Reply on RC2

General comments

I have read the manuscript "RFDTM: A national-scale and wall-to-wall 30 m resolution mangrove sub-canopy topography dataset for New Zealand derived from ICESat-2 ATLAS and multi-band SAR". This manuscript presents RFDTM—a national-scale 30 m resolution mangrove sub-canopy topography dataset for New Zealand generated entirely from publicly available satellite observations. Overall, the dataset presented in this study is highly useful, the methodological integration is innovative, and the application value is clear. However, some minor revisions are still needed to further improve the quality of the manuscript. My specific suggestions are as follows.

Reply: We sincerely thank you for your highly positive evaluation and constructive comments on our manuscript "RFDTM: A national-scale and wall-to-wall 30 m mangrove sub-canopy topography dataset for New Zealand derived from ICESat-2, SAR and Sentinel-2". We deeply appreciate your recognition of the novelty, methodological integration, and application value of our dataset. Your detailed suggestions regarding the inclusion of Sentinel-2 in the title and abstract, the earlier introduction of New Zealand, the structural split of the data sections, the clarification of mangrove extent sources, the distinction between ICESat-2 and airborne LiDAR, the relocation of error analyses, and the refinement of the Conclusion are incredibly valuable. Incorporating your feedback has significantly enhanced the clarity, structure, and rigor of our manuscript.

Below, we provide a point-by-point response to your comments. For your convenience, our direct responses are formatted in blue text, while the specific new content incorporated into the revised manuscript is presented in blue italics.

Comment 1:

The method proposed in this paper uses Sentinel-2 optical remote sensing imagery in addition to SAR data. It is recommended that the authors include the relevant information in the title

and abstract.

Reply 1:

Thank you for this valuable suggestion regarding the inclusion of Sentinel-2 optical imagery in the description of the data sources. We fully agree that the title and abstract serve as the most crucial entry points for readers to grasp the core methodology. Since our approach relies on a synergistic fusion of SAR penetration capabilities and optical spectral features, explicitly stating both in the title and abstract is essential to provide a comprehensive representation of the multi-source inputs. Accordingly, we have meticulously revised both the title and the abstract to prominently feature the Sentinel-2 multispectral optical imagery, ensuring that the data integration strategy is immediately clear and accurately reflects the multi-modal nature of our framework from the outset.

Modifications in the revised manuscript (Title and Abstract):

Title: RFDTM: *A national-scale and wall-to-wall 30 m mangrove sub-canopy topography dataset for New Zealand derived from ICESat-2, SAR and Sentinel-2.*

Abstract: The dataset was developed by integrating ICESat-2 photon-counting LiDAR data with dual-frequency C-band and L-band SAR observations and Sentinel-2 multispectral optical imagery. First, a Hierarchical Multi-Constraint Filtering (HMCF) strategy was employed to extract reliable ground photons, thereby improving the reliability of terrain elevation estimates beneath dense mangrove canopies. Subsequently, multi-source terrain, vegetation, spectral, and radar backscatter features were constructed and optimized within a Random Forest regression framework to reconstruct continuous sub-canopy topography and generate the RFDTM product.

Comment 2:

It is recommended that New Zealand be introduced earlier in the background paragraph of the Introduction, that the rationale for selecting New Zealand as the study area be explained, and that the importance and significance of New Zealand mangroves be highlighted.

Reply 2:

Thank you for this highly constructive suggestion. We completely agree that introducing New Zealand earlier and clearly articulating the rationale for its selection significantly strengthens the logical flow and research context. Emphasizing the ecological significance of New Zealand's mangroves—particularly their role in coastal habitat provision and blue carbon sequestration—helps ground the study. Furthermore, highlighting the unique advantage of the study area, specifically the coexistence of comprehensive nationwide satellite coverage and high-quality airborne LiDAR reference data, justifies our ability to both generate a national-scale product and conduct rigorous local validations. Consequently, we have restructured the background paragraph to integrate these elements seamlessly.

Modifications in the revised manuscript (Section 1, Introduction):

Section 1：Mangrove ecosystems are widely distributed in tropical and subtropical coastal zones and serve as critical transitional areas connecting terrestrial and marine environments (Hu et al., 2020). They play essential ecological roles in wave attenuation, carbon sequestration and emission reduction, biodiversity conservation, and coastal stabilization (Prihantono et al., 2022; Hu et al., 2020). These functions are particularly relevant in New Zealand, where mangroves contribute to coastal habitat provision and blue carbon research. New Zealand was selected as the study area because its mangrove distribution provides an opportunity to investigate sub-canopy topography at the national scale, while publicly available satellite observations and airborne LiDAR reference data support the development and local validation of a spatially continuous topographic dataset. Influenced jointly by tidal processes, hydrodynamic conditions, and sedimentary environments, mangrove regions are generally characterized by low and relatively flat terrain but exhibit significant spatial variability in topography (Hu et al., 2020). Such variability exerts a decisive influence on tidal inundation patterns, hydrological connectivity, and the distribution of vegetation types (Xie et al., 2022). Therefore, high-precision mangrove sub-canopy topography data not only provide a fundamental basis for understanding mangrove ecological processes and ecosystem services, but also supply critical topographic information for assessing sea-level rise, storm-surge inundation risks, and environmental changes in coastal zones (Huang et al., 2024b; Xi et al.,

2022). However, the canopy structure and complex vegetation height variations of mangroves severely limit the ability of traditional remote sensing techniques to effectively retrieve sub-canopy topography (Li et al., 2021; Li et al., 2023).

Comment 3:

The section title "2.2.3 Sentinel data (C-band, Sentinel-2)" is not appropriate. It is recommended that this section be split into two separate subsections. This would make the data description clearer and more consistent with the structure of the methods.

Reply 3:

Thank you for your valuable suggestion regarding the manuscript's structural clarity. We completely agree that grouping radar (SAR) and optical data under a single, broad title can obscure their fundamentally different physical properties and data processing requirements. Splitting this section is highly beneficial, as it not only aligns perfectly with the distinct methodological workflow of our model but also provides a much clearer, independent description of the Sentinel-1 SAR and Sentinel-2 optical remote sensing data. To address this, we have divided the original section into two standalone subsections, detailing the specific sensors, characteristics, and acquisition platforms for each dataset separately.

Modifications in the revised manuscript (Section 2.2.3 and Section 2.2.4):

Section 2.2.3：2.2.3 Sentinel-1 SAR data

The Sentinel satellites, developed by ESA, provide high-resolution Earth observation data. Sentinel-1 operating in Interferometric Wide Swath IW mode provides C-band synthetic aperture radar observations with VV and VH polarizations, enabling all-weather and day-and-night imaging capabilities. Compared with longer-wavelength SAR systems, C-band backscatter is particularly sensitive to vegetation canopy structure and temporal dynamics, making it effective for forest cover monitoring and phenological change detection (Torres et al., 2012). The data were accessed and processed via the Google Earth Engine (GEE) platform (https://code.earthengine.google.com/).

Section 2.2.4： 2.2.4 Sentinel-2 optical data

Sentinel-2's Multispectral Instrument (MSI) captures 13 spectral bands at native spatial resolutions of 10–60 m (Li et al., 2025). In this study, Sentinel-2 Level-1C top-of-atmosphere (TOA) reflectance imagery acquired in 2020 was used, including the cirrus band B10 at a native spatial resolution of 60 m. The data were accessed and processed via the GEE platform (https://code.earthengine.google.com/).

Comment 4:

Section 2.1 mentions GMW v3.0, while Section 2.2.5 mentions the GLC_FCS30 product. Therefore, which dataset was ultimately used as the mangrove extent in this paper requires further confirmation and explanation from the authors.

Reply 4:

Thank you for pointing out this potential ambiguity regarding the data sources used to define the mangrove extent. We appreciate the opportunity to clarify the distinct roles of these two datasets. To be absolutely clear, the Global Mangrove Watch (GMW) v3.0 dataset was exclusively used to delineate the spatial extent and generate the spatial mask of the mangroves. In contrast, the GLC_FCS30-2020 dataset was solely incorporated as one of the land-cover predictor features within the Random Forest model to aid in terrain estimation, and it was not used to define the mangrove boundaries. We have explicitly detailed this distinction in the revised manuscript to ensure methodological transparency and prevent any confusion for the readers.

Modifications in the revised manuscript (Section 2.1 and Section 2.2.6):

Section 2.1：The study area is located in New Zealand, spanning approximately 34°–47° S latitude and 166°–178° E longitude, with a total mangrove area of approximately 2–9 km² within the selected regions. The region is low-lying and characterized by mangroves (Avicennia marina subsp. australasica) distributed mainly along estuaries and intertidal zones. The mangrove extent used in this study was delineated using the Global Mangrove Watch (GMW)

v3.0 dataset, which provided the spatial mask for RFDTM generation and subsequent analyses. The area exhibits a large tidal range, with estuarine and coastal sedimentary environments interspersed, forming typical mangrove wetlands. Mangrove distribution is patchy and spatially heterogeneous, making the region representative for studies of sub-canopy terrain and vegetation structure. The region experiences a temperate oceanic climate, characterized by mean annual temperatures of 14–16 °C and annual precipitation of 1200–1500 mm, which provide favorable conditions for mangrove development. The study area is shown in Fig. 1.

Section 2.2.6： GLC_FCS30-2020 is a 30 m global land cover dataset developed by RADI and collaborators, containing 29 classes, with forests further divided into 12 subtypes (Zhang et al., 2021; Zhang et al., 2024), and the dataset updated in 2020 was used in this study. GLC_FCS30-2020 was used solely as a land-cover predictor in the Random Forest model, rather than to delineate mangrove extent. The modeling domain and final product extent were defined by the GMW v3.0 mangrove mask. GLC_FCS30-2020 supports fine-scale land cover analysis and is available at https://doi.org/10.5281/zenodo.3986872.

Comment 5:

The manuscript mentions both ICESat-2 LiDAR and airborne LiDAR. It is recommended that the two be clearly distinguished throughout the paper to avoid confusion between them.

Reply 5:

Thank you for your valuable suggestion regarding the clear distinction between ICESat-2 and airborne LiDAR data. We fully agree that explicit differentiation is critical given their distinct sampling densities and spatial coverage. Throughout the revised manuscript (including data descriptions, methodology, results, and figure captions), we have systematically clarified their respective roles. Specifically, we have made it clear that the spaceborne ICESat-2 ground elevations are utilized as the response variable for training the Random Forest model, whereas the airborne LiDAR-derived terrain elevations are strictly reserved as independent, high-accuracy reference data for the final accuracy assessment. This distinction ensures the integrity of the modeling and validation processes and prevents any potential reader confusion.

Modifications in the revised manuscript (Section 2.2.7, Section 3, Section 5.1, Section 5.2 , and Section 5.3):

Section 2.2.7： 2.2.7 Airborne LiDAR DEM data

To validate the derived terrain parameters, high-resolution airborne LiDAR elevation data were obtained from the open data service of Land Information New Zealand. The Northland LiDAR 1 m DEM dataset was used as reference terrain data, and the datasets acquired between December 2018 and February 2020 were selected for analysis. New Zealand's mangroves are confined to the northern part of the North Island, with no naturally occurring mangroves on the South Island. RFDTM covers the mapped mangrove extent nationwide. However, owing to the limited spatial coverage of airborne LiDAR reference data available for the study period, accuracy assessment was restricted to overlapping mangrove areas in Northland, representing a subset of the national mangrove extent. The DEM was derived from airborne laser scanning observations collected using the Leica TerrainMapper-LN system, with an average point density of ~4 points m^{-2} and a reported vertical accuracy of approximately 0.2 m. Elevations referenced to NZVD2016 were converted to EGM2008 to ensure consistency with ICESat-2 observations. The data are available at https://data.linz.govt.nz/data/.

Section 3： ICESat-2-derived ground elevations were used as the response variable for Random Forest model training, whereas airborne LiDAR-derived terrain elevations were used for accuracy assessment of the resulting RFDTM.

Section 5.1： In representative regions, Fig. 6 shows the elevation maps of RFDTM and the airborne LiDAR DEM for areas a and b in the right panels, along with scatter plots comparing the two datasets. The scatter plots demonstrate a high correlation, with R^2 = 0.99, and low error levels, with RMSE = 0.94 m, MAE = 0.76 m, and bias = 0.36 m, indicating a high level of agreement between RFDTM and the airborne LiDAR reference DEM.

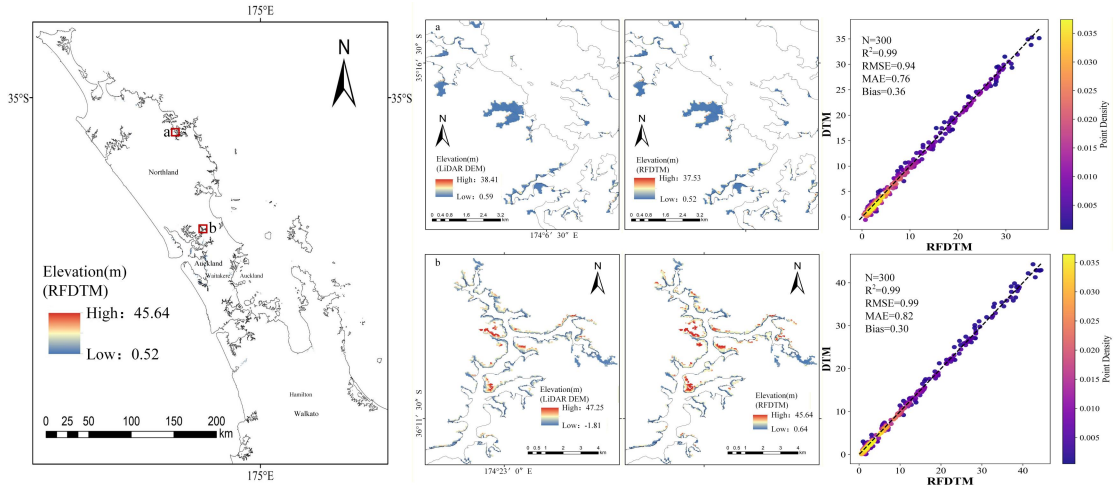


Fig. 6. Mangrove sub-canopy topography profiles in two representative regions. Spatial distribution and validation of mangrove sub-canopy topography derived from the RF model (RFDTM). The left panel shows the study area and the locations of two representative sample regions (a, b). The right panels show the resulting maps of RFDTM and the airborne LiDAR DEM for areas a and b, as well as scatter plots that compare them.

Section 5.2：Moreover, differences in data resolution further amplify uncertainty. The evaluated DEMs typically have resolutions ranging from 10 m to 30 m, while RFDTM is generated at 30 m resolution using ICESat-2-derived ground elevation samples and multiple predictors, and evaluated against airborne LiDAR-derived terrain elevations. Differences in spatial resolution between the airborne LiDAR reference DEM and the evaluated terrain products introduce scale-dependent representation errors, which may be more pronounced in mangrove areas with substantial terrain variability (Renshaw et al., 2026). Coarser DEMs tend to smooth terrain changes, making it difficult to capture sub-canopy microtopography, whereas higher-resolution DEMs may contain more noise and local artifacts. Consequently, the observed uncertainty reflects not only model performance but also the combined effects of data resolution, spatial sampling, and terrain complexity (Dusseau et al., 2023).

Section 5.3：Table 4 presents the evaluation results of the proposed RFDTM's accuracy compared to several widely used DEM products, including FABDEM, SRTM, NASADEM, ASTER GDEM, TanDEM-X, DiluviumDEM, and DeltaDTM, based on four statistical indicators: R^2, RMSE, MAE, and bias. These indicators quantify the elevation differences relative to the airborne LiDAR-derived reference terrain elevations.

Comment 6:

In Section 4.2 of the Results, the discussion in lines 370–375 explaining the sources of errors in SRTM, NASADEM, ASTER, and TanDEM-X should be moved to the Discussion section because this content is interpretive rather than a direct presentation of results.

Reply 6:

Thank you for your valuable suggestion regarding the logical organization of the manuscript. We completely agree that the Results section should be strictly reserved for the objective presentation of data, while interpretive content—such as analyzing the physical mechanisms behind the error sources of SRTM, NASADEM, ASTER, and TanDEM-X—belongs in the Discussion section. Moving this content not only maintains the scientific rigor of the Results but also allows for a more in-depth, integrated analysis when compared with existing literature. Consequently, we have relocated the relevant discussion from Section 4.2 to a newly established subsection in the Discussion (Section 5.3).

Modifications in the revised manuscript (Section 5.3):

Section 5.3：Table 4 presents the evaluation results of the proposed RFDTM's accuracy compared to several widely used DEM products, including FABDEM, SRTM, NASADEM, ASTER GDEM, TanDEM-X, DiluviumDEM, and DeltaDTM, based on four statistical indicators: R^2, RMSE, MAE, and bias. These indicators quantify the elevation differences relative to the airborne LiDAR-derived reference terrain elevations. Additionally, Fig. 10 displays scatter plots that illustrate the relationship between each DEM and the reference elevations, visually highlighting the differences and trends in elevation accuracy among the datasets.

Table 4 Accuracy comparison between the inverted RFDTM and DEMs.

Data	*R2*	*RMSE(m)*	*MAE(m)*	*Bias(m)*
RFDTM	*0.99*	*1.01*	*0.80*	*0.43*

FABDEM	*0.98*	*3.87*	*1.79*	*1.08*
SRTM	*0.87*	*5.28*	*4.27*	*4.13*
NASADEM	*0.89*	*6.95*	*4.62*	*4.28*
ASTER GDEM	*0.73*	*9.30*	*7.87*	*-7.16*
TanDEM-X	*0.82*	*8.64*	*6.71*	*-6.28*
DiluviumDEM	*0.97*	*3.66*	*2.25*	*-0.97*
DeltaDTM	*0.75*	*2.73*	*2.24*	*1.93*

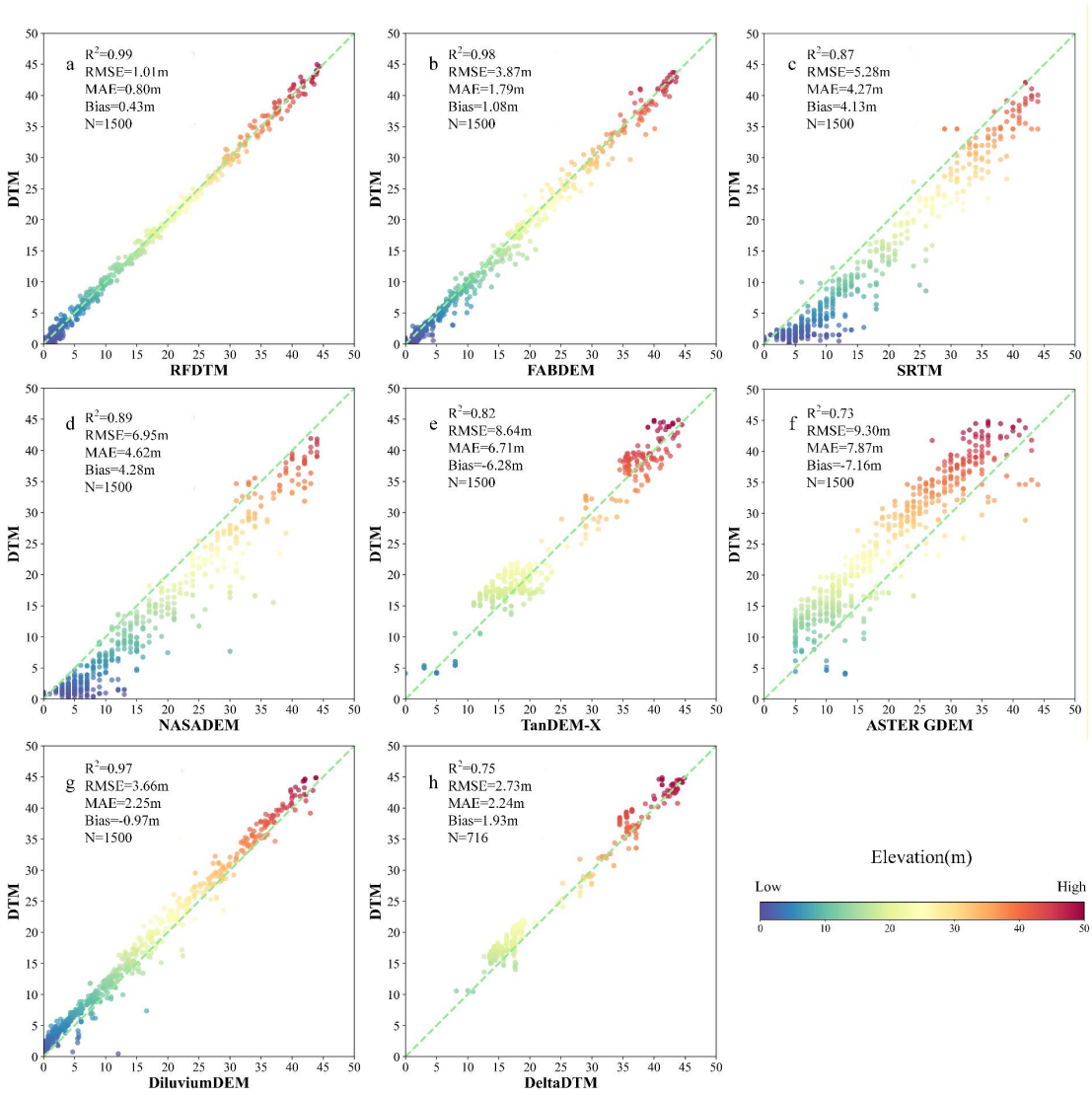


Fig. 10. Accuracy Comparison Scatter Plot. (a) RFDTM scatter plot; (b) FABDEM scatter plot; (c) SRTM scatter plot; (d) NASADEM scatter plot; (e) TanDEM-X scatter plot; (f) ASTER GDEM scatter plot; (g) DiluviumDEM scatter plot; (h) DeltaDTM scatter plot.

The results in Table 4 and Fig. 10, N denotes the number of scatter points. For DeltaDTM, only 716 scatter points due to its random distribution within a small coastal subset of the latitude–longitude range. The RFDTM derived from the estimation model in this study was subjected to a systematic accuracy analysis. RFDTM advantages significant across all indicators: R^2 = 0.99, RMSE = 1.01 m, MAE = 0.80 m, Bias = 0.43 m. High consistency between the inverted DTM and measured terrain, and far superior precision to existing DEM products.

Compared with other DEMs, the superiority of RFDTM is even more pronounced. FABDEM exhibits a relatively high overall correlation R^2 = 0.98 with RMSE and MAE of 3.87 m and 1.79 m, respectively, but it is still clearly inferior to RFDTM. The accuracies of SRTM, NASADEM, ASTER GDEM, and TanDEM-X are lower, with RMSE values ranging from 5.28 to 9.30 m and considerable bias, indicating systematic overestimation or underestimation. These limitations are largely attributable to their data acquisition and processing mechanisms. Radar interferometry and optical stereo matching are strongly affected by vegetation canopy, layover, and shadowing, which reduces vertical precision in forested areas (Huang et al., 2024c; Huang et al., 2025). DiluviumDEM and DeltaDTM show slightly better accuracy RMSE 2.73–3.66 m, likely due to ground filtering or interpolation, yet they still cannot match the fine-scale precision of ICESat-2–derived RFDTM, which directly captures forest sub-canopy topography through photon measurements combined with multi-source predictors (Dusseau et al., 2023).

From the overall comparison in Table 4 and Fig. 10, the RFDTM inverted in this study demonstrates excellent performance in local elevation recovery, overall terrain continuity, and error control. It more accurately reflects the terrain characteristics of the study area, providing a reliable data basis for subsequent terrain analysis and related applications, thereby validating the effectiveness and high-precision advantage of the estimation model.

Comment 7:

It is recommended that the Conclusion simplify the technical details and instead emphasize the limitations, future prospects, and the value and utility of the dataset.

Reply 7:

Thank you for your valuable suggestions regarding the refinement of the Conclusion section. We fully agree that a strong conclusion should not merely reiterate technical workflows but should instead focus on broader scientific implications and the utility of the research. To address this, we have significantly streamlined the section by reducing excessive procedural details. We have placed greater emphasis on the inherent limitations of the current study (such as the restricted spatial coverage of the validation domain), outlined clear future research directions, and highlighted the practical value and wide-ranging utility of the RFDTM dataset for regional coastal management and global-scale blue carbon research.

Modifications in the revised manuscript (Section 7):

Section 7：To address the persistent lack of accurate and spatially continuous sub-canopy terrain information in mangrove ecosystems, this study produced RFDTM, the first national-scale 30 m mangrove sub-canopy topography dataset for New Zealand generated entirely from publicly available satellite observations. By integrating ICESat-2-derived ground elevations with SAR, optical, and ancillary satellite-derived features, RFDTM provides spatially continuous terrain estimates across New Zealand's mapped mangrove extent. Owing to the limited spatial coverage of airborne LiDAR reference data available for the study period, accuracy assessment was restricted to overlapping mangrove areas in Northland. Within this validation domain, RFDTM achieved an R^2 of 0.99, an RMSE of 1.01 m, an MAE of 0.80 m, and a bias of 0.43 m. These results support the potential of the proposed framework for national-scale mangrove terrain mapping.

Ablation experiments highlight the contribution of L-band SAR to sub-canopy terrain estimation, with C-band SAR providing complementary information. RFDTM generation relies on publicly available satellite observations without requiring airborne LiDAR data for model training, supporting reproducibility and large-scale implementation. The dataset provides a spatially continuous 30 m terrain baseline across New Zealand's mapped mangrove extent, with potential applications in regional coastal inundation assessment, habitat evaluation, preliminary ecological restoration planning, and blue carbon research. The proposed

framework has the potential to support large-scale terrain mapping across mangrove ecosystems worldwide.

Thank you so much for all comments to this manuscript, which significantly improve this manuscript. In the revised manuscript, all revised contents are highlighted in blue font. Please see the revised details in the manuscript. If some issues still need to be addressed in the revised manuscript, please give us an opportunity to revise and improve it again.

Best regards.