In blue: Reviewer's comments. [ ] = Numbering

In black: Answers to referees.
P=Page; L=Line; Track change version
In black and italic: Modification added to text.

Reviewer #1:

Synopsis:

This paper represents a review of spaceborne microwave remote sensing utility and recent applications for Arctic-boreal regional (ABR) studies. The targeted audience for the paper is the carbon cycle science community, with a primary focus on monitoring land-atmosphere carbon (CO_2 and CH_4) fluxes and environmental controls. The authors include a useful summary of microwave remote sensing principles, satellites, and sensors pertinent to ABR applications. They then follow with a detailed review and discussion of major biophysical retrievals and attributes, and data records obtained from microwave sensors, and associated ABR applications from the recent literature. The authors also include an informative review highlighting both the challenges and opportunities of microwave remote sensing. Overall, the paper is well written, comprehensive, and informative; covering most of the major microwave remote sensing derived variables affecting carbon fluxes available from the recent literature. The paper is also timely given the increasing ABR importance in global climate change along with major new microwave satellite missions coming online in the next few years. The paper should be suitable for publication pending moderate revisions to address the following comments.

Despite the focus of this paper on the microwave utility to capture carbon fluxes (both CO_2 and CH_4) and related environmental attributes, there's no mention of the application of microwave remote sensing for monitoring fractional surface water (FW) cover dynamics, which contribute strongly to ABR methane emissions (e.g. Watts et al. 2014). The FW parameter is particularly relevant in the ABR owing to the regional abundance of small inland water bodies and wetlands that contribute CH_4 emissions, but that can also contaminate microwave land parameter retrievals; here FW is a first-order response variable that has been used to assess and reduce water contamination effects on other ABR land parameter retrievals (e.g. Touati et al. 2019), which might otherwise incur significant bias (e.g. Kim et al. 2019. Remote Sensing 11). SAR is mentioned for wetlands mapping in the paper, which is good, but passive microwave has particular importance by providing full ABR coverage and daily monitoring of FW dynamics. Therefore, FW should be discussed in the paper given its importance for ABR CH_4 emissions and significance for other ABR land parameter retrievals.

Similarly, lake and river ice phenology, including the seasonal timing of ice on/off and ice cover duration, influences the seasonality and magnitude of ABR CH_4 emissions, and has been readily documented from the microwave record (e.g. Murfitt and Duguay 2021). This should also be mentioned in the paper given its importance to CH_4 emissions (e.g. Matthews et al. 2020).

The focus of this article is on land carbon cycle. Although important, aquatic carbon processes are much different form the land and fall out of the scope of this article. We think that adding lake and river carbon processes, which are very different than land will increase the length of the paper and decrease the focus of our manuscript. It was more clearly specified that the article focuses on land carbon cycles with a few remarks added on freshwater bodies in Sect. 3.6 (Land cover).

Title: Reviews and syntheses: Recent advances in microwave remote sensing in support *terrestrial* carbon cycle science *of arctic-boreal regions*

P1, L17-19: Although direct measurements of carbon fluxes are not feasible, spaceborne microwave radiometers and radar can monitor various important surface and near-surface variables that affect *terrestrial* carbon cycle processes…

P1, L27-29: Given rapid climate warming across the ABR and the associated carbon cycle feedbacks to the global climate system, this review argues for the importance of rapid integration of microwave information into ABR *terrestrial* carbon cycle science.

P4, L116-118: This paper aims to introduce to the C cycle science community the potential of spaceborne microwave remote sensing to help overcome some of the challenges specifically posed by the ABR for *terrestrial* C cycle science and monitoring.

P15, L424-429: SAR imagery has shown to be especially useful for delineating inundated areas (Bowling et al., 2003) or wet and moist tundra (Morrissey et al., 1996; Merchant et al., 2022) *which has a strong impact on* CH_4 *emission (Watts et al., 2014). Microwave observations can also be used to monitor freshwater bodies (FW) extent dynamics (Murfitt and Duguay, 2021). FW can act as important* CH_4 *emission sources, especially during ice melt but aquatic carbon cycle processes are much different than land carbon processes and were not within the scope of this review (Matthews et al., 2020).*

P39, L1220-1222: *Matthews, E., Johnson, M.S., Genovese, V., Du, J., and Bastviken, D.: Methane emission from high latitude lakes: methane-centric lake classification and satellite-driven annual cycle of emissions. Sci. Rep., 10, 12465, doi: 10.1038/s41598-020-68246-1, 2020.*

P41, L1300-1301: *Murfitt, J., and Duguay, C.: 50 years of lake ice research from active microwave remote sensing: Progress and prospects. Remote Sens. Environ., 264, 112616, doi: 10.1016/j.rse.2021.112616, 2021.*

P51, L1731-1732: *Watts, J., Kimball, J., Bartsch, A., and McDonald, K.: Surface water inundation in the boreal-Arctic: potential impacts on regional methane emissions. Environ. Res. Lett., 9, 075001, doi: 10.1088/1748-9326/9/7/075001, 2014.*

Specific comments:

[1] Figure 3a: Include the Feng Yun-3 microwave radiation imager (FY-3 MWRI) in the figure; the global MWRI record extends from 2008-present and provides similar TB observations helping bridge the gap between AMSR-E and AMSR2.

The FengYun-3 MWRI satellite mission was added in Fig. 3(a) and Table A1.

P52, L1769-1771: *Xian, D., Zhang, P., Gao, L., Sun, R., Zhang, H., and Jia, X.: Fengyun Meteorological Satellite Products for Earth System Science Applications. Adv. Atmos. Sci., 38, 1267–1284, doi:10.1007/s00376-021-0425-3, 2021.*

[2] Figure 4: Include FW cover and lake/river ice dynamics, which are particularly important for ABR methane emissions, and where active/passive microwave sensors are well suited for monitoring. Also, it took me a while to figure out that the magnifying glass and green monster J denotes microbial processes; alternatively, it may be better to more clearly represent a below-ground layer in the figure showing soil litter decomposition and Rh; this would also remind the reader about the unique capability of microwave remote sensing to detect below-ground properties.

The freshwater aquatic carbon cycle fells out of the scope of this article that focuses on land carbon cycle. We however acknowledge the importance of lake and river carbon processes in the discussion. See answer to the general comments above.

The green monster was removed.

[3] Figure 4 Cont: Recent work shows some success for active/passive microwave retrievals of surface soil organic carbon, which has strong ABR importance for soil carbon storage and Rh (e.g. Bartsch et al. 2016; Yi et al. 2022). I recommend including this information in the figure and discussion.

The potential for upper soil layer organic carbon retrieval from active and passive microwave was added in the biomass section. (Sect. 3.4).

P13, L378-381: *Although the low AGB of the Arctic tundra is challenging to monitor from microwave observations, studies have shown that it is possible to estimate the upper soil organic C (up to 30 cm from the soil/atmosphere interface) using active and passive microwave observations (Bartsch et al. 2016; Yi et al. 2022).*

P25, L631-634: *Bartsch, A., Widhalm, B., Kuhry, P., Hugelius, G., Palmtag, J., and Siewert, M. B.: Can C-band synthetic aperture radar be used to estimate soil organic carbon storage in tundra? Biogeosciences 13(19), 5453-5470; doi: 10.5194/bg-13-5453-2016, 2016.*

P53, L1789-1791: *Yi, Y., Chen, R., Kimball, J., Moghaddam, M., Xu, X., Euskirchen, E., Das, N., and Miller, C.: Potential satellite monitoring of surface organic soil properties* *in arctic tundra from SMAP. Water Resour. Res., 58(4), e2021WR030957, doi: 10.1029/2021WR030957, 2022.*

[4] Section 3.1. A key challenge in developing effective microwave soil moisture retrievals in the ABR is the predominance of highly organic soils and their unique dielectric properties; these conditions aren't well represented in traditional dielectric models (although Miranov and a few others have made meaningful advances), which can contribute significant SM retrieval uncertainty. More information is needed on this.

The challenge of model parametrization for rich organic soils was added. Since the article is mostly aimed at the carbon cycle science community, we did not further expand on organic soil specific challenges since it was not done with the other challenges (e.g., surface roughness).

P9, L236-238: The sensitivity of the microwave signal to soil moisture content has been widely demonstrated previously but several challenges remain including accounting for vegetation attenuation and scattering related to the surface roughness (Das and Paul, 2015; Colliander et al., 2022), *as well as organic soil model parametrization (Mironov and Savin, 2015; Bircher et al., 2016)*.

P25, L644-646: *Bircher, S., Demontoux, F., Razafindratsima, S., Zakharova, E., Drusch, M., Wigneron, J.-P., and Kerr, Y.: L-Band Relative Permittivity of Organic Soil Surface Layers—A New Dataset of Resonant Cavity Measurements and Model Evaluation. Remote Sens., 8(12), 1024, doi:10.3390/rs8121024, 2016.*

P40, L1267-1269: *Mironov, V., and Savin, I.: A temperature-dependent multi-relaxation spectroscopic dielectric model for thawed and frozen organic soil at 0.05–15 GHz. Phys. Chem. Earth Parts ABC, 83–84, 57–64, doi: 10.1016/j.pce.2015.02.011, 2015.*

[5] Table 1: The AMSR-E/2 soil moisture product provided from Du et al., 2017 should be listed as "2002-ongoing", rather than from 2012.

The starting date was corrected in Table 1.

[6] Ln 268: Include net ecosystem productivity (NEP) in Figure 4 or note the relationship with NEE in the text.

NEE and NEP relationship can be found in Fig. 4 caption.

P8, Fig.4: b) relationships of net primary productivity and net ecosystem productivity (NEP = **-** net ecosystem exchange [NEE]), and their component fluxes with ecosystem respiration [ER] = $R_a + R_h$.

[7] Ln 275: The Jones et al. LST reference should be Jones et al. 2010 (IEEE JSTARS) rather than their 2007 TGARS paper that refers to soil temperature. Here the microwave LST uncertainty is less than the reported soil temperature retrieval RMSE (~3-4K).

The Jones et al. reference was corrected. Jones et al. (2010) LST uncertainty still fall in the microwave LST range of other studies (1-5K)

P10, L274-277: Retrieval of LST from microwave remote sensing is technically more challenging and results in lower precision than similar products from thermal infrared remote sensing, 1-5 K for microwave LST vs. 0.2-2K for thermal infrared (Jiménez-Muñoz and Sobrino, 2006; Jones et al., *2010*; Osińska-Skotak, 2007; Krishnan et al., 2020; Zhang and Cheng, 2020).

P34, L995-997: *Jones, L.A., Ferguson, C.R., Kimball, J.S., Ke Zhang, Chan, S.T.K., McDonald, K.C., Njoku, E.G., Wood, E.F.: Satellite Microwave Remote Sensing of Daily Land Surface Air Temperature Minima and Maxima From AMSR-E. IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens., 3(1), 111–123, doi:10.1109/jstars.2010.2041530, 2010.*

[8] Ln 280: Microwave observations have also been used to retrieve soil temperatures in the ABR (e.g. Jones et al. 2007 TGRS); the ability to sense soil temperatures is an important advantage over thermal-IR remote sensing, which can only detect surface skin temperatures and which are subject to significant atmospheric contamination. This should be noted.

This advantage of microwave soil temperature was added to section 3.2.

P10, L282-284: *Microwave can be used to sense soil temperature up to a few centimeters deep because of its soil penetration depth. It is an important advantage over thermal infrared remote sensing, which can only detect LST and is subject to significant atmospheric contamination (Jones et al., 2007).*

[9] Ln 285: The Jones et al. LST reference should be Jones et al. 2010 (IEEE JSTARS). The UM AMSR global land parameter data record (LPDR) includes daily temperature retrievals from both AMSR-E and AMSR2 (rather than just AMSR-E), and extending from 2002-present; although the record isn't operational as correctly noted.

The Jones et al. reference was corrected and AMSR2 reference was added.

P11, L289-290: Microwave LST algorithms typically achieve a precision of 2-5 K using data from AMSR-E*/2* (Jones et al., *2010*; Zhang and Cheng, 2020) and…

[10] Table 2: The numbering of SMAP and ASCAT in the column headings should be switched to match the numbering in the table footnote.

The footnote numbering was corrected.

[11] Ln 488: "multi-frequency" should be included here, in addition to "multi-polarization" and "multi-angular" measurements; whereby, the variable sensitivity of the different microwave frequencies (e.g. AMSR) has been used to disentangle the integrated

microwave signal to obtain multiple complimentary land parameter retrievals (e.g. Du et al. 2017. ESSD).

The use of multi-frequency measurements for disentangling the microwave signal was added. We used a reference from a land application (Larue et al., 2018) instead of a lake ice application (Du et al., 2017) because it corresponds more to the scope of the article.

P16, L497-498: Recent advances have been made for both passive and active data to decouple the signal in boreal forests by exploiting multi-polarization, multi-angular *and multi-frequency* measurements (*Larue et al., 2018;* Cohen et al., 2019; Konings et al., 2019; Roy et al., 2020).

P36, L1094-1096: *Larue, F., Royer, A., De Sève, D., Roy, A., and Cosme, E.: Assimilation of passive microwave AMSR-2 satellite observations in a snowpack evolution model over northeastern Canada, Hydrol. Earth Syst. Sci., 22, 5711–5734, doi:10.5194/hess-22-5711-2018, 2018.*

[12] Ln 490: Here, introduce FW abundance as a key challenge for remote sensing of ABR land parameters, which is then expanded upon below (Ln 501).

The challenge of FW abundance was moved from section 5.2 (intra-pixel variability) to section 5.1 (disentangling the integrated microwave signal).

P18, L506-507: Microwave data processing must account for the high density of shallow water bodies in ABR, and recent efforts have sought to remove their effect on passive microwave observations mixed pixels (Touati et al., 2019).

[13] Ln 510: Here, clarify that the tower network is particularly sparse in the ABR, while referring back to Figure 1. The sparse regional tower network adds to the difficulty for effective regional calibration and validation given the strong ABR heterogeneity.

We added a mention on the sparsity of the eddy covariance network in section 5.2.

P18, L521-522: Still, most of the terrestrial biosphere model performance evaluation is done using eddy covariance data which is the most trusted and widely used reference for C flux measurements at large scales. However, *the sparsity of the measurement network in ABR reduce our capacity to represent ABR heterogeneity in terrestrial biosphere model* (*Fig. 1;* Fisher et al., 2018).

Reviewer #2:

Synopsis:

The high latitudes are experiencing significant environmental changes that necessitate precise, large-scale, and long-term measurements of the interconnected hydrological and ecological systems. Microwave remote sensing is a critical tool for tracking gradual and sudden changes in the region and revealing the underlying relationships and mechanisms. This paper offers a timely and perceptive overview of microwave remote sensing in high-latitude environments, which is likely to benefit the scientific community and aid in the advancement of remote sensing research in carbon studies. Overall, the paper was clearly structured and nicely written. However, there are a few corrections and improvements to be made before I recommend it for publication:

Specific comments:

[1] Fig. 3(a): please change “Forest” to “Vegetation”;

The correction was made in figure 2(a).

[2] Fig. 3(b): The figure illustrates three soil-vegetation interaction components, which are not shown in the associated equation and labels. A more complete equation consistent with the figure and accounting for the first-order scattering process is preferred.

Since the manuscript is mainly aimed at the carbon cycle science community, we think that going deeper in the vegetation scattering processes of microwaves would dilute the focus of our manuscript. We clarified in the Fig. 2 caption that the equation’s vegetation term is an approximation of all first-order vegetation scattering processes.

P6, Fig. 2: *The* σ_{veg} *term is an approximation for the first-order vegetation scattering processes.*

[3] Fig. 4(a): Radar observations similar to passive microwave remote sensing are also affected by vegetation water content. Please consider to have “Vegetation water storage” under “Passive and Active” category.

Vegetation water storage was moved from the Passive column to the Passive and Active column in Fig. 4.

[4] Table 1: For the AMSR-E/2 column, the temporal coverage should start from 2002 instead of 2012.

The starting date was corrected in Table 1.

[5] Line 310: The statement “The rapid decrease of εsoil in freezing soils translates into a much higher microwave emission and backscattering from the surface” is not accurate.

The decrease of soil dielectric constant typically corresponds to weaker radar backscattering from soil. However, for a complex high-latitude scenario with mixed soil, snow and vegetation, landscape freeze/thaw transitions can cause both enhanced or weakened microwave scattering depending on its frequencies. A nice reference explaining the rationale can be found at:

Zwieback, S., Bartsch, A., Melzer, T. and Wagner, W., 2011. Probabilistic Fusion of Ku- and C-band Scatterometer Data for Determining the Freeze/Thaw State. IEEE transactions on geoscience and remote sensing, 50(7), pp.2583-2594.

The statement was corrected, and references were added for the microwave emission and backscattering impact.

P11, L315-316: The rapid decrease of ε_{soil} in freezing soils translates into a much higher microwave emission *(Rautiainen et al., 2012)* and *weaker radar* backscattering *(Zwieback et al., 2011)* from the surface.

P54, L1814-1816: *Zwieback, S., Bartsch, A., Melzer, T. and Wagner, W.: Probabilistic Fusion of Ku- and C-band Scatterometer Data for Determining the Freeze/Thaw State. IEEE T. Geosci. Remote, 50(7), 2583-2594, doi: 10.1109/JSTARS.2015.2476358, 2011.*

[6] A recent work focusing on the possibility of detangling AGB and the vegetation water content from VOD (e.g. Line 392) can be found at:

Dou, Y., Tian, F., Wigneron, J.P., Tagesson, T., Du, J., Brandt, M., Liu, Y., Zou, L., Kimball, J.S. and Fensholt, R., 2023. Reliability of using vegetation optical depth for estimating decadal and interannual carbon dynamics. Remote Sensing of Environment, 285, p.113390.

The reference to the more recent work on AGB was added.

P14, L404-406: The microwave VOD sensitivity to both AGB and vegetation water status complicates its interpretation, although the study of the temporal and spatial trends of VOD can allow to distangle AGB vs the vegetation water content *(Dou et al., 2023)*.

P29, L796-798: *Dou, Y., Tian, F., Wigneron, J.P., Tagesson, T., Du, J., Brandt, M., Liu, Y., Zou, L., Kimball, J.S. and Fensholt, R.: Reliability of using vegetation optical depth for estimating decadal and interannual carbon dynamics. Remote Sens. Environ., 285, 113390, doi: 10.1016/j.rse.2022.113390, 2023.*

[7] For section 5.2, I recommend additional review of recent machine-learning based downscaling studies, which help to resolve the spatial heterogeneity of land parameters. For example, below is a recent paper on soil moisture downscaling:

Du, J., Kimball, J.S., Bindlish, R., Walker, J.P. and Watts, J.D., 2022. Local Scale (3-m) Soil Moisture Mapping Using SMAP and Planet SuperDove. Remote Sensing, 14(15), p.3812.

A quick overview of the results from Du et al. (2020) recent work was added to section 5.2.

P18, L518-520: *A recent study from Du et al. (2020) showed promising results in downscaling soil moisture to 3 m spatial resolution using machine-learning with microwave spaceborne data.*

P29, L812-813: *Du, J., Kimball, J.S., Bindlish, R., Walker, J.P. and Watts, J.D.: Local Scale (3-m) Soil Moisture Mapping Using SMAP and Planet SuperDove. Remote Sens., 14(15), 3812, doi: 10.3390/rs14153812, 2022.*

[8] I also recommend the authors add a short summary of the satellite GNSS-R technique for high-latitude studies. The novel approach shows promise in soil moisture, vegetation, water body and freeze/thaw detections. Here is a nice reference:

Rautiainen, K., Comite, D., Cohen, J., Cardellach, E., Unwin, M. and Pierdicca, N., 2021. Freeze–Thaw Detection Over High-Latitude Regions by Means of GNSS-R Data. IEEE Transactions on Geoscience and Remote Sensing, 60, pp.1-13.

The potential of the novel GNSS-R approach was added in Sect. 5.3 (Potential and upcoming spaceborne microwave remote sensing missions).

P19, L535-539: *Furthermore, the novel approach of opportunistic use of spaceborne reflectometry of the Global Navigation Satellite System (GNSS) (Li et al., 2022; Yu et al., 2022) already showed promising results in evaluating soil moisture (Edokossi et al., 2020), soil freeze/thaw state (Rautiainen et al., 2021) and snow water equivalent (Royer et al. 2021).*

P29, L822-824: *Edokossi, K., Calabia, A., Jin, S., and Molina, I.: GNSS-Reflectometry and Remote Sensing of Soil Moisture: A Review of Measurement Techniques, Methods, and Applications. Remote Sens., 12, 614, doi: 10.3390/rs12040614, 2020.*

P45, L1456-1458: *Rautiainen, K., Comite, D., Cohen, J., Cardellach, E., Unwin, M., and Pierdicca, N.: Freeze–Thaw Detection Over High-Latitude Regions by Means of GNSS-R Data. IEEE Trans. Geosci. Remote Sens., 60, 1-13, 4302713, doi: 10.1109/TGRS.2021.3125315, 2022.*

P46, L1521-1523: *Royer, A., Roy, A., Jutras, S., and Langlois, A.: Review article: Performance assessment of radiation-based field sensors for monitoring the water equivalent of snow cover (SWE). Cryosphere, 15, 5079–5098, doi: 10.5194/tc-15-5079-2021, 2021.*

P37, L1121-1123: *Li, W., Cardellach, E., Ribó, S., Oliveras, S., and Rius, A.: Exploration of Multi-Mission Spaceborne GNSS-R Raw IF Data Sets: Processing, Data Products and Potential Applications. Remote Sens., 14, 1344. doi: 10.3390/rs14061344, 2022.*

P53 L1793-1794, LX: *Yu, K., Han, S., Bu, J., An, Y., Zhou, Z., Wang, C., Tabibi, S., and Cheong, J. W.: Spaceborne GNSS Reflectometry. Remote Sens., 14, 1605, doi: 10.3390/rs14071605, 2022.*