

The authors thank the reviewer for the careful and detailed review of the manuscript. The comments helped improve the organization, clarity and presentation of the paper, and the manuscript has been revised accordingly.

The Introduction now describes the role of C-band observations in soil F/T mapping, states the knowledge gap and central goal of the study more clearly, and presents the objectives as four scientific questions that follow the structure of the Results. The manuscript has been reorganized so that background and method details no longer appear in the Results, and the interpretation of the findings and their comparison with previous studies are presented in the Discussion. Statements that could not be supported by the available data have been removed or rewritten, and explanations that could not be tested are presented as possible causes. Observations for winter 2023–24 are now shown in Figures 5 and 6 and described in the Results. Since snow wetness was not measured, the term "dry snow" is no longer used to describe the observations, and the possible effect of wet snow is noted as a limitation.

During the revision, an error was also identified in one of the SAR data processing steps. After it was corrected, all SAR images were reprocessed and every result derived from them was recomputed. In addition, all figures now use color-blind-friendly palettes, station names are used consistently throughout. Following a suggestion from the other reviewer, the I2EM section has also been removed. Responses to each specific comment are provided below.

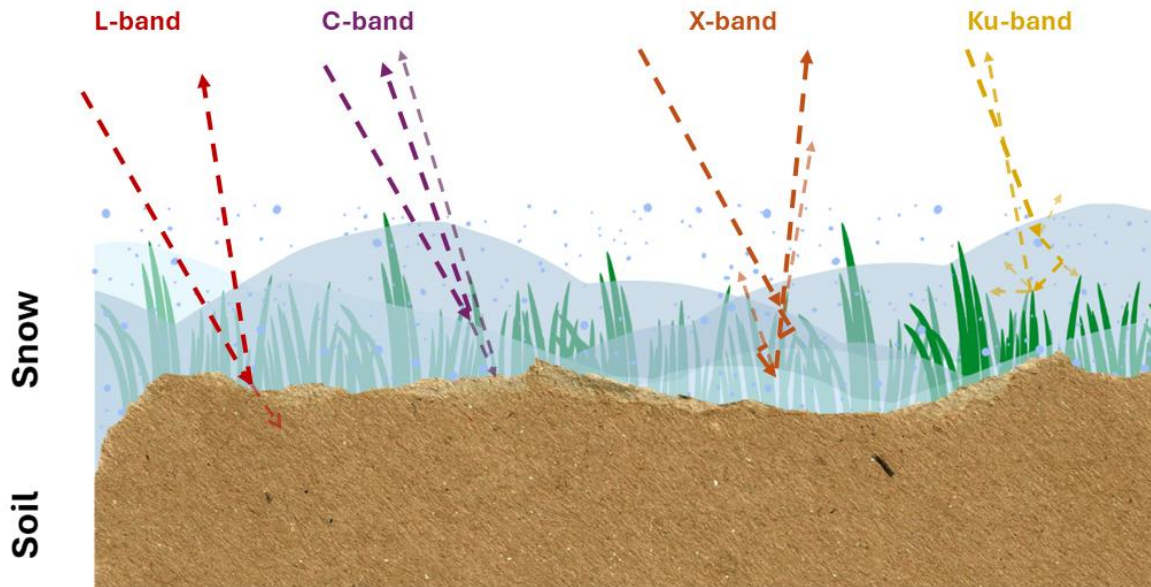
1. “Microwave remote sensing, both passive and active, has been applied for this purpose (Bateni et al., 2015; Prince et al., 2019; Rowlandson et al., 2018; Cohen et al., 2021).” Consider including more recent studies to better reflect the current state of the literature.

Response: We thank the reviewer for this suggestion. Two recent studies have been added to better reflect the current state of the literature: Crevier et al. (2026), and Cohen et al. (2024).

1. Crevier, C., Langlois, A., Derksen, C., & Roy, A. (2026). A multi sensor C-band synthetic aperture radar (SAR) approach to retrieve freeze/thaw cycles: a case study for a low Arctic environment. *The Cryosphere*, 20(6), 3369-3385.
2. Cohen, J., Lemmetyinen, J., Ruiz, J. J., Rautiainen, K., Ikonen, J., Kontu, A., & Pulliainen, J. (2024). Detection of soil and canopy freeze/thaw state in the boreal region with L and C Band Synthetic Aperture Radar. *Remote Sensing of Environment*, 305, 114102.

2. The schematic presented in Figure 1 is overly simplified, particularly for the higher microwave frequencies. It does not represent scattering processes occurring within the snowpack itself. Including these interactions would improve the physical realism and clarity.

Response: We thank the reviewer for this suggestion. Figure 1 has been revised to better represent the scattering processes occurring within the snowpack across different microwave frequencies, including volume scattering from snow grains and frequency-dependent penetration depth. The revised figure is provided below.



3. The phrase “dense time series of L-band airborne polarimetric” is vague.

Response: Thank you for this comment. We have removed the word "dense" and now describe the dataset specifically: ten airborne L-band polarimetric SAR acquisitions at 1 m resolution over two winters.

4. The Introduction provides a good background of microwave remote sensing of soil FT processes. However, the current narrative does not sufficiently establish the scientific gaps, motivation, or the specific questions the study aims to address. At present, the objectives read more as methodology or analysis oriented tasks rather than clearly defined scientific objectives or hypotheses. The repeated use of the terms “high” and “low” is ambiguous. Please clarify these definitions and their scientific relevance. The scientific purpose of the study should be articulated more clearly, and vague terminology should be reduced throughout the Introduction and objectives. It would also help to more explicitly state the central goal of the study.

Response: Thank you for this helpful comment. We have revised the last paragraph of the Introduction to state the knowledge gap and the motivation more clearly: most SAR studies of soil F/T have used C-band data, and the L-band response over heterogeneous agricultural fields, which is relevant to missions such as NISAR, remains poorly understood. The central goal of the study is now stated explicitly, and the objectives have been rewritten as four scientific questions that follow the structure of the Results. We have also removed the ambiguous use of "high" and "low": the terms describing low and high backscatter and field variability are no longer used.

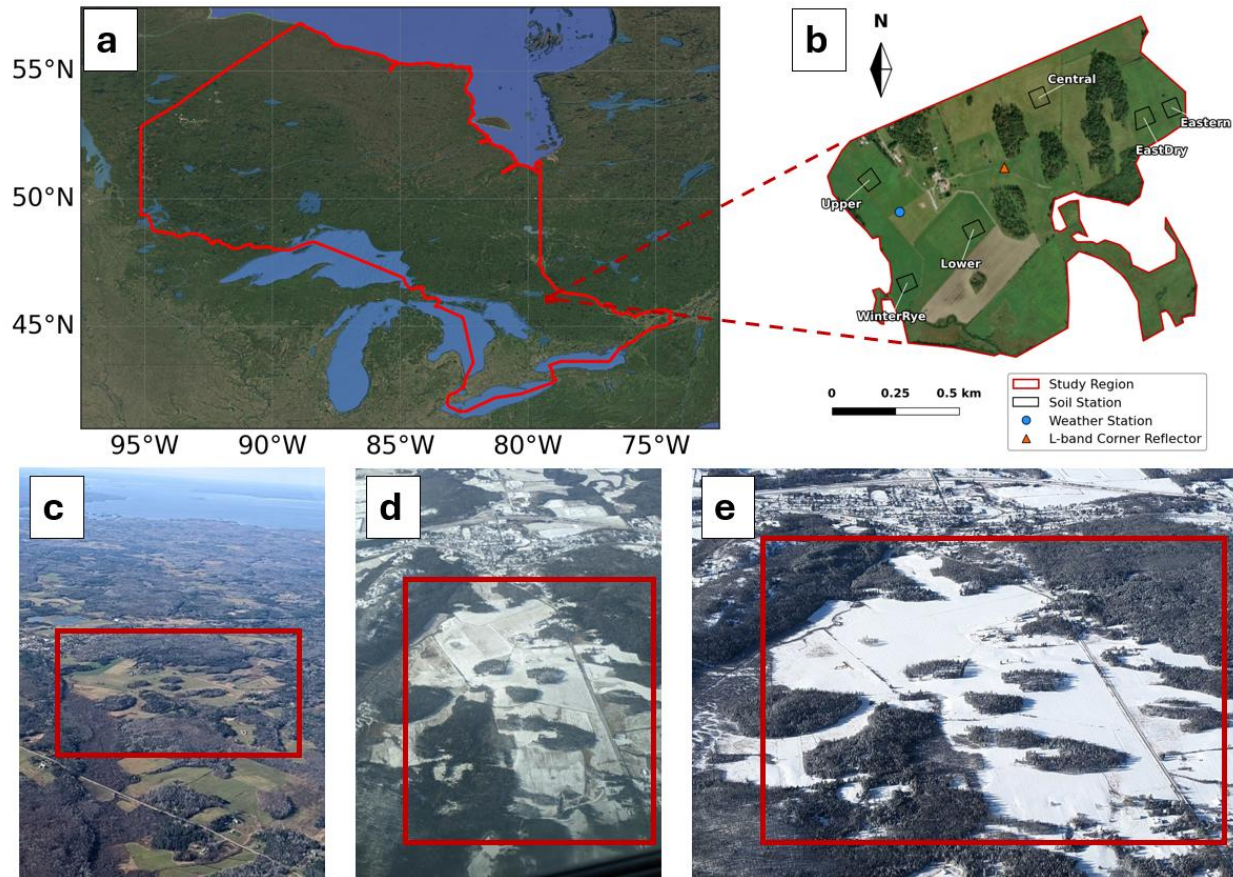
5. The Introduction also largely overlooks the role of C-band microwave observations in FT mapping. Providing this context would help better justify the scientific need for the present study and clarify how it addresses existing gaps in FT monitoring.

Response: Thank you for this comment. We have expanded the Introduction to describe the role of C-band observations in soil F/T mapping. The revised text notes that C-band SAR has been widely applied to F/T monitoring and retrieval, but that its sensitivity to the soil is reduced under vegetated cover compared with L-band. The paragraph on polarimetric methods now also reviews the C-band studies of Khaldoune et al. (2008), Jagdhuber et al. (2014) and Zhou et al. (2021). Building on this, the last paragraph of the Introduction states the resulting gap: most SAR studies of soil F/T have relied on C-band data, while the L-band response over heterogeneous agricultural fields remains poorly understood. The revised text on C-band reads:

On the other hand, lower-frequency signals such as C- (4-8 GHz) and L-band (1-2 GHz) experience minimal scattering from dry snow, as the snow grain size is much smaller than the L-band wavelength (Deeb et al., 2011; Marshall et al., 2021; Palomaki and Sproles, 2023; Shi et al., 2016; Cohen et al., 2018). Although C-band is among the most widely used frequencies for soil monitoring and penetrates snow more effectively than Ku- and X-band, its ability to sense the underlying soil is limited over vegetated surfaces and becomes largely infeasible beneath dense canopies (Zhou et al., 2021; Cohen et al., 2018). C-band SAR has also been applied to soil F/T monitoring and retrieval (Khaldoune et al., 2008; Crevier et al., 2026; Zhou et al., 2021), though, as noted above, its sensitivity to subnivean soil conditions is reduced under vegetated cover compared to L-band. L-band, by contrast, can penetrate vegetation canopies and is less affected by surface vegetation, enabling deeper interaction with the underlying soil (Bahrami et al., 2022; Akhavan et al., 2021).

6. Figure 2: Please indicate on the map the locations corresponding to panels (c)–(e). Adding these locations would improve figure clarity and help readers better understand the spatial context of the site photographs/views.

Response: Thank you for this suggestion. Panels (c)–(e) are oblique photographs taken from the aircraft during the campaign, and each one shows the entire study area rather than a single location within it. For this reason, we could not mark them as individual points on panel (b). Instead, we have outlined the study area with a rectangle in each photograph and revised the caption to make this clear.



7. The first few sentences of Section 2.1 appear to fit more appropriately in Section 2.2. Moving this material may improve the organization and overall flow of the manuscript.

Response: Thank you for this suggestion. We have moved the opening sentences of Section 2.1 to Section 2.2.

8. Line 135: Please specify the distance between the two sensors.

Response: Thank you for this suggestion. We have added the distance between the two HydraProbes at each station to the text: "The two HydraProbes at each station were separated by approximately 2–8 m." The station-specific distances are listed below for reference.

Station	Distance between Hydraprobess (m)
Upper	2.059
WinterRye	3.44
Lower	7.61
Central	2.98

EastDry	3.98
Eastern	3.15

9. Figure 5: The caption states that “the bottom plot presents snow temperature measured at three heights just above the ground surface, highlighting the evolution of snowpack temperatures as the snow depth varied throughout the observation period.” However, for example, in mid-January around the time of the first flight, the reported snow depth is approximately 20 cm while a temperature measurement at 25 cm above the ground is still shown as snow temperature. Please either revise the time series to account for periods when the probe was likely not in contact with the snowpack, or clarify in the caption that these measurements do not necessarily represent snow temperatures throughout the entire observation period.

Response: We thank the reviewer for catching this. We agree that a probe positioned above the actual snow surface would record air rather than snow temperature, which could mislead interpretation of the time series. To address this, we implemented depth-threshold masking: each probe's temperature is set to missing whenever the measured snow depth falls below that probe's height above the ground (e.g., the 25 cm probe is masked whenever snow depth is below 25 cm). As a result, each line in the revised Figure 5 is shown only when the corresponding probe is confirmed to be within the snowpack, ensuring the plotted values represent true snow temperature rather than air temperature. This masking has been applied consistently across all three probe heights, and the figure caption has been updated to reflect this.

10. Figure 5 (and, more generally, all figures): Please consider using a color-blind-friendly color palette. The current use of red and green together is difficult to distinguish for some readers and reduce figure accessibility.

Response: Thank you for this suggestion. We have revised Figure 5 and all other figures in the manuscript to use color-blind-friendly palettes.

11. Figure 6: The figure quality and resolution need to be improved. In its current form, it is difficult to distinguish between the temperature time series from Sensors 1 and 2.

Response: Thank you. We have improved the resolution of Figure 6 and now use solid and dashed lines to distinguish Sensor 1 from Sensor 2, with a color-blind-friendly palette. In some periods the two lines still overlap closely because the sensors, installed 2–8 m apart in the same soil layer, recorded very similar temperatures.

12. Figure 6: It would be helpful to include an additional panel showing the variability in temperature across the different sites. For example, an envelope representing the

minimum and maximum temperatures among the stations at each time step could provide a clearer view of the spatial variability and its evolution over time.

Response: Thank you for this suggestion. We added a panel to Figure 6, directly below the weather station data, showing the range of soil temperature across the stations at each time step (grey band) together with their mean (black line). In winter 2022–23 the stations stayed within a narrow range close to 0 °C under the snowpack, while in winter 2023–24, with much shallower snow, soil temperature followed air temperature more closely and differed more between stations. For 2023–24 the range is based on the three stations with soil records.

13. Figure 6: Please clarify in the caption what the red and gray shaded regions represent.

Response: The shading in Figure 6 has changed with the new color-blind-friendly palette. Frozen soil is now shown in blue and thawed soil in orange, while transitional periods are left unshaded. The caption now explains this.

14. Line 250: More detail is needed regarding the permittivity criterion. For example, was a range of threshold values tested, and was any validation performed to support the selected threshold? In addition, the statement “This approach reduced false detections caused by temperature sensor noise or permittivity variability” requires supporting evidence or analysis.

Response: Thank you for this comment. To check how sensitive the classification is to the permittivity threshold, we repeated it with thresholds from 7 to 12 at all six stations. The thawed fraction hardly changed, varying by about one percentage point, because thawed periods generally had permittivity well above 12. Changing the threshold mainly moved periods between the transitional and frozen classes. The choice of threshold therefore affects how periods close to the freezing boundary are labelled, but not whether clearly thawed soil is detected. We kept $\epsilon' = 10$ as a middle value within this range. We have also removed the statement about reduced false detections from the revised manuscript.

15. Lines 253–254: Please consider adding these site characteristics (e.g., vegetation type, grazing condition/stage, elevation, etc.) to Table 1. In particular, elevation information does not currently appear anywhere in Section 2.1.

Response: Thank you for this suggestion. We have added the elevation of each station to Table 1, extracted from a LiDAR-derived digital elevation model of the study area. The general site characteristics (pasture under different grazing intensities, a recently ploughed field, and wet and dry zones) are described in Section 2.3. Detailed vegetation type and grazing stage were not recorded for each individual station, so these could not be added to the table.

16. Lines 256–257 appear to fit better within the methodology section, preferably near Table 1 where the monitoring stations are introduced and described.

Response: Thank you for this suggestion. We moved these lines to Section 2.1, directly after the stations are introduced and Table 1 is cited. The moved text now reads:

"Station names were chosen based on crop types present and/or their physical locations within the study area to assist with field identification and data management."

17. Instead of numbering the stations in Figure 2, consider using the original station names to provide more context for the reader and make it easier to distinguish differences among the sites. This would also improve consistency, as the stations are referred to by their original names throughout the text. At minimum, please ensure a consistent naming convention is used across the manuscript (e.g., original names in both text and figures, or numbering consistently throughout).

Response: Thank you for this suggestion. Figure 2 now shows the original station names, and the same names are used throughout the text and in all other figures.

18. "Missing soil temperature values were filled using Inverse Distance Weighting (IDW), with available measurements from other stations at the same timestamp weighted by the inverse square of their geographic distance, ensuring temporal continuity for analysis." Consider moving this description to the methodology section, as it describes a data processing procedure.

Response: Thank you for this suggestion. We moved the description of the IDW gap-filling to Section 2.3 (In Situ Data), where it now reads:

"Data gaps in the soil records were filled using Inverse Distance Weighting (IDW), with available measurements from other stations at the same timestamp weighted by the inverse square of their geographic distance, ensuring temporal continuity for analysis."

19. Consider summarizing some of the detailed descriptions in Lines 265–285 using visualizations or summary tables. For example, precipitation could be added to Figure 6 as an additional axis with color coding by precipitation type, while the number and timing of freeze–thaw events could be summarized in a table. This would improve readability and make the temporal patterns easier to interpret.

Response: Thank you for this suggestion. We have shortened this part of the text and moved the details into figures and tables. Rain events recorded at the ECCC North Bay station are now marked in the weather panel of Figure 6. Since only three rain events occurred during the observation periods, we marked them individually rather than adding a separate precipitation axis. A new table (Table 6) gives the number of frozen and thawed episodes and

the date of first thaw at each station, and Table 5 summarizes the proportion of time each station spent in each F/T state. The earlier close-up plot of soil temperature has also been replaced by a panel in Figure 6 showing the range of soil temperature across stations.

20. “Cross-polarized channels showed less consistent variation, underscoring VV’s sensitivity to dielectric changes.” Please provide supporting evidence or a direct reference to the corresponding analysis/figure that supports this statement.

Response: Thank you for pointing this out. This statement reflected general knowledge from the literature rather than a result of our own analysis, which the original wording did not make clear. We have rewritten it as a background statement with a supporting reference and moved it, together with the rest of the justification for using VV, to the end of Section 2.2 (CryoSAR Polarimetric SAR Observations): "Cross-polarized channels are generally less sensitive to soil dielectric changes than co-polarized channels (Gupta et al., 2026)."

21. Section 3.2: The first paragraph reads more as background information or discussion rather than presentation of results. The Results section should focus more directly on the findings of the study, with clear reference to the supporting analyses, figures, or observations.

Response: Thank you for this comment. We have revised Section 3.2 so that it focuses on the results of this study. Background material has been removed from this section, and the text now presents the backscatter findings with direct reference to the supporting figures and in situ observations

22. Figures 7, 9, 10, and 13: Please consider using a more conventional and readable date format for the panel titles. In addition, while the station locations are outlined with red boundaries, it would be helpful to label the stations directly on the figures, particularly since they are discussed in detail in Lines 315–320.

Response: Thank you for this suggestion. We kept the ISO date format (YYYY-MM-DD) in the panel titles to stay consistent with the acquisition table (Table 2) and the rest of the manuscript. We have labeled each station directly on the maps, with an arrow pointing from each name to its field boundary, and the boundaries are now drawn in black for better contrast.

23. Figure 7: Consider using a color palette

Response: Thank you for this suggestion. Figure 7 now uses a color-blind-safe palette instead of grayscale, in line with the other figures.

24. Lines 300–310: Time series from the 2023–2024 winter season are needed to support and contextualize the discussion of the 12 January 2024 observations. This becomes particularly important later when the authors state that “The winter of 2023–24 displayed unique characteristics compared to typical mid-latitude Canadian winters. November 2023 did not experience persistent cold conditions, resulting in an unusually high backscatter response, which confirmed that soil remained unfrozen.” Without showing the corresponding time series, it is difficult for the reader to evaluate and interpret the results for this season.

Response: Thank you for raising this point. Observations for winter 2023–24 are now included. Air temperature and snow depth from the local weather station for 15 November 2023 to 15 January 2024 have been added to Figure 5 (right panel), together with the snowpack temperatures. Soil permittivity and temperature for the three available stations with records in this season (WinterRye, Upper and Lower) are shown in Figure 6, with F/T states based on the same criteria as in winter 2022–23. The VV backscatter at the stations for the two 2023–24 acquisitions (24 November 2023 and 12 January 2024) is shown in Figure 8. These records show that air temperatures did not stay persistently below freezing in November 2023 and that all three stations were thawed at the time of the 24 November acquisition, which supports our interpretation for this season.

25. “In contrast, 1 March 2024 exhibited a high backscatter response, coinciding with thaw conditions, an increase in 2 m air temperature, and higher soil permittivity across all stations (Fig. 6).” Please verify the year in this statement. Should this refer to 1 March 2023 or 1 March 2024?

Response: Thank you for catching this. We have carefully checked all dates in the revised text against the acquisition table and corrected them where needed.

27. Line 310: Some of the discussed dates appear to correspond to periods when the snowpack may have been at or near the melting stage. Therefore, the use of the term “dry snow” is questionable in this context, particularly when attributing changes in backscatter primarily to soil freeze–thaw conditions. Additional evidence or clearer justification is needed to separate the influence of snowpack wetness from soil-state effects on the radar response.

Response: Thank you for this important point. We agree that without measurements of snow wetness, we cannot fully separate the effect of snowpack wetness from that of soil state on the radar response. We have therefore removed the term “dry snow” from the description of our observations and revised the text so that changes in backscatter are no longer attributed solely to soil F/T state. We have also added a sentence to the Discussion acknowledging that wet snow may have contributed to the backscatter on some dates, and that separating these effects would require snow wetness measurements in future campaigns.

28. Line 314: Please clarify what is meant by “within soil moisture regions of interest.” The terminology is currently unclear.

Response: Thank you for pointing this out. This phrase referred to the fixed areas around each of the six soil monitoring stations, which were left undisturbed throughout the observation period so that changes in SAR backscatter could be tracked consistently at these locations. The term has been removed in the revised manuscript.

29. Line 317: I am not entirely sure how Figure 7 supports the stated finding.

Response: Thank you for this comment. While revising the manuscript, we found an error in one of the SAR data processing steps. After correcting it and reprocessing all SAR images, the backscatter values changed, and we rewrote this section accordingly. The statement referred to here is no longer part of the text. Figure 7 has also been revised. In the new text, each panel is described using the backscatter values at the stations and their in situ soil state on the same date, so it should now be clear how the figure supports what we report.

30. Figure 8: Since the backscatter measurements represent discrete observations, it would be more appropriate to display them as scatter points rather than as continuous lines.

Response: Thank you for this suggestion. We agree that the backscatter should not be shown as continuous lines. In the revised Figure 8, each acquisition is shown as a separate boxplot at its date, so no continuity between flights is implied. We chose boxplots rather than single points because each one summarizes all pixels within the area around each soil station, showing the median and the spread of values on that date. Since the variability of backscatter within and between stations is an important part of this study, this adds information that a single point per date would not show. The figure has also been redesigned so that the in situ soil state at each station appears directly above its backscatter.

31. Section 3.3: Similar to Section 3.2, the distinction between background/discussion and presentation of results is not always clear.

Response: Thank you for this comment. We have revised the section "Changes in Polarimetric Decomposition Parameters" (previously Section 3.3, now Section 3.4) so that it focuses on the results. The interpretation of these results and the comparison with previous studies are now in the Discussion.

32. Line 33: It would be helpful to clarify what the authors mean by “high” and “low” responses. Relative to what reference or baseline are these terms defined?

Response: Thank you for this comment. We could not find the terms "high" and "low" responses in Line 33 of the original manuscript and suspect the comment may refer to another line. In the revised manuscript, the figures showing backscatter and scattering maps now identify their panels as the dates with the lowest and highest mean values, or the lowest and highest variability between stations, across all acquisitions, and the corresponding values are given in the text.

33. Line 333: Figure 9?

Response: Thank you for catching this. The reference has been corrected. Because of the renumbering of figures in the revised manuscript, this figure is now Figure 10.

34. Figure 9 and all similar figures: Please add the monitoring stations to the maps and label them with their station names.

Response: We thank the reviewer for this suggestion. The monitoring stations have been added to and labeled with their station names on all map-based figures.

35. Figures 9–10: The color bars are missing units.

Response: We thank the reviewer for pointing this out. The appropriate units have been added to the color bars in the corresponding figures (now Figures 10 and 11).

36. Line 420: Could you clarify whether any analysis was performed to attribute the observed errors to soil moisture or surface roughness effects? Please provide the supporting evidence for this statement. If this interpretation is only a hypothesis, it should be clearly stated as such and would be more appropriately placed in the Discussion section rather than the Results section.

Response: Thank you for this comment. This sentence was part of the Improved Integral Equation Model section, which has been removed from the revised manuscript following the other reviewer's suggestion.

37. Line 430: The use of the term “homogeneous” to describe the study region appears inconsistent with earlier sections of the manuscript, where spatial variability in soil moisture, surface roughness, elevation, and other site characteristics is discussed. Please clarify what is meant by “homogeneous” in this context and specify which properties or spatial scales this description refers to.

Response: Thank you for this comment. This sentence was part of the original F/T maps section, which has been rewritten and now includes a quantitative validation against the in situ stations (Section 3.3). The statement describing the study region as homogeneous has been removed. In the revised manuscript, the term is used only in Section 2.3, where it refers to the local area in which each soil station was placed, away from field edges, and in Section 3.2, where it describes the spread of backscatter values within each station area.