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):
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> *"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.
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> *"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:
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> *"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:
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> *"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:
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> *"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).