Brief Communication: Limitations of Medical X-ray Computed Tomography for Estimating Ice Content in Permafrost Samples

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Abstract. X-ray Computed tomography (CT) is increasingly used to estimate ice contents in permafrost samples. In this study, CT-derived estimates of volumetric ice content obtained from medical CT scans were compared with laboratory measurements for 261 samples from northern Canada (Nunavut and Yukon). The results shows~~ed~~ that medical CT systematically underestimates~~d~~ ice content in sediment-rich and organic-poor samples, and overestimated it in ice-rich, organic-rich samples. Agreement improves~~d~~ only when ice contents exceeded ~75% and organic matter was ~~low~~approximately 10% to 20%. These discrepancies arise from ice occurring at scales smaller than the CT voxel resolution, misclassification of organic matter as ice, and sensitivity to threshold selection~~Errors arose from ice occurring at scales smaller than the CT voxel resolutionunresolved pore ice, organic matter misclassified as ice, and threshold sensitivity~~. Given these limitations, along with the associated cost and processing effort, medical CT is better suited for visualizing cryostructures and sample heterogeneity than for routine quantification of ice content. While higher-resolution CT systems may help resolve some of these limitations, their ability to provide more accurate quantification in permafrost samples requires further investigation and is identified as a key direction for future research.~~we conclude that medical CT is better suited for visualizing cryostructures and heterogeneity than for routine quantification of ice content. By contrast, higher-resolution industrial CT can provide more accurate quantification of ice contents in suitable samples.~~

Key words: Permafrost; Ground ice; Volumetric ice content; X-ray computed tomography (CT); Pore ice.

Commented [ZM1]: Comments of R1: Benoit Faucher: The manuscript addresses an important methodological question regarding the use of medical CT scans for quantifying volumetric content in frozen sediments, which is highly relevant for permafr research. The dataset is substantial, and the comparison with laboratory measurements is valuable.
However, I believe that minor revisions are needed to clarify sev aspects of the interpretation before the manuscript is ready for publication. Below, I outline comments and questions aimed at clarifying the interpretation of CT-derived versus laboratory-measured volumetric ice content, with particular attention to the direction and magnitude of bias, the proposed influence of organ matter, and the consistency between the figures and the accompanying discussion.

Commented [ZM2]: R0: ice content?

Commented [ZM3R2]: Addressed.

Commented [ZM4]: R1: According to Figure 1, it appears th CT overestimates VIC in ice-poor sediments and underestimates ice-rich sediments. The text seems to describe the opposite trend should be revised for consistency.

Commented [ZM5R4]: Thank you for bringing this to our attention. The apparent inconsistency arose from an error in Fig. mismatch between the plotted values and axis labels), and the fig has been corrected. After correcting Fig. 1a, the figures and text now consistent.

Commented [ZM6]: R0: how much is low?

Commented [ZM7R6]: To clarify, the term "low" has been replaced with a quantitative range (10–20%).

Commented [ZM8]: R0: explain?

Commented [ZM9R8]: The term "unresolved pore ice" has replaced with " ice occurring at scales smaller than the CT voxel resolution"

1 Introduction

Quantifying ground ice is fundamental for understanding permafrost stability and predicting thaw-related ground deformation (Hjort et al., 2022; Mohammadi and Hayley, 2023). Historically, descriptive systems by Pihlainen and Johnston (1963) and Linell and Kaplar (1966) have been widely adopted in geotechnical applications in North America. These methods rely on visual assessments~~,~~ and ice characteristics are described by terms such as hardness (e.g., hard or soft), structure (e.g., clear, porous, or stratified), and colour. Over the years, these two descriptive approaches have proven to be unreliable, inconsistent, and sometimes misleading, being too general to precisely describe permafrost cryostructures. French and Shur (2010) proposed an alternative and more precise way to describe permafrost ~~where~~ , in which cryostructures are systematically classified based on the amount and spatial distribution of ground ice, allowing rapid identification of distinct cryofacies. ~~cryostructures associated with excess ice content can be rapidly identified~~. ~~Yet~~However, the primarily visual nature of this approach can lead to subjective interpretation and reduced reproducibility ~~it is a visual description which results can be difficult to reproduce among~~when applied by ~~people~~ individuals with ~~varied~~ varying level of experience ~~of~~ in permafrost description. These visual logs are typically supplemented by a limited number of laboratory measurements, in which volumetric ice content is determined from mass and volume measured in the frozen state and after oven-drying to constant mass. Despite its simplicity, laboratory measurement is constrained by cost, time, and handling effort, and it is destructive. As a result, spatial coverage is limited and repeat measurements on the same specimen are not possible.

Computed tomography (CT) has been proposed as a non-destructive alternative, providing detailed visualization of permafrost samples and offering the potential for quantitative estimation of ice, sediment, and gas fractions (Calmels and Allard, 2004, 2008; Dillon et al., 2008; Fortier et al., 2012; Lapalme et al., 2017; Fan et al., 2021; Roustaei et al., 2025). Medical CT typically operates at millimetre to sub-millimetre resolution with anisotropic voxels, whereas micro-CT provides much finer, typically isotropic voxel sizes, allowing more detailed imaging of pore-scale structures. However, translating CT imaging into reliable estimates of soil components is not straightforward.

CT images are composed of voxels, which are 3D pixels formed by stacking 2D slices with specific spacing. Each voxel has an in-plane resolution defining the x–y dimensions, while the slice spacing defines the third dimension. The CT resolution sets its detection limit, with features needing to be at least twice the voxel size to be detected (Capowiez et al., 1998). When a voxel contains more than one component, their densities are averaged, producing the partial volume effect (Capowiez et al., 1998), which complicates quantitative analysis and leads to errors in volume estimation. (Roustaei et al., 2025). In the case of permafrost soils, pore ice~~-~~within fine-grained ~~samples~~ materials (ice occupying the natural pore spaces within the soil matrix), is commonly unresolved at the resolution of medical CT scanners, which can lead ~~leading~~ to systematic underestimation of ice content (Calmels et al., 2004, 2010). These errors are further compounded by density threshold segmentation, which often misclassifies materials such as ice, pore ice, and organic matter because of overlapping density range. Organic matter adds another level o~~n~~f complexity, as ~~it~~ its density typically ~~has~~ spans a wide range ~~of density~~ due to ~~its~~ ~~various~~varying degrees of ~~states of~~ decomposition, ranging from poorly decomposed fibrous peat to well-decomposed humified organic soils (Calmels

Commented [ZM10]: R1: This sentence is unclear and woul benefit from rephrasing.

Commented [ZM11R10]: Thanks for your input, sentence h been rephrased.

Commented [ZM12]: R0: formulation?

Commented [ZM13R12]: Thanks for your input, sentence h been rephrased.

Commented [ZM14]: R0: maybe introduce this?

Commented [ZM15R14]: Definition added. "pore ice" is defined as "(ice occupying the natural pore spaces within the soil matrix)

Commented [ZM16]: R0: is this a conclusion of this study? suggested by the abstract? or is a conclusion form the revision of literature? Would be recommended to add citations.

Commented [ZM17R16]: ZM: I agree with the reviewer, we have used this to interpret our resul @Mahya, Do we have a citation to add?

Commented [ZM18]: R0: improve formulations

Commented [ZM19R18]: The text has been revised.

et al., 2010; Lapalme et al., 2017). This variability can lead to misclassification in CT-based segmentation, resulting in discrepancies between CT-derived and laboratory-measured ice contents.~~As a result, volumetric ice content derived from medical CT scans might differ substantially from laboratory values.~~

~~-~~ This study presents a comparison of medical CT-derived and laboratory-measured ice contents was conducted for 261 permafrost samples collected in the Canadian Arctic. The analysis focuses on assessing the suitability of medical CT for quantifying volumetric ice content and on identifying the methodological challenges associated with resolution, partial volume effects, and segmentation approaches. S~~A s~~pecial attention is given to the impact of organic matter content on the CT-based volumetric ice content estimates~~ using CT~~.

2 Methods and Materials

2.1 Sample provenance

Permafrost cores were collected on Bylot Island, Nunavut under the Arctic Development and Adaptation to Permafrost in Transition program (ADAPT) ~~program~~ and during field campaigns in 2016 and 2019 at representative wet and mesic sites (73°09′″ N, 80°00′ W; 73°08′ N, 79°58 W). Additional cores were collected in 2015 near Beaver Creek, Yukon (62°24″ N, 140°52″ W). The cores were extracted using a portable permafrost core drill with a 10 cm diameter barrel, sealed, labelled, and maintained below 0 °C from field to laboratory until analysis. The cores were subsequently subsampled into segments of approximately 5–20 cm in length for CT scanning and laboratory measurements.~~Cores extracted using a portable core drill, and were sealed, labelled, and kept below 0 °C from field to laboratory until analysis.~~

2.2 CT scanning and image processing

The same samples were scanned at ~~Institut~~Institute National de la Recherche Scientifique (INRS), Quebec City, using a commercial medical CT scanner (Siemens SOMATOM Sensation 64) with voxel resolutions of 0.18–0.24 mm in the x–y plane and 0.4–0.6 mm in the z direction, with minor variations depending on sample size and scan configuration to ensure full coverage of each core.~~.~~ These differences are small relative to the inherent resolution of medical CT and are therefore not expected to significantly affect the CT-based estimations.

Samples were maintained in a frozen state throughout scanning. During CT acquisition, samples were stored in freezers at approximately −20 °C and wrapped in insulating materials (plastic and foam layers) to limit heat exchange. Exposure to ambient conditions during handling and scanning was brief (on the order of minutes), and no phase change was observed. Medical CT scans were relatively rapid, and the duration of scanning did not significantly affect the thermal state of the samples.

CT scan images were processed in Dragonfly (Version 2020.2) to isolate the samples and remove external elements such as the stage, bags, and air. Regions of interest (ROIs) were defined to isolate the sample volume from surrounding elements (e.g., air, sample holder, and wrapping materials) using a classifier trained on 30 ADAPT project samples. The classifier was used

Commented [ZM20]: R0: conclusions? references?

Commented [ZM21R20]: Same as above

Commented [MR22R20]: I think the new version does not references.

Commented [ZM23]: R0: what are the alternative methods t evaluate the ice content estimated?

Commented [ZM24R23]: Not sure if I understand the comm

Commented [MR25R23]: I responded to that

Commented [ZM26]: R0: *I am not sure about the method us to evaluate the ice content in the samples. It seems the authors dr and saturated/froze their samples to obtain an independent meas of ice content in the samples and evaluate the estimates obtained means of CT. In such case I am not sure whether we compare ice content in a sample with potential ice-content. Moreover, no information is given on how the authors kept frozen samples duri the scan. In my opinion the scan takes time in order to increase t resolution. However, no information is given about the time for t scan, the logistics to keep the sample frozen and other settings fo ct scan. However, these issues may be addressed by the authors during the revision and may be that other experts agree on the methodology used.*

Commented [ZM27R26]: The reviewer also suggested addi more details about methodology to an appendix, to keep the leng the paper within the acceptable range.

Commented [MR28R26]: I added all the info, and I think w are still in the acceptable range

Commented [ZM29]: R0: hwo were the cores stored and tak avid change sin the ice content? prior to the analysis?

Commented [ZM30R29]: @Daniel

Commented [MR31R29]: All covered in this section and th following ones

Commented [ZM32]: R0: information on the settings for the scanning are missing

Commented [ZM33R32]: @Daniel

Commented [MR34R32]: Unfortunately there is no data fro scan setting available in the thesis, @Dan, what do you suggest

Commented [ge35R32]: The setting are standards used by INRS. They are not revealed with the scan report. We could prob obtain them by contacting INRS. I can do that if needed but I'd le like you replied and see if it passes.

to differentiate the sample from the background, not to segment individual phases. The resulting ROIs were visually inspected and corrected where necessary. Ice, sediment, and gas were segmented using published Hounsfield Unit (HU) ranges (gas: –1024 to –321, ice: –320 to 560, sediment: 561 to 3071) (Calmels and Allard, 2004; Calmels et al., 2010; Taina et al., 2008). The segmentation results were visually inspected for each sample to verify that the selected HU ranges adequately captured the main phases and their spatial ~~distribution, and~~distribution and adjusted where necessary to ensure consistency in phase identification. Organic matter was not segmented directly due to its variable density, which often caused misclassification as ice or sediment.

2.3 Laboratory measurements

Volumetric ice content was derived from measurements of sample mass and volume in the frozen and oven-dried states, using gravimetric water content and frozen bulk density. All measurements were performed on natural, undisturbed permafrost samples, preserving their ~~in-situ~~in-situ ice content. No artificial saturation or re-freezing procedures were applied prior to analysis. Sample volume was obtained using the water displacement method, whereby the volume of liquid displaced by an immersed vacuum-sealed frozen sample in a plastic bag is measured, providing an accurate estimate of bulk volume even for irregularly shaped specimens. This approach assumes that all water present in the sample at the time of measurement was frozen and therefore contributes to the measured ice content. To minimize disturbance effects, the outer 2–3 mm of each core, potentially covered by drilling mud~~affected by drilling-induced disturbance~~ or minor thaw, was removed prior to analysis. Measurements were obtained for 261 samples, with organic matter content determined for a subset of 81 samples. Organic matter content was determined for a subset of 81 samples using the loss on ignition (LOI) method: samples were oven-dried at 105 °C, combusted at 550 °C for 4 h, and the mass loss attributed to organic matter. Based on the distribution of measured organic matter~~values~~, the samples were classified into three groups: < 10 %, 10–20 %, and > 20 % organic matter. The 10% threshold is approximately the median, and the 20% threshold isolates the upper tail of the dataset (≈85th percentile), enabling clearer evaluation of organic-rich samples. The dataset, including laboratory and CT-derived volumetric ice contents, is available on Zenodo (https://doi.org/10.5281/zenodo.17451138) (Fortier et al., 2025).

3 Results

3.1 Comparison of CT and laboratory values

To evaluate the performance of medical CT scans for quantifying ice, laboratory measurements of ice content (V_{Lab}^{ice}) were compared with CT-derived estimates (V_{CT}^{ice}) across all 261 samples. While comparison of V_{CT}^{ice} with excess ice is more appropriate (e.g., Lapalme et al., 2017; Roustaei et al., 2025; Nitzbon et al., 2022), laboratory-measured excess ice content were not available; therefore, total ice content was used as the basis of comparison.

Commented [ZM36]: R1: Consider adding a typical HU rang for organic matter to provide context for the classification.

Commented [ZM37]: R0:is this way suitable to measure the content in the sample or the potential ice content?

Commented [ZM38R37]: An explanation has been added stating that samples are assumed to be fully frozen at the time of measurement (i.e., no unfrozen water content), as laboratory measurements were conducted at a temperature of [X] °C.

Commented [ZM39R37]: @Danile: Please add the sample temperature when submerged to measure volume

Commented [MR40R37]: Please check my response to this comment first.

Commented [ZM41]: R1: Lapalme et al. (2017) suggested th CT imagery may be better suited to estimating EIC, particularly w pore-space diameters are within pixel resolution. Why was CT segmentation not compared with EIC in this study? Clarification would be helpful.

Commented [ZM42R41]: We acknowledge that CT derived content is more appropriately compared with excess ice content. However, laboratory measurements of excess ice were not availa for this dataset; only total volumetric water content measurement were obtained. Consequently, CT-derived ice content was compa with laboratory-measured total water content.

A sentence have been added to the opening paragraph of the Sect 3.1 to clarify this.

Commented [ZM43]: R1: Please provide justification for the chosen organic matter classification thresholds (<10%, 10–20%, >20%).

Commented [ZM44R43]: Justification have been added to t text.

Results were also checked using alternative cutpoints (e.g., quant based bins), and the observed trends were not materially changed

Commented [ZM45]: R0: are those two quantities comparab the CT scan was conducted just after drilling ?

Commented [ZM46R45]: Thank you for this comment. To address points raised by other reviewers, additional explanation h been added to clarify the rationale for comparing laboratory-measured and CT-derived ice content. The Methodolo section has also been expanded to describe sample collection, handling, and the timing of CT scanning, providing clearer conte the measures taken to minimize sample disturbance and support t comparability of the two measurements.

Commented [ge47]: I'm not sure about this reply. Yes we di measure excess ice but the goal was not to see if CT was good to measure excess ice, in fact it is pretty good for that, but to measu total ice content. SO I don't know if we have to formulate it this v minimizing the outcome of the research. We could mention that i good for excess ice only in the reply to reviewers, not in the pape

Figure 1 summarizes these comparisons. CT estimates were positively correlated with laboratory values but diverged systematically from the 1:1 line (Figure 1a). Residuals ($\Delta V_{ice} = V_{Lab}^{ice} - V_{CT}^{ice}$) showed a mean bias of –12.9% and a root mean squared deviation of 25.6%. ~~Underestimation exceeded 60% at the low end of the V_{Lab}^{ice} range, while overestimation reached about 30% in ice-rich, organic-rich samples (Figure 1b)~~.

Commented [ZM48]: R1: The statement "Underestimation exceeded 60% at the low end of the *VLab ice* range, while overestimation reached about 30% in ice-rich, organic-rich samp appears inconsistent with Figure 1b, which suggests the opposite pattern. This should be reconciled.

Commented [ZM49R48]: Thank you for this comment. The has been revised to better reflect the trends shown in Figures 1a a 1b.

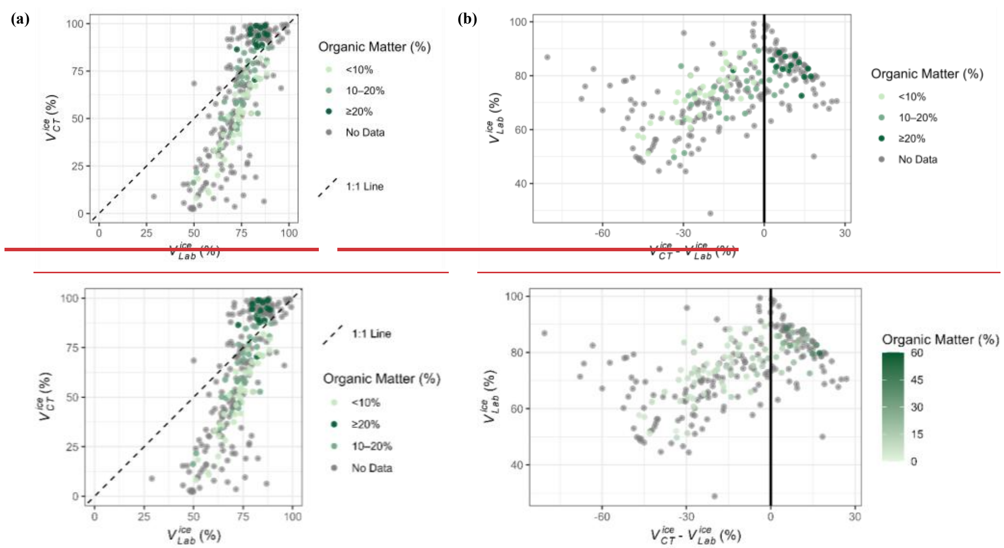

Figure 1. (a) Lab-measured (V_{Lab}^{ice}) vs. CT-estimated (V_{CT}^{ice}) volumetric ice content. Divergence from the 1:1 line shows bias. Results show systematic underestimation of V_{ice} for ice poor samples, shifting toward systematic overestimation for ice rich samples (b) Residuals ($\Delta V_{ice} = V_{Lab}^{ice} - V_{CT}^{ice}$) plotted against lab-measured volumetric ice content.

Commented [ZM50]: R1: The text states systematic underestimation in ice-poor samples and overestimation in ice-ric samples. Based on Figure 1, the trend appears reversed.

Commented [ZM51R50]: Figure 1a has been revised to cor an error caused by a mismatch between the axis titles and the plo values. The updated figure is now consistent with the text and interpretations presented in the manuscript.

Figure 1b shows that residuals were strongly dependent on sample composition. For V_{Lab}^{ice} < 75%, V_{CT}^{ice} generally tends to underestimate V_{Lab}^{ice}, as indicated by negative residuals exceeding 60% in some cases~~residuals were predominantly negative, indicating systematic underestimation~~. For V_{Lab}^{ice}≥ 75%, a consistent trend of either underestimation or overestimation is more difficult to identify; however, the majority of data points indicate a tendency toward overestimation. Where overestimation occurs ($\Delta V_{ice} > 0$), residuals generally decrease with increasing V_{Lab}^{ice} from 70% to 100%~~residuals were smaller and more symmetrically distributed about zero, although both underestimation and overestimation occurred~~. In the subset with organic matter (OM) data, low-OM samples (0–10%), which in this dataset generally coincide with lower ice contents, consistently showed negative residuals. In contrast, higher-OM samples displayed positive residuals, with the largest positive bias observed

Commented [ZM52]: R1: The phrase "…indicating systema underestimation" appears inconsistent with the plotted data, whic suggest overestimation.

Commented [ZM53R52]: No additional revisions were required, as the figure and accompanying text are consistent after update to Figure 1a (see response to previous comments).

in the ≥20% OM class. Overall, volumetric ice content was underestimated in all low-OM samples and overestimated in nearly all high-OM samples.

3.2 Sensitivity of CT estimates to HU threshold selection

This study also assessed the sensitivity of CT-derived ice content estimates to Hounsfield Unit (HU) thresholds. Previous work has applied widely varying thresholds for ice segmentation, resulting in inconsistent outcomes. To examine this effect, published thresholds were applied to two representative samples. This variability partly reflects differences in material type, as sea ice generally shows less variability in HU values due to its relative homogeneity, whereas permafrost exhibits greater variability because of its heterogeneous composition. . As shown in Table 1, estimated ice volumes content varied substantially, from strong underestimation (up to -64%) to marked overestimation (up to +31%) relative to laboratory values. Sample 1 from Bylot Island exhibited a broad density range (–1024 to 3071 HU), whereas Sample 2 from Beaver Creek showed a narrower range (–1024 to 2847 HU). Figure 2 illustrates segmentation of a region of interest from Sample 1, where ice is highlighted in blue using the –320 to 560 HU threshold. These results demonstrate that CT-based estimates are highly sensitive to threshold selection, which restricts their reproducibility for volumetric ice quantification.

Table 1. Volumetric ice content of two representative samples estimated using HU thresholds from this study and previous literature, with laboratory measurements shown for reference.

Study / Source		ID (Figure 2)	HU Thresholds (Low–High)	Volumetric Ice ContentVolumetric Ice Content (%)		Residual(a) (%)	
				Samplee 1	Sample -2	Sample 1	Sample 2
Laboratory (reference)		—	—	64.2817,77	65.9380,95	0	0
This study		A	−320 to 560	62.8524,60	70.4251,12	-1-60.8	+54.5
Kawamura (1988)	Sea Ice	B	~−50 to −40	3.4513,80	2.2268,35	-610.8	-63.764
Dillon et al. (2008)	Basal glacier ice	C	−864(ba) to −241(ab)	3.327,71	5.38,21	-61-60.9	-61-60.6
Calmels et al. (2010)	Natural permafrost cores	D	−150 to −40	25.627,14	20.320,28	-38.69	-45.646
Crabeck et al. (2016)	Sea Ice	E	−74(cb)	0.3209,11	0.377,30	-63.94	-65.66
Lapalme et al. (2017)	Natural permafrost cores (low-organic, sandy)	F	−320 to 750	67.82,36	85.21,03	+3.64	+19.3
Lieb-Lappen et al. (2017)	Sea Ice	G	~−464(ba, ed) to 1071(ba, de)	76.4554,74	96.9324,52	+12.22	+31

Commented [ZM54]: R1: The statement that low-OM sampl were underestimated and high-OM samples overestimated does n appear to align with Figure 1. Please clarify.

Commented [ZM55R54]: Thanks for pointing this out. Following the update to Figure 1a, the text is now fully consisten with the figure.

Commented [ZM56]: R0: why not add a percentage deviatio to avoid the qualitative assessment?

Commented [ZM57R56]: Internal discussion: I had to chan the table format- previously volume were reported- changed that ice content, and also added the residual column- Added % to the based on table

Commented [ZM58R56]: Response: Table 1 has been upda to report volumetric ice content rather than ice volumes. In additi a Residuals column has been added for each method to provide a more quantitative basis for comparison. The residual bounds are explicitly described in the text.

Wendy (2025)	Natural permafrost cores	H	−170 to −83	10624,49	8.1368,98	-54.2	-587.8

Notes:
(a) Calculated as the difference between laboratory-measured and CT-derived ice content. Negative values indicate underestimation. Converted from gray levels
(b) Converted from gray levelsFor pure ice
(c) For pure ice For sea ice
(d) For sea ice

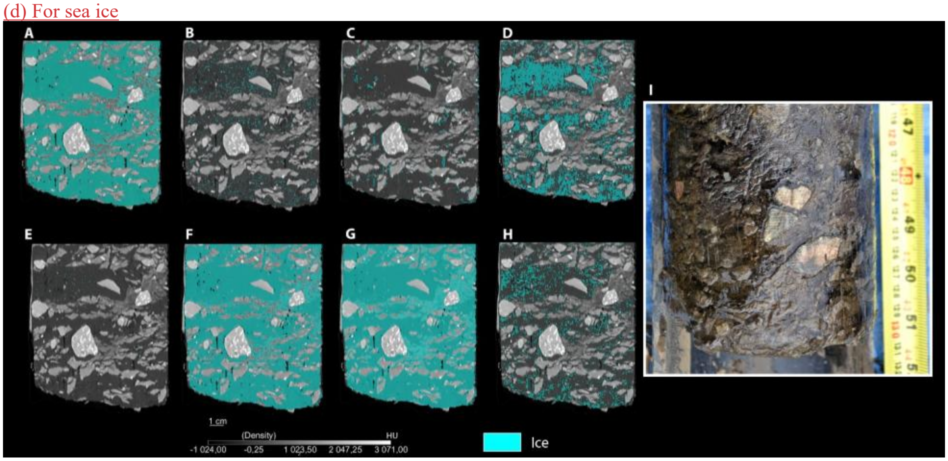

Figure 2. Ccomparison of ice volumes estimated for Sample 1 using the density thresholds from this study (A) and those reported in the literature (B–H), corresponding to study IDs in Table 1. Panel I shows a photograph of the sample, consisting of suspended sandy silt and gravel within an ice matrix.

4 Discussion and outlook

This study highlights the main key limitations of commercial medical CT for estimating volumetric ice content of permafrost samples. Scans of 261 permafrost cores clearly demonstrate that medical CT systematically misestimates volumetric ice content, with discrepancies strongly linked to sample composition. Overall, the results indicate CT-derived ice content tending to underestimate laboratory values at lower ice contents and showing a weak tendency toward overestimation at higher ice contents. This limitation is largely results from the mismatch between scanner resolution and the characteristic pore-ice-organic structure of permafrost materials. At the resolution of medical CT, which is -much coarser than sediment porosity, pore ice typically occupies volumes smaller than a voxel, and mixed voxels record averaged density values that fall outside the ice range. These partial-volume artifacts lead to systematic underestimation when the sediment fraction is high (Capowiez et al., 1998; Clausnitzer and Hopmans, 2000;; Calmels et al., 2010). Organic matter adds further complications. In organic-rich samples, positive residuals arise from the overlap in density between organic matter and ice. Portions of the organic fraction

Commented [ZM59]: R1:The general statement regarding systematic misestimation should reflect the direction of bias obse in Figure 1.

Commented [ZM60R59]: A sentence has been added to cla the direction of the bias

Commented [ZM61]: R1: The explanation invoking mixed voxels would typically result in an underestimation of ice conten However, Figure 1 appears to show overestimation in ice-poor samples. Please clarify how this mechanism explains the observe bias.

Commented [ZM62R61]: Figure 1 a has been update and n shows underestimation of ice content for ice-poor sample, in agreement with the discussion.

Commented [ZM63]: R0: check

Commented [ZM64R63]: Edited.

fall within the HU range assigned to ice and are therefore misclassified, producing overestimation (Calmels et al., 2010; Roustaei et al., 2025). This effect was most pronounced in samples with ≥20% organic matter.

Threshold selection introduces an additional source of error. Published HU ranges vary widely, and applying different thresholds to the same samples in this study produced results that ranged from severe underestimation to substantial overestimation relative to laboratory values. Even when thresholds are calibrated against reference data, unresolved pore ice, organic matter misclassification, and the partial-volume effect introduce uncertainties that limit the transferability of correction factors (Lapalme et al., 2017).

Together, these findings show that systematic underestimation in ice-poor samples, overestimation in organic-rich samples, and sensitivity to HU thresholds all stem from CT imaging artifacts. As a result, empirical corrections may reduce error within a single dataset but cannot overcome the fundamental limitations imposed by CT resolution and material density overlap. The large variability observed in Table 1 further demonstrates that HU-based segmentation is inherently non-unique, as different threshold ranges produce substantially different estimates for the same sample. Consequently, no single or transferable HU threshold can be defined for permafrost materials with varying composition. Therefore, medical CT cannot reliably quantify volumetric ice content using HU-based segmentation and cannot be recommended for this purpose. However, improved approaches based on sample-specific or scan-specific calibration, such as the use of reference materials or density-based normalization, may enhance the robustness of medical CT-derived estimates and partially reduce these uncertainties. Instead, its primary value lies in the qualitative identification of cryostructures and sample heterogeneity within permafrost cores, particularly through the visualization of features such as ice lenticular~~enses~~, layered, reticulate and suspended cryostructures, sedimentary stratifications, and large-scale heterogeneities~~y~~, which are critical for interpreting permafrost formation processes and mechanical behaviour. Higher-resolution CT (e.g., micro-CT) may reduce partial-volume effects by resolving finer-scale structures and, when combined with calibrated acquisition and advanced segmentation approaches, may further improve the quantitative assessment of ice content in permafrost materials. ~~While medical CT cannot be recommended as a routine method for quantifying volumetric ice content, it remains valuable for identifying cryostructures and characterising sample heterogeneity, providing essential qualitative insight into the internal structure of frozen cores.~~

5 Code and data availability

The dataset used in this study, including laboratory-derived volumetric ice contents, CT-derived volumetric compositions, and associated metadata, is available at Zenodo (https://doi.org/10.5281/zenodo.17451138) (Fortier et al., 2025). Image processing workflows were performed in Dragonfly (Version 2020.2). No custom code was developed beyond standard segmentation and regression analysis.

Commented [ZM65]: R1: The manuscript states that organic matter misclassification produces overestimation. However, Figu does not clearly demonstrate that ≥20% OM samples exhibit the strongest overestimation; many appear underestimated. Quantitat support or clarification would strengthen this interpretation.

Commented [ZM66R65]: Please refer to the updated Figure This discrepancy arose from an error in the previous version of Figure 1a, which has now been corrected. The revised figure clea shows overestimation of ice content for samples with >20% orga matter.

Commented [ZM67]: R0:would be good to have a clear percentage of misfit instead of a qualitative assessment

Commented [ZM68R67]: Internal discussion: Not sure if w need to mention any number! I think it is better to keep it qualitat as the observed trends are generally weak

Commented [MR69R67]: Zakieh this is what we did in our PACs CT paper, we provided R squares, can you take that from t data? @Dan what do you think?

Commented [ZM70]: R1: The summary statement describin underestimation in ice-poor samples and overestimation in organ rich samples appears inconsistent with Figure 1 and should be revised.

Commented [ZM71R70]: Please see the updated version of Figure 1a.

6 Author contributions.

DF contributed to conceptualization of the study. JD, MR, ZM carried out data curation. JD, MR, ZM performed the formal analysis and data processing. JD conducted the laboratory and CT analyses and supported the overall investigation. DF, JD contributed to methodology development, including creation of the classifier in Dragonfly. DF was responsible for funding acquisition. DF, MR provided supervision and guidance. MZ conducted validation of results. MZ prepared the original draft, and all authors contributed to writing, review, and editing of the manuscript.

7 Competing interests

At least one of the (co-)authors is a member of the editorial board of The Cryosphere.

8 Acknowledgment

We thank Elisabeth Hardy-Lachance for providing permafrost samples from Bylot Island, Nunavut and Michel Sliger for his help in the laboratory to measure volumetric water content of permafrost samples.

9 **Financial support**

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