewer.*

- *R261: 10x10 xx (scale is missing)*

Author's response: The scale of the squares within graticule is not essential, is not known to the author and are not typically reported in plant macrofossil studies. In this case, it means that a 10 x 10 square grid can be seen within the microscopes' field of view, allowing the relative proportions of plant materials within the grid to be quantified by counting their occurrences within the squares. In response to this comment we have opted to change the wording for clarity:

Previous text (L275-277): " Botanical composition was estimated as percentages under a low-powered microscope at between 10–100 X magnification, using a 10 x 10 eyepiece graticule for quantification."

Changed text: "Botanical composition was estimated as percentages under a low-powered microscope at between 10–100 times magnification, using a 10 x 10 grid eyepiece graticule to aid quantification of plant remains".

- *R283: NPPs (abbreviation is not explained)*

Author's response: *Abbreviation added as requested by reviewer*

- *R293: (reported as particles cm^{-3} yr^{-1}**)** parenthesis is missing.*

Author's response: *Changes made as requested by reviewer.*

- R306: g cm^{-3}(incorrectly stated units of density)

Author's response: We thank the reviewer for pointing this out. We have made the suggested change, although we will opt to change the units of density to g/cm^3 as this format is more frequently seen in other published literature.

- *R332: „Clinker emissions" Explain this term, please.*

Author's response: We thank the reviewer for pointing out most readers will not be familiar with cement production processes (like how I was before I started writing this paper!) and that this might affect accessibility and clarity. Clinker is the main component of cement and is formed by heating up lumps of limestone along with a few other 'ingredients. The process of clinker production at Kunda was the root cause of most of the emissions from the factory, including GHGs, fly ash, trace metals and the fine alkaline dust, so this is simply another way of saying cement dust plus other by-products. It is an accurate term so we will keep it in, but we will include some lines to explain the meaning.

In response to this comment, we have included a definition of clinker emissions, L355 – 357): "(Clinker emissions being the emissions produced during the production of clinker, the primary ingredient of cement, created by the high-temperature heating of limestone and other materials)".

- *R355: The age scale is missing from Figure 4. This makes it difficult to easily compare the time period referenced in the text (R365) with the lead and cement curve shown in Figure 4, which currently only includes a depth scale.*

Author's response: The reviewer is correct to point this out. Originally, I didn't want to distract too much from the simple visual comparisons between the two trends which is the purpose of this figure, but the reviewer is correct to note that specific periods are referenced in the text in relation the figure, therefore an age-scale is necessary. This will be added as requested.

Also, the figure caption was changed to reflect this change (L383): Added text: "Age ranges are based upon the median ages from the age-depth model".

- *R436: The sentence is missing a verb. The broken stick model showed that the first two components together **explained** a significant proportion…*

Author's response: Change made as suggested, tense changed to the present tense.

- *R663-666: In my opinion, this statement is not right. I do not think that replacement of Sphagnum by monocots such as Carex spp. and Eriophorum vaginatum indicates* *wetter local conditions. You do not know, which Sphagnum (whether hummock or hollow species) were replaced by monocots. It could be interpreted the exact opposite (also shrubs are increasing since that time).*

Author's response: We appreciate the reviewer's perspective and agree that their alternative interpretation is both valid and defensible. However, we believe that several lines of evidence from our dataset support our original conclusion, which we will strengthen in the revised text. Around the time of this transition, our water table reconstruction indicates a shift towards wetter conditions, potentially with standing water at the site.

Although we could not identify *Sphagnum* to species level, due to time constraints, we were able to assign to subsections, which are associated with broad environmental preferences and characteristic microforms. During this period, taxa from subsections *Acutifolia* and *Sphagnum,* which are typically associated with drier conditions, decline, while there is a small but notable increase in subsection *Cuspidata*, generally associated with wetter habitats, alongside an increase in unidentifiable *Sphagnum* remains. Although it is not possible to say what subsection these remains related to, it is known that *Sphagnum* litter from subsection *Cuspidata* preserve less well than those of subsections *Acutifolia* and *Sphagnum* (Bengtsson et al., 2016) and are therefore likely to represent remains of plants that are of this subsection- although this isn't very scientific so we will not use this line of reasoning in the manuscript.

This interpretation is also informed by field observations of contemporary bog pools where *Sphagnum* may be rare or absent in shallow or temporary bodies of water on the peat surface, while monocots, particularly but not exclusively *Eriophorum* species thrive, E.g. the NVC bog pool community (M3).

While we maintain that our interpretation is reasonable considering these observations, we acknowledge the limitations imposed by the relatively low taxonomic resolution of the plant macrofossil reconstruction, the possibility of alternative interpretations like that suggested by the reviewer, and the lack of argumentation of our case in the text. We have made the below changes to the text to clarify and defend our position, L708 – 716:

Previous text: "By c. 1570 cal CE, the site had transitioned into a wetter, more minerotrophic fen, indicated by the gradual replacement of *Sphagnum* by monocots such as *Carex* spp. and *Eriophorum vaginatum* in the plant macrofossil record (Figure 9)."

Changed text: "By c. 1570 cal CE, the site had transitioned into a wetter, more minerotrophic fen, indicated by the gradual replacement of *Sphagnum* by monocots such as *Carex* spp. and *Eriophorum vaginatum* in the plant macrofossil record and an increase in *Sphagnum* section *Cuspidata* remains and subsequent declines in *Sphagnum* subsection *Acutifolia* and subsection *Sphagnum* (Figure 9), and a shift towards wetter conditions during this period indicated by the testate amoebae reconstruction, possibly indicating permanent or seasonal standing water at this time (Figure 10). This interpretation is consistent with observations from contemporary bog pools, where *Sphagnum* is often rare or absent in shallow or temporary water bodies on a peatland's surface, while monocots such as *Eriophorum* species are abundant, as exemplified by the Nritish National Vegetation Classification (NCV) bog pool community classification (M3) (Rodwell, 1998)".

- *R704-709: I do not understand why the recent presence of Tomentypnum nitens (a calciphilous species) is explained by the upward movement of mineral-rich water from deeper peat layers (and how this could be possible?). Why can't the occurrence* *of T. nitens be linked to cement dust emissions? Furthermore, if a Sphagnum species has returned to the site since its disappearance, which species is it? This is important! Sphagnum species are good indicators of mineral content, and some are calcitolerant species (e.g., S. obtusum, S. teres, S. warnstorfii).*

Author's response: The presence of *Tomentypnum nitens* on the contemporary bog surface is interpreted as resulting from the upward movement of water moving through the peat profile via capillary rise. Cement dust emissions had all but ceased by the time the samples were taken, and the dust is buried by c. 20 cm of peat. Therefore, this mechanism explains how the legacy cement dust can continue to influence the present-day vegetation communities at the surface, by the mobilisation of Ca^{2+} ions derived from the $CaCO_3$ deposits within the cement dust layer. While reduced contemporary cement dust deposition from the factory in the present day, as well as from nearby agricultural sources, may provide an additional source of alkaline deposits, we find no evidence for this for the uppermost peat layers in our XRF data.

We agree that *Sphagnum* identification to species level is highly useful given their strong sensitivity to water chemistry, and it is regrettable that no plant surveys were undertaken along with the coring exercises at the time of sampling, or that high-taxonomic resolution identification was made during the plant macrofossil analysis. However, in both cases we were limited in terms of resources and time. Contemporary data from published literature on the site's botanical communities are sparce, to our knowledge there is only one source (abstract only online) for the composition of *Sphagnum* communities in Varudi (Ploompuu, 1997), describing the area as supporting 'fen *Sphagnum*' species only. Future survey work would be valuable to clarify species composition and to better assess mineral influence on recolonisation at Varudi. In the case of Varudi and related sites, it was not the loss of a single *Sphagnum* species, but the decline of all *Sphagnum* that was significant, therefore the occurrence of any species at all is likely to reflect recovery, while we acknowledge that the species present could provide further evidence for the degree of this recovery.

In response to this comment, we have decided to clarify our position by adding information relevant to what is stated above in the discussion. Specifically, we made the following changes (L758 – 771):

Previous text: "…we find no evidence for botanical succession toward pre-disturbance conditions in the plant macrofossil record (Figure 9), while the presence of calciphilous *Tomentypnum nitens* at the core surface reflects the legacy of alkaline conditions (Malmer et al., 1992; Hájek et al., 2006; Apolinarska et al., 2024), most likely resulting from the upward movement of mineral-rich water from deeper peat layers, although *Sphagnum* has returned to the site since its disappearance".

Changed text: "…We find no evidence for botanical succession toward pre-disturbance conditions in the plant macrofossil record (Figure 9), while the presence of calciphilous *Tomentypnum nitens* at the core surface reflects the legacy of alkaline conditions at the site (Malmer et al., 1992; Hájek et al., 2006; Apolinarska et al., 2024), likely resulting from the movement of mineral-rich water, enriched by the buried cement dust as it is transported upwards via capillary rise, indicating that these cement deposits continue to influence surface water chemistry and vegetation communities at the site, although *Sphagnum* has returned to the site since its disappearance, indicating a degree of recovery. Identification and monitoring of the species present on the site could provide additional insight into the extent of this recovery".

- *R804-810: This is quite a big problem – your pH estimates are significantly shifted towards lower values. It could be caused by an imbalanced calibration dataset, where samples with low pH are predominant. Is this the case, or is there another explanation? You should discuss this more in the discussion section.*

Author's response: We fully agree with the reviewer on this point. The Amesbury et al., (2016) transfer function was based on samples taken from a great many peatlands across Europe, however samples from sites with higher pHs were excluded from the dataset to improve the predictive potential of the models for reconstructing WTD, therefore the calibration dataset is likely to be imbalanced as the reviewer suggests. We will add the point made by the reviewer to the discussion section where limitations of the transfer function are discussed.

In response to this comment, we have added a couple of lines, one stating the above point by the Reviewer and the other describing how the data may be reevaluated in the future, to improve estimates of tipping points due to pH (L879 – 886): "…possibly due to the removal of high-pH samples from Amesbury *et al.,* (2016)'s dataset, causing the range of pH measurements to be low and biased towards more acidic conditions. This may warrant future re-evaluation of our data using transfer functions specifically developed for reconstructing pH in polluted peatlands."

- *R810-813: Also drainage may have played an important role in driving vegetation changes*

&

- *R838-845: You only take into account pH changes as a main driver of ecosystem shifts. However, you also have results regarding water-table depth changes (Fig. 14). You should also consider these results and point out that local ecosystem changes at Varudi could also be affected by water-table depth changes (caused by drainage and peat extraction).*

Author's response: The two comments above are related and will be addressed together here. We fully agree with the reviewer that this is most definitely the case and that the discussion requires a more in-depth exploration of the role that water table has or may have had in the development of Varudi at the time. We will add a paragraph to the discussion detailing the difficulty of disentangling drivers from the palaeoecological record (L906 – 916): "Furthermore, disentangling the effects of alkalinisation from those of drainage is challenging, as both factors may influence plant community composition, carbon accumulation rates, overall ecosystem functioning (Word et al., 2022) and possibly resilience to alkalinisation in peatlands. Since significant drainage and cement production appear to have begun at roughly the same period in the site's history, some of the ecological variability attributed here to cement dust pollution may instead be the result of drainage impacts. However, it is notable that despite reconstructed pH values increasing following the cessation of significant emissions from Kunda, water table depths have not recovered. This indicates that drainage is unlikely to have influenced the apparent modest ecosystem recovery observed at Varudi in recent decades."

We also acknowledge the probable influence of drainage in the conclusion (L923): "…along with later drainage".

We also added a short line to another relevant section of the text (L885): “...and, significantly- drainage...