



Contrasting Catchment Characteristics and Carbonate Buffering Capacity Shape Acidification Susceptibility and CO₂ Source-Sink Dynamics in Tropical Lagoons

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Abstract. Coastal ecosystems face increasing anthropogenic pressure, driving acidification and shifting them from carbon sinks to sources, yet comparative assessments across contrasting catchment types remain limited, particularly in the Indian Ocean region. We investigated carbonate chemistry in two contrasting tropical Sri Lankan lagoons, Negombo Lagoon, impacted by intensive anthropogenic and marsh-derived inputs, and minimally disturbed Rekawa Lagoon. In Negombo, low-
25 pH, low total alkalinity (TA), and high-CO₂ river water and acid-sulfate marsh inputs, combined with weaker carbonate buffering, intensified acidification ($\text{pH} = 7.66 \pm 0.45$) and sustained CO₂ outgassing ($9.1 \pm 10.2 \text{ mmol m}^{-2} \text{ d}^{-1}$). The lowest pH and weakest buffering occurred in the inner lagoon, and increased toward the seawater inlet through river-sea mixing. In contrast, catchment-derived higher-pH, higher-TA, lower-CO₂ river water and strong buffering in Rekawa supported higher
30 pH (8.31 ± 0.52) and net CO₂ uptake ($-1.8 \pm 0.9 \text{ mmol m}^{-2} \text{ d}^{-1}$). Our simulations showed that riverine alkalinity enhancement (292-526 $\mu\text{mol kg}^{-1}$ TA addition) mitigated acidification and CO₂ outgassing in Negombo within 40-50 days. Our regional data synthesis showed that pH increased significantly with increasing TA/DIC ratio across estuaries and lagoons. These findings highlight carbonate buffering and catchment management as key strategies for mitigating coastal acidification and CO₂ emissions.



1 Introduction

35 Coastal ecosystems are dynamic and multifaceted interfaces between land and open ocean, serving as critical transition zones that regulate energy and material fluxes (Bauer et al., 2013; Hyndes et al., 2014; Gruber, 2015). Although they occupy a much smaller surface area than the open ocean (Laruelle et al., 2013), their high productivity accounts for nearly 9% of annual oceanic CO₂ uptake (Nemcek et al., 2008; Dai et al., 2022; Friedlingstein et al., 2022). Yet, the release of untreated or partially treated effluents from expanding human activities, including urbanization, industrialization, and agriculture, is
 40 increasing the partial pressure of CO₂ ($p\text{CO}_2$) in coastal waters, thereby accelerating acidification and compromising ecological integrity (Feely et al., 2010; Cai et al., 2011b). This effect is particularly pronounced in inland coastal systems, such as estuaries and lagoons, where elevated $p\text{CO}_2$ can cause the air-water interface to become a net source of CO₂ to the atmosphere (Rosentreter et al., 2023).

Rivers draining urbanized and agricultural landscapes often deliver acidic, nutrient- and carbon-enriched waters to lagoons,
 45 thereby altering their carbonate chemistry (Cai and Wang, 1998; Jiang et al., 2008; Abril et al., 2014). In addition, carbon-rich, acidic waters originating from adjacent marsh systems can be transported through rivers or discharged directly into lagoons, further influencing lagoon carbonate dynamics (Jiang et al., 2008; Neubauer and Anderson, 2003). Such inputs can stimulate primary production and enhance respiration, collectively modulating pH and $p\text{CO}_2$ dynamics (Hopkinson and Smith, 2005; Cai et al., 2011a; Cloern et al., 2014). The extent of these changes is further governed by the buffer capacity of
 50 coastal waters, which is determined by the balance between total alkalinity (TA) and dissolved inorganic carbon (DIC) (Eggleston et al., 2010; Hagens et al., 2015; Carstensen and Duarte, 2019). Natural enrichment of TA, for example through mineral weathering, can substantially strengthen this buffering capacity and thereby confer greater resistance to acidification and regulate $p\text{CO}_2$ changes (Kreuzburg et al., 2025; Bach and Boyd, 2021). Building on this understanding of the importance of buffering capacity in mitigating acidification and enhancing atmospheric CO₂ uptake, research on artificial alkalinity
 55 enhancement in coastal waters, whether through direct addition to seawater or via riverine dosing, has gained considerable momentum in recent years (Köhler et al., 2010; Bach, 2024; Mendes et al., 2025; Biçe et al., 2025). In addition, river-sea mixing processes strongly shape spatial and temporal variability in carbonate system parameters (Guo et al., 2008; Sarma et al., 2015).

Anthropogenic pressures on tropical coastal ecosystems such as lagoons and estuaries in the Indian Ocean are increasing, as
 60 much of the region is bordered by developing countries with intensive agricultural activities, high population densities, and poorly managed waste discharges (FAO, 2003; Wafar et al., 2011). In addition, such coastal systems in this region, when associated with large marsh systems, are further shaped by marsh-derived inputs that can substantially alter their carbonate chemistry (Koné and Borges, 2008; Proum et al., 2018). Despite this, comparative assessments of carbonate chemistry dynamics (especially with measured water-surface pH and $p\text{CO}_2$) across coastal systems experiencing differing catchment
 65 characteristics in the Indian Ocean remain limited. This study examines the spatiotemporal variability of measured pH, $p\text{CO}_2$, TA, and DIC along with calculated air-water CO₂ flux and carbonate buffer parameters, and their potential drivers in



two tropical Sri Lankan lagoons, Negombo Lagoon and Rekawa Lagoon, which differ markedly in catchment characteristics and anthropogenic influence. Negombo Lagoon is located in an urbanized area and is therefore likely to experience greater anthropogenic influence (Hsieh et al., 2021). In addition, it is hydrologically connected to the largest coastal peatland in Sri Lanka, the Muthurajawela marsh, which has experienced a substantial reduction in extent associated with ongoing urbanization (Athukorala et al., 2021). In contrast, Rekawa Lagoon is situated in a predominantly rural setting with comparatively limited direct human activity. Hence, we hypothesized that differences in catchment characteristics and associated land-derived inputs contribute to contrasting acidification susceptibility and air-water CO₂ source-sink dynamics between the two lagoons. Furthermore, we combine simulations with regional data synthesis to assess how changes in TA (natural or artificial) regulate the carbonate buffering capacity of coastal waters, thereby influencing their capacity to resist acidification and regulate CO₂ outgassing. Through this comparative approach, we aim to elucidate how catchment characteristics, carbonate buffer capacity, and associated biogeochemical and physical processes interact to influence lagoon carbonate system dynamics, thereby providing insights relevant to the management and preservation of coastal ecosystem integrity.

2 Materials and Methods

2.1 Study area

Two tropical lagoons in Sri Lanka, Negombo and Rekawa, were selected for this study (Figure 1). Negombo Lagoon is situated in the western region of Sri Lanka, whereas Rekawa Lagoon lies in the southern region. These lagoons experience two distinct monsoonal periods annually, categorized into southwest (wet season) and northeast (dry season) monsoons (Tomczak and Godfrey, 2003). During the onset of the southwest monsoon, heavy rainfall can be expected in the western and southern regions, whereas lower precipitation can be observed during the northeast monsoon (Amarathunga and Fernando, 2016).

Both Negombo and Rekawa are choked lagoons with narrow channels connecting them to the Indian Ocean (Figure 1). Negombo Lagoon is located in a highly urbanized, densely populated area and is therefore influenced by a range of human activities, including fishing and tourism (Table S1), as well as domestic wastewater inputs (Hsieh et al., 2021). The lagoon is bordered along its southern margin by the Muthurajawela Marsh (Athukorala et al., 2021), which contains acid sulfate soil (Vithana et al., 2022). Negombo Lagoon receives substantial freshwater input from two major rivers (Figure S1), the Ja-Ela River and Dandugam Oya River, which flow through an urbanized catchment. Both rivers connect to each other and drain through the marsh system before discharging into the lagoon at its southern end. Accordingly, the combined inflow from these rivers was treated as a composite end-member. The water residence time of the lagoon is about 2-14 days (Rydberg and Wickbom, 1996; Rajapaksha and Jayasiri, 2000).

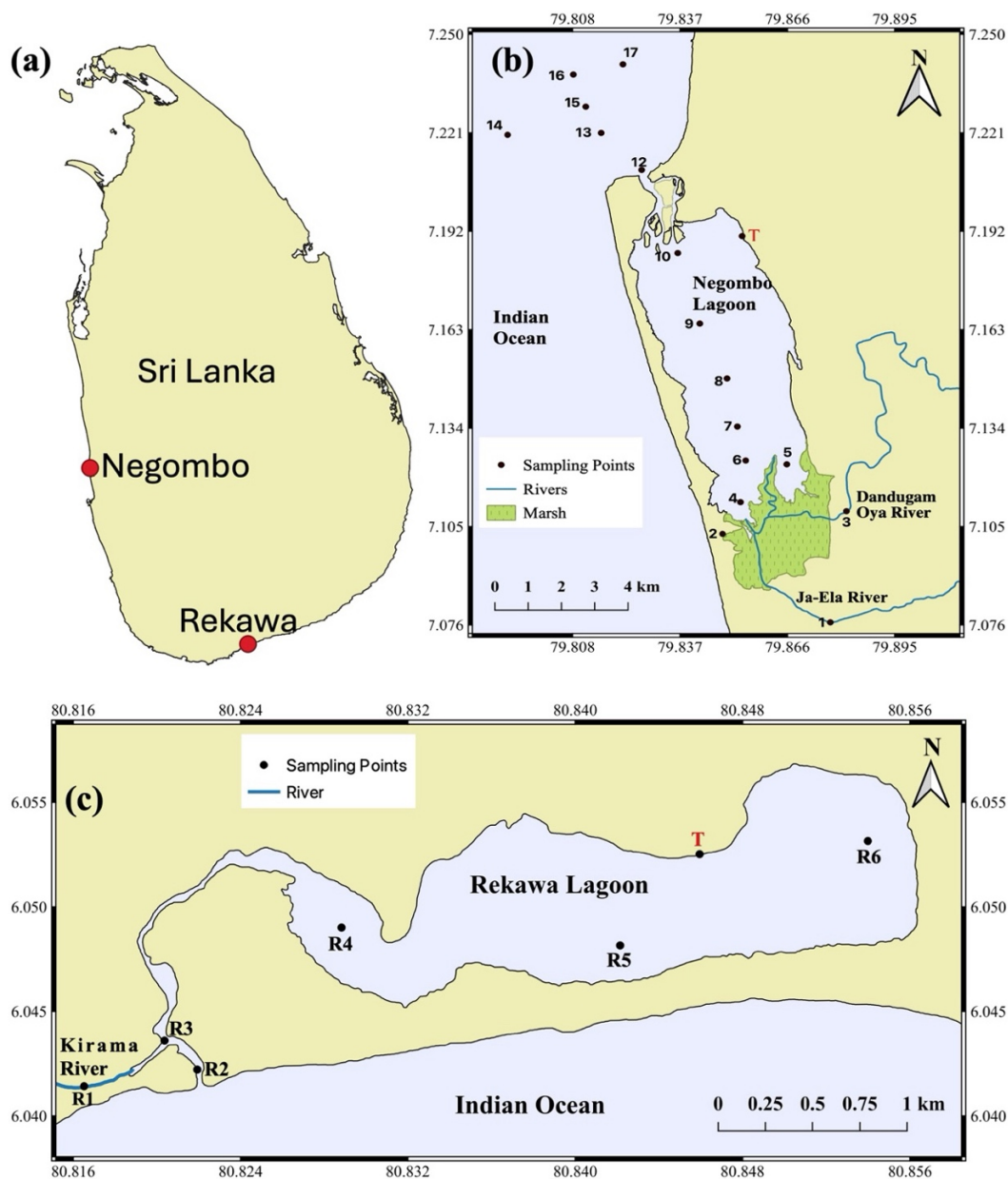


Figure 1. Maps showing the study region. (a) Locations of Negombo and Rekawa lagoons on the Sri Lanka map, (b) Negombo lagoon, and (c) Rekawa lagoon. Time-series stations are labeled “T”. In panel (b), the Muthurajawela marsh is highlighted in green.

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In contrast, anthropogenic pressures in Rekawa Lagoon are limited due to lower population density, reduced fishing and tourism activities (Table S1), and the lagoon is characterized by mangrove vegetation and seagrass meadows (Suwandhahannadi et al., 2023; Suwandhahannadi et al., 2024). The main freshwater source to Rekawa Lagoon is the



Kirama Oya (Gunaratne et al., 2010), which has a relatively lower discharge compared to the rivers feeding Negombo Lagoon. (Table S1). Rekawa Lagoon has a longer residence time, estimated to be around 30 days (Thushara and Wijeratne, 2007).

2.2 Data recording, sampling, and analysis

Field visits were conducted in both wet and dry seasons to investigate the spatial and temporal variations of carbonate system parameters (Table S2). The sampling period from February 2020 to August 2022 was impacted by the COVID-19 pandemic, resulting in an inconsistent sampling pattern during the study period from 2019 to 2023. During each field visit (a total of seven field campaigns), surface water samples were collected at pre-determined stations along the lagoons, as well as from a time series station at intervals of 3 to 6 hours (Figure 1) to measure dissolved inorganic carbon (DIC), total alkalinity (TA), and pH_{NIST}. Water samples were also collected from both river and ocean endmembers (Figure 1). Water was collected using a pre-cleaned plastic bucket, and immediate measurements were taken for water temperature (WTW Cond 3110, with an accuracy of ± 0.1 °C) and salinity (WTW Cond 3110, with an accuracy of ± 0.1). Filtered water samples (Whatman Polycap GW cartridge filter, 0.45 μ m) were transferred to 250 mL borosilicate bottles and subsequently poisoned with 100 μ L of HgCl₂. All samples were shipped back to Taiwan and stored in the laboratory at National Sun Yat-sen University at a controlled room temperature of 25 ± 1 °C until analysis was conducted.

DIC was measured using a DIC analyzer (AS-C6L, Apollo SciTech, precision: ± 2 μ mol kg⁻¹), which was connected to a CO₂/H₂O analyzer (LI-7000, LI-COR, accuracy: 1% nominal). TA was determined via open-cell gran titration, as originally described by Gran (1952) and further outlined by Huang et al. (2012), using the AS-ALK2 titration system (Apollo SciTech, precision: ± 1 -2 μ mol kg⁻¹). To ensure quality control of the data, certified reference materials were obtained from Andrew Dickson at Scripps Institution of Oceanography, USA. The pH of the water samples was assessed on the NIST scale using a Thermo Scientific Orion Star A211 benchtop pH meter, calibrated with buffer solutions of pH 4.01, 7.01, and 9.00 (HANNA, NIST-traceable, accuracy of ± 0.01 pH units at 25 °C).

Continuous measurements of water surface temperature, salinity, pH, and *p*CO₂ were conducted over 24-hour cycles at a time series station (Figure 1) using a laboratory-built autonomous buoy during field campaigns in October 2019 (wet season) and February 2023 (dry season). The instrument was equipped with a non-dispersive infrared CO₂ sensor (K30, Senseair; accuracy: $\pm 3\%$ of reading, range: 0-10000 ppm), a temperature sensor (PT-1000, Atlas Scientific; accuracy: ± 0.1 °C), a salinity sensor (ENV-10-EC-K1.0, Atlas Scientific; accuracy: $\pm 2\%$ of measured value), and a pH sensor (Atlas Scientific; accuracy: ± 0.01). The air-water equilibration method was used to determine *p*CO₂, and detailed descriptions of the instrument and methodology are provided in Weerathunga et al. (2024) and Yuan et al. (2026). Air temperature, wind speed, and rainfall data were obtained from the Department of Meteorology in Sri Lanka for the study period. Data were collected from the nearest weather stations to Negombo (Katunayake weather station) and Rekawa (Hambanthota weather station) lagoons.



2.3 Modelling and calculations

To quantify the changes in DIC and TA in surface lagoon waters under the mixing of freshwater from rivers and seawater, two end-member mixing models were performed following the method described by Huang et al. (2012; 2018) and Yao et al. (2020). Here, we assumed that salinity is a conservative parameter, thus linearly changing with the mixing of river water and seawater. The explanation for the river-sea mixing model is as follows,

$$DIC_{\text{mixing}} = ((S_S - S_i) \times DIC_{\text{River}} + (S_i - S_R) \times DIC_{\text{Sea}}) / (S_S - S_R) \quad (1)$$

$$TA_{\text{mixing}} = ((S_S - S_i) \times TA_{\text{River}} + (S_i - S_R) \times TA_{\text{Sea}}) / (S_S - S_R) \quad (2)$$

DIC_{mixing} and TA_{mixing} refer to the DIC and TA at a specific salinity point of two-end member mixing, where the seawater and river water salinities are S_S and S_R , respectively. S_i is the in-situ salinity at station “ith”. DIC_{River} and DIC_{Sea} denote the DIC of river and ocean endmembers, respectively. TA_{River} and TA_{Sea} refer to the TA of river and ocean endmembers, respectively. End-member values used for calculations are listed in the Supplementary Table S3.

The DIC_{excess} was calculated as the difference between measured DIC (DIC_{measured}) and calculated DIC from the two endmember mixing models (DIC_{mixing}) (Eq. 3). Similarly, TA_{excess} was calculated as the difference between measured TA (TA_{measured}) and calculated TA from the two endmember mixing models (TA_{mixing}) (Eq. 4).

$$DIC_{\text{excess}} = DIC_{\text{measured}} - DIC_{\text{mixing}} \quad (3)$$

$$TA_{\text{excess}} = TA_{\text{measured}} - TA_{\text{mixing}} \quad (4)$$

Mixing models and excess DIC and TA calculations were applied only to Negombo Lagoon, as mixing effects on carbonate system dynamics were minimal in Rekawa Lagoon. For Rekawa Lagoon, normalized TA (nTA) and normalized DIC (nDIC) were calculated to account for evaporation and precipitation effects, following the approach of Chou et al. (2021). Normalization was performed separately for the wet and dry seasons using seasonal mean salinities of Rekawa Lagoon.

The temperature sensitivity of pCO_2 ($\partial \ln pCO_2 / \partial T$) and salinity sensitivity of pCO_2 ($\partial \ln pCO_2 / \partial \ln S$) for each lagoon were calculated separately using the equations provided by Takahashi et al. (1993) and Sarmiento and Gruber (2006). Using these coefficients, the temperature-normalized pCO_2 ($TnpCO_{2w}$) and salinity-normalized pCO_2 ($SnpcO_{2w}$) values were determined following the methods outlined by Joesoef et al. (2015).

The air-water CO_2 flux was calculated based on the gradient between air pCO_2 (pCO_{2a}) and in-situ water pCO_2 (pCO_{2w}), the solubility of CO_2 (K_0) in seawater, and the gas transfer velocity (k) (Eq. 5). To account for uncertainty, four different gas transfer velocity models described by Wanninkhof (1992; Eq. 6), Nightingale et al. (2000; Eq. 7), Ho et al. (2006; Eq. 8), and Wanninkhof (2014; Eq. 9) were applied in Eq. 5, and the CO_2 fluxes were subsequently computed.

$$CO_2 \text{ Flux} = k \times K_0 (pCO_{2w} - pCO_{2a}) \quad (5)$$

$$k_{660}W92 = (0.31 \times U_{10}^2) \quad (6)$$

$$k_{660}N00 = (0.222 \times U_{10}^2) + (0.333 \times U_{10}) \quad (7)$$

$$k_{660}H06 = (0.266 \times U_{10}^2) \quad (8)$$

$$k_{660}W14 = 0.251 \times U_{10}^2 \quad (9)$$



170 Here, U_{10} refers to the wind speed at 10 m height. The air $p\text{CO}_2$ values were acquired from the NOAA monitoring laboratory, recorded at the site Bukit Kototabang in Indonesia.

To evaluate the relative contributions of physical and biogeochemical factors to air-water CO_2 exchange, we calculated fluxes normalized for temperature, salinity, and wind speed. Temperature-normalized and salinity-normalized CO_2 fluxes were calculated by substituting $p\text{CO}_{2w}$ in Eq. 3 with $Tnp\text{CO}_{2w}$ and $Snp\text{CO}_{2w}$, respectively. Similarly, wind-normalized CO_2 flux was computed by replacing the in-situ wind speed with the average wind speed recorded during each sampling campaign. For instance, deviations between the temperature-normalized flux and the in-situ flux may reveal the extent to which temperature variations influence CO_2 exchange. When the normalized fluxes for temperature, salinity, and wind closely track the in situ flux, it may suggest that variations in water surface $p\text{CO}_2$ could exert the dominant control on CO_2 flux variability.

180 The buffer parameters γ^{DIC} , γ^{TA} , β^{DIC} , and β^{TA} were determined using measured DIC, TA, temperature, and salinity, employing equations established by Egleston et al. (2010) (Eqs. 10 to 13). These calculations were conducted using the SeaCarb Package (Author: James Orr), implemented in R software (Version 1.4.1106).

$$\gamma^{\text{DIC}} = \left(\frac{\partial \ln[\text{CO}_2]}{\partial \text{DIC}} \right)^{-1} \quad (10)$$

$$\gamma^{\text{TA}} = \left(\frac{\partial \ln[\text{CO}_2]}{\partial \text{TA}} \right)^{-1} \quad (11)$$

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$$\beta^{\text{DIC}} = \left(\frac{\partial \ln[\text{H}^+]}{\partial \text{DIC}} \right)^{-1} \quad (12)$$

$$\beta^{\text{TA}} = \left(\frac{\partial \ln[\text{H}^+]}{\partial \text{TA}} \right)^{-1} \quad (13)$$

The γ^{DIC} and β^{DIC} represent the capacity of the lagoon water to buffer changes in CO_2 concentration ($[\text{CO}_2]$) and pH, respectively, in response to the variations in DIC. Values of these two parameters are always positive, and higher values indicate higher resistance to changes in CO_2 concentration and pH under increasing DIC. Conversely, γ^{TA} and β^{TA} denote the capacity of lagoon water to buffer changes in CO_2 concentration and pH, respectively, under the variations in TA. Values of these two parameters are always negative, and higher negative values indicate a higher ability to resist changes in CO_2 concentration and pH in lagoon water (Egleston et al. 2010).

2.4 Box-model simulation of carbonate system response to riverine TA perturbation

195 To evaluate the critical role of continuous natural TA enrichment from the river feeding Rekawa Lagoon in sustaining its characteristic carbonate chemistry, we performed a simulation in which the Rekawa River TA and DIC end-member values were replaced with the corresponding Negombo River TA and DIC values for the same season, using the same zero-

dimensional, well-mixed carbonate-system mass-balance model adapted from Sarmiento and Gruber (2006). The instantaneous rate of change of TA and DIC over time (t) in Rekawa Lagoon ($\frac{\partial TA}{\partial t}$ and $\frac{\partial DIC}{\partial t}$, respectively), when receiving river water with substituted (Negombo) TA and DIC concentrations (TA_{River} and DIC_{River} , respectively), were calculated using Eqs. 14 and 15, where TA_{Lagoon} and DIC_{Lagoon} represent lagoon TA and DIC concentrations, respectively, and τ is the lagoon water residence time (30 days).

$$\frac{\partial TA}{\partial t} = \frac{TA_{River} - TA_{Lagoon}}{\tau} \quad (14)$$

$$\frac{\partial DIC}{\partial t} = \frac{DIC_{River} - DIC_{Lagoon}}{\tau} \quad (15)$$

Differential equations were integrated using the forward Euler numerical method with a 0.5-day time step over a 150-day simulation horizon to resolve the approach toward riverine equilibrium. At each discrete numerical time step, the simulated TA and DIC concentrations were combined with the corresponding seasonal temperature and salinity and passed to PyCO2SYS (v1.8.3; Humphreys et al., 2024) to solve the nonlinear carbonate-system equilibria, generating time-series estimates of pH_{NIST} and the pCO_2 .

To evaluate whether enhanced alkalinity in its riverine end-member could mitigate acidification in Negombo Lagoon and shift it from a CO_2 source to a sink, we simulated a $CaCO_3$ alkalinity-enhancement scenario. Negombo Lagoon receives freshwater inflow from river discharge and marine exchange from tidal ocean inflow. The relative mixing fractions for riverine (f_{River}) and marine (f_{Ocean}) end-members were calculated as the proportion of volumetric discharge contributed by each respective water source to the total combined volumetric inflow. To evaluate alkalinity enhancement, simulated $CaCO_3$ dosing (D , $\mu mol\ kg^{-1}$) was applied to the riverine end-member, modifying inflow TA (TA_{River}^D) and DIC (DIC_{River}^D) assuming a 2:1 stoichiometric yield. The composite inflow TA_{inflow} and DIC_{inflow} concentrations entering the lagoon were defined through flow-weighted end-member mixing using Eqs. 16 and 17.

$$TA_{inflow} = (f_{River} \times TA_{River}^D) + (f_{Ocean} \times TA_{Ocean}) \quad (16)$$

$$DIC_{inflow} = (f_{River} \times DIC_{River}^D) + (f_{Ocean} \times DIC_{Ocean}) \quad (17)$$

An iterative search was performed over a riverine dose range (0 to $1000\ \mu mol\ kg^{-1}$), using increments of $10\ \mu mol\ kg^{-1}$. For each candidate dose, the resulting flow-weighted riverine-oceanic inflow TA and DIC concentrations were calculated and passed to PyCO2SYS (v1.8.3; Humphreys et al., 2024) to determine the corresponding carbonate chemistry. The minimum dose that simultaneously achieved the pre-industrial target conditions of $pH \geq 8.2$ and $pCO_2 \leq 280\ \mu atm$ was identified as the optimal dose. The selected dose was then incorporated into the riverine end-member and continuously supplied to the lagoon through the riverine inflow during the subsequent time-dependent simulation. By applying the optimally dosed river-endmember TA and DIC values to Eqs. 16 and 17, the optimal inflow concentrations of TA ($TA_{opt\ inflow}$) and DIC ($DIC_{opt\ inflow}$) were calculated. These optimized values were then applied to Eqs. 18 and 19 to calculate the corresponding instantaneous rates of change of TA and DIC over time (t) in Negombo Lagoon ($\frac{\partial TA}{\partial t}$ and $\frac{\partial DIC}{\partial t}$, respectively), where



TA_{Lagoon} and DIC_{Lagoon} represent lagoon TA and DIC concentrations, respectively, and τ is the lagoon water residence time (14 days).

$$\frac{\partial \text{TA}}{\partial t} = \frac{\text{TA}_{\text{opt inflow}} - \text{TA}_{\text{Lagoon}}}{\tau} \quad (18)$$

$$\frac{\partial \text{DIC}}{\partial t} = \frac{\text{DIC}_{\text{opt inflow}} - \text{DIC}_{\text{Lagoon}}}{\tau} \quad (19)$$

Then, following the same approach used for the Rekawa Lagoon calculations, the simulated TA and DIC time series were combined with the corresponding seasonal mean temperature and salinity and input into PyCO2SYS (v1.8.3; Humphreys et al., 2024) to calculate the time-series estimates of pH_{NIST} and the $p\text{CO}_2$.

To quantify and propagate uncertainty in the simulations for both lagoons, we employed a Monte Carlo framework with 1,000 realizations. For each realization, TA, DIC, temperature, and salinity were independently sampled from normal distributions defined by their respective measured means and standard errors (SE). Each randomized parameter set was then propagated through the time-dependent mass-balance model and PyCO2SYS (v1.8.3; Humphreys et al., 2024) calculations.

The resulting ensemble of simulations was used to estimate uncertainty in the simulated pH_{NIST} and the $p\text{CO}_2$. The mean riverine, oceanic, and lagoon DIC and TA concentrations, temperature, salinity, and lagoon physical characteristics used as model inputs are provided in Tables S1, S3, and S4.

3 Results and Discussion

3.1. Catchment Pressure Drives Coastal Acidification and CO₂ Outgassing

Contrasting pH and air-water CO₂ exchange dynamics observed in Negombo and Rekawa may reflect differences in catchment pressure and material delivery. Water pH in Negombo Lagoon was lower during the wet season (mean = 7.38 ± 0.49) than during the dry season (mean = 7.83 ± 0.44) (Figure 2a and 2b). During both seasons, the lowest pH occurred in the low-salinity inner lagoon near the river mouth (Figure 2a and 2b), reflecting the influence of river water, whose pH was 6.49 ± 0.08 in the wet season and 6.82 ± 0.20 in the dry season. Negombo Lagoon consistently acted as a net source of atmospheric CO₂ (annual average of $9.1 \pm 10.2 \text{ mmol m}^{-2} \text{ d}^{-1}$) both during wet and dry seasons (Figure 3a and 3b), corresponding to annual emissions of approximately 4.6 kt-CO₂. In contrast, Rekawa Lagoon maintained a consistently higher pH across both seasons (Figure 2e and 2f). The mean pH of Rekawa was 8.03 ± 0.36 during the wet season and 8.72 ± 0.36 during the dry season. River water entering Rekawa had a higher pH than that entering Negombo during both the wet (pH = 7.72) and dry (pH = 7.79) seasons. Meanwhile, Rekawa consistently acted as a net sink of atmospheric CO₂ (annual average of $-1.8 \pm 0.9 \text{ mmol m}^{-2} \text{ d}^{-1}$), with annual uptake about 0.1 kt-CO₂ (Figure 3c).

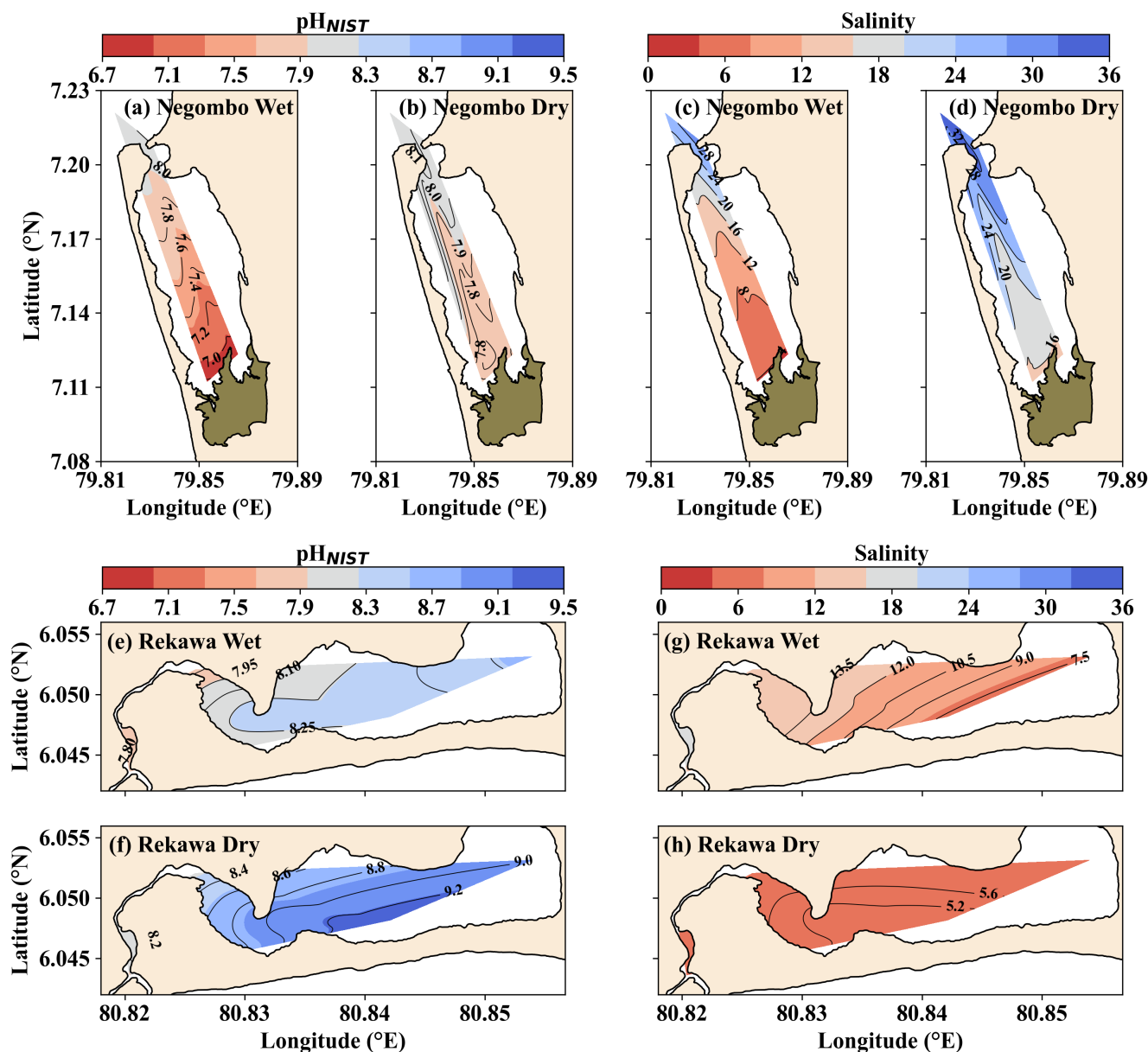
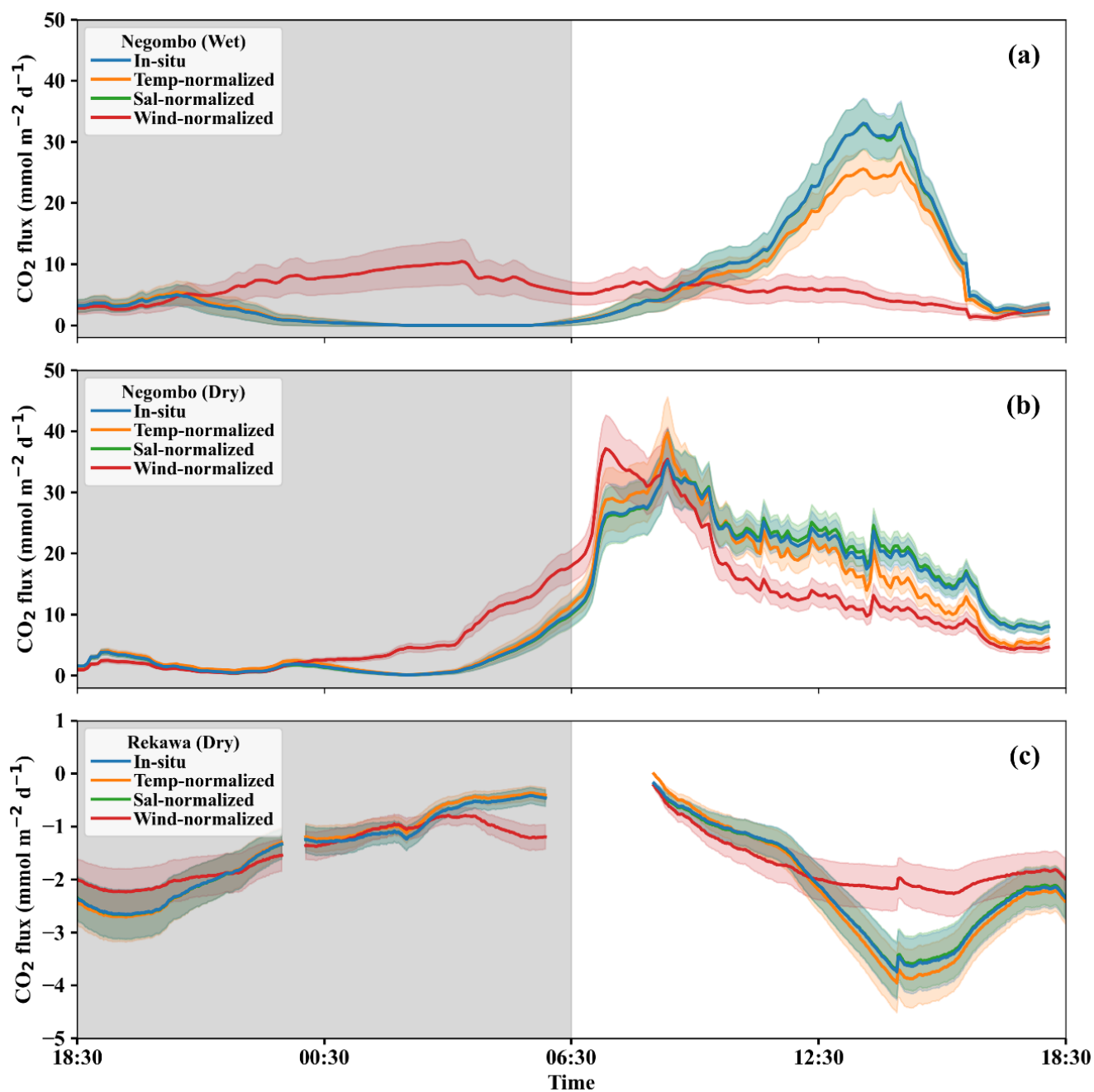


Figure 2. Spatial variations of pH_{NIST} (a, b, e, f) and salinity (c, d, g, h) during wet and dry seasons in Negombo Lagoon (a-d) and Rekawa Lagoon (e-h). Contour lines show interpolated isolines, with values labeled directly on each panel. The brown shaded area in (a) to (d) denotes the Muthurajawela Marsh bordering Negombo Lagoon. Data were interpolated onto a regular grid using cubic interpolation of discrete field measurements.



265 **Figure 3. Diurnal variations of air-water CO₂ fluxes (a) during the wet season (October 2019) in Negombo Lagoon, (b) during the dry season (February 2023) in Negombo Lagoon, and (c) during the dry season (February 2023) in Rekawa Lagoon. Shaded areas refer to the nighttime (18:30 to 6:30), and the non-shaded regions refer to daytime (6:30 am to 18:30). The Shaded envelopes around the lines denote ±1 standard deviation derived from fluxes calculated using four different gas transfer velocity parameterizations.**



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Substantial anthropogenic pressure around Negombo Lagoon, compounded by material inputs from the adjacent large marsh system, may drive pronounced acidification and persistent CO₂ outgassing. Anthropogenic pressure within Negombo Lagoon and its catchment is intensive, with population density, tourism, and fishing pressure all substantially greater than around Rekawa (Table S1), generating large organic matter and nutrient loads. Such material loading is reinforced by the marsh system bordering the southern part of Negombo Lagoon, whose soils are enriched in acid sulfate materials and organic carbon (Vithana et al., 2022) and are characterized by low soil and porewater pH, ranging from 2.5 to 7.5 (Dissanayake, 1984; Pitawala et al., 1994). Rivers draining into Negombo Lagoon first pass through the urbanized catchment, picking up organic carbon matter and nutrient loads, before flowing through the marsh system, where they acquire acidified, organic matter-rich soil water, arriving at the lagoon already substantially altered by both sources (Figure 1b and S1). Consequently, rivers draining into Negombo Lagoon deliver acidified, high-CO₂ waters (Table S3) enriched in nutrients and organic carbon (Hsieh et al., 2021). In addition to riverine transport, the marsh may also exchange water and material directly with the inner lagoon. Acid-sulfate soils release large amounts of acidity upon exposure to oxygen (Burton et al., 2006), and ongoing urban expansion within the marsh area may increase soil oxidation (Vithana et al., 2022), thereby intensifying acidification within the lagoon. Moreover, a large garbage dumping site adjacent to the inner lagoon (Figure S1) may further add nutrient and organic-matter loading through leaching. Following the delivery of organic matter and nutrient loading from all these sources, the inner lagoon may itself become a site of enhanced acidification. The accumulated organic matter fuels respiration and decomposition within the lagoon, promoting eutrophication in both wet and dry seasons (Hsieh et al., 2021). These processes directly elevate DIC and *p*CO₂, driving acidification and sustaining persistent CO₂ outgassing. These localized processes produce a pronounced along-lagoon acidification gradient, with the lowest pH in the inner lagoon, increasing progressively toward the seawater inlet during both wet and dry seasons (Figure 2a and 2b).

The catchment of Rekawa Lagoon presents a contrasting profile. The river feeding Rekawa Lagoon exhibits higher pH and lower *p*CO₂ values (Table S3), consistent with drainage through a catchment with relatively limited anthropogenic disturbance (Figure S2). This area also serves as an important sea-turtle nesting ground and is designated a protected conservation area by the Sri Lankan Department of Wildlife, which restricts extensive land-use change and other human activities in the surrounding catchment (IUCN, 2005; Dushani et al., 2021). As a result, population density, tourism, and fishing pressure around Rekawa Lagoon are substantially lower than around Negombo Lagoon (Table S1). Moreover, unlike Negombo, Rekawa Lagoon has no adjacent large marsh system. Mangroves and associated vegetation fringe the lagoon instead (Cooray et al., 2021; Dushani et al., 2023; Suwandhahannadi et al., 2024), contributing organic matter and nutrient inputs, but likely at a scale far smaller than the acidic, organic-rich fluxes reaching Negombo from its marsh and urban catchment. Hence, these contrasting catchment characteristics likely mitigate acidification (Figure 2e and 2f) in Rekawa Lagoon and favor its function as a net CO₂ sink (Figure 3c).



3.2 Contrasting Carbonate Buffering Capacity Governs the pH and CO₂ Dynamics

Carbonate buffer capacity varies sharply between the two lagoons, causing them to respond differently to comparable biogeochemical forcing. The TA/DIC ratio in Negombo Lagoon was significantly lower in both seasons, meaning its water is intrinsically less able to resist pH and $p\text{CO}_2$ change for a given perturbation in DIC or TA (Figure 4a). Significantly higher TA/DIC ratio in Rekawa Lagoon confers correspondingly stronger resistance (Figure 4a). These contrasting carbonate buffering capacities are directly reflected by the calculated buffer factors. The β^{DIC} and β^{TA} buffer factors, which quantify the lagoon's capacity to resist pH change in response to changes in DIC and TA (Egleston et al., 2010), respectively, were both significantly weaker in Negombo than in Rekawa (Figure 4b and 4c). A weaker buffer factor in Negombo means that a given input of CO₂ or acidic water (from the marsh, rivers, or within-lagoon respiration and decomposition) produces a proportionally larger drop in pH, whereas Rekawa's stronger buffering resists pH changes from comparable inputs of CO₂ and acidified water far more effectively. The γ_{DIC} and γ_{TA} buffer factors, which quantify the lagoon's capacity to resist $p\text{CO}_2$ change for a given change in DIC and TA (Egleston et al., 2010), showed the same pattern; both were significantly weaker in Negombo than in Rekawa (Figure 4d and 4e). Consequently, CO₂ accumulation drives a disproportionately large rise in $p\text{CO}_2$ in Negombo Lagoon. Rekawa, by contrast, can absorb CO₂ effectively, producing only a comparatively small change in $p\text{CO}_2$.

The stronger carbonate buffering capacity of Rekawa Lagoon is best understood as the result of several compounding, mutually reinforcing processes rather than any single mechanism. First, the TA concentration and TA/DIC ratio of the river feeding Rekawa Lagoon are both higher than those of the river feeding Negombo Lagoon (Table S3). This higher river TA can be attributed to catchment geology. The region surrounding Rekawa Lagoon contains land-based seashell deposits (Katupotha et al., 2003) and Miocene limestone beds within the river's catchment (IUCN, 2006), providing continuous natural enrichment of TA to the lagoon. To directly test the importance of this natural TA enrichment, we simulated a counterfactual scenario in which the TA and DIC of the river feeding Rekawa Lagoon were replaced with the corresponding seasonal values from the river feeding Negombo Lagoon. Under this substitution, simulated pH declined (Figure 5a), while simulated $p\text{CO}_2$ rose sharply (Figure 5b) in both the wet and dry seasons, indicating that Rekawa Lagoon would lose much of its buffering capacity if it received river water having lower TA and a lower TA/DIC ratio. This result demonstrates that the naturally elevated TA supplied by the river enhances the Rekawa Lagoon's carbonate buffering capacity, thereby mitigating acidification and supporting its persistence as a net CO₂ sink. Second, seasonal seagrass proliferation in Rekawa (Suwandhahannadi et al., 2023) likely draws down DIC directly through photosynthesis while indirectly sustaining primary production through enhanced nutrient recycling (Orth et al., 2006). Furthermore, the shallow depth of Rekawa Lagoon (mean depth ≈ 0.5 m) allows efficient light penetration, amplifying primary production and thereby driving DIC removal relative to TA.

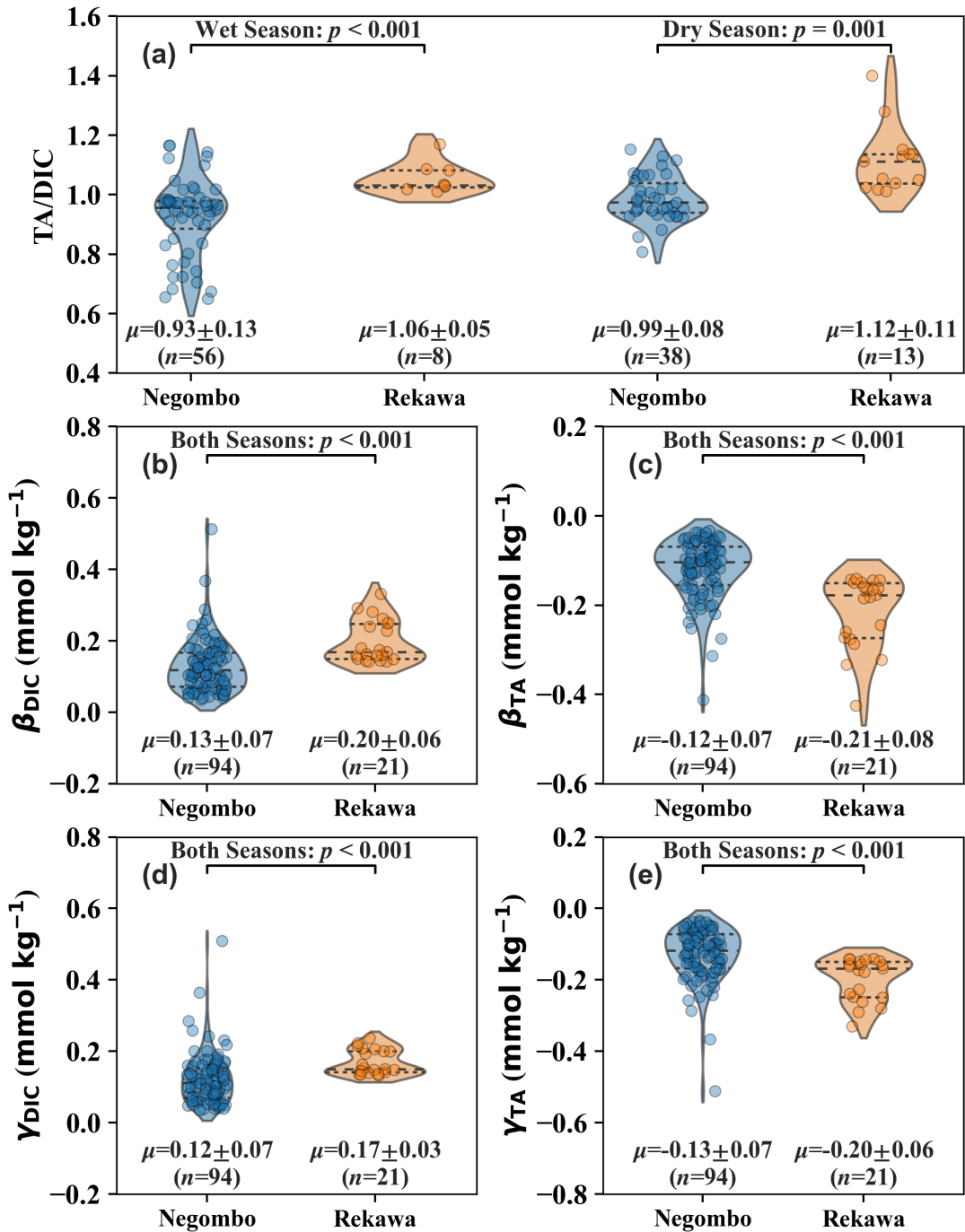


Figure 4. Contrasting carbonate buffering capacity between Negombo and Rekawa lagoons. (a) TA/DIC ratio during the wet and dry seasons in both lagoons. (b–e) Buffer factors β_{DIC} , β_{TA} , γ_{DIC} and γ_{TA} respectively, combined across both seasons. Violin plots show the full data distribution, with individual measurements; horizontal lines within each violin indicate the quartiles. Mean $\pm$ standard deviation (n) is reported below each distribution. Brackets denote pairwise comparisons between lagoons (two-sample t-test), with p -values shown above each bracket.

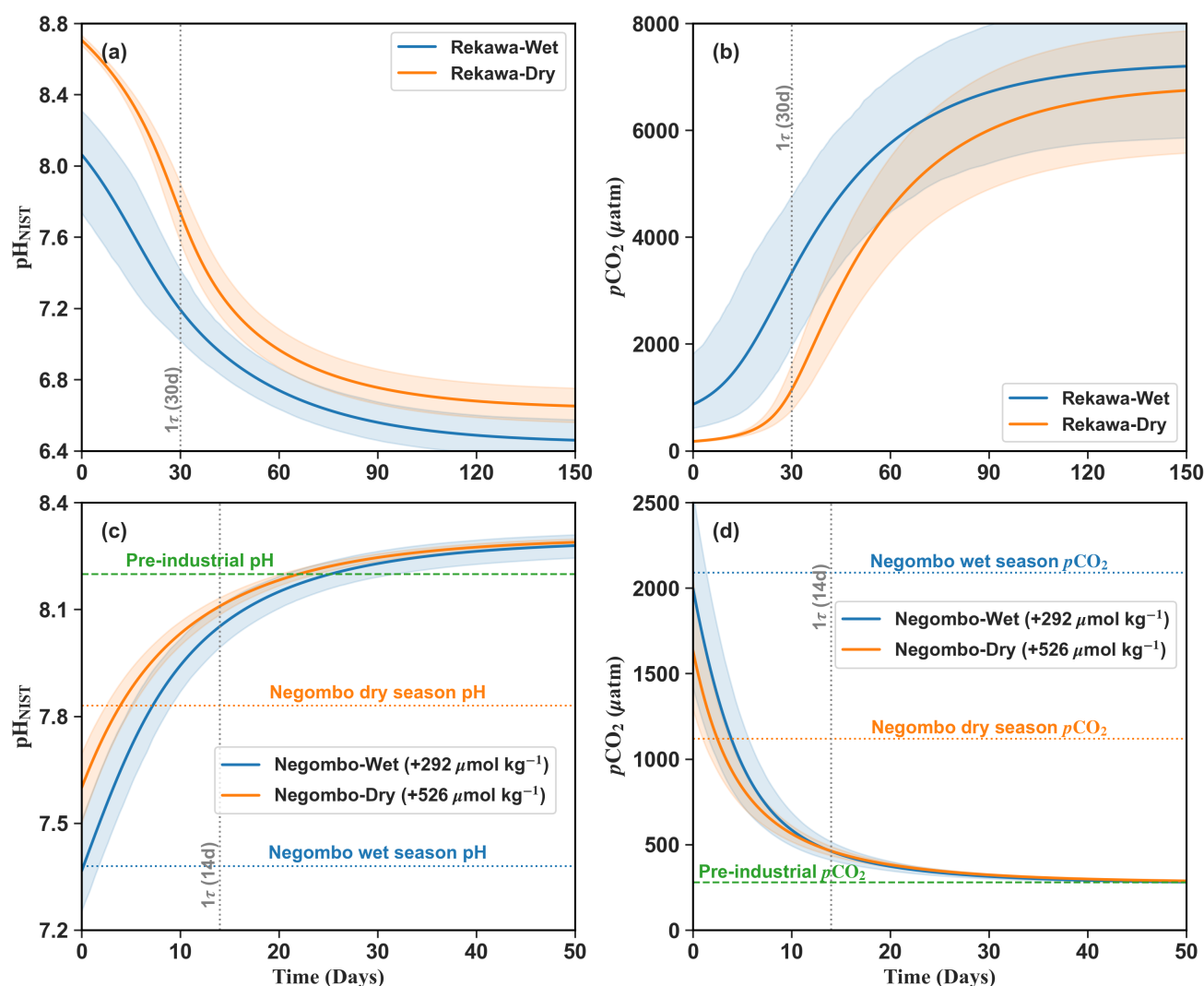


Figure 5. Simulated response of lagoon carbonate chemistry to riverine alkalinity enhancement. (a) Simulated pH_{NIST} and (b) pCO_2 in Rekawa Lagoon under the counterfactual scenario in which its river TA and DIC end-members are replaced with the corresponding seasonal Negombo River values, illustrating the lagoon's projected trajectory in the absence of its naturally TA-enriched river input. (c) Simulated pH_{NIST} and (d) pCO_2 in Negombo Lagoon under the optimal $CaCO_3$ river-dosing scenario identified to meet pre-industrial target conditions ($pH \geq 8.2$, $pCO_2 \leq 280 \mu atm$). Solid lines show the ensemble mean and shaded bands show the 95% confidence interval. Vertical gray dotted lines mark one lagoon water residence time (τ).

A closely analogous system, the shallow (mean depth ≈ 0.5 m), seagrass-dominated Dongsha Inner Lagoon in Taiwan, shows the same combination of strong acidification buffering and net CO_2 uptake (Chou et al., 2021; Chou et al., 2025), where sulfate reduction in organic-rich sediments releases H_2S that diffuses into carbonate-mineral-rich oxic layers, drives carbonate dissolution, and releases additional TA to the overlying water. The normalized TA-DIC relationship in Rekawa



(Figure S3b) could be consistent with this combination of primary production, sulfate reduction, and carbonate dissolution, suggesting that similar sediment-mediated pathways may also operate in Rekawa Lagoon. These similarities imply that mechanisms analogous to those identified in Dongsha Lagoon may also contribute to the part of elevated buffering capacity observed in Rekawa Lagoon. However, targeted geochemical investigations integrating sediment processes with surface water carbonate system measurements are required in the future to fully resolve the relative importance of these pathways.

3.3 River-Sea Mixing Shapes Spatial Variations in the Carbonate System

Mixing between riverine and seawater end-members with contrasting carbonate chemistry, together with the strength of mixing, structures the spatial variation of pH, TA, and DIC within each lagoon. In Negombo Lagoon, water surface salinity increased steadily from the inner lagoon (near the river mouth) toward the outer lagoon (closer to the sea) in both seasons (Figure 2c and 2d), reflecting the underlying river-sea mixing gradient. The quantitative signature of this mixing is unambiguous, as both TA and DIC showed strong, significant relationships with salinity in both seasons, and these relationships closely tracked the predictions of two end-member mixing models (Figure 6a and 6b, Table S5). The TA/DIC ratio itself varied significantly along this gradient, lowest in the low-salinity inner lagoon, and increasing progressively toward the high-salinity outer lagoon (Figure 6c, Table S5). This shows that river-sea mixing shapes not only DIC and TA concentrations, but also carbonate buffering capacity, as the inner lagoon could be weakly buffered while the outer lagoon, closer to seawater, could be strongly buffered. Following these along-lagoon variations, pH increased from the inner to the outer lagoon during both seasons (Figure 2a and 3b), directly reflecting the mixing of low-pH river water with high-pH seawater (Table S3). This along-lagoon pH gradient was more pronounced during the wet season than the dry season, following the similarly sharper salinity gradient during that period. Rainfall during the wet season was more intensive than during the dry season in the Negombo Lagoon region (Figure S4e, Table S1). Such higher wet-season rainfall may increase river discharge (Table S1), delivering more organic carbon, nutrients, and acidic water to the inner lagoon, which may consequently become both fresher and lower in pH.

River-sea mixing has no significant effect on Rekawa Lagoon's carbonate chemistry, although river discharge still may influence its spatial pH pattern. Salinity was significantly lower during the dry season than during the wet season (Figure 2g and 2h, Table S4), attributable to the intermittent connection of the lagoon to the ocean, which occurs only during the wet season. Neither TA, DIC, nor the TA/DIC ratio showed a significant relationship with salinity in either season (Figure 6a-6c, Table S5), indicating that physical mixing is not a dominant control on carbonate chemistry gradients in Rekawa Lagoon. Yet pH increased from the outer lagoon (near the river mouth) toward the inner lagoon in both seasons (Figure 2e and 2f). Water pH was lower in the outer lagoon during the wet season, when river discharge was higher (Table S1), and river-water pH was slightly lower (Table S3), indicating that river input still measurably shapes spatial and seasonal patterns despite the absence of a significant river-sea mixing process.

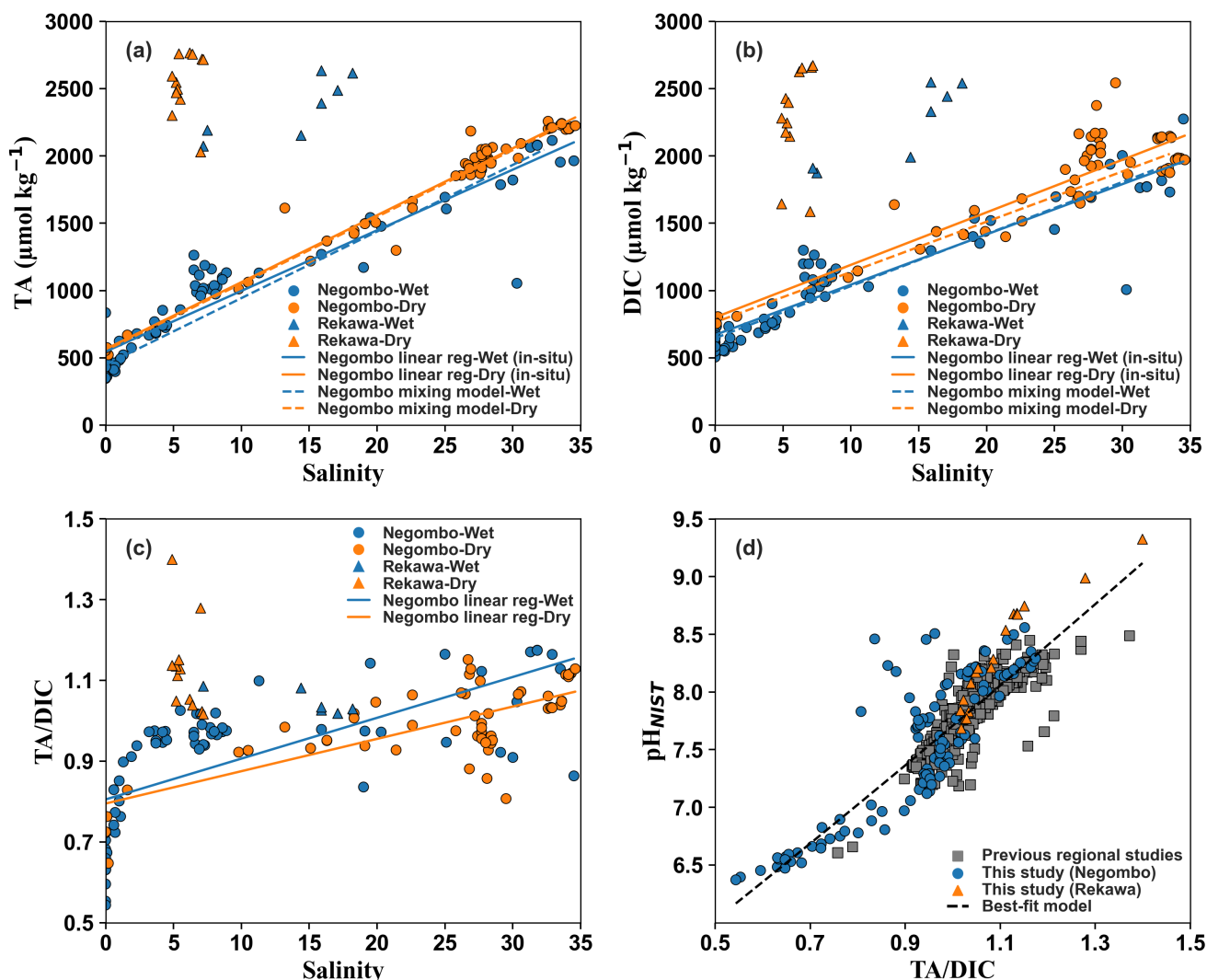


Figure 6. Carbonate system gradients and mixing relationships. River-sea mixing effects on (a) TA, (b) DIC, and (c) the TA/DIC ratio during wet and dry seasons in Negombo and Rekawa lagoons. (d) Relationship between pH_{NIST} and TA/DIC ratio, based on combined data from this study and previously published lagoon and estuarine studies in the region. Solid circles, triangles, and squares denote observations from Negombo Lagoon, Rekawa Lagoon, and previous regional studies, respectively. Sources of the regional data are listed in Supplementary Table S6.

3.4 Biogeochemical and Physical Forcing on Carbonate System Dynamics

Diurnal variations in pH, $p\text{CO}_2$, and air-water CO_2 flux in Negombo Lagoon can be driven by biogeochemical processes such as photosynthesis, respiration, and sulfate reduction. Water surface pH exhibited pronounced diurnal cycles, increasing during the daytime and declining at night (Figure S5c). Water surface $p\text{CO}_2$ followed an inverse diurnal pattern, decreasing



during the day and rising at night (Figure S5d). These diurnal patterns closely follow air and water temperature variations, both of which track the strength of solar radiation received by these shallow water bodies (Shinohara et al., 2021; Weerathunga et al., 2024). Air temperature (Figure S4a) and water temperature (Figure S5a) increased during the daytime, indicating strong solar radiation input. Increased solar radiation during the day can enhance photosynthetic rates, resulting in elevated pH and decreased $p\text{CO}_2$ (Yang et al., 2019). Conversely, the absence of solar radiation at night suppressed photosynthesis, leading to a decline in pH and an increase in $p\text{CO}_2$ as respiration becomes dominant.

Furthermore, deviations of some DIC and TA values from the mixing model predictions in Negombo may indicate contributions from biogeochemical processes (Figure 6a and 6b). Superimposed on the mixing signal, the $\text{TA}_{\text{excess}} - \text{DIC}_{\text{excess}}$ relationships in Negombo Lagoon indicate a combined influence of primary production and sulfate reduction during the wet season, whereas during the dry season, the signal falls between respiration and sulfate reduction (Figure S3a). In brackish water systems such as Negombo Lagoon, which receive substantial organic matter inputs, sulfate reduction is expected to be particularly active, especially within sediments and pore waters (Raymond et al., 2000; Chou et al., 2021). The release of H_2S produced during sulfate reduction into the water column, followed by its re-oxidation, can also contribute to lagoon acidification.

Similar diurnal patterns were observed in Rekawa Lagoon, though with substantially smaller amplitude than in Negombo. Water pH followed the same day-night cycle, rising during the day and falling at night, but remaining consistently high (ranging from 8.33 to 8.91) throughout the day (Figure S5g). Water surface $p\text{CO}_2$ likewise decreased during the day and increased at night, yet staying undersaturated relative to the atmosphere at all times (Figure S5h). Although these diurnal variations are smaller, biogeochemical influence is nonetheless evident from the normalized TA and DIC relationship, which likely reflects the combined signals of sulfate reduction, carbonate dissolution, and primary production (Figure S3b). This suggests that the influence of these biogeochemical processes on pH and $p\text{CO}_2$ variability is dampened by the higher carbonate buffer capacity of Rekawa Lagoon (Figure 4). In contrast, the combination of weaker buffer capacity (Figure 4) and intensive biogeochemical processes in Negombo Lagoon likely drives its much larger diurnal variations.

To disentangle these biogeochemical effects from physical controls, we also quantified the sensitivity of $p\text{CO}_2$ to changes in water temperature and salinity in both lagoons. In Negombo, temperature sensitivity of $p\text{CO}_2$ ($\partial \ln p\text{CO}_2 / \partial T$) was determined to be $0.0304 \pm 0.0006 \text{ } ^\circ\text{C}^{-1}$. Salinity sensitivity of $p\text{CO}_2$ ($\partial \ln p\text{CO}_2 / \partial \ln S$) was determined to be 0.32 ± 0.1 . The temperature sensitivity coefficient of $p\text{CO}_2$ in Rekawa Lagoon was $0.0394 \pm 0.0004 \text{ } ^\circ\text{C}^{-1}$, while salinity sensitivity of $p\text{CO}_2$ was determined to be 0.48 ± 0.02 .

As our time series data were collected only at a single, pre-determined location in each lagoon, we acknowledge that the observed trends and magnitudes of diurnal variations in pH and $p\text{CO}_2$ may not be uniform across the lagoons. Time series measurements were conducted during both the wet and dry seasons in Negombo Lagoon, enabling a comprehensive assessment of seasonal dynamics. In contrast, our time series measurements in Rekawa Lagoon were limited to the dry season due to logistical constraints. While we observed clear differences in the magnitude of diurnal pH and $p\text{CO}_2$ variations



430 between the two lagoons, conducting measurements across all seasons in both lagoons would provide a more comprehensive understanding of these dynamics.

3.5 Drivers of Temporal Variability in Air-Water CO₂ Flux

Variations in water surface $p\text{CO}_2$ and wind speed are primary drivers of the seasonal and diurnal dynamics of air-water CO₂ flux. During the wet season in Negombo Lagoon, $p\text{CO}_2$ remained consistently above 800 μatm throughout the day (Figure S5d), sustaining CO₂ outgassing (Figure 3a). Despite $p\text{CO}_2$ being lower during the day than at night, in-situ CO₂ fluxes were paradoxically higher during the day, peaking between 13:00 and 14:30, coinciding with the period of highest wind speed (Figure S4c). This indicates that wind speed, rather than $p\text{CO}_2$ alone, controlled the diurnal flux pattern during the wet season, as confirmed by substantial discrepancies between in-situ and wind-normalized CO₂ fluxes during the daytime (Figure 3a). The largest differences between in-situ and temperature-normalized fluxes occurred between 11:30 and 15:30 (Figure 3a), coinciding with peak water temperature (Figure S5a), indicating that temperature also exerted a secondary influence on daytime flux variability. During the dry season, $p\text{CO}_2$ reached its maximum in the morning (Figure S5d), which corresponded with peak CO₂ fluxes (Figure 3b), suggesting that water surface $p\text{CO}_2$ exerted a stronger control over air-water CO₂ exchange than wind speed during this period. Discrepancies between in-situ and wind-normalized fluxes were smaller during the dry season, while only minor daytime differences were evident between in-situ and temperature-normalized fluxes (Figure 3b). The close agreement between in-situ and salinity-normalized fluxes throughout both seasons indicates that salinity variations exerted little influence on the diurnal variability of CO₂ flux (Figure 3a and 3b).

Rekawa Lagoon functioned as a consistent sink for atmospheric CO₂, exhibiting relatively small diurnal variations in flux (Figure 3c). Lower water surface $p\text{CO}_2$ (Figure S5h) combined with relatively steady daytime wind speeds (Figure S4d) may lead to enhanced CO₂ uptake during the day relative to nighttime (Figure 3c). Furthermore, the largest differences between in-situ and wind-normalized fluxes occurred around 14:00, suggesting that strong winds enhanced CO₂ uptake during this time window (Figure 3c). In-situ CO₂ fluxes closely aligned with both temperature- and salinity-normalized fluxes, indicating that variations in temperature and salinity have minimal effect on the diurnal variability of CO₂ exchange in Rekawa Lagoon (Figure 3c).

Here, CO₂ fluxes were calculated using gas transfer velocity parameterizations developed for the open ocean, which may introduce uncertainty when applied to shallow, semi-enclosed lagoon systems (Rosentreter et al., 2017). To partially address this limitation, we employed four commonly used gas transfer velocity formulations and report the mean CO₂ flux together with the associated standard deviation, thereby providing an estimate of the uncertainty arising from differences among parameterizations.

3.6 Summary and Implications

460 Water pH and CO₂ dynamics in shallow tropical lagoons are governed by the interplay among catchment-derived material loading, carbonate buffering capacity, and the physical and biogeochemical processes that modulate them across space and



time, as illustrated by our conceptual diagram (Figure 7). In Negombo Lagoon, intensive urbanization and hydrological connection to an acid-sulfate marsh together deliver acidified, low TA, and high CO_2 water to the inner lagoon, causing intense acidification and a lower TA/DIC ratio, and therefore weaker buffering capacity (Figure 7a). River-sea mixing then produces a corresponding pH and TA/DIC gradient along the lagoon, from the strongly acidified, weakly buffered inner lagoon to the higher-pH, more strongly buffered outer lagoon. This catchment pressure and weaker carbonate buffer capacity together cause biogeochemical processes (respiration, primary production, decomposition, and sulfate reduction) to produce disproportionately large swings in pH and $p\text{CO}_2$, while sustaining persistent acidification and CO_2 outgassing (Figure 7a). Rekawa Lagoon shows the opposite pattern with minimal catchment disturbance and the absence of an adjacent marsh limiting material loading, while river-sea mixing correspondingly exerts little influence on the lagoon's carbonate chemistry (Figure 7b). Meanwhile, the input of higher TA river water and the presence of seagrass meadows within the lagoon may promote DIC drawdown through primary production, thereby enriching TA relative to DIC and strengthening carbonate buffering. Consequently, the higher buffering capacity may constrain the effects of biogeochemical forcing, thereby mitigate acidification and maintain lower $p\text{CO}_2$ levels, allowing it to function as a net CO_2 sink (Figure 7b). In most cases, regional coastal inland waters (South Asia, Southeast Asia, and East Africa) act as sources of atmospheric CO_2 , with reported fluxes ranging from 1 to 267 $\text{mmol m}^{-2} \text{d}^{-1}$ (Table S6). The average CO_2 flux in Negombo Lagoon ($9.1 \pm 10.2 \text{ mmol m}^{-2} \text{d}^{-1}$) falls within this regional range, corresponding to annual emissions of approximately 4.6 kt-CO_2 . In contrast, only a few systems in the region function as CO_2 sinks (Table S6); among them, Rekawa Lagoon absorbs about 0.1 kt-CO_2 annually.

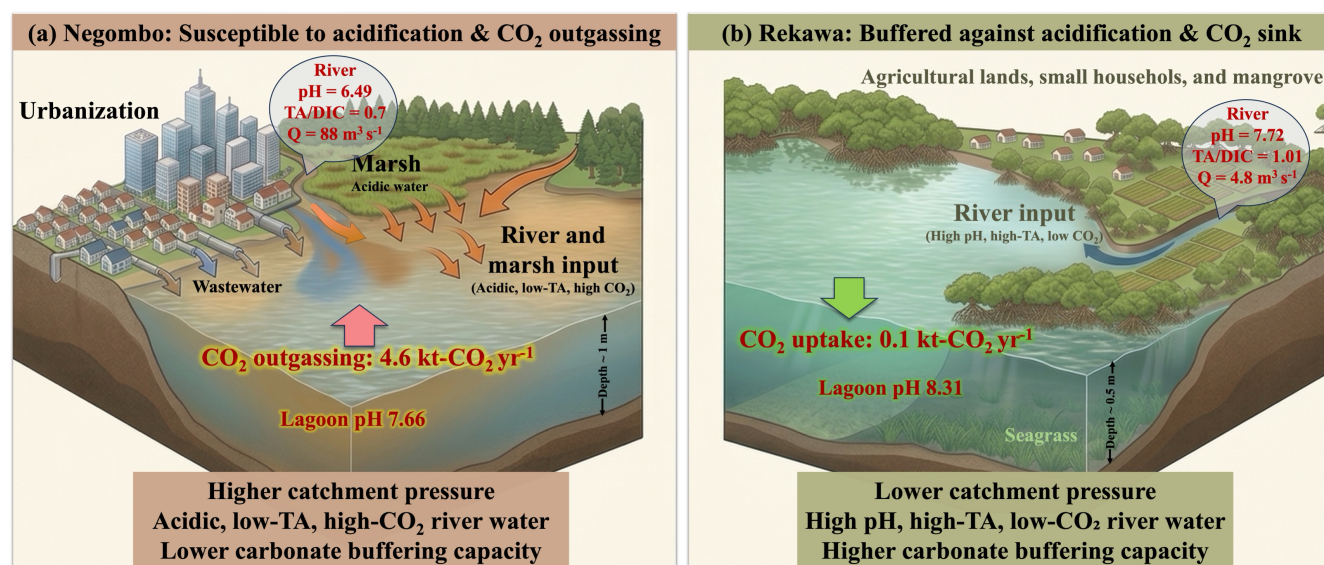


Figure 7. Conceptual diagram illustrating the interplay of catchment pressure and biogeochemical processes, influencing the carbonate system dynamics in (a) Negombo Lagoon and (b) Rekawa Lagoon. Q refers to river discharge.



We assessed alkalinity enhancement as a potential strategy to restore pH and $p\text{CO}_2$ of Negombo Lagoon toward pre-industrial values through optimal CaCO_3 dosing of its river end-member. Continuous TA enrichment at the optimum dose (292 and 526 μmol per kg of river water for the wet and dry seasons, respectively) increased simulated pH above 8.2 (Figure 5c) and decreased $p\text{CO}_2$ to near 280 μatm (Figure 5d) within 40-50 days, given the lagoon's residence time of approximately 14 days. This response highlights the key role of carbonate buffering and suggests that alkalinity enhancement could shift impacted systems such as Negombo Lagoon from CO_2 sources toward neutral or net-sink conditions on management-relevant timescales, while offering a broadly applicable strategy for coastal acidification mitigation worldwide. However, successful implementation hinges on continuous riverine CaCO_3 dosing, making long-term financial viability a critical factor to evaluate. Real-world dynamics such as dissolution kinetics, particle settling, and local hydrodynamics may also affect the efficiency of alkalinity enhancement for a given amount of alkaline material (Ringham et al., 2024; Wang et al., 2023). Furthermore, prior experimental testing is essential to confirm safety for marine life and ensure trace elements do not leach from the alkaline material (Bednaršek et al., 2025; Guo et al., 2022).

To evaluate the role of carbonate buffering in coastal acidification at a regional scale, we combined our measurements with previously published data from lagoons and estuaries. Our analysis revealed a significant relationship between pH and the TA/DIC ratio ($R^2 = 0.74$, $p < 0.001$), highlighting the critical influence of carbonate buffer capacity on acidification (Figure 6d). As the TA/DIC ratio increased, reflecting enhanced carbonate buffering capacity, pH increased rapidly, indicating reduced susceptibility of coastal waters to acidification. In this analysis, a range of pH values can be observed for the same TA/DIC ratio, and these variations could be attributed to other processes, such as river-sea mixing, that affect pH independently of buffering capacity.

Overall, our results suggest two complementary strategies to mitigate acidification and CO_2 outgassing. The first is a policy-driven strategy to reduce inputs of catchment-derived acidic, CO_2 -rich, and nutrient- and organic-carbon-loaded waters through sustainable land use and improved wastewater management. Our comparisons of low-TA and high-TA coastal waters using in situ measurements, simulations, and regional data assessments revealed that natural TA enrichment or ocean alkalinity enhancement (OAE) has the potential to increase buffering capacity. Hence, as the second strategy, we propose targeted ocean OAE to directly restore the buffering capacity of coastal waters where catchment pressure cannot be fully reversed. Prioritizing both strategies together offers a concrete pathway for shallow tropical lagoons to resist coastal acidification and contribute meaningfully to regional net-zero emissions targets.

Data availability

The environmental data (air temperature, rainfall, and wind speed), surface physicochemical parameters (salinity, water temperature, pH_{NIST} , DIC, and TA), and temporal CO_2 flux data that support the findings of this study are available <https://doi.org/10.6084/m9.figshare.31120042>.



515 **Author contributions**

V.W., W.J.H., and C.C.H. conceptualized the study. V.W., W.J.H., W.S.W., F.L.Y., and K.J.K. conducted data collection and sample analyses. V.W. performed data compilation, data analysis, and visualization and drafted the original manuscript. W.J.H., C.C.H., W.S.W., F.L.Y., K.J.K., W.C.C., H.H.H., K.R., P.N.R., and W.K.S. critically reviewed and revised the manuscript. All authors approved the final version of the manuscript.

520 **Competing interests**

The authors declare that they have no conflict of interest.

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