

# Ground ice estimation in permafrost samples using industrial Computed Tomography

*Roustaei et al.*

## 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

### 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.

### Introduction

- Add which other methods are commonly used for ice content estimation and why you decided to use CT in your study.
- 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”.
- 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.

### 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
- 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.
- Industrial Micro Computed Tomography: Please can you add one or two sentences what physical mechanism/principle is the basis for the method and describe 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?
- 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.

### Results and Discussion

- Image Segmentation: What is the accuracy of the classification?
- 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.
- 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.

### Conclusions

- 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.

### **Specific comments and technical corrections**

Line 9: „However“ -> „Commonly used“

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

Line 18: Please add here the temperature-based permafrost definition.

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

Line 36: Could you please add here the difference between CT scanning and  $\mu$ CT scanning?

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

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

Line 45: What non-destructive method?

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

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

Line 75: “, where ...”

Line 75:  $W_v$  → italic

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.

Line 100: Which “mathematical algorithm”?

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”

Line 110: “10cm” → “10 cm”

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

Line 130: “population)with” → “population) with”

Line 138: How close was the agreement? Can you provide some values here?

Line 139: “overestimation”: What is the range of the overestimation?

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.

Line 155: “multiple image processing steps”: Which steps? Please be more precise here.

Line 161: “et al., 2024” → “et al. (2024)”

Line 168-174: These lines should be rather shifted for example to Material and Methods.

Line 191: “Pumple et al., 2024”: Why do you need the reference here?

Line 193: Please describe why is the organic content relevant here.

Line 213-215: Why is there such a big discrepancy between the ice content estimated from cuboid physical measurements and CT scanning?

Line 226: “Figure 7C” → “Figure 8C”

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.

Line 267: “50  $\mu\text{m}$ ”: How did you estimate this value?

Line 267: “which is likely the difference between the results of these two scans”: Please try to reformulate this part of the sentence.

Line 288: “25  $\mu\text{m}$ ”: There is a problem with the format of the unit.

Line 289-290: “subsampling to a smaller size”: What is the size?

Line 290: “25  $\mu\text{m}$ ” → “25  $\mu\text{m}$ ”

Line 293: Sounds repetitive. You wrote that already above.

Line 300: “permafrost regions” → “arctic permafrost regions”

Line 300: “new calibration method”: Please specify which calibration method or what is your calibration based on

Line 302-303: “automatic thresholding technique”: What is the technique based on?

Line 315-317: Try to include the sentence in the paragraph above to avoid having a paragraph with only one sentence.

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.

Figure 4: Please add in the sample labels also the core IDs.

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?

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.

Figure 11: In the caption: “um” → “μm”

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

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.