Manuscript ID: egusphere-2025-6519

Revised Title: Landscape- and site-scale spatial variability of blue carbon stocks and greenhouse gas fluxes in tropical intertidal seagrass meadows

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Dear Referee and Editor

Thank you very much for your constructive and thorough follow-up review of our manuscript. Your comments have greatly helped us to improve quality of our manuscript. Below, we provide a detailed response to each of your comments, outlining the exact theoretical framing, analytical adjustments, and text revisions (in blue font) implemented in the revised manuscript.

Comment 1: *"In L61–65, the discussion of CH_4 offsets and radiative balance remains unclear. First, please quantify what time scale is meant by 'sufficiently long-time scales' (e.g., 20 years, 100 years, or millennia). Second, please clarify whether the sites cited in Asplund et al. (2022) and Burkholz et al. (2020), as well as your own study sites, are restored or natural meadows, as CH_4 offsets of this magnitude are predominantly correct in constructed or restored sites rather than mature natural systems. As noted in my previous comment, comparing snapshot measurements of CH_4 and CO_2 fluxes to imply that one offsets the other is problematic. Radiative offset evaluations should consider the full ecosystem lifetime and sustained flux dynamics rather than comparing instantaneous flux magnitudes alone. Furthermore, Text in L61-65 feels disconnected from the core focus of the paragraph on geomorphic environmental gradients and GHG drivers. Please, re-evaluate this text or frame this around geomorphic settings."*

Response: We thank the reviewer for these points and have revised the passage accordingly.

Regarding the time scale, we have removed the vague phrase "sufficiently long-time scales" and now refer explicitly to standard 20- and 100-year Global Warming Potential horizons (Neubauer & Megonigal, 2015).

Regarding site status, we were unable to confirm from Asplund et al. (2022) and Burkholz et al. (2020) whether their sites are natural, restored, or constructed, and we therefore no longer characterize them as such. We instead note the broader pattern that CH_4 emissions of this magnitude are predominantly reported in constructed, restored, or disturbed systems, while clarifying that our own study sites are mature natural intertidal meadows (except Eagle Bay, a reclaimed lagoonal site), where fluxes are typically lower.

We agree that using instantaneous snapshot fluxes to imply that CH_4 "offsets" CO_2 accumulation is problematic, and we have removed the offset comparison (the "~12–78 times the CO_2 equivalents" statement and the associated net-radiative-balance claim). We now note only that a full radiative assessment requires sustained accounting over the ecosystem lifetime rather than instantaneous flux magnitudes.

Finally, to reconnect the passage with the paragraph's focus on geomorphic gradients and GHG drivers, we have reframed the text so that it links anoxia and organic-matter supply directly to how geomorphic settings modulate CH_4 production, leading into the Kirwan et al. (2023) hypothesis.

Location: Introduction, Section 1, Lines 61–69 (within the existing paragraph).

Revised Text: "However, the same anoxic conditions and high organic matter inputs in seagrasses that promote high C_{org} burial and sequestration can also favour the production and emission of greenhouse gases such as methane (CH_4) (Rosentreter et al., 2021). Seagrass meadows generally emit negligible to moderate CH_4 fluxes , (Asplund et al., 2022; Burkholz et al., 2020) although emissions of the higher magnitudes sometimes reported are more commonly associated with patchy seagrass cover associated with disturbed settings than with mature natural meadows (Halim et al., 2024). Because CH_4 flux magnitude is strongly linked with geomorphic setting and its surrounding environmental controls—such as organic matter loading, fine-sediment (mud) content, and electron acceptor availability—estuarine and sheltered lagoonal meadows, where C_{org} stocks are potentially higher, may also sustain conditions more conducive to methanogenesis than exposed or reef-associated settings. We note, however, that robustly assessing the climatic significance of these fluxes requires sustained accounting over the ecosystem lifetime e.g., 20- to 100-year Global Warming Potential horizons rather than comparisons of instantaneous flux magnitudes (Neubauer and Megonigal, 2015).

Location: Methodology, Section 2, Lines 85–86.

Revised Text: "The study was conducted on six mature natural intertidal seagrass meadows (except Eagle Bay, a reclaimed lagoonal site) across the tropical island state of Singapore (Fig. 1)."

Comment 2: (Section 3.3 & Discussion L258–259) *"In Section 3.3, and in discussion L258-259 authors state that geomorphology showed an overall effect in the multivariate CO2 driver model, suggesting indirect influence through linked environmental gradients. However, the text does not specify the direction or nature of this effect. Rather than stating only that an effect was present, please report which geomorphic settings exhibited higher or lower CO2 emissions relative to others, and clarify how these differences depended on specific environmental drivers."*

Response: We agree that reporting only the presence of an effect was incomplete. Both sections now specify direction, magnitude (adjusted EMMs with Tukey-corrected pairwise contrasts), and the drivers (water temperature, mud fraction, dissolved oxygen) through which geomorphology operates.

Location: Section 3.3 (Results, L242-246) and Section 4.2 (Discussion, L270–273).

Revised Text (Section 3.3): " Adjusted EMMs showed that estuarine settings had significantly higher baseline sediment-surface CO_2 emissions (38.2 ± 6.4 mg m^{-2} h^{-1}) than lagoonal (22.1 ± 5.1 mg m^{-2} h^{-1}) and reef-associated settings (20.4 ± 5.8 mg m^{-2} h^{-1}; Tukey-adjusted $p = 0.038$). These elevated estuarine emissions were associated with higher near-surface mud fractions and lower dissolved oxygen during low-tide exposure, while CO_2 fluxes across all settings declined significantly with increasing water temperature ($\beta = -12.4$, $p = 0.011$)."

Revised Text (Section 4.2): " However, in the multivariate CO_2 driver model that accounted for covarying environmental conditions (including temperature, oxygen and sediment texture), geomorphology showed an overall effect by structuring environmental gradients. Estuarine meadows promoted higher respiration than lagoonal and reef-associated settings through the combined influence of finer sediment texture (% mud) and lower surface-water oxygenation."

Comment 3: *"Line 270 attributes dark CO2 uptake to 'novel microbiota that can respire in the absence of light.' Virtually all plants, algae, and aerobic organisms respire in the dark. Please rephrase this sentence to clarify what specific novel metabolic pathway is being referenced."*

Response: We intended dark inorganic carbon *fixation*, not dark respiration, and have specified the chemosynthetic pathway involved.

Location: Discussion, Section 4.1, Line 284-86.

Revised Text: " However, this has been observed in other coastal ecosystems and linked to the presence of microbiota that can respire in the absence of light through novel metabolic pathway. This microbiota included acetogens, chemosynthetic microbes able to sequester CO_2 in dark conditions linked to chemoautotrophic pathways, in which chemolithoautotrophs and acetogens fix inorganic carbon without light via the Calvin-Benson-Bassham (CBB) and Wood–Ljungdahl pathway (Rodriguez et al., 2025)."

Comment 4: *"In L277, the text attributes CH4 consumption to sulfate-reducing bacteria. Sulfate reducers are obligate anaerobes involved in sulfate reduction and compete with methanogens; they do not consume CH4 (methanotrophy is driven by aerobic or anaerobic methanotrophs). Please revise this statement to reflect correct microbial ecology."*

Response: We appreciate this correction. Methane oxidation is performed by aerobic methanotrophs in oxic zones and by anaerobic methanotrophic archaea (ANME) via AOM in anoxic zones; ANME associate syntrophically with sulfate-reducing bacteria (SRB), but the SRB themselves reduce sulfate rather than oxidize CH_4. The text is corrected accordingly.

Location: Discussion, Section 4.1, Line 292-297.

Revised Text: "The relatively low CH_4 emissions observed likely reflect active methane consumption within sediment profiles. CH_4 produced in deeper anoxic zones is efficiently oxidized before reaching the atmosphere—by aerobic methanotrophs in surface oxic layers and by anaerobic methanotrophic archaea (ANME) operating in syntrophy with sulfate-reducing bacteria in anoxic sub-surface sediments (Orphan et al., 2001; Reeburgh, 2007). Such pathways can consume up to 90% of sediment-generated CH_4 (Reeburgh, 2007)."

Comment 5: *"In the discussion or limitations section, the authors should consider how sampling scale and driver ranges may constrain their findings. For instance, environmental drivers such as salinity or conductivity may not have emerged as key predictors of CH4 fluxes simply due to a narrow spatial range in Singapore (e.g., lacking a full oligohaline-to-euhaline gradient). Additionally, driver responses often operate on temporal scales distinct from* *snapshot spatial measurements. These constraints would provide important context for why certain expected predictor–response relationships were absent."*

Response: Thank you for your comment. We have expanded Sections 2.7 and 4.3 to note that (i) Singapore's polyhaline-to-euhaline range (22.4–31.3 psu) lacks a full oligohaline gradient, so salinity exerts little control on CH_4 here, and (ii) snapshot low-tide fluxes capture high-frequency exchange rather than the seasonal-to-decadal processes that structure sediment carbon pools.

Location: Methodological Limitations Section 2.7 L174-177and Discussion Section 4.3, L365-373

Revised Text (Section 2.7): "First, while we targeted high-resolution spatial replication within sites of ≤15 soil cores, 27 chambers per site, gas flux measurements are limited in temporal replication e.g., diel/seasonal variability and high-tide conditions and tidal range variability among sites were not sampled therefore the effect of driver responses which often operate on temporal scales such as salinity may constraint results."

Revised Text (Section 4.3): "However, we note that the absence of significant CH_4–salinity or CH_4–conductivity relationships must be interpreted within our sampling constraints. First, Singapore's polyhaline-to-euhaline seascape (22.4–31.3 psu) lacks the low-salinity conditions under which sulfate limitation typically enhances methanogenesis; within this narrow range, salinity exerts minimal control on CH_4 dynamics. Second, driver responses operate on temporal scales distinct from snapshot spatial measurements: low-tide static chambers capture instantaneous sediment–air exchange sensitive to short-term temperature and microtopography, whereas sediment carbon accumulation and microbial community structure integrate biogeochemical processes over seasonal to decadal scales. These scale mismatches explain why classical macro-scale predictor–response relationships were absent at our intermediate landscape scale."

Comment 6:*"L242: How 'plot-summed' stocks were calculated? Please, clarify why plot-summed carbon stocks were compared against plot-mean flux values, rather than using consistent spatial aggregation (e.g., plot means) across both stocks and fluxes."*

Response. We thank the reviewer for raising this, and we are happy to clarify. "Plot-summed" stock denotes the sum of C_{org} across successive 5 cm depth increments (0–5, 5–10, 10–15, 15–

20, 20–25 cm, or to refusal) within a plot's soil core—that is, it is simply the plot's 0–25 cm C_{org} stock. Because each plot was represented by a single core, this quantity already resides at the plot scale. Gas fluxes, by contrast, are more sensitive to fine-scale microclimatic variation in seagrass meadows than are soil stocks, so three flux chambers were deployed per plot and averaged to a plot-mean value. The stock–flux comparison was therefore made consistently at the plot level. We have revised the text to make this spatial consistency explicit.

Location: Section 3.3 (L252-256), and Figure 5.

Revised Text (Section 3.3): "To evaluate stock–flux relationships at a consistent spatial scale, we compared plot-level 0–25 cm C_{org} stocks (Mg C_{org} ha^{-1}) with plot-mean GHG fluxes. In a linear mixed model with site as a random intercept, plot-mean CO_2 flux decreased significantly with increasing plot-level C_{org} stock ($\beta = -8.61$, $p = 0.044$; Fig. 5a), whereas plot-mean CH_4 flux showed no detectable association ($\beta = -2.25$, $p = 0.469$; Fig. 5b)."

Comment 7: *"At L274, please report the full range of values for consistency, similar to how ranges are reported for CO2 fluxes."*

Response: L274 now reports minimum–maximum alongside the mean ± SD, matching the CO_2 reporting format.

Location: Discussion Section 4.1, Line 289-291.

Revised Text: "Plot-mean CH_4 emissions averaged 0.5 ± 18.2 µg m^{-2} h^{-1} (range −66.4 to 57.5 µg m^{-2} h^{-1}; n = 54 plots; Fig. 4), within the lower range of reported values of sediment-water and sediment-air CH_4 fluxes for tropical and temperate seagrasses in the region and globally."

Comment 8: Figure 1 Caption Restructuring *"The opening phrase of the Figure 1 caption ('extent of seagrass across Singapore') is confusing, as seagrass extent is not depicted on the main map. If this phrase refers to the site inset maps, please move this text into the inset description rather than using it as the opening sentence of the caption."*

Response: We thank the reviewer for this helpful observation. To clarify, seagrass extent is in fact depicted on the main regional map, but because Singapore's seagrass meadows occupy such a small area, they are barely discernible at the scale of the main map. This is precisely why inset maps were included—to make the seagrass extent visible for the two largest studied meadows. To avoid confusion, we have revised the caption so that the opening sentence describes the main regional site map, and the reference to the mapped seagrass extent is now carried in the inset description.

Location: Figure 1 Caption.

Revised Caption: "Figure 1. Locations of study sites across estuarine, lagoonal, and reef-associated geomorphic settings in Singapore (orange circles = estuarine; blue diamonds = lagoonal; green triangles = reef-associated). Seagrass extent across Singapore is shown on the main map but is barely visible owing to its limited areal cover; inset maps therefore show seagrass meadow boundaries (Tan et al., 2022) at higher resolution for the two largest studied meadows, Chek Jawa and Cyrene Reef."

Comment 9: Figure Axis Formatting (Subscripts and Superscripts) *"Ensure all figure axis labels use proper subscripts and superscripts for units and formulas."*

Response: Figures 2–5 have been re-rendered with correct typography throughout: chemical formulas as subscripts (CO_2, CH_4, C_{org}) and units as superscript exponents (Mg C_{org} ha^{-1}, mg m^{-2} h^{-1}, μg m^{-2} h^{-1}).

Location: Updated vector graphics for Figures 2, 3, 4, and 5.

Comment 10: *"Remove repetitive phrasing, such as lines 119–121 regarding core depth restrictions. Check lines 130–131 for duplicated words. I would recommend the authors to avoid non-specific terms like 'etc.' (e.g., L51, L347) with explicit lists."*

Response: We have made all requested edits: L51 — "etc." replaced with "water depth, hydrodynamic energy, and tidal exposure frequency"; L119–121 — redundant core-depth phrasing removed (already detailed in Section 2.3); L130–131 — duplicated wording corrected; L347 — "etc." replaced with "salinity, organic matter quality, sediment grain size, or plant biomass."