We would like to thank the reviewer for their thoughtful and constructive feedback. We have carefully considered all comments and made the necessary revisions. Their comments have substantially improved the quality and rigour of the work. Below, we provide a point-by-point response to each comment. Reviewer comments are shown in *black,* and our responses follow in blue text. Where applicable, revised text from the manuscript is shown in **bold**.

Reviewer 1

General

Methodological paper that also show range and magnitude of tropical root exudation over seasons. The paper provide novel advances in belowground biogeochemistry methodology for coastal wetlands. It is well written, and the main comments are around clarification for some method aspects, and accuracy/usefulness of the scaled-up calculations.

We thank the reviewer for this positive overall assessment and for the targeted, constructive suggestions. We address each specific comment below.

Abstract

- Make sure genera are italicised throughout paper

Modified as suggested, thank you. We have checked the entire manuscript and ensured that all genus names (*Rhizophora, Avicennia, Bruguiera*) are consistently italicised throughout.

- Line 27-30- because the rate errors (range) are so large it's causing the non-significant, although the means are are 2-2.5-fold different depending on the comparison. Suggest making that clearer in abstract

We agree that the large variability underlying the non-significant differences deserves explicit acknowledgement in the abstract. We have revised the relevant sentence as follows:

"Mean root exudation rates were 126 ± 172 µg C g^{-1} h^{-1} for *Avicennia* and 68.5 ± 96.1 µg C g^{-1} h^{-1} for *Rhizophora*, with seasonal rates of 52.4 ± 67.2 µg C g^{-1} h^{-1} for the wet season and 135 ± 168 µg C g^{-1} h^{-1} for the dry season, similar in magnitude to those of terrestrial forests**. Although dry-season rates were 2.6-fold higher than wet-season rates and *Avicennia* rates were approximately twice those of *Rhizophora*, differences were not statistically significant, reflecting the high individual-level variability inherent to root exudation measurements.**

We have also expanded on this briefly in the discussion:

"Exudation rates did not differ significantly between *Avicennia*-dominated stands and *Rhizophora*-dominated stands, nor between wet and dry seasons (Fig. 6**). Though the mean differences were substantial in magnitude: dry-season rates were 2.6-fold**

higher than wet-season rates (135 vs. 52.4 µg C g^{-1} h^{-1}) and *Avicennia* rates were approximately twice those of *Rhizophora* (126 vs. 68.5 µg C g^{-1} h^{-1}).This non-significant difference could reflect a genuine absence of biological differences between treatments, insufficient contrast in the underlying drivers (explored in Sect. 4.3), or limited statistical power stemming from the unbalanced and modest sample sizes."

- Clarify if the GPP value just for the ecosystems in Vietnam?

The GPP value of 16–20 Mg C ha^{-1} yr^{-1} (Adame et al., 2024) is a global mean for mangroves, not specific to Vietnam. We have clarified this in the manuscript:

> Relative to a global mean mangrove GPP of 16–20 Mg C ha^{-1} yr^{-1} (Adame et al., 2024), **median-based estimates correspond to approximately 2.7% of GPP in *Rhizophora*-dominant and 2.8% of GPP in *Avicennia*-dominant plots, respectively, while mean-based estimates reach 5.7–11.3% respectively. Site-specific GPP measurements for Cần Giờ were unavailable, which would have allowed a more precise comparison and should be prioritised in future studies."**

Intro

- L50: It's not clear what 'other carbon fluxes' refers to

We have now rephrased as follows to increase clarity:

> "Quantifying root exudation is therefore essential not only to close the carbon budget, but also to understand how labile root-derived carbon might shape **the soil biogeochemistry."**

- L66: not clear how the ad hoc adapted method is insufficient and misses carbon production

We have now revised this sentence to be more specific about the limitations of the ad hoc method:

> " Although this quantification pushed the frontier of root exudation quantification, the **cuvette used in that study was neither sealed against water ingress nor buried under sediment, limiting its applicability to more tidally challenging mangrove environments**. The measurements were limited to *Bruguiera gymnorhiza (L.) Lam.* in a single subtropical system and have not yet been extended to the globally dominant *Rhizophora* and *Avicennia* genera or to typical tropical mangroves, limiting the representativeness of these root exudation estimates **for tropical mangroves** (Kato et al., 2026)."

Methods

- Two different sized cuvette beads between the seasonal measures adding to the variability. How will this change the interpretation between the seasons or what approach readers should use when replicating the method?

This is an important point. We have now expanded the discussion of this in Section 4.5 to explicitly acknowledge it as a source of potential inter-seasonal variability and to provide guidance for replication:

> **"We also note that bead size differed between seasons (750 µm + 4 mm in the wet season; 2 mm in the dry season) due to logistical constraints. Sasse et al. (2020) showed that particle size affects root morphology rather than exudates. Nonetheless, standardising to a layered combination of fine (750 µm) and coarse (4 mm) beads across campaigns is recommended in future applications of this method."**

- Typically DOC samples are preserved with zinc chloride to stop any turnover/shift in DOC. Understanding this may be complex to do in the field, but 7 d storage at 4C may cause unintended changes in DOC. Have the authors tested how the 0.22um filtration would select for some types/sizes of DOC while also removing living organisms? Please state if this may impact the results for both exudate and sediment control DOC including in discussion as required.

We thank the reviewer for raising this point. Regarding filtration, the use of 0.22 µm PVDF syringe filters follows directly from Phillips et al. (2008), and is consistent with the guidelines for *in situ* root exudation studies (Oburger & Jones 2018). The choice of 0.22 µm over 0.45 µm is deliberate: 0.22 µm represents the accepted sterility threshold for biological organisms, making removal of microbes from the sample at the point of collection more thorough. This is particularly important given the 4 °C storage period, as any residual microbial activity could alter DOC quantity and composition before analysis. While some studies have reported minor compositional differences between filtrates at different pore sizes (Nimptsch et al., 2014), others find no significant difference in DOC quantification between 0.2 and 0.7 µm filtrates (Chow et al., 2022). Importantly, root exudates are dominated by low-molecular-weight compounds (sugars, organic acids, amino acids), which pass freely through 0.22 µm membranes; any excluded colloidal fraction would likely represent a minor and consistent proportion of the signal across all samples and controls alike.

Regarding storage: samples were filtered immediately after collection and stored at 4 °C in the dark for a maximum of 7 days prior to TOC analysis. Cook et al. (2016) examined cold storage of tropical DOC samples at 4 °C for 6–12 weeks and found that DOC concentrations increased by only ~6% over six weeks and by 8–11% over twelve weeks compared to ambient storage, concluding that 4°C cold storage is an acceptable preservation method for tropical DOC for moderate time periods and preferable to freezing or ambient temperature storage. Our 7-day maximum storage falls well within this validated window.

Regarding $ZnCl_2$ preservation: we did not use chemical preservation as it is not standard practice in root exudate studies (Phillips et al., 2008, Oburger & Jones 2018). Importantly, while $ZnCl_2$ does not interfere with bulk DOC quantification via TOC analysis, its addition could interfere with compound-level characterisation of exudate composition, making it unsuitable if future studies aim to move beyond bulk DOC. We acknowledge that a direct comparison of $ZnCl_2$-preserved versus purely cold-stored filtered samples from our system would be a useful methodological validation, and we recommend this as a priority for future work. We have adapted the manuscript as follows:

> "We passed the recovered solution through a 0.22 µm PVDF syringe filter (Millex; MilliporeSigma, Burlington, MA, USA) **following Phillips et al. (2008),** collected it in sterile Falcon™ polypropylene tubes (Corning Inc., Corning, NY, USA), wrapped them in aluminium foil, and stored them at 4 °C for up to 7 days before DOC analysis, **a duration shown to preserve DOC in tropical settings with minimal concentration drift (Cook et al., 2016)"**
>
> **"Samples were not chemically preserved in this study; cold storage at 4 °C for up to 7 days has been shown to preserve tropical DOC with minimal concentration drift (Cook et al., 2016). Future studies could consider chemical preservation methods, though these may alter DOC composition (Chow et al., 2022) and limit comparability with existing studies and suitability for compound-level characterisation of exudate composition (Chow et al., 2022)."**

- 4.1. Where the two sizes of beads used or the 2 mm kind?

The waterproofing pilot test (Sect. 2.4.1) and the incubation duration time series (Sect. 2.4.2) were conducted in the wet season, so they used the layered combination of 750 µm and 4 mm beads. We have now clarified this in the relevant section 2.3.2:

> **"In the pilot tests (Sect. 2.4.1 and 2.4.2) and during** the wet season, we used a layered combination of fine (750 µm) and coarse (4 mm) beads to avoid valve clogging; in the dry season, due to logistical constraints (i.e. availability), we used a uniform 2 mm bead size."

- Can the author clarify why DBD was taken for only the top 5 cm while most of the other measures were to 30 cm? Will this bias the ecosystem scale calculations?

BD does not feed into the ecosystem-scale flux calculations; those use fine-root biomass from the 30 cm cores directly. We acknowledge that measuring BD consistently to 30 cm would have provided a more complete characterisation of the physical environment across the full rooting zone, and this is something we recommend for future studies. We have clarified the purpose of the BD measurement in the manuscript:

> "**To characterise topsoil physical properties across species and seasons,** we measured bulk density by collecting three replicate soil cores **(5 cm depth × 4.9**

cm diameter) from the topsoil in each quadrat. For each core, we oven-dried samples at 105 °C to constant mass. Bulk density (BD, g cm^{-3}) was calculated as oven-dry mass divided by total core volume."

Results

- There seem to be exudation spikes, ie outliers in figure 6. What may be happening here that is causing such broad ranges of exudate production? Was there any trend or consistent factor related to those samples in particular?

We thank the reviewer for this observation. We investigated whether the high-value samples were associated with any consistent factor, including species, season, plot, sampling date, root traits, soil properties, and meteorological variables. No systematic pattern was identified. We confirmed that total C recovered was positively correlated with root dry mass (Spearman r = 0.43, p = 0.002), indicating that the DOC signal scales with root biomass as expected, consistent with genuine root-derived carbon rather than background contamination. This level of variation is also common in cuvette studies (Kato et al., 2026; Meier et al., 2020). We therefore retained all samples but have now added discussion of this variability in the manuscript (Section 4.1):

"Although occasional signs of water ingress into the box were observed, these were not associated with high DOC values. High DOC **(Fig. 6)** also did not coincide with potential water ingress contamination; although undetected contamination cannot be fully excluded. **The high-value samples showed no consistent association with any of the variables we measured, species, season, root traits, soil EC, pH, or bulk density (Appendix A; Fig. 7), though we cannot exclude that an unmeasured variable, such as local porewater redox conditions or root phenological state, may explain part of this variability**. Similar individual-level variability has been reported in other cuvette studies, **for example in temperate beech forests where coefficients of variation exceeded 80% (Meier et al., 2020), and rates spanning two orders of magnitude in the only other mangrove cuvette study published until now (10–970 µg C g^{-1} h^{-1}; Kato et al., 2026).** The variability likely reflects natural heterogeneity in root activity rather than methodological noise (Meier et al., 2020; Phillips et al., 2008)."

- For ecosystem-scale calculations, the exudation values are so wide (SD is much higher than the mean), that reporting means here may not be the best approach for scaling to annual flux. It may be more transparent to report the ranges of the scaled-up values.

Yes, thank you, we agree that the high variability warrants transparency. Mean, SD, and median are already reported in Section 3.7. Given the right-skewed distribution, we have additionally added the range (min–max) to make the full spread explicit and added a note in Section 4.4 that the median is likely more representative than the mean given that SD > mean in all groups.

We did not report ranges for the GPP-normalised estimates, as these are derived by scaling the same flux values by a fixed constant and would not provide additional information beyond the flux ranges already reported.

> "Fine-root exudation from the wet season dataset was upscaled to the soil and ecosystem level using fine-root biomass densities measured in the upper 30 cm of soil. In *Avicennia*-dominated sites (n = 13), areal fluxes averaged 586 mg C m^{-2} day^{-1} (median = 142; SD = 1144; **range = 4.56–4184 mg C m^{-2} day^{-1}**). This corresponded to a mean annual flux of 2140 kg C ha^{-1} yr^{-1} (median = 519; SD = 4175; **range = 16.6–15270 kg C ha^{-1} yr^{-1}**). *Rhizophora*-dominant sites (n = 21) showed mean daily fluxes of 299 mg C m^{-2} day^{-1} (median = 144; SD = 433; **range = 6.43–1811 mg C m^{-2} day^{-1}**), yielding a mean annual flux of 1093 kg C ha^{-1} yr^{-1} (median = 526; SD = 1581; **range = 23.5–6610 kg C ha^{-1} yr^{-1}**)."
>
> **"This study observed that *Avicennia* stands supported greater fine-root biomass than *Rhizophora*, and this structural difference translated into higher ecosystem-scale exudation fluxes: mean annual inputs were approximately 2140 kg C ha^{-1} yr^{-1} (SD = 4175; range = 16.6–15270 kg C ha^{-1} yr^{-1}) in *Avicennia*-dominant plots, and 1093 kg C ha^{-1} yr^{-1} (SD = 1581; range = 23.5–6610 kg C ha^{-1} yr^{-1}) in *Rhizophora*-dominant plots. However, given that SD exceeds the mean in both cases, median values are considered more representative of typical fluxes (*Avicennia*: 519 kg C ha^{-1} yr^{-1}; *Rhizophora*: 526 kg C ha^{-1} yr^{-1})."**

Discussion

- L423: since senescence in this case is an experimental artifact, rather than natural, it would be worth restricting exudate measure in the future to the 24-48 hour period. How would the shock and senescence also impact the scaled up results?

We thank the reviewer for this point. We have now made it clear in the manuscript that we advise 24h stabilisation period, followed by 24h incubation for root exudation quantification. In addition, we have removed the term 'senescence', which might not be the most accurate, replacing it with the more mechanistically precise description that prolonged incubations risk increasing microbial consumption and root re-uptake, progressively decoupling measured DOC from true gross exudation. Conversely, prolonged incubations risk deflating estimates through increasing microbial consumption and root re-uptake. The 48 h protocol (24 h recovery + 24 h effective incubation) avoids both biases. We have now made those points clearer in the manuscript as follows:

"The pilot time series revealed a biphasic pattern, with DOC rising over the first 48 hours and declining by 72 hours (Fig. 4). **The initial increase is consistent with the accumulation of exudates described for cuvette-based methods, where exudation rates are highest immediately after equilibration (Phillips et al., 2008; Zhang et al., 2024), while the subsequent decline may result from microbial degradation and root re-uptake of compounds offsetting gross exudation at longer incubation times** (Oburger and Jones, 2018; Phillips et al., 2008; Zhang et al., 2024). [...] This increased variability supports the idea that roots require a short recovery period after disturbance (Döll et al., 2024; Oburger and Jones, 2018), **and that 48 h measurements (24 h recovery + 24 h effective incubation) are therefore more reliable for flux calculations**. Similarly, prolonged incubation **risks increasing microbial consumption and root re-uptake, each of which progressively decouple measured DOC from true gross exudation rates** (Oburger and Jones, 2018), which, when coupled with the need to fit tidal access windows while capturing a complete diurnal cycle in exudation, suggests the use of a 48 h total protocol (24 h recovery + 24 h effective incubation)."

- Given the methodological development focus of the paper, low replication and high variability in exudation, I suggest the scaling-up exercise be presented as a back-of-the-envelope calculation in the discussion with a subset of data that takes into account the potential bias/limitation of the data. Or else the scaling-up results should be remove in this instance, and revisited in future studies.

We agree. The upscaling section has been reframed in Section 4.4 as a first order, back-of-envelope approximation, with explicit caveats regarding low replication, single-season biomass data, and high individual-level variability. We retain the results rather than removing them, as order-of-magnitude estimates are valuable for contextualising a previously unquantified flux, but we now add median-based estimates (given that SD exceeds the mean in both species). Ranges have been added throughout. The revised paragraph reads as follows:

"Given the low replication, high individual-level variability, and single-season biomass data, the ecosystem-scale flux estimates presented here should be treated as first order, back-of-envelope approximation rather than precise flux measurements. This study observed that *Avicennia* stands supported greater fine-root biomass than *Rhizophora*, and this structural difference translated into higher ecosystem-scale exudation fluxes: mean annual inputs were approximately 2140 kg C ha^{-1} yr^{-1} in *Avicennia*-dominant plots and 1093 kg C ha^{-1} yr^{-1} in *Rhizophora*-dominant plots."

- Could plant productivity measures or indicators be useful in explaining root exudation?

We agree this is a valuable avenue for future research. In principle, plant productivity indicators such as GPP, leaf area index, or photosynthetic rate would be useful predictors of root exudation, as exudates are ultimately sourced from recently assimilated photosynthate (Kuzyakov et al., 2003; Mencuccini & Hölttä, 2010). In our dataset, the available tree-level proxies for productivity (DBH, height, and tree density) showed no significant correlation with exudation rate (Spearman $r = 0.09, -0.13, -0.10$, respectively, all $p > 0.4$), likely because these structural variables are poor proxies for instantaneous carbon allocation to roots. Direct productivity measurements such as photosynthesis measurements, or sap flow were beyond the scope of this study but would be valuable co-variables in future work, and we have now highlighted it the manuscript as follows:

> **"The measured tree-level proxies for productivity (DBH, height, tree density) that we measured did not explain root exudation rates, likely because structural variables are poor proxies for instantaneous carbon allocation to roots. Future studies should consider incorporating direct measurements of plant carbon status, such as photosynthetic rate (Canarini et al., 2019; Brunn et al., 2025) alongside sap flow and leaf-level stress indicators, as additional co-variables."**
>
> **"Future studies should also consider incorporating direct plant productivity measurements, as proxies for carbon allocation to roots."**

- Is there value of including more than 1 root in the cuvette if the data are normalised to mass or volume of the roots. Would that simulate a more natural rhizosphere condition?

This is an interesting methodological consideration that we have considered. In principle, multi-root incubations could be explored in systems where root density and morphology allow it, and this may be worth evaluating in future methodological work as it could indeed better represent the collective rhizosphere environment and reduce the influence of individual root variability on exudate measurements. In practice, including multiple roots in a single cuvette was not feasible at our study site: mangrove fine roots are highly fragile, making it very difficult to excavate more than one intact root of sufficient length simultaneously without damaging them. Fitting multiple roots through the rubber stopper seal while maintaining an airtight closure would also have been technically impractical given the cuvette design. We therefore retained a one-root-per-cuvette approach and account for the resulting individual-level variability by reporting full distributions alongside means. We have now added this point in the discussion:

> **"Incubating multiple roots could better reflect root–root interactions and reduce individual-level variability, but this option was not feasible here given the fragility of mangrove fine roots and the difficulty of maintaining an airtight seal around multiple roots simultaneously. This warrants evaluation in future methodological work in systems where root density and robustness allow it."**

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