Reviewer #1: Michel Allard, 05 Jul 2024

Dear Prof. Michel Allard

Thank you so much for your constructive comments on this manuscript, we have taken all the comments, suggestions and queries as an opportunity to improve the quality of this manuscript. Please find below responses to general and specific comments. In addition, all the notes have been responded to in the pdf version.

Regards

Mahya Roustaei

General comment: Over roughly the past 20 years, computed tomography scanning (CT-Scan) has been proven as a fantastic technology to image undisturbed, frozen, permafrost cores. We must add that Ct-Scan appeared in permafrost science about at the same time as portable drills became of widespread use after the initial publications of Calmels et al. (2005, 2004), making easy the sampling of intact permafrost cores by field researchers. Before the application of Ct-Scan to permafrost, destructive methods were almost exclusively available to measure permafrost properties and quantitatively determine its composition in sediments, ice, water and gaz. This manuscript brings forward useful and interesting new advances in the use of CT-Scan.

I am of the opinion, however, that the manuscript needs substantial revisions in order to be raised to the level of a strong journal paper. As it is now, it appears more as a methodological technical report of medium quality. It presents comparative results between automated methods and destructive methods, making a good validation of CT-Scan analysis (and MCSL) and a demonstration of capabilities. The paper can be very much improved on three aspects: 1- it should relate the approaches and the results with some fundamental permafrost concepts and key properties, for instances cryotexture, cryostructure and phase composition.

Response: We appreciate the perspective on the paper, but do emphasize that the paper is focused on methodological developments and application of industrial CT scanning to a diverse (though not comprehensive) set of permafrost samples. In particular, we present the first use of calibrated density of permafrost materials (rather than Hounsfield units); the use of Otsu splits in the segmentation and comparison of these results with destructive analyses at similar spatial resolution; and demonstrate some of the advantages of the higher spatial resolution and greater energies available using Industrial CT scanning. We think these methods will be more widely used in permafrost studies as Industrial CT scanners become more available in research environments. However, we have taken the suggestions of Dr. Allard and incorporated opportunities to clarify and improve the text. Following Dr. Allard's and R2s suggestions, we've rewritten the introduction to the paper, reducing its length by about 50% and we hope for a much clearer presentation and set up for the paper.

2- it should have at least an integrated paragraph on general theorical aspects of CT-Scan in permafrost explaining basic concepts such as energy, scanning time, sample size, voxel size (defining resolution and limits of detection of constituents), and image segmentation based on distribution of density units.

> **Action**: General theoretical aspects of CT-Scan were added in different section through the whole text as the following sentences (please also see the response to comment #21 for the image segmentation steps):
>
> *"This imaging method captures radiograph images through the production of x-rays which pass through the cabinet and are recorded by the detector panel opposite the source. The sample is placed between the source and the detector panel and the resulting relative absorption of the x-rays energy is recorded by the detector panel creating the radiograph image. To collect a 3 dimensional image a set of two-dimensional X-ray radiographs are collected at multiple angles, and secondly reconstructed to form a 3D image. The final measurement unit which is commonly visualised in a histogram is the linear attenuation coefficient which depends on both the density and the electron density of the material (Ketcham and Carlson, 2001)."*
>
> *"Scan times ranged from 30 to 45 minutes per core, with a maximum height of ~12 cm scanned per core due to vertical stage movement limitations and inclusion of calibration materials. The subsampled cubes from the cores were scanned with the rotating reflection target source at 225 Kv 133 µa with an exposure time of 125 ms and a voxel size of 25 µm. Scan times for the subsampled cubes were 30 minutes per cuboid."*
>
> *"Although the CT scanner can hold samples up to ~ 30 cm wide by 35 cm high, the area that is able to be scanned is dependent on the desired voxel size and the width of the sample."*

3- Important: improve the writing, argumentation and style. Make technological details easily understandable for general readers of the permafrost community.

> **Action**: Writing, argumentation and style have been improved through the whole text to make technological details easily understandable, details can be found in the following responses to the detailed comments.

In the following lines, I refer to key comments already in the revised pdf that I am also sending back with this assessment. More notes, mostly stylistic suggestions, are to be found on the revised pdf.

Specific Comments:

Comment #1: Lines 10-20: The introductory statements could be stronger. Why not say that permafrost contains various types of ground ice: pore, segregation, aggradational (a variant of segregation ice), wedge ice, intrusive, massive, etc. that create a variety of cryostructures and cryotextures (cite permafrost glossary, NRC, 1988). Those types of ground ice are associated with diverse landforms. Melting of ground ice generates thaw settlement.Being able to analyse frozen, undisturbed, cores of permafrost allows to better understand how it formed, internal permafrost transforming processes and predict the amplitude of thaw settlement and consolidation.

CT-scan offers the capability to analyse cores and, even, measure some basic properties from image analysis, such as density and thermal conductivity.Line 18. You seem to focus on excess ice because it is important for engineering and geomorphic applications. But excess ice is only one component. With CT-scan much more can be done. Excess ice (i.e. ice content greater than natural void ratio) is only one case. CT-scan can image all kinds of ice and support development of new knowledge. Quantifying excess ice is one problem among many.

Action: Introduction was edited to address all the remarks of this comment as follows:

"Permafrost is rock or soil that has remained below 0°C for at least two consecutive years. Within permafrost, several different types of ground ice can form: pore ice within the void spaces between soil or rock particles; segregation ice as distinct lenses formed through migration of water within permafrost; aggradational ice, a type of segregation ice, that forms as the permafrost table rises; vein or wedge ice that forms within thermal contraction cracks; intrusive ice that forms when water is injected under pressure; or massive ice that refers to relatively pure bodies of ice within permafrost. (Subcommittee on, Permafrost., 1988). These differing types of ground ice have distinctive associations of cryotextures, which refer to the appearance and characteristics of ice crystals, gas bubbles and their interfaces with soil particles at a more microscopic scale; and cryostructures which refer to the three-dimensional patterns and arrangements of ice bodies within the frozen ground (such as layered, lenticular, or reticulate patterns) (Murton and French, 1994; French and Shur, 2010). Taken together, these ice-related features help identify the genesis of perennially frozen sediments and can provide insights into the conditions under which the permafrost formed, which can aid in understanding potential ground ice distribution. Of particular importance is excess ice – or ground ice that exceeds the natural pore volume that the sediment would have under unfrozen conditions. When excess ice melts, it causes thaw settlement and ground subsidence, making its quantification increasingly critical as warming temperatures degrade permafrost across permafrost regions (e.g. Kokelj et al., 2024). Projections of widespread permafrost thaw by the end of this century (e.g. Cai et al., 2020) highlight an urgent need for standardized methods to measure and map excess ice distribution to better predict future landscape change.

Cryostructural approaches to ground ice classification, building on Russian literature, particularly Katasonov's (1969, 1978) cryofacies methods, focus on understanding permafrost genesis and development through systematic analysis of the shape, size and spatial patterns of ice inclusions in frozen ground. This approach contrasts with the more commonly used North American engineering-focused descriptive systems developed by Pihlainen and Johnston (1963) and Johnston (1981), which rely primarily on visual descriptions and simple field tests, such as thawing samples to observe supernatant water content similar to the method described in Kokelj and Burn (2003). While the descriptive approach provides practical field-based classifications useful for engineering applications, the cryostructural approach offers more process-based insight into permafrost formation processes and potential ground ice distribution, which is increasingly important for predicting thaw settlement and landscape response to climate warming."

Comment #2: Line 20. It is the reverse that is true. It is thaw settlement that is proportional to ground ice content.

Action: Corresponding line was edited.

"Of particular importance is excess ice – or ground ice that exceeds the natural pore volume that the sediment would have under unfrozen conditions (Brown et al., 1997; Zhang et al., 1999; Cai et al., 2020; Van Everdingen, 1998). When excess ice melts, it causes thaw settlement and ground subsidence, making its quantification increasingly critical as warming temperatures degrade permafrost across permafrost regions (e.g. Kokelj et al., 2024). Projections of widespread permafrost thaw by the end of this century (e.g. Cai et al., 2020) highlight an urgent need for standardised methods to measure and map excess ice distribution to better predict future landscape change."

Comment #3: Line 28. I suggest you consult the definition of cryotextures (micro, sub-visual) and cryosructures (macro, visible) in the permafrost glossary and in some key papers (see for instance Shur and French and Murton and French...).

Action: Corresponding section was modified with respect to cryotextures that is consistent with the comment.

"Cryostructural approaches to ground ice classification, building on Russian literature, particularly Katasonov's (1969, 1978) cryofacies methods, focus on understanding permafrost genesis and development through systematic analysis of the shape, size and spatial patterns of ice inclusions in frozen ground. This approach contrasts with the more commonly used North American engineering-focused descriptive systems developed by Pihlainen and Johnston (1963) and Johnston (1981), which rely primarily on visual descriptions and simple field tests, such as thawing samples to observe supernatant water content similar to the method described in Kokelj and Burn (2003). While the descriptive approach provides practical field-based classifications useful for engineering applications, the cryostructural approach offers more process-based insight into permafrost formation processes and potential ground ice distribution, which is increasingly important for predicting thaw settlement and landscape response to climate warming."

Comment #4: Lines 30-35. See also Ducharme et al. (2015) (in GeoQuébec) for the determination of thermal conductivity of permafrost based on sediment, ice and air contents through CT-scan.

Action: Ducharme et al. (2015) was added to the references and the text as well.

"Micro-computed tomography (μCT) has emerged as a promising solution to the limitations of traditional permafrost characterization methods since the pioneering work of Calmels and Allard (2004, 2008), who demonstrated its utility for measuring ice and gas contents in permafrost and linking these to processes of ground ice formation. Subsequent studies have expanded the application of CT scanning to examine cryostructures (Calmels et al., 2010; Fan et al., 2021), excess ice (Lapalme et al., 2017), soil degradation in freeze-thaw cycles (Nguyen et al., 2019; Wang et al., 2018, 2017; Roustaei et al., 2022), quantification of micro-lenticular ice lens formation (Darrow and Lieblappen, 2020), unfrozen water content (Roustaei et al., 2022), soil-ice relations (Torrance et al., 2008), and permafrost composition (Nitzbon et al., 2022)."

Comment #5:Lines 38-39. What classification methods are you referring to here? what are these classification methods? How are permafrost cryostructures classified, on what principles? by who? add references. Classification is a mental exercise. How can methods can be limited?

Action: Introduction was edited to address this comment.

"Cryostructural approaches to ground ice classification, building on Russian literature, particularly Katasonov's (1969, 1978) cryofacies methods, focus on understanding permafrost genesis and development through systematic analysis of the shape, size and spatial patterns of ice inclusions in frozen ground. This approach contrasts with the more commonly used North American engineering-focused descriptive systems developed by Pihlainen and Johnston (1963) and Johnston (1981), which rely primarily on visual descriptions and simple field tests, such as thawing samples to observe supernatant water content similar to the method described in Kokelj and Burn (2003). While the descriptive approach provides practical field-based classifications useful for engineering applications, the cryostructural approach offers more process-based insight into permafrost formation processes and potential ground ice distribution, which is increasingly important for predicting thaw settlement and landscape response to climate warming.

Traditional approaches to permafrost characterization, whether using more descriptive engineering-oriented approaches (Pihlainen and Johnston, 1963; Johnston, 1981) or more detailed cryostructural classifications (Murton and French, 1994; French and Shur, 2010), rely heavily on visual description of exposures and cores (Kanevskiy et al., 2011; Stephani et al., 2014). While these approaches have advanced our understanding of permafrost, they require substantial experience of the analyst, and are difficult to standardise. Quantitative methods typically require destruction of samples to measure ice and moisture contents, which works well for ice-rich mineral soils but presents challenges for organic-rich materials where water may be retained in thawed samples. These limitations have driven the development of non-destructive methods like Computed Tomography (CT) scanning that can systematically analyse intact frozen cores, providing standardised, quantitative data on ground ice while preserving samples for additional analyses. This approach offers the potential to better understand permafrost formation, internal structure, and likely response to thaw while developing more consistent and interoperable methods applicable across different permafrost materials."

Comment #6: Line 40. Five cores make for a very small sample size given the immense variety of permafrost settings and characteristics in natural conditions. It seems your results are more a report on a few methodological tests to ultimately develop the technological application on a wider scale. You are making a demonstration.

Action :Following lines were added to the text to address this comment: *"While our sample set does not capture the full heterogeneity of permafrost materials and ground ice abundance, it provides a rigorous test of CT methods for quantifying ground ice in common permafrost materials, with the goal of developing more robust and standardised approaches for permafrost characterization and mapping."*

Comment #7: Line 43. It is unclear to me if the water standard that you scan with the core is liquid or ice at the time of scanning since it is enclosed within insulation cooled with freeze packs. One calibration point of density is air (?), the other is either liquid water or ice (no?)

Action: We tested both water and ice calibration standards, but found water to be the most accurate and reproducible. The following lines were added to the calibration section to address this concern: "*The water and aluminum were located outside of the insulated container during the core scans to avoid freezing. The cube scans had only the water located directly above the cube sample but isolated from the sample and dry ice by insulated foam to minimize the exposure to the cold air temperature within the insulated container.*"

Comment #8: Lines 48-49. I agree that results of this study will improve data acquisition. But too much generalization seems an over ambitious goal statement at this testing stage.

Action: Corresponding line was edited.

"*While our sample set does not capture the full heterogeneity of permafrost materials and ground ice abundance, it provides a rigorous test of CT methods for quantifying ground ice in common permafrost materials, with the goal of developing more robust and standardized approaches for permafrost characterization and mapping.*"

Comment #9: Line 52. Why try to limit lateral heterogeneity? drilled cores are by nature unidimensional samples.

Action: Following lines were added to address this concern: *"Lateral heterogeneity would cause noise in our results when comparing multiple data acquisition methods within the same material but not identical sample volumes (Figure 1). This effort is explained further by Pumple et al. (2024)."*

Comment #10: Line 79. You introduce the word "cuboid method" in the text. Not all readers know of your lab terminology. You must explain. Why subsampling small cubes is necessary? Is it just to make comparisons with destructive methods or also to allow scanning at higher resolutions (25 micrometers voxels) on subsamples of smaller sizes? Both?

Action: "cuboid method" was deleted from this line and the reason for subsampling was highlighted in the revised version as the following line:

"To independently assess density and ice content measurements and also being able to perform scans at higher resolutions, the cores were subsampled as 2x2x4cm cubes."

Comment #11: Line 85. "takes advantage of the ice-rich properties of frozen cores which allow for a greater degree of sampling precision" A kind of overstatement. I guess cutting nice and smooth-faced cubes in coarser soils (sand, granules...) would be more difficult…

Action: We have adjusted the text as follows to provide clarity.

"*The cuboid method, described by Bandara et al. (2019), is similar to other volumetric and gravimetric methods used to measure bulk density and ice content, but takes advantage of the frozen state of the material which allows for a greater degree of sampling precision. Processing is undertaken in a walk-in freezer following methods outlined in Pumple et al. (2024).*"

Comment #12: Line 93. Lin et al. 2020. Not in references at the end. What is this equation? I gave a quick look at this reference and did not see an equation for volumetric ice content (?), only eq. 1. Check.

> **Response:** Thank you for your comment. We have added the reference to the reference section. We are referring to Equation (6) on page 11 of the paper.

Comment #13:Line 121. How many minutes or seconds is the duration of a scan for one sample? does the sample have the time to start melting? Do you have a freezer at hand from where you can take the sample out for a very short duration?

> **Action**: Added in approximate scan times for both cores and cuboids to section 2.3. Revised a sentence in section 2.3 to emphasize that samples are not at risk of melting. Added in a comment that samples were taken from a chest freezer and quickly added into core housing.
>
> *"Scan times ranged from 30 to 45 minutes per core, with a maximum height of ~12 cm scanned per core due to vertical stage movement limitations and inclusion of calibration materials.*
>
> *"Cores were taken from a nearby chest freezer, quickly placed in a larger styrofoam container with an inner diameter of 12 cm in the vertical position and an ice pack was placed directly above them (Figure 2B and C)."*

Comment #14: Line 124. Specify in the text what is the maximum sample size (height, width, volume) than can fit in your industrial CT-scanner.

> **Action**: Added in maximum sample height and width measurements as follows:
>
> *"Although the CT scanner can hold samples up to ~ 30 cm wide by 35 cm high, the area that is able to be scanned is dependent on the desired voxel size and the width of the sample."*

Comment #15: Line 126. A general comment. I think it would be useful to have a paragraph describing the relationship in CT-scanning between sample volume, resolution (minimum voxel size), scanning duration and energy. You could comment on the choice of these parameters for different goals of research (general permafrost characterization, search of maximum details possible in cryotexture, defining standardization methods, interpret permafrost incipience and growth, etc.

> **Response:** Our paper aims to present initial results of CT scanning for permafrost core characterization rather than to review or refine scanning techniques. Since we did not test multiple scan settings, we focused on selecting practical parameters to balance resolution and processing time, which are described in enough detail for replication. A broader discussion of scanning parameters is what we will be looking into in the future.

Comment #16:Line 138. Please explain more...why aluminium? I guess a given density (?) frozen or not? it is better explained in Pumple et al., 2024

> **Action**: Following lines were added to address this concern: *"Aluminum was chosen for its consistent density of 2.71 g/cm^3 representing an upper limit of the expected bulk density within the selected materials."*

Comment #17: Line 139. Is this in the frozen water vial? other question: was that standard made of water frozen in the freezer? it may have contained less air bubbles than the excess permafrost ice, hence the apparent density difference (?).

Action: Following lines were added to address this concern and provide more details: *"The ice calibration was a 15 ml falcon tube filled and frozen at -5C to minimize expansion issues and bubbles."*

Comment #18: Line 142. i.e. you identified on images a group of pixels on a slice with the same density as the standard. Correct?

Response: The pixels for calibration were selected based on avoiding artifacts and capturing a representative population of the observed gray values within the water volume.

Comment #19: Line 166. Subtitle of section 3. Reorganize subtitles and some text accordingly: I think it is better to separate results (presentation of obtained results) and discussion (comments on new methodological improvements and findings, limitations met, new potential, some autocriticism..).

Action: Section 3 was restructured and the subtitles were reorganized.

Comment #20: Line 170. Replace "close densities" by "narrow unimodal density distributions".

Action: "*close densities*" was replaced by "*narrow unimodal density distributions*" in the revised text.

Comment #21: Lines 173-174. "The voxel size can impact the image segmentation through the partial volume effect which relates directly to the finite spatial resolution of the scan and for geological samples, the grain size distribution" This is uselessly complex language and poor pedagogy. This simply means that the voxels in CT-scan currently always contain mixtures of sediments, ice, unfrozen water and gaz. This is more so for finer grain size materials because their pore size is smaller.

Action: The section was revised as follows:

"The second stage, segmentation or the ability to differentiate materials, depends on their respective linear attenuation coefficients, meaning materials with divergent densities and/or atomic numbers are easier to differentiate (Kyle and Ketcham, 2015). Analysing a multi-modal histogram of a CT image is straightforward for material differentiation while materials with narrow unimodal density distributions close densities appear as a single peak in the histogram. In addition to the relative density of the scanned materials, the image resolution or voxel size also directly impacts the image segmentation process. The voxel size can impact the image segmentation through the partial volume effect which relates directly to the resolution or voxel size of the scan and for geological samples, grain size, minimal pore size, and organic content (Soret et al., 2007; Nitzbon et al., 2022)."

Comment #22: Line 179. In fact, you do not differentiate 5 different materials, but rather 5 different classes of sediment/ice composition ratios. Do you observe some different micro-structural elements (mico-lenses, cristals, etc.) in those different classes?

Action: Very good comment, "*5 different materials*" was replaced by "*5 different classes of sediment/ice ratios*".

Response: We did not examine the micro-structures in different classes since this study focused on differentiating the sediment/ice composition ratios rather than investigating the micro-structural elements within each class.

Comment #23: Line 184. On figure 5, the air distribution fits closely with the sediment-poor ice (segregated ice lenses in the matrix of the till). How air is discriminated: in bubbles (black in F)?

Response: This is just a visualization error in 3D images due to the shadows and artificial lighting. However, the first row of figure 4 shows the clear differentiation of air phase from sediment-poor ice (in black). In this study we did not differentiate bubbles within ice from voids.

Comment #24: Line 231. This highlight the effects of difference in location of ROIs in the permafrost mass. General remark: when you make measurements of small volumes or sub-samples in a heterogenous medium like till, it is normal to find spatial variations. This raises the question of what sampling or sensing volume is pertinent for a given geological material in a permafrost characterization study.

Response: We completely agree that different geological materials have different minimum sample size requirements to have a representative sample. The selected sizes of cubes in this study looked sufficient for almost all the cores (with very few exceptions that is already mentioned in the text)

Comment #25: Line 243. Here I find it interesting that despite the absence of visible micro ice lenses (or not mentionned), the uniformly textured permafrost contains a fraction (5% red line on C) of excess ice, i.e. above void volume. But you show no Cuboid-EIC...Why?

Response: The EIC being picked up by the CT scan is real in that, in the frozen state, the core has a small percentage of ice in the form of microstructures beyond the natural pore space within the host sediment. However, upon thawing, the surrounding sediment absorbs the moisture into the available pore space, resulting in no EIC during the destructive analysis. Section 2.3 also mentions this in relation to organic-rich samples (Johnson, 1981).

Comment #26: Line 251. What do you think was the effect of pressing peat samples a little bit like sponges? Discuss.

Action: The following line was added to provide the effect of pressing peat samples: *"As it was previously discussed, this pressure will release the excess water that was absorbed by the peat skeleton upon thaw (Johnston, 1981)."*

Comment #27: Line 253. Same question/comment. To accurately determine what is ice and what is sediment, one needs to detect at a resolution equal or smaller than pore space. This is barely possible in sand but difficult with these methods in silt, and worse in clay. With your capacity to reach a 25 micron resolution, you are seriously improving the potential use of CT Scan, but it requires subsampling in the larger volume. Then you have to recompute the total across the whole volume. An interesting problem. But we could learn a lot about permafrost by doing this.

Response: Thank you for this comment and reflection on the progress in the Permafrost Micro CT world to answer some difficult questions. The finer grained ice-poor samples are the more difficult samples to extract pore ice volumes but our goal in this paper was to highlight the CT's ability to extract excess ice contents and only hint at the possibility of pore ice contents if the sample had favorable physical properties (ie. coarse grained and ice-rich).

Comment #28: Line 281. A question: in figure 14, peat samples on the graphs seem to plateau at about 45% excess ice (?). Would you think that the ice-forming capability or ice concentration process in peat is different than in mineral soils? only saturation by pore ice between organic grains and fibers? Is there possibility of water migration and segregation?

Response: This is an interesting observation. Peat acts like a sponge and is able to wick up moisture from it's surrounding. This continued wicking and retention of moisture is not similarly present in mineral soils and so it is safe to say that peat has high ice concentration potential relative to soils but will not form segregated lens or bodies of ice seen in ice rich mineral soils (Kujala et al., 2008). As such, the ice commonly found within peats is not in the form of lens or layers but rather impregnated within the structure of the peat itself. I believe there is a possibility that the trend you observed within the CT vs Cuboid EIC results for the peat could be due to the variable nature of the applied force used to extract the "excess" moisture from the peat cubes. This is a question we will be looking into in the future.

Kujala, K., Seppälä, M., & Holappa, T. (2008). Physical properties of peat and palsa formation. Cold Regions Science and Technology, 52(3), 408-414.

Comment #29: Line 293. You should comment on why Ct-Scan provides valid measurements of excess ice contents. Is it because most of the excess ice content occupies volumes larger than voxel size (25 micrometers), i.e. larger than the average void size?

Response: CT scans provide better estimations of EIC compared to MSCL methods because it is able to segment out the visible ice voxels from the remaining sediment. With MSCL, we are able to estimate the total water content of the cores, but at 65 micrometer voxel size, the CT method will not be able to pick up both visible and pore ice. At higher resolutions (closer to the pore size in the core), CT and MSCL methods are more comparable for VIC estimations.

Action: The following sentence was added to line 293: *"Visible ice can be segmented and isolated from the remaining sediment and pore ice when scanning split cores at 65 µm voxel size, allowing the opportunity to better estimate EIC values compared to MSCL methods".*

Comment #30: Line 300. Is there a reason why you do not refer to resolution as voxel size, and keep a distinction between the two in the text? Maybe I am wrong and do not understand something..(?)

Response: The terms resolution and voxel size are used interchangeably in the text, with the use of "voxel size" when referring to the specific size in micrometers, and the use of "resolution" when referring to the more general concept of image quality. In line 300, I agree that the term "voxel size" is better suited for this sentence and will be changed accordingly.

Action: Changed "*spatial resolution*" to "*voxel size*".

Comment #31: Line 304. Why do you think excess/visible ice has a lower density than pore ice? presence of air bubbles? see Ducharme et al., 2015 and also Slusarchuck and Watson, 1975**.**

> **Action**: The following lines were added to the text to address the reason for excess ice lower density and to make this clear for all future reader:
>
> *"It should be noted that the pore ice inclusions within the mineral soil matrix are often smaller than the spatial resolution of the CT and the resulting gray value of a voxel is then a mixture of low-density ice and high-density minerals. This phenomenon, called partial volume effect, is the main reason why the high ice appears denser."*

Comment #32: Line 307. Do really organic material and ice have close densities? This is an artefact of the method. In fact organic matter is very light. Therefore, saturated peat always contains abundant ice. As a result, the average density of saturated frozen peat is slightly below density of ice (0.9).

> **Response:** The difficulty with frozen saturated peat is a combination of the relative density difference and the spatial relation between the ice and organics in that the ice is often embedded within the structure of the peat itself making image segmentation very difficult at the resolutions presented in this study.

Comment #33: Line 321. My opinion: there is so much yet to discover and for improving our understanding of permafrost with Ct-Scan. Prioritizing automation, machine learning, big databases and AI will not compensate for scientific culture and will lead to more technological wandering and not so many new discoveries.

> **Action:** This is definitely right, the corresponding line was edited as follows:
>
> *"The next steps can be followed by improving our understanding and techniques of scanning permafrost as well as using machine-learning-based image segmentation methods to generate datasets and explore the relations between physical permafrost properties."*

Comment #34: Figure 1. The caption should provide better definitions of what it contains; the reader needs to search the info in text : black cuboids-true sub-samples for destructive analysis; Pink virtual cuboids for comparisons by CT-scan; center line for MSCL at 10 mm resolution, overlapping blue circles for comparative high resolution spots (5mm 25 microns) CT, etc.

> **Action**: Caption was edited as follows:
>
> *"Figure 1: Image of a core highlighting the destructive subsample locations relative to the non-destructive data collection transects (black: subsampled cubes for destructive measurements, purple: subsampled cubes for CT scans)."*

Comment #35: Figures 6-10. I suggest that the axis title in C should simply be Ice content (%), because ice contents from many modes of measurements are shown, not only excess ice.

> **Response:** To be able to have a constant color between EIC measurements and graphs, we decided to use the top horizontal axis for EICs in red (same as EIC curves) while the bottom one was used for VIC in black (same as corresponding curves and values). This will help a clear differentiation between EICs (in red) and VICs (in black).

Reviewer #2: Anonymous Referee #2, 14 Jul 2024

Dear Reviewer

Thank you so much for your comments on this manuscript, and for dedicating a significant amount of time to review it with such precision. We have taken all the comments, suggestions and queries as an opportunity to improve the manuscript. Please find below the answers to general and specific comments.

Regards

Mahya Roustaei

Summary

This manuscript presents the estimation of excess and volumetric ice content in permafrost samples based on Industrial Computed Tomography. The results of the study show that CT scanning is a suitable tool to non-destructively estimate ice content in permafrost samples. The results were compared and validated with estimates by a destructive (cuboid density measurements) and another non-destructive (MSCL) method. Additionally, the authors conducted a sensitivity analysis to investigate the impact of spatial resolution in the segmentation process of CT scans. The study is relevant for the cryosphere community, but several parts of the manuscript are of poor quality. In the introduction the relevance of the study is well explained but the current state of research in using CT scanning for ice content estimation, the research gap built on recent literature and the main objective/research questions are missing. The section material and methods is poorly structured and the description of the methods used in this study is in some parts confusing. The results are described in detail but a critical discussion including e.g., putting the results in context of the literature and the link to relevant (and comparable) references presented in the introduction is missing. These issues together with some specific comments and technical corrections (see below) need to be addressed. Due to the relevance of the method for permafrost investigations, I recommend accepting this manuscript with major revisions.

General Comments:

Comments #1:

Abstract

• Please try to be more concise in the abstract. What is missing here is:
- What is the objective of the study?
- What samples have been used in the study?
- Laboratory or field scale?
- What is the main outcome/message?
- Give the reader a range of the deviations you measured between the different methods.

Action: The Abstract was revised as follows to cover all the above mentioned concerns:

"Permafrost contains a variety of ground ice types (e.g., pore, segregated, intrusive, vein, or massive ice) that have a diversity of cryotextures which organise to form distinctive cryostructures. The distribution and abundance of those ground ice types determines the potential for thaw subsidence and terrain effects of permafrost landscapes. Analysis of permafrost samples allows improved understanding of ground ice formation, internal and external permafrost processes, and improved tools to predict thaw settlement and consolidation. However, most methods to characterise permafrost are destructive and of low resolution. Here, some of the limitations of traditional destructive methods are overcome using industrial Computed Tomography scanner (CT). We use this laboratory-based method to systematically characterize five permafrost samples. We visualize cryostructures, measure frozen bulk density, and estimate volumetric and excess ice contents non-destructively and compare these results with traditional destructive analyses at similar spatial scales.

The results show strong agreement between traditional destructive analyses (RMSE's for density, VIC, and EIC are 0.12 g/cm3 and 3% and 6%, respectively) as well as recent developments using a Multi-Sensor Core Logger (MSCL) (RMSE's for density and VIC are 0.08 g/cm3 and 7%, respectively). These results , demonstrate that these non-destructive approaches can produce consistent results, and provide the added benefit of archiving images and enhancing digital permafrost datasets.. Development of standardised and interoperable methods for permafrost characterization has the potential to build more robust permafrost datasets and strengthen efforts to understand future thaw trajectories of permafrost landscapes"

Comments #2: Add which other methods are commonly used for ice content estimation and why you decided to use CT in your study.

Action: Introduction was edited to cover a brief review of the traditional methods of ice content estimation.

"Permafrost is rock or soil that has remained below 0°C for at least two consecutive years. Within permafrost, several different types of ground ice can form: pore ice within the void spaces between soil or rock particles; segregation ice as distinct lenses formed through migration of water within permafrost; aggradational ice, a type of segregation ice, that forms as the permafrost table rises; vein or wedge ice that forms within thermal contraction cracks; intrusive ice that forms when water is injected under pressure; or massive ice that refers to relatively pure bodies of ice within permafrost. (Subcommittee on, Permafrost., 1988). These differing types of ground ice have distinctive associations of cryotextures, which refer to the appearance and characteristics of ice crystals, gas bubbles and their interfaces with soil particles at a more microscopic scale; and cryostructures which refer to the three-dimensional patterns and arrangements of ice bodies within the frozen ground (such as layered, lenticular, or reticulate patterns) (Murton and French, 1994; French and Shur, 2010). Taken together, these ice-related features help identify the genesis of perennially frozen sediments and can provide insights into the conditions under which the permafrost formed, which can aid in understanding potential ground ice distribution. Of particular importance is excess ice – or ground ice that exceeds the natural pore volume that the sediment would have under unfrozen conditions. When excess ice melts, it causes thaw settlement and ground subsidence, making its quantification increasingly critical as warming temperatures degrade permafrost across permafrost regions (e.g. Kokelj et al., 2024). Projections of widespread permafrost thaw by the end of this century (e.g. Cai et

al., 2020) highlight an urgent need for standardized methods to measure and map excess ice distribution to better predict future landscape change.

Cryostructural approaches to ground ice classification, building on Russian literature, particularly Katasonov's (1969, 1978) cryofacies methods, focus on understanding permafrost genesis and development through systematic analysis of the shape, size and spatial patterns of ice inclusions in frozen ground. This approach contrasts with the more commonly used North American engineering-focused descriptive systems developed by Pihlainen and Johnston (1963) and Johnston (1981), which rely primarily on visual descriptions and simple field tests, such as thawing samples to observe supernatant water content similar to the method described in Kokelj and Burn (2003). While the descriptive approach provides practical field-based classifications useful for engineering applications, the cryostructural approach offers more process-based insight into permafrost formation processes and potential ground ice distribution, which is increasingly important for predicting thaw settlement and landscape response to climate warming."

Traditional approaches to permafrost characterization, whether using more descriptive engineering-oriented approaches (Pihlainen and Johnston, 1963; Johnston, 1981) or more detailed cryostructural classifications (Murton and French, 1994; French and Shur, 2010), rely heavily on visual description of exposures and cores (Kanevskiy et al., 2011; Stephani et al., 2014). While these approaches have advanced our understanding of permafrost, they require substantial experience of the analyst, and are difficult to standardise. Quantitative methods typically require destruction of samples to measure ice and moisture contents, which works well for ice-rich mineral soils but presents challenges for organic-rich materials where water may be retained in thawed samples. These limitations have driven the development of non-destructive methods like Computed Tomography (CT) scanning that can systematically analyse intact frozen cores, providing standardised, quantitative data on ground ice while preserving samples for additional analyses. This approach offers the potential to better understand permafrost formation, internal structure, and likely response to thaw while developing more consistent and interoperable methods applicable across different permafrost materials."

Comments #3: It is mentioned that there are other studies which have aimed to estimate excess ice content and volumetric ice content based on CT scanning but what are the outcomes of these studies and what are remaining open questions? Please try to put your objective in context of the main results of the other studies published so far. These points should be later discussed in "Results and Discussion".

Action: Introduction and Discussion were edited to cover the gap of previous studies and highlight the objectives of this study in covering those gaps.

"Micro-computed tomography (μCT) has emerged as a promising solution to the limitations of traditional permafrost characterization methods since the pioneering work of Calmels and Allard (2004, 2008), who demonstrated its utility for measuring ice and gas contents in permafrost and linking these to processes of ground ice formation. Subsequent studies have expanded the application of CT scanning to examine cryostructures (Calmels et al., 2010; Fan et al., 2021), excess ice (Lapalme et al., 2017), soil degradation in freeze-thaw cycles (Nguyen et al., 2019; Wang et al., 2018, 2017; Roustaei et al., 2022), quantification of micro-lenticular ice lens formation (Darrow and Lieblappen, 2020), unfrozen water content (Roustaei et al., 2022), soil-ice relations (Torrance et al., 2008), and permafrost composition (Nitzbon et al., 2022).

However, despite these advances, there have been few systematic comparisons of high-resolution CT scanning (< 100 μm) with established methods for differentiating excess ice from pore ice across different permafrost materials. This study addresses this gap by using industrial CT scanning, which offers higher peak power and resolution than medical CT scanners, to analyse five different permafrost cores representing a range of typical properties. We develop a new approach using an internal water standard to calibrate linear attenuation coefficients to real density values, and systematically compare CT-derived measurements of frozen bulk density, excess ice, and volumetric ice contents with both destructive physical measurements and Multi-Sensor Core Logging (MSCL) results from Pumple et al. (2023). We include a sensitivity analysis to examine how spatial resolution affects excess ice estimation. While our sample set does not capture the full heterogeneity of permafrost materials and ground ice abundance, it provides a rigorous test of CT methods for quantifying ground ice in common permafrost materials, with the goal of developing more robust and standardised approaches for permafrost characterization and mapping."

Comments #4: It is hard to understand what the actual research gap and the research question in the study is and what is the relation to recent literature. Please be more precise here.

Action: Introduction was edited to highlight the novelty of the study, please check the response to the previous comment.

Comment #5: (Methods and Materials): This section needs to be improved. Currently, it reads like a tutorial with a weak description of the different steps. Some parts are confusing and important information is missing. Please try to restructure this section. I would propose the following structure: 1) Samples description + sampling (e.g., How did you choose the sampling locations?) + ROI**,** 2) CT method including CT calibration and image processing**,** 3) Complementary methods: physical density measurements, MSCL, organic content measurements**.**

Action: The methods and material section was restructured and improved significantly to make all study steps clear enough. Please see the response to the following comment as well.

Comment #6: Samples description: Where did you collect the samples? Are all samples completely frozen? Which materials did you sample? Try to describe the characteristics of the samples. **(DONE)**

Action: A new subsection called "Field site and sampling" was added (as follows) to this section to cover all the sampling questions.

"2 Methods and Materials

2.1 Field site and coring

Five cores were compared in this study, each representing common materials encountered in permafrost regions and containing a relatively simple vertical cryostratigraphy to minimize the impact of lateral heterogeneity (Table 1). Lateral heterogeneity would cause noise in our results when comparing multiple data acquisition methods within the same material but not identical sample volumes (Figure 1). This effort is explained further by Pumple et al. (2024).

These cores were collected as a result of two separate field campaigns during the summers of 2013 and 2019. Following extraction the cores were bagged, labelled and stored at subzero temperatures via a pre chilled cooler and quickly transported to the field base where a chest freezer was present. The chest full of cores was then transported to the Permafrost ArChives Science (PACS) Laboratory. The samples were then archived into the PACS Lab walk-in archive freezer space. PACS Laboratory hosts a specialized imaging space where both the Nikon XTH 225 ST and the Geotek multi-sensor core logger (Pumple et al., 2024) are located. The imaging space is kept at 23 °C and as a result, special consideration has to be taken when working with frozen materials. An insulated sample container was used to keep the samples frozen during the scanning process discussed further in section 2.3.

2.2 Sampling Process

In this study the samples were prepared for two different stages; non-destructive scans and destructive physical measurements. We took considerations in both stages to ensure the destructive and non-destructive results were comparable. As such for the non destructive scans, physical cores were cut in half and run through all non-destructive data collection methods.. For the second stage, a duplicate transect of cuboid samples was collected from the middle of the core to allow non-destructive data analysis at a higher resolution on one set of the subsampled cubes. As seen in Figure 1, this resulted in the cuboids flanking either side of the MSCL and CT results which were collected from a central transect on the half-core samples."

Comment #7: Industrial Micro Computed Tomography: Please can you add one or two sentences what physical mechanism/principle is the basis for the method and describes how it is used here. Later, you mention that you used a new calibration method. Could you please add a Figure (maybe in the Appendix) showing the calibration curve?

Action: A couple of sentences were added to the text regarding the basics of CT (as follows), and regarding the calibration method, we tried to clarify it as much as possible in the text since all calibration processes were handled within the software and we are unable to present the curves.

"This imaging method captures radiograph images through the production of x-rays which pass through the cabinet and are recorded by the detector panel opposite the source. The sample is placed between the source and the detector panel and the resulting relative absorption of the x-rays energy is recorded by the detector panel creating the radiograph image. To collect a 3 dimensional image a set of two-dimensional X-ray radiographs are collected at multiple angles, and secondly reconstructed to form a 3D image. The final measurement unit which is commonly visualised in a histogram is the linear attenuation coefficient which depends on both the density and the electron density of the material (Ketcham and Carlson, 2001)."

"It should be noted that all cores were scanned with ice, water, and aluminum calibration pieces of which water proved to be in closest agreement with destructive analyses. The water and aluminum were located outside of the insulated container during the core scans to avoid freezing. The cube scans had only the water located directly above the cube sample but isolated from the sample and dry ice by insulated foam to minimize the exposure to the cold air temperature within the insulated container. The aluminum calibration piece generally underestimated the bulk density while the ice calibration piece

resulted in a slight overestimation. Aluminum was chosen for its consistent density of 2.71 g/cm3 representing an upper limit of the expected bulk density within the selected materials. The ice calibration was a 15 ml falcon tube filled and frozen at -5C to minimize expansion issues and bubbles. Overall the water calibration produced the most accurate results apart from ice-poor sediments. The Nikon CT Pro 3D software uses a linear two-point calibration with the first fixed point being air (equal to zero) and the second a user-defined value based on a user-selected pixel population. A representative (local) population of pixels was selected from our water sample in a 2D slice of the scan and informed the expected average target value (1 g/cm3). This results in displaying grey values in g/cm3. The shape of the histogram changes with the proportion of the component materials and thus approximates the volumetric content in a sample (Calmels et al. 2010)."

Comment #8: Image Processing: It would be more helpful to describe what methods are used by the software instead of describing only what software has been used. Otherwise, the experiment can be only repeated by using the same software.

Action: Image Processing subsection was restructured to make all steps clear enough and to give the opportunity of repeating the experiments by following the steps (please see below):

"Image preprocessing usually consists of two main stages; 1) selection of the Region of Interest or (ROI), 2) segmentation. In this study both stages were done using Dragonfly software (ORS 2021). This software enabled us to process the three-dimensional reconstructed X-ray tomographs of the frozen materials to segment, quantify, calculate, and illustrate the cores' physical properties. For the first stage, a series of ROIs were created in the half core CT results down the central vertical axis of the cores to mimic the data collection points of the MSCL as presented in Pumple et al. (2024). Figure 1 displays the relative location of these ROIs which were sized to match the spot size of the gamma-ray at the surface of the core, ~10 mm in diameter. The central point of each ROI was placed 5 mm apart resulting in a significant overlap between adjacent data points, again similar to the data collection process for the MSCL. In this study, all cores were calibrated so the histogram values were displayed in g/cm3. To extract the frozen bulk density from each ROI, the mean grey values were extracted in calibrated density values (g/cm3).

The second stage, segmentation or the ability to differentiate materials, depends on their respective linear attenuation coefficients, meaning materials with divergent densities and/or atomic numbers are easier to differentiate (Kyle and Ketcham, 2015). Analysing a multi-modal histogram of a CT image is straightforward for material differentiation while materials with narrow unimodal density distributions close densities appear as a single peak in the histogram. In addition to the relative density of the scanned materials, the image resolution or voxel size also directly impacts the image segmentation process. The voxel size can impact the image segmentation through the partial volume effect which relates directly to the resolution or voxel size of the scan and for geological samples, grain size, minimal pore size, and organic content (Soret et al., 2007; Nitzbon et al., 2022).

In this study, an automatic image thresholding method named "Otsu " was used. . The algorithm of this method, proposed by Nobuyuki Otsu (1979), performs automatic clustering-based image thresholding, assuming that there are two classes of pixels which are "foreground" and "background" pixels of the image. The optimum thresholding is calculated by distinguishing the two classes so that the minimum class variance is obtained (Kumar and Tiwari, 2019). This method was applied to the selected regions of *interest from stage one to differentiate sediment and ice. In each image processing step, we tried to isolate the materials within our scans based on density and slowly slice away the lighter density portion (ice) until we are certain we have collected the target material range (often a mixture of ice and sediment). Figure 3 shows the ice (less dense material) being segmented from the surrounding sediment through multiple image processing steps using the Otsu method where only the background (less dense) portion of the previous step is added to the final result. This approach shows that applying the first image processing step will mainly extract the visible ice while using multiple Otsu analyses additional lower-density ice-rich mixtures (mainly pore ice) are extracted, e.g., the area shown inside the red circle of Figure 3B-D. Note that all the above mentioned segmentation steps can also be done by visual inspections instead of automatic thresholding method but it can vary significantly between users, leading to inconsistent results."*

Comment #9: Image Segmentation: What is the accuracy of the classification?

Response: The accuracy of the classification is reflected in the RMSE of the comparison between the CT, Cuboid and MSCL results, the results were also added to the introduction (please check the response to the first comment)

Comment #10: The main parameters investigated here are EIC and VIC. Please can you describe and highlight the difference between the two parameters in more detail in material and methods or even in the introduction.

Action: A clear description of the differences between EIC and VIC was added to section 2.4. As follows:

"Ground-ice content is typically expressed either as the gravimetric moisture/ice content (the ratio of the mass of the ice in a sample to the mass of the dry sample) or the volumetric moisture/ice content (the ratio of the volume of ice in a sample to the volume of the whole sample) (Van Everdingen, 1998) while excess ice refers to the amount of ice in the soil that exceeds the volume of the pore space in the unfrozen state."

Comment #11: A critical discussion about the results and putting the results in the context of recent literature about the estimation of ice content based on CT scanning is missing.

Action: Conclusion was edited to address this comment and the following one:

"This study investigated the application of high-resolution industrial CT scanning as a non-destructive method to tackle the limitations of traditional destructive methods (e.g., visual acuity, poor reproducibility, and low resolution) in permafrost characterization. Investigations were done by systematically logging permafrost cores, visualising cryostructures, measuring bulk density, and estimating volumetric and excess ice contents, independently. Five permafrost cores, representing common materials encountered in permafrost regions, were scanned at voxel sizes of 65 and 25 µm. A new calibration method was used to extract real densities in g/cm3 directly from CT images. Image segmentation results using Otsu automatic image thresholding method illustrated the effectiveness of this method in generating robust segmentation results while the visual inspection method has its own drawbacks, e.g. inspector's visual acuity and poor reproducibility."

Comment #10: Please highlight in the beginning of the conclusions what is the main idea of the manuscript and what is the difference to other papers published so far.

Action: Conclusion was edited to address this comment, please check the response to the previous comment.

Specific comments and technical corrections:

Line 9: „However“ -> „Commonly used“ ???

Action: The line was edited.

Line 11: Add a point here and continue the second part of the sentence with: “The method systematically…”

***Action**: The line was edited.*

Line 18: Please add here the temperature-based permafrost definition. **Action**: The line was edited. *“Permafrost, rock or soil that has remained below 0°C for at least two consecutive years”*

Line 30: Please add a sentence about what CT scanning is and what is the physical principle behind.

Action: A couple of sentences were added: *“This imaging method captures radiograph images through the production of x-rays which pass through the cabinet and are recorded by the detector panel opposite the source. The sample is placed between the source and the detector panel and the resulting relative absorption of the x-rays energy is recorded by the detector panel creating the radiograph image. To collect a 3 dimensional image a set of two-dimensional X-ray radiographs are collected at multiple angles, and secondly reconstructed to form a 3D image.*

Line 36: Could you please add here the difference between CT scanning and µCT scanning?

Action: The difference was added to the introduction: *“The main difference between an industrial µCT scanner and a medical CT scanner is the higher peak power (greater penetration potential) and higher image resolution (voxel size) of the industrial µCT scanner.”*

Line 38: What are the traditional methods and what are their actual limitations?

Action: A brief review of the traditional methods and their limitations were added to the text. Please check the responses to comment #2 and 3

Line 40: Add what type of samples you investigated and from which site.

Action: A new section was added to cover more details about the samples and the field site. Please check the response to commnet #6.

Line 45: What non-destructive method?

Action: MSCL (multi-sensor core logger) was added to this line.

Line 59: What is the “destructive” and the “non-destructive” method here?

Action: The line was edited: *“In this study the samples were prepared for two different stages; non-destructive scans and destructive physical measurements.”*

Line 59-63: Hard to understand how you collected the samples.

Action: Subsection 2.2 (sampling process) was edited, please see the response to comment #6.

Line 75: “, where …”

Action: The line was edited.

Line 75: Wv → italic

Action: The line was edited.

Line 65-86: From your text it is not fully clear how you measured the physical density of your samples. Please try to make it more concise.

Action: The section was edited and more details were added: *“To independently assess density and ice content measurements and also being able to perform scans at higher resolutions, the* *cores were subsampled as 2x2x4cm cubes. The subsampling process was done in a walk-in freezer maintained at −7°C. The initial step involved removing material from the outer edges of the whole core that might have thawed during coring or been affected by sample storage. Core segments were split lengthwise with a rock saw equipped with a 35 cm diameter diamond-cutting wheel. Cuboid aliquots were cut from one half of the split core, while the other half was retained as an archive. The rounded edges were removed from the half core to expose an internal slab. For this study, a duplicate set of cuboids was obtained by cutting the internal slab in half. Approximately 3 cm³ aliquots were subsampled from the cores to ensure that the cuboids did not fracture or disintegrate during sampling due to the lower ice content. Digital calipers (±0.01 mm) and a digital analytical balance (±0.01 g precision) were used to measure physical dimensions and mass, respectively, to calculate the frozen bulk density. The cuboids were then thawed at room temperature for 24 hours in glass beakers covered with Parafilm to minimize evaporative loss.. Excess moisture was removed from the beakers containing the thawed samples, and the sample weight was recorded again to calculate excess moisture content. The cuboids were then dried in an oven for 24 hours at 105°C and reweighed to determine both volumetric ice content and gravimetric moisture content. Finally, the remaining dried material was heated at 550°C for 4 hours to determine the percent organic content via loss on ignition."*

Line 100: Which "mathematical algorithm"? **Action**: Since the reconstruction is performed using the proprietary Nikon software, which handles the algorithmic details internally, the "*mathematical algorithm*" was deleted from the text to clear this confusion for future readers.

Line 101: Remove "histogram" here. The histogram is only the type of visualization. You can add e.g., ", which is commonly visualized in a histogram"

Action: The "*histogram*" was removed.

Line 110: "10cm" → "10 cm" **Action**: The line was edited.

Line 116-120: Please be more concise here. The methodology is not fully clear.

Action: The section was edited to make the methodology clear enough,

"This project was completed during development of an insulated sample holder for use in the CT scanner. Both cubes and cores were housed in the same style of a styrofoam container, however, the internal setup varied due to the size of the sample under investigation. Cores were taken from a nearby chest freezer, quickly placed in a larger styrofoam container with an inner diameter of 12 cm in the vertical position and an ice pack was placed directly above them (Figure 2B and C). For this experiment, all ice packs were cooled to -80 C prior to being added to the container at the start of the scan.The cubes were held in a slightly smaller container with an inner diameter of 9 cm in a small plastic vial with a foam divider directly above (Figure 2D). The cubes were cooled with a small amount of dry ice placed on a perforated foam divider to bathe the underlying sample with cold air during scanning. Both setups are able to hold the core's surface temperatures below freezing for the full duration of the scan time.

It should also be noted that the partial results for most full cores are due to a height restriction encountered during the helical scans. Although the CT scanner can hold samples up to ~ 30 cm wide by 35 cm high, the area that is able to be scanned is dependent on the desired voxel size and the width of the sample. This restriction was resolved after cores were subsampled for the destructive method. This means for some of the cores we were unable to compare the complete vertical data sets of the MSCL, destructive, and CT results (e.g. peat core)."

Line 130: "population)with" → "population) with" **Action**: The line was edited.

Line 138: How close was the agreement? Can you provide some values here?
Action: The agreement for the water calibration is presented in the RMSE results already presented in the paper.
Line 139: “overestimation”: What is the range of the overestimation?
Action: This would be presented in the RMSE results as discussed above.

Line 143-144: “This results in the histogram…”: The result is not a histogram, just an array of numbers which can be further presented in a histogram.
Action: The lines were edited as follows: *“This results in displaying grey values in g/cm3. These densities can then be presented in a histogram where the shape of it changes with the proportion of the component materials and thus approximates the volumetric content in a sample (Calmels et al. 2010).”*

Line 155: “multiple image processing steps”: Which steps? Please be more precise here. **Action**: Following lines were added to the image processing section to clear the steps: *“In this study, an automatic image thresholding method named “Otsu " was used. . The algorithm of this method, proposed by Nobuyuki Otsu (1979), performs automatic clustering-based image thresholding, assuming that there are two classes of pixels which are “foreground” and “background” pixels of the image. The optimum thresholding is calculated by distinguishing the two classes so that the minimum class variance is obtained (Kumar and Tiwari, 2019). This method was applied to the selected regions of interest from stage one to differentiate sediment and ice. In each image processing step, we tried to isolate the materials within our scans based on density and slowly slice away the lighter density portion (ice) until we are certain we have collected the target material range (often a mixture of ice and sediment). Figure 3 shows the ice (less dense material) being segmented from the surrounding sediment through multiple image processing steps using the Otsu method where only the background (less dense) portion of the previous step is added to the final result. This approach shows that applying the first image processing step will mainly extract the visible ice while using multiple Otsu analyses additional lower-density ice-rich mixtures (mainly pore ice) are extracted, e.g., the area shown inside the red circle of Figure 3B-D. Note that all the above mentioned segmentation steps can also be done by visual inspections instead of automatic thresholding method but it can vary significantly between users, leading to inconsistent results.”*
Line 161: “et al., 2024” → “et al. (2024) **Action**: The line was edited
Line 168-174: These lines should be rather shifted for example to Material and Methods.
Action: These lines were shifted Material and Methods .
Line 191: “Pumple et al., 2024”: Why do you need the reference here?
Response: As the reference of the MSCL non-destructive method.
Line 193: Please describe why is the organic content relevant here.
Response: Because high organic content could result in water absorption by soil matrix upon thaw and more complexity in measuring excess ice contents. This was added to section 2.4 to make this clear for future readers.
Line 213-215: Why is there such a big discrepancy between the ice content estimated from cuboid physical measurements and CT scanning?

Response: Although there is a discrepancy between EIC values due to the resolution difference (e.i., CT resolution is 0.5 cm while cuboid is 2 cm), both graphs are following the same trend and the discrepancy between VICs are due to the insufficient resolution of 65 um in extracting pore ice while the VICs extracted from 25 um scans are very well aligned with the cuboid results.
Line 226: "Figure 7C" → "Figure 8C" ***Action**: The figure's number was corrected.*
Line 238-243: In Figure 9C the discrepancy between CT-VIC and Cuboid-VIC/CT-Cubes-VIC is large. What might be the reason for that? It is not answered here.
Response: Please check the response to the same comment for lines 213-215, the main source of discrepancy as it is also explained in the text (section 3.3) is different resolutions between non-destructive and destructive methods. Moreover for this specific core, there was around 5% excess ice detected by CT while upon thaw this water was absorbed by soil skeleton resulting in zero amount of supernatant water (zero cuboid-EICs)
Line 267: "50 µm": How did you estimate this value?
Action: This is just a rough estimation based on the grain size results for these samples which showed an average grain size of 40-50 um dominated by fine sand and coarse silts. This is more of a speculation that the change in the results is likely due to an improvement on the visualization of the pore space within the cube. We removed the reference to an average pore size as we agree it is misleading.
Line 267: "which is likely the difference between the results of these two scans": Please try to reformulate this part of the sentence.
Action: This line was edited as follows to clarify both comments and make it clear for all future readers. *"These results illustrate the sufficiency of 25 µm resolution in extracting trapped ice inside pore spaces of this sandy silt sample which could be due to the smaller size of pores than the resolution."*
Line 288: "25 µm": There is a problem with the format of the unit.
Action: The unit was corrected.
Line 289-290: "subsampled to a smaller size": What is the size?
Action: The size of cubes was added (2x2x4 cm).
Line 290: "25 um" → "25 µm"
Action: The unit was corrected.
Line 293: Sounds repetitive. You wrote that already above.
Action: The paragraph was edited as follows to address this comment: *"It is worth noting that the MSCL provides a more rapid method for collecting bulk density and volumetric ice content estimations in comparison with the CT method. However, in addition to bulk density and volumetric ice content estimations, the CT method can provide direct estimates of excess ice content. Visible ice can be segmented and isolated from the remaining sediment and pore ice when scanning split cores at 65 µm voxel size, allowing the opportunity to better estimate EIC values compared to MSCL methods. Therefore, in terms of a non-destructive method for identifying and quantifying excess ice within permafrost cores the CT method provides a more robust approach although the image processing and acquisition costs are significantly greater."*
Line 300: "permafrost regions" → "arctic permafrost regions"
Action: This change was not applied since not all the sites in this study are in the Arctic region.
Line 300: "new calibration method": Please specify which calibration method or what is your calibration based on.

Action: Calibration section was edited (please check the response to comment #7).
Line 302-303: “automatic thresholding technique”: What is the technique based on?
Action: Image segmentation was edited (please check the response to comment #8).
Line 315-317: Try to include the sentence in the paragraph above to avoid having a paragraph with only one sentence.
Action: The paragraph was edited.

Figures
Figure 3: To highlight the differences between the image processing steps, you can consider having just one plot with the different extents of the ice as edge lines with different colors. **Response:** Authors tried this before but the figure became very busy so it’s more clear to show different steps separately.
Figure 4: Please add in the sample labels also the core IDs.
Action: Figure 4 was edited

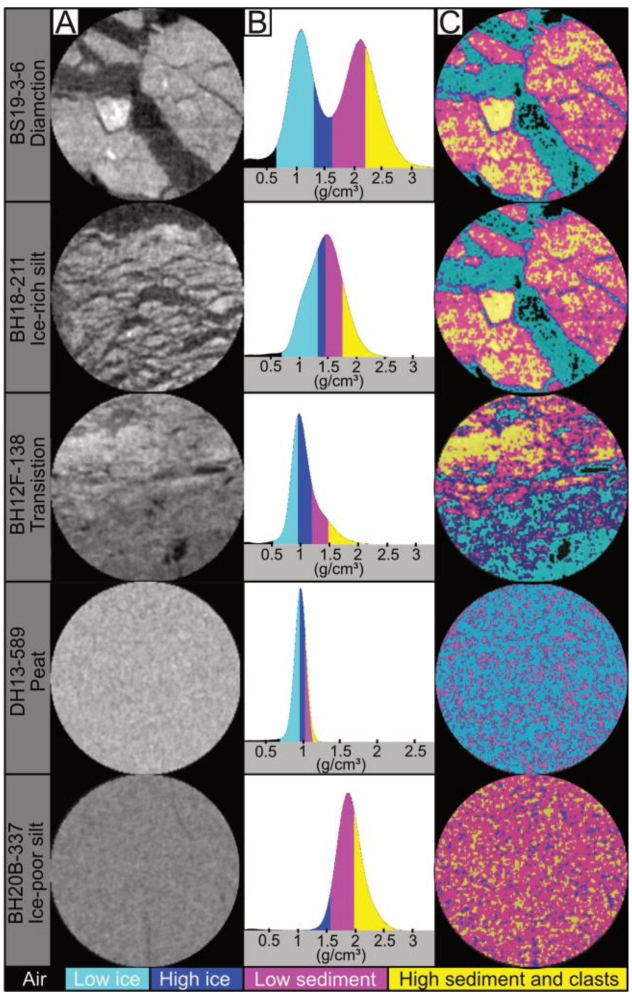

Figure 4: (A) overview of slices from the permafrost cores before image processing (B) histograms, and (C) image segmentation results

Figure 5: A point at the end of the figure caption is missing. The subplots look like there are some areas not only in one class but different classes. Is that just a visualization problem? **Action**: Yes,

it is just a visualization problem, the clear segmentation is shown in Figure 4 (first top row) with no overlap between different classes.

Figure 10: Subplot C: Why are there no data between 0-12 cm depth in the CT-VIC and the CT-EIC? Subplots D and E are missing.

Response: Since this core is a peat one, all the organic contents are around 95-100% and so we choose not to burn the samples to collect the LOI results and instead went on the assumption that the OCC is in the area of 95-99%. Subplot E like all other figure captions for the core figures should have been removed as we choose to remove the black and white image that highlighted ice distribution as we are still refining that method.

The reason for missing half of the core is the height restriction we encountered during the helical scans. Although the CT scanner can hold samples up to ~ 30 cm wide by 35 cm high, the area that is able to be scanned is dependent on the desired voxel size and the width of the sample. This restriction was resolved after cores were subsampled for the destructive method. This means for the cores included in this study we were unable to compare the complete vertical data sets of the MSCL, destructive, and CT results (e.g. peat core).

Figure 11: In the caption: "um" → "µm" **Action**: The units were corrected.

Figure 12: Subplot numbering/ labelling is missing. Please add what the blue-colored areas are in the top subplot.

Action: Figure 12 was edited.

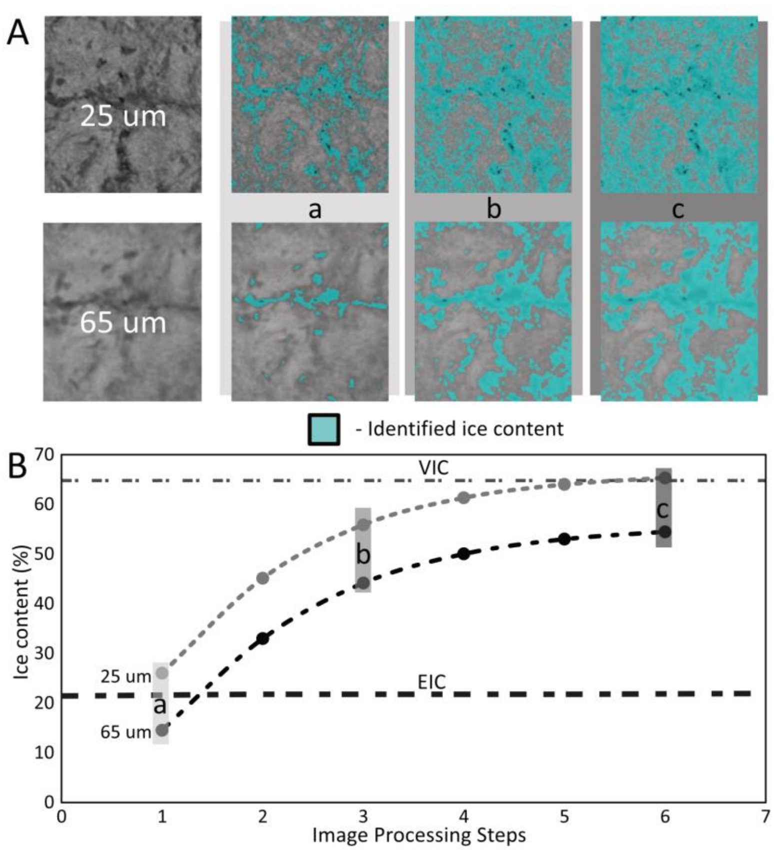

Figure 12: (A) CT ROI's taken from the 65 µm and 25 µm cube scans (BH12F-138-10-12 cm), (B) Identified ice contents at each image processing step using the Otsu split method.

Figure 13-17: I would recommend merging the figures in one figure with several subplots. Additionally, try to make the figure size 1:1, describe in the symbology what the line represents, and use only one category to differentiate between the dots. So far, you used edge line style and different colors.

Response: Although we acknowledge this recommendation, due to the reduction in readability when combining all the figures, we did not change this figure.