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Dissolved Inorganic Carbon Dynamics in Tropical Mangrove Ecosystems: The Roles of Tidal Exchange, Porewater, and River-Coast Connectivity

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ABSTRACT

Mangrove ecosystems influence coastal carbon cycling through organic-carbon storage and lateral transport of dissolved constituents. Dissolved inorganic carbon (DIC) is a major component of these transfers, but its sources, hydrological pathways, and downstream fate vary among settings. This narrative literature review synthesizes evidence assembled through Scopus-based backward-reference and forward-citation tracking around an established review published in 2022. Studies were evaluated across four themes: DIC production and source attribution, porewater exchange, tidal and seasonal forcing, and river–mangrove–coastal connectivity. The literature shows that DIC in mangrove creeks reflects sediment mineralisation and carbonate-related reactions as well as external inputs from catchments and groundwater. Tidally driven porewater flushing and submarine groundwater discharge can transfer substantial DIC to creeks and estuaries, but the direction and magnitude of net exchange depend on local hydrology, geomorphology, and observation period. Individual ecosystems exhibit both DIC export and net DIC import. DIC concentration, total alkalinity, partial pressure of CO_2, and atmospheric CO_2 exchange represent different measurements and cannot be substituted for lateral DIC fluxes. After reaching coastal waters, DIC may undergo mixing, biological transformation, and air–water CO_2 exchange or continue offshore; transport does not establish long-term storage. An integrated conceptual framework distinguishes carbon provenance, internal production, hydrological transfer, and coastal fate. Comparable source-resolved budgets, consistent system boundaries, and observations spanning tidal, seasonal, and disturbance timescales are needed to assess mangrove contributions without equating lateral export with permanent sequestration.

Keywords: Dissolved inorganic carbon; Mangrove ecosystems; Porewater exchange; Tidal dynamics; Submarine groundwater discharge; Lateral carbon export; River–coast connectivity

INTRODUCTION

Mangrove ecosystems connect terrestrial biogeochemical processes with carbon exchange in estuaries and coastal seas. In addition to storing organic carbon in biomass and sediments, mangroves transfer carbon through porewater, subsurface flow, and tidal channels. These lateral pathways

carry dissolved and particulate constituents that are not fully represented by estimates of soil carbon stocks. Lateral export, commonly termed outwelling, is therefore an important component of coastal carbon budgets (1,2).

Dissolved inorganic carbon (DIC), comprising dissolved CO_2, bicarbonate (HCO_3^-), and carbonate (CO_3^{2-}), is a major component of these exchanges. DIC may accumulate in sediment porewater before being transported to mangrove creeks and estuaries. Koné and Borges (3) associated DIC enrichment in mangrove channels with heterotrophic metabolism, porewater inputs, and changing hydrological conditions. Although DIC is closely related to total alkalinity (TA) and the partial pressure of CO_2 (pCO_2), these quantities are not interchangeable; a change in one does not necessarily imply an equivalent change in inorganic carbon transport (4).

The importance of DIC has become more apparent as studies have quantified the movement of dissolved carbon from mangrove sediments into coastal waters. (1) estimated global mangrove DIC export at approximately 365 Tg C yr^{-1} using a compilation of 32 flux measurements from different locations. The same review estimated alkalinity export at approximately 17.3 Tmol yr^{-1}, underscoring the need to account for inorganic processes. These global figures nevertheless combine observations from ecosystems differing in geomorphology, hydrology, sediment properties, and biogeochemical conditions, and should be interpreted in that context.

Not all DIC found within mangrove systems originates from processes occurring under mangrove vegetation. In a river–mangrove system on Panay Island, the Philippines, (5) identified upstream carbonate weathering and estuarine organic matter decomposition as important influences on DIC dynamics. Mangrove-derived DIC accounted for approximately 8–31% of DIC leaving the estuary, even though DIC dominated total estuarine carbon flux. (6) likewise identified both organic matter degradation and terrestrial groundwater inputs as contributors to porewater DIC accumulation in Qinglan Bay, China.

The fate of DIC becomes more complex after it leaves mangrove creeks. (7) documented bicarbonate transport toward the continental shelf in Brazil and contrasting directions of air–water CO_2 exchange between mangrove creeks and receiving coastal waters. (8)reported that most exported DIC reached an adjacent estuary without immediate CO_2 loss in a subtropical island mangrove. (9) identified net DIC import from marine and mud-bank sources into the Sinnamary mangrove system in French Guiana, despite concurrent dissolved organic carbon export.

Research on the sources and export of mangrove DIC has advanced substantially, but comparisons among ecosystems remain difficult. Relationships between hydrological conditions and carbon export that are pronounced at individual sites may not apply across contrasting geomorphological settings. (1) found no simple relationships between dissolved carbon export and several environmental variables in a cross-site compilation, whereas individual studies identified strong local effects of tides and hydrological variability. This contrast calls for a synthesis that explicitly accounts for carbon sources, biogeochemical mechanisms, hydrological setting, and the boundaries used to define each flux.

The unresolved issue is therefore not whether DIC sources and outwelling pathways exist, as these have been documented extensively. Rather, it is how evidence on carbon provenance, sediment processes, porewater transport, and coastal transformation can be interpreted consistently across interconnected compartments. Source attribution is needed to avoid assigning all estuarine DIC to internal mangrove production, while explicit system boundaries are needed to prevent the same carbon from being counted repeatedly as it passes through successive compartments. Evidence of transport

beyond a creek or estuary also does not necessarily establish the subsequent fate or long-term retention of DIC in marine waters. This review critically examines the sources, biogeochemical processes, hydrological controls, and transport pathways of DIC in tropical mangrove ecosystems and their river–coastal connections. Specifically, it evaluates DIC generation and source attribution, the roles of porewater and groundwater exchange, tidal and seasonal variability, and uncertainties associated with coastal export and subsequent carbon fate. Findings are integrated into a conceptual framework distinguishing carbon origin, internal DIC production and transformation, hydrological transport, and processes in receiving waters. The objective is to improve the comparability and interpretation of mangrove DIC studies rather than propose a universal export rate or an untested sequestration mechanism.

MATERIALS & METHODS

1. Review Approach

This study employed a narrative literature review with structured thematic synthesis to examine DIC dynamics in tropical mangrove ecosystems. The approach integrated findings on DIC sources and production, sediment biogeochemistry, porewater exchange, tides, and hydrological connectivity among rivers, mangroves, and coastal waters. Reported observations, methods, and interpretations were compared to identify established mechanisms, context-dependent differences, and remaining uncertainties. The review was designed as a critical synthesis rather than a systematic literature review or meta-analysis.

2. Literature Sources and Citation Tracking

The anchor publication was (1), "Lateral Export and Sources of Subsurface Dissolved Carbon and Alkalinity in Mangroves: Revising the Blue Carbon Budget," published in the Journal of Marine Science and Engineering. It was selected for its synthesis of dissolved carbon sources, sediment mineralisation, porewater transport, and the contribution of DIC and alkalinity export to mangrove carbon budgets. Its scope provided a common reference point for integrating hydrological and biogeochemical evidence. Scopus was used to trace publications citing this review and the references listed within it.

Forward-citation tracking was conducted using the Scopus Cited by function for (1). An export dated 12 September 2026 contained 41 citing publications, including their bibliographic information and available abstracts. These records provided a means of identifying studies published after the anchor review and assessing recent developments. The number refers to the exported records and should not be confused with a separately verified total citation count for the anchor article.

Backward-reference tracking identified 139 cited references in the Scopus bibliographic metadata for (1). Of these, 120 were available in an RIS export and 19 were supplemented from a CSV reference list. The two directions of tracking yielded 180 initial bibliographic records, excluding the anchor review itself. This figure describes the starting corpus, not the number of full texts examined or the number of studies ultimately cited in the manuscript.

3. Literature Organization and Relevance Assessment

Records were organised in a bibliographic matrix containing author names, year, title, DOI, abstract availability, and topical focus. Potential duplicates were checked using DOI information where available, with title, author, and publication year used for records without complete identifiers. The matrix also documented preliminary relevance and the type of evidence accessible for each record. This procedure supported transparent organisation without imposing systematic-review screening criteria.

Relevance was assessed according to each publication's contribution to mangrove DIC sources, mineralisation, porewater transport, tidal exchange, and carbon connectivity across rivers, mangroves, estuaries, and

coastal waters. Records were classified as core studies, supporting mechanistic literature, or contextual evidence. Studies from adjacent or nontropical coastal systems were retained where they illuminated relevant processes, but were not presented as direct evidence for all tropical mangroves. Scientific relevance and the traceability of reported findings took precedence over publication date alone.

4. Thematic Analysis and Evidence Synthesis

The thematic synthesis addressed four interconnected topics: (i) DIC sources and biogeochemical production in mangrove sediments and associated waters; (ii) porewater dynamics, sediment–water exchange, and subsurface DIC transport; (iii) tidal forcing, seasonal change, freshwater input, and hydrological variability; and (iv) river–mangrove–coastal connectivity, estuarine mixing, lateral export, and potential transformations in receiving waters. The themes were used to organise empirical evidence before interpreting their relationships. They are analytical categories rather than independent stages through which all carbon must pass.

Within each theme, studies were compared by location, ecosystem setting, measurement approach, reported processes, controlling variables, major findings, and limitations. Particular attention was given to distinctions among DIC concentration, mass flux, alkalinity, pCO_2, and atmospheric CO_2 exchange. Quantitative values were retained with their original units and observation contexts; estimates from non-equivalent methods or system boundaries were not pooled. Four synthesis tables were constructed to support comparisons across the literature.

5. Methodological Limitations

Evidence availability also differed among full-text publications, abstracts, and bibliographic records lacking abstracts. Empirical statements were therefore constrained by information that could be traced to the accessible source material, and claims requiring additional methodological context were treated cautiously. These limitations are especially important when comparing carbon flux magnitudes, source contributions, and implications for blue-carbon accounting. Differences in environmental setting and observation scale further constrain the generalisability of cross-site comparisons.

RESULT

1. Sources and Biogeochemical Production of Dissolved Inorganic Carbon

Organic matter mineralisation is a major source of DIC within mangrove sediments. In seven mangrove forests in Timor-Leste, (10) showed that surface sediment respiration did not necessarily represent carbon mineralisation throughout the sediment profile. In some higher-elevation forests, subsurface carbon mineralisation associated with sulfate reduction exceeded estimates based on surface carbon oxidation. DIC concentrations in drainage waters were comparable to those in porewater, consistent with subsurface transfer of mineralisation products to mangrove channels.

Sulfate reduction and related sulfur cycling can influence both DIC production and alkalinity dynamics in organic-rich mangrove sediments. (11) identified associations between pyrite stocks and alkalinity export in settings where sulfate reduction was important. The study estimated global mangrove alkalinity production associated with pyrite formation at approximately 3 mol m^{-2} yr^{-1}, while indicating that pyrite formation did not explain all exported alkalinity. This distinction matters because DIC generation and alkalinity change are coupled through certain reactions but are not equivalent carbon-budget terms.

Mineralisation of previously buried organic matter can also contribute to present-day DIC production. Using radiocarbon and stable isotopes, (12) linked DIC released from a subtropical mangrove to organic carbon buried at an average depth of approximately 40 cm, corresponding to

roughly a century of sediment accumulation. (13) similarly identified organic carbon older than 100 years as a source of creek DIC in a subtropical Japanese mangrove. (1) also discussed deeper sediment layers as potential contributors, including carbon deposited before the establishment of the present mangrove forest.

External DIC contributions become apparent when catchment processes are examined alongside mangrove estuaries. (5) attributed part of the DIC in the Panay Island river–mangrove system to upstream groundwater associated with carbonate weathering, while organic matter decomposition contributed within the mangrove-influenced estuary. Short-term observations suggested that mangrove-derived DIC represented approximately 8–31% of estuarine DIC outflow. River and groundwater inputs thus need to be distinguished from internal DIC formation when interpreting export measured at an estuary mouth.

In Qinglan Bay, Hainan, (6) identified organic matter degradation through sulfate reduction and terrestrial groundwater input as contributors to porewater DIC accumulation. The study estimated that organic matter degradation accounted for 59.8% and terrestrial groundwater for 40.2% of the DIC addition in the studied porewater system. These percentages describe a site-specific partitioning of porewater DIC addition rather than universal shares of mangrove DIC export. Their interpretation therefore depends on the compartment and system boundary to which the estimate applies.

In carbonate-rich mangrove settings, mineral dissolution adds another dimension to inorganic carbon dynamics. (14) reported alkalinity export of 403 ± 17 mmol m^{-2} d^{-1} from carbonate mangrove sediments in the Red Sea, associated with carbonate dissolution. (15) subsequently used biogeochemical simulations to examine potential increases in alkalinity from anaerobic respiration and $CaCO_3$ dissolution following blue-carbon ecosystem restoration. These findings concern alkalinity production or export and cannot be treated directly as measurements of DIC generation or DIC flux.

Table 1. Sources and biogeochemical processes affecting DIC in mangrove ecosystems.

Study / site	Process / method	Principal finding and scope	Ref.
Timor-Leste	Surface respiration; porewater and creek DIC	Subsurface mineralisation may be missed by surface respiration; elevation-dependent.	(10)
Ras Dege, Tanzania	Stable isotopes; 24-h tidal cycle	Marine organic matter may provide substrates; limited to one observation day.	(16)
Ca Mau, Vietnam	DIC, TA, pCO_2 and oxygen	DIC enrichment linked to heterotrophy; specific reaction pathways unresolved.	(3)
Australia and Florida	Pyrite stocks; alkalinity export	Pyrite formation associated with TA production; TA is not a DIC flux.	(11)
Red Sea carbonate mangrove	Sediment alkalinity flux	TA export: 403 ± 17 mmol m^{-2} d^{-1}; not a measurement of DIC flux.	(14)
Panay Island, Philippines	River–mangrove–estuarine DIC	Mangroves supplied 8–31% of estuarine DIC outflow; upstream inputs also important.	(5)
Qinglan Bay, China	^{222}Rn mass balance; sediment reactions	Porewater DIC addition: 59.8% organic degradation, 40.2% terrestrial groundwater.	(6)
Global mangroves	Synthesis of 32 DIC measurements	DIC export ~365 Tg C yr^{-1}; global extrapolation from heterogeneous sites.	(1)

Study / site	Process / method	Principal finding and scope	Ref.
Blue-carbon ecosystems	Simulated anaerobic respiration and $CaCO_3$ dissolution	Restoration may increase TA; modelling evidence, not a directly measured flux.	(15)
Japanese mangrove sediment	Root-exudate incubation	HCO_3^- increased ~20% in one treatment; field-scale export was not assessed.	(17)
Subtropical Japan	Sediment and DIC radiocarbon	Organic matter buried >100 years can contribute to DIC production.	(13)

Note: DIC = dissolved inorganic carbon; TA = total alkalinity. TA fluxes are not equivalent to DIC fluxes.

2. Porewater Dynamics and Subsurface DIC Transport

Porewater exchange links sediment biogeochemical processes to dissolved carbon dynamics in adjacent mangrove waters. DIC produced or stored below the sediment surface can reach tidal creeks through advective flow, groundwater discharge, and tidally driven exchange. Mangrove sediments contain complex flow pathways associated with pore spaces, roots, burrows, and drainage channels. (18) highlighted subsurface transport as an important carbon-budget component because mineralisation products may enter surface waters without first crossing the sediment–water interface by molecular diffusion.

A contrasting outcome was reported by (19) from Kooragang Island, Australia. A ^{222}Rn tracer approach yielded mean porewater exchange of 14.0 ± 6.3 cm d^{-1}, influenced by tidal pumping and crab burrows. Although the exchanged water transported dissolved organic carbon, nutrients, and trace metals, the wetland was a net DIC sink during the observation period. This temperate mangrove case cannot be generalised to tropical settings, but demonstrates that porewater exchange does not necessarily produce net export of every dissolved carbon species.

(20) demonstrated the influence of tidal conditions on groundwater discharge and carbon export in the Indian Sundarbans. High-resolution observations and a radon mass-balance approach indicated that submarine groundwater discharge (SGD) increased by 352% from neap to spring tides, reaching approximately 65.6 cm d^{-1}. Dissolved organic and inorganic carbon and alkalinity exports approximately doubled between these tidal states. SGD accounted for up to 86.7% of DIC export during spring tides, indicating an important subsurface transport pathway in the studied macrotidal system.

(21) examined porewater release and carbonate chemistry in two Brazilian mangrove creeks. During low tide, ^{222}Rn and pCO_2 increased as pH and dissolved oxygen declined, consistent with the input of chemically distinct porewater. Mean pCO_2 increased by 50 ± 30% from high to low tide, with further differences between neap and spring tides. These changes cannot be interpreted as equivalent increases in DIC flux because pCO_2 describes the carbonate system and potential CO_2 exchange, not the total mass transport of all DIC species.

Radium isotopes extend the analysis of porewater-derived carbon beyond individual creeks. (7) combined porewater, creek-water, and cross-shelf observations in two Brazilian mangrove settings. Bicarbonate export toward the continental shelf was estimated at 27–72 mmol m^{-2} d^{-1}, indicating that dissolved inorganic carbon can travel beyond neighbouring creeks and embayments. However, transport to the shelf is not sufficient evidence that the exported carbon remains stored over long periods.

Efficient water exchange can alter the fraction of DIC transferred to receiving waters before atmospheric loss. In a subtropical island mangrove in Japan, (8) used radium isotopes and carbon measurements to estimate DIC outwelling of 189 ± 18 mmol m^{-2} d^{-1}. Approximately

89% of exported DIC reached the estuary without immediate CO_2 release, a result associated with effective exchange and a creek-water residence time of about one day. Its longer-term fate nevertheless requires observations beyond the estuary.

Table 2. Porewater exchange, subsurface transport, and DIC outwelling.

Study / site	Process / method	Principal finding and scope	Ref.
Timor-Leste	Sediment respiration and drainage DIC	Drainage-water DIC resembled porewater; elevation influenced the relationship.	(10)
Palau	Two-creek comparison; tidal exchange	DIC export differed by ~8-fold between nearby creeks.	(22)
Kooragang, Australia	^{222}Rn balance; 25-h tidal observation	Porewater exchange 14.0 ± 6.3 cm d^{-1}; wetland was a net DIC sink.	(19)
Qinglan Bay, China	SGD; ^{222}Rn mass balance	SGD ~165 cm d^{-1} and related DIC export 107 g C m^{-2} d^{-1}; site-specific.	(6)
Indian Sundarbans	SGD; ^{222}Rn; neap–spring tides	SGD accounted for up to 86.7% of DIC export during spring tides.	(20)
Brazilian tidal creeks	^{222}Rn, pCO_2, pH and oxygen	pCO_2 increased by 50 ± 30% from high to low tide; not a DIC flux.	(21)
Brazilian coast	$^{224}Ra/^{223}Ra$; cross-shelf transects	HCO_3^- export 27–72 mmol m^{-2} d^{-1}; long-term retention unresolved.	(7)
Pearl River Delta	Porewater DIC/DOC; morphometry	DIC–DOC correlation r = 0.870; correlation does not measure transport.	(23)
Subtropical island, Japan	Radium, DIC and CO_2 exchange	DIC export 189 ± 18 mmol m^{-2} d^{-1}; 89% reached estuary without immediate CO_2 loss.	(8)

Note: SGD = submarine groundwater discharge; pCO_2 = partial pressure of CO_2. Concentrations, gas exchange, and lateral fluxes are distinct.

3. Tidal Exchange and Hydrological Variability

Mangrove DIC dynamics vary over timescales ranging from individual tidal cycles to seasons and extreme hydrological events. Hydrological forcing influences DIC concentration, carbonate chemistry, and carbon transport between sediment, tidal creeks, and receiving waters. These responses need not move in the same direction because water volume, residence time, mixing, and biogeochemical transformations may change simultaneously. Table 3 therefore compares hydrological setting and the specific carbonate or flux variable measured, rather than treating every reported response as DIC export.

Time-series observations from two Brazilian mangrove creeks documented marked carbonate-system variability (21). Mean pCO_2 increased by 50 ± 30% from high to low tide, by 9 ± 22% from day to night, and by 57 ± 5% between neap and spring tidal conditions. Tidal-scale differences were larger than the mean diel contrast at the studied locations. Because pCO_2 is not total DIC concentration or DIC mass flux, these percentages cannot be applied directly to estimates of lateral carbon export.

Tidal control of export was quantified (20) in the Indian Sundarbans. Groundwater discharge increased by 352% from neap to spring tides, with an estimated maximum of 65.6 cm d^{-1}, and SGD contributed as much as 86.7% of DIC export during spring tides. These findings show that changing tidal inundation can alter carbon transport substantially within a period shorter than a season. The measured response is specific to

the hydrological configuration of the investigated macrotidal mangroves.

In systems with small tidal ranges, seasonal freshwater inputs can exert particularly strong influences. (24) investigated carbonate chemistry and CO_2 emission in microtidal Fort-de-France Bay, Martinique, where tidal amplitude was approximately 20 cm. Wet-season CO_2 emissions were approximately five times greater than during the dry season, and small river mouths draining mangrove creek networks accounted for about 73% of the seasonal increase. Those observations establish a hydrological influence on CO_2 exchange but cannot be converted directly into DIC flux without information on water transport and carbonate speciation.

Extreme events may alter carbon export for longer than the event itself. (25) examined 2014–2019 records of dissolved organic and inorganic carbon outwelling from a mangrove estuary in the Florida Everglades that experienced a Category 3–4 hurricane in 2017. Reported carbon outwelling was suppressed for up to two subsequent years, although the mechanisms proposed to explain the response require further testing. Because the study concerns a subtropical estuary, it provides evidence of a possible disturbance response rather than a universal prediction for tropical mangroves.

The contrast between site-specific hydrological responses and cross-site syntheses complicates generalisation. (1) reported no simple correlations between compiled dissolved carbon or alkalinity fluxes and several variables, including tidal range, annual rainfall, salinity, and temperature. This does not contradict the pronounced tidal or seasonal controls observed within particular mangrove systems, because the spatial and temporal scales differ. Annual environmental averages can obscure episodic transport processes, and a single cross-site relationship may conceal different mechanisms across geomorphic settings.

Table 3. Effects of tidal exchange, seasonality, and disturbance on DIC dynamics.

Study / site	Process / method	Principal finding and scope	Ref.
Ca Mau, Vietnam	Dry- and wet-season observations	Wet season diluted DIC and TA; CO_2 emissions did not consistently decline.	(3)
Palau	Two creeks; monsoon observations	DIC export differed ~8-fold; geomorphology limits generalisation.	(22)
Sinnamary, French Guiana	Tides and mobile mud banks	Net DIC import from marine and mud-bank sources; not universally seaward.	(9)
Brazilian tidal creeks	^{222}Rn and pCO_2 time series	pCO_2: +50 ± 30% (high–low tide); +57 ± 5% (neap–spring tides).	(21)
Indian Sundarbans	Neap–spring tidal cycle; SGD	SGD increased 352%; DIC and TA exports approximately doubled.	(20)
Pearl River Delta	Tidal-flow duration; morphometry	Porewater DIC varied with tidal duration (R^2 = 0.918); not an export flux.	(23)
Martinique	Microtidal bay; seasonal hydrology	Wet-season CO_2 emissions ~5-fold higher; not equivalent to DIC flux.	(24)
Indian Sundarbans	Monthly chemistry, 2014–2022	TA correlates shifted between freshwater input and productivity indicators.	(26)
Everglades, Florida	Hurricane; 2014–2019 time series	DIC and DOC export remained reduced for up to two years after the event.	(25)

Note: DIC and TA concentrations, pCO_2, and atmospheric CO_2 fluxes represent different variables and should not be directly equated.

4. River–Mangrove–Coastal Connectivity and DIC Export

River–mangrove–coastal connectivity influences the origin, direction, and magnitude of DIC transport. Within this continuum, carbonate weathering in catchments, organic matter mineralisation in mangrove sediments, groundwater inputs, and exchange with marine waters can all affect the DIC observed in tidal creeks and estuaries. Their contributions depend on the boundaries used to construct a carbon budget. Studies spanning upstream and coastal environments therefore need to distinguish external carbon inputs, transformations within mangroves, and export across the seaward boundary (1,5,27). Evidence of a catchment contribution comes from Panay Island, the Philippines. (5) observed that DIC represented approximately 90–95% of total estuarine carbon flux during dry- and wet-season campaigns, but estimated that mangrove-derived DIC contributed only 8–31% of DIC outflow. This difference demonstrates that the chemical predominance of DIC in carbon transport cannot be equated with its production inside mangrove sediments. Groundwater and weathering-related DIC from upstream contribute to the measured estuarine budget.

The direction of DIC exchange is not uniformly seaward. In the Sinnamary estuary, French Guiana, (9) reported net DIC input from marine and mobile mud-bank sources of approximately 0.90 g C m^{-2} d^{-1}, while DOC export was estimated at 8.14 g C m^{-2} d^{-1}. Coastal sediment dynamics, mixing, and tides contributed to this distinct pattern. The case illustrates that a mangrove system can import one carbon fraction while exporting another, and therefore cannot be represented by a universal assumption of net DIC outwelling.

Small mangrove estuaries can help resolve local DIC additions through water and carbon mass balances. (28) investigated an estuary with a principal exchange channel and estimated DIC export at 1.36 g C m^{-2} d^{-1} in winter and 3.35 g C m^{-2} d^{-1} in summer. Such estimates depend on conservative-mixing assumptions, the identification of freshwater and marine end-members, and the mangrove area used for normalisation. They are therefore informative for the studied system but require care in comparisons with larger estuaries or differently defined fluxes.

Carbon transport can extend well beyond a mangrove creek mouth. Using radium isotopes, (27) examined carbon and alkalinity exchange across a groundwater–creek–continental shelf continuum in the Amazon region. Their analysis suggested transport of mangrove-associated carbon beyond the continental shelf on a timescale of approximately 22 ± 7 days. This finding documents connectivity at a broader coastal scale, but a tracer-derived transport timescale should not be interpreted as the duration of long-term DIC storage in the ocean.

In a subtropical Japanese island mangrove, (8) estimated DIC outwelling at 189 ± 18 mmol m^{-2} d^{-1} and reported that approximately 89% of this export reached the adjacent estuary without immediate CO_2 evasion. During the observations, the receiving estuarine waters showed net CO_2 uptake, whereas the mangrove creek was a source of CO_2. Such contrasting air–water fluxes emphasise the need to follow carbon beyond the mangrove boundary. The fraction reaching the estuary should not, however, be conflated with a fraction proven to remain in long-term ocean storage.

Table 4. River–mangrove–coastal connectivity and DIC transport.

Study / site	Process / method	Principal finding and scope	Ref.
Sinnamary, French Guiana	Marine exchange and mobile mud banks	Net DIC import of 0.90 g C m^{-2} d^{-1} despite concurrent DOC export.	(9)
Panay Island, Philippines	Catchment weathering and mangrove DIC	Mangrove DIC 8–31% of outflow; DIC 90–95% of total estuarine carbon flux.	(5)
Qinglan Bay, China	Groundwater without direct upstream river input	DIC ~98% of exported dissolved carbon; multiple carbon origins.	(6)
Amazon, Brazil	$^{223}Ra/^{224}Ra$; groundwater–shelf continuum	Bicarbonate dominated; transport beyond shelf on ~22 ± 7 d timescale.	(27)
Global mangroves	Cross-site DIC export synthesis	Export ~365 Tg C yr^{-1}; source attribution and scaling remain uncertain.	(1)
Indian Sundarbans	Spring-tide porewater release	SGD supplied up to 86.7% of DIC export across the observed boundary.	(20)
Brazilian coast	Creek–bay–continental shelf transects	HCO_3^- export 27–72 mmol m^{-2} d^{-1}; receiving waters showed CO_2 uptake.	(7)
Subtropical island, Japan	Creek-water residence time ~1 day	DIC outwelling 189 ± 18 mmol m^{-2} d^{-1}; ~89% reached the estuary without immediate CO_2 release.	(8)
Martinique	Small river mouths; monsoon variability	River mouths explained 73% of seasonal increase in CO_2 emissions.	(24)
Everglades, Florida	Hurricane disturbance and upstream connectivity	DIC/DOC export remained suppressed for up to two years after a hurricane.	(25)

Note: Import and export refer to specific system boundaries. Transport to coastal waters does not by itself establish long-term carbon storage.

DISCUSSION

1. Integrating DIC Sources and Biogeochemical Processes

Variation in mangrove DIC concentration and export cannot be explained by organic carbon production or sediment mineralisation alone. DIC measured in a tidal creek reflects external inputs from rivers and groundwater, carbon generated through sediment reactions, and exchange with estuarine waters. These components describe different terms in a carbon budget and should not be conflated. (5,6,29) illustrate how DIC at a downstream boundary may include carbon produced before water enters the mangrove as well as carbon generated within the ecosystem.

Source partitioning becomes particularly difficult when groundwater is both a transport pathway and a source of dissolved constituents. At Qinglan Bay, (6) attributed 59.8% of porewater DIC addition to organic matter degradation through sulfate reduction and 40.2% to terrestrial groundwater. These percentages describe the source budget for porewater DIC addition, whereas the 8–31% estimate of (5) refers to mangrove-derived DIC in estuarine outflow. Comparing the figures as equivalent contributions would overlook their different denominators and spatial boundaries. A groundwater-associated DIC flux is not necessarily equal to the rate of internal DIC production.

Microbial reactions and mineral transformations also complicate the relationship between DIC and alkalinity. (11) associated pyrite formation with alkalinity export from blue-carbon systems, while noting that this pathway could not explain all exported alkalinity. Simulations (15) indicated that anaerobic respiration and calcium carbonate dissolution may increase alkalinity following ecosystem restoration. These processes operate through different

reaction pathways, so neither a change in alkalinity nor a change in DIC can be attributed to one universal sediment mechanism.

The implications extend directly to mangrove carbon-budget boundaries. The large export estimates compiled by (1) demonstrate that dissolved transport can be an important term, but an outward flux is not synonymous with internal ecosystem production. (29) described carbon inputs to Shark River from upstream marshes, mangroves, and carbonate-related processes, illustrating a combined source signature in coastal outflow. Attribution matters for blue-carbon assessments: DIC crossing a mangrove creek boundary cannot all be counted as newly captured atmospheric CO_2 by the mangrove vegetation.

A more robust source assessment therefore requires hydrochemical observations tied to hydrology and explicit flux boundaries. Sampling across river water, groundwater, porewater, mangrove creeks, and estuarine waters could identify changes in carbon composition along transport pathways, particularly when combined with discharge estimates and mixing analyses. Concentration measurements or hydrological tracers alone may still be insufficient to resolve several simultaneous production pathways. The appropriate conclusion depends on what was measured, the resolution of the observations, and the geomorphological setting in which carbon is accumulated, transformed, and exported.

2. Hydrological Controls and Spatial–Temporal Heterogeneity

Hydrological controls on mangrove DIC dynamics are unlikely to be represented by a single predictor applicable to every ecosystem. (1) found no simple cross-site correlations between dissolved carbon flux and factors such as tidal range, annual rainfall, salinity, or temperature, whereas individual investigations have documented pronounced tidal and seasonal responses. The apparent discrepancy reflects a difference in scale and environmental context, rather than proof that tides or rainfall are unimportant. Site-level controls should thus be interpreted separately from relationships derived by aggregating heterogeneous mangrove systems.

Tidal forcing depends on more than water-level amplitude: inundation duration, flow direction, and exchanged water volume also matter. In the macrotidal Sundarbans (20) linked spring-tide overtopping of creek banks to increased groundwater discharge and carbon export. In contrast, (30) observed elevated pCO_2 during neap tides in a subtropical Japanese mangrove when tidal asymmetry prolonged inundation. These findings need not conflict, because the first addresses groundwater-associated carbon transport, whereas the second concerns the carbonate-system response to inundation time. The identity of the measured variable is essential to interpreting a tidal effect.

An increase in DIC concentration must be distinguished from an increase in carbon mass transport. Flux depends on both the concentration and the volume and direction of exchanged water, which can vary throughout a tidal cycle. (21) documented strong pCO_2 responses on tidal and diel timescales, but pCO_2 is not a direct measurement of the flux of all inorganic carbon species. Consequently, claims that tidal forcing increases DIC export should be based on integrated water and carbon mass balances rather than high- versus low-tide chemistry alone.

Water residence time may alter the balance between DIC enrichment and export. (3) associated high DIC and pCO_2 with relatively small water volumes and longer residence times in certain Vietnamese mangrove channels. In contrast, (8) linked efficient exchange in an island mangrove with rapid DIC transport to an estuary. High concentrations in slowly exchanged waters therefore need not yield greater export than lower concentrations in a system with more rapid circulation. Residence time shapes opportunities for reaction, whereas the exchange rate controls the mass that crosses a specified boundary.

Extreme events introduce another temporal dimension. (25) reported reduced DIC and DOC export from a Florida Everglades mangrove estuary for up to two years after a major 2017 hurricane. Vegetation damage, changes in root respiration, and carbon release during the event were proposed as possible explanations, but those mechanisms require additional testing. This long-lived response illustrates that hydrological disturbances may alter ecological processes beyond the immediate storm period. It should not be regarded as a universal mangrove response, particularly across distinct tropical and subtropical settings.

Methodological heterogeneity compounds these spatial and temporal differences. Radon and radium tracers can constrain particular water-exchange pathways, but their interpretation depends on tracer behaviour, mass-balance assumptions, and the study boundary. High-resolution DIC or pCO_2 measurements can characterise carbonate-system variability without necessarily establishing exchanged water volumes. Conversely, groundwater discharge estimates require suitable chemical information before they can be converted into carbon fluxes. Comparisons should therefore evaluate the measured variable, observation period, boundary, and denominator, rather than focusing only on units that appear superficially compatible.

This synthesis suggests that hydrological influences on DIC can be interpreted through three interacting elements: the sources and composition of incoming water, the direction and intensity of water exchange, and the residence time available for biogeochemical transformation. Together, these elements help explain why tides and seasons may produce contrasting concentration and export responses across mangrove systems. They should be treated as a conceptual interpretation of the available evidence, not as a quantitatively validated universal model. The same framework provides a basis for examining the subsequent mixing and transformation of exported DIC in coastal waters.

3. The Fate of Exported DIC in Coastal Waters

Exported DIC may follow several pathways after leaving a mangrove, and movement across the ecosystem boundary does not establish long-term carbon storage. In creeks, estuaries, and coastal waters, DIC may change chemical form, exchange CO_2 with the atmosphere, mix with other water masses, or participate in biological production and respiration. The importance of these pathways depends on carbonate chemistry, hydrological transport, and characteristics of the receiving waters. This distinction is central to interpreting mangrove contributions to coastal carbon budgets and potential climate mitigation (1,8,21).

An exported carbon flux need not have the same atmospheric consequence throughout the coastal continuum. (7) found that mangrove creeks in Brazil released CO_2, whereas adjacent bays and shelf waters exhibited net atmospheric CO_2 uptake during the observations. (8) similarly reported net estuarine CO_2 uptake alongside CO_2 release from an adjacent island mangrove creek. These contrasting directions show that the carbon-exchange status of a creek cannot be assigned automatically to its receiving waters. Nor can coastal CO_2 uptake be attributed entirely to mangrove DIC without addressing biological activity, mixing, and additional carbon sources.

Carbonate chemistry further modifies the fate of exported DIC. In six Australian mangrove creeks, (4) found that lateral DIC and alkalinity exchange could influence coastal acid–base conditions, including local increases in pH. The study also documented variation in the direction of DIC exchange, including net import at some locations. Accordingly, a DIC increase alone cannot establish whether mangrove inputs aggravate coastal acidification or contribute to its buffering. Both DIC and alkalinity,

together with carbonate speciation and mixing, must be considered.

Evidence also indicates that some mangrove-derived carbon can travel beyond the estuary without immediate CO_2 loss. (27) used radium isotopes along a groundwater–creek–continental shelf continuum in the Amazon region and identified bicarbonate as a dominant form of dissolved carbon. Tracer-based analysis suggested carbon transport beyond the continental shelf on a timescale of approximately 22 ± 7 days. This is evidence of the spatial extent and timing of transport, not evidence that DIC remains isolated from the atmosphere for an equivalent or substantially longer period.

The origin of exported carbon creates a separate challenge for claims about atmospheric carbon removal. (5) traced some estuarine DIC to catchment groundwater associated with carbonate weathering, whereas (13) showed that DIC may derive from organic carbon buried more than 100 years earlier. These carbon pools differ in provenance and storage history. Consequently, all DIC transported through a mangrove boundary should not be credited as atmospheric CO_2 newly taken up by mangrove vegetation during the observation period.

Uncertainty in coastal fate also complicates global extrapolation. (4) estimated global mangrove DIC export at 3.6 ± 1.1 Tmol C yr^{-1} from a six-creek Australian dataset under explicit global scaling assumptions. (1), using a broader compilation, estimated approximately 365 Tg C yr^{-1}, equivalent to around 30.4 Tmol C yr^{-1}. These contrasting values illustrate sensitivity to study coverage, local environments, measurement approaches, and extrapolation. They are not evidence of a temporal trend because the underlying methods and datasets differ. Neither can be directly translated into long-term atmospheric CO_2 removal without a source-resolved downstream carbon budget.

The literature thus supports three distinct levels of interpretation. The first is lateral export: DIC passing from mangrove porewater or creeks into an adjacent aquatic compartment. The second is coastal transport and transformation: mixing, carbonate re-equilibration, atmospheric CO_2 exchange, biological activity, and movement toward more open waters. The third is long-term storage, which requires additional evidence of carbon provenance and persistence in marine reservoirs. Keeping these levels separate makes it possible to interpret outwelling without equating it automatically with permanent atmospheric carbon sequestration.

4. An Integrated Conceptual Framework

The combined evidence on DIC sources, sediment biogeochemistry, porewater exchange, and river–coastal connectivity supports an integrated conceptual framework. Individual pathways of DIC generation and export are well documented, but their relative contributions vary with ecosystem setting and the boundary at which they are measured. DIC dynamics therefore cannot be represented as one fixed sequence operating identically in all mangroves. Figure 1 distinguishes four connected components-carbon provenance, internal biogeochemical production and transformation, hydrological transport, and coastal fate-while retaining the distinction between concentrations, production rates, and export fluxes.

The first component concerns the provenance of carbon entering the river–mangrove–coastal system. (5) identified catchment carbonate weathering as a relevant source of DIC to a Philippine mangrove estuary, while (6) documented terrestrial groundwater inputs into a mangrove creek lacking direct upstream river discharge. These examples show that DIC arriving at the mangrove boundary may have been produced outside the mangrove ecosystem. For attribution purposes, external input is defined by the location of carbon formation relative to the assessed boundary, not merely by whether water arrives through a river or subsurface pathway.

The second component comprises DIC generation and transformation within mangrove sediments and associated waters. These reactions occur under different redox conditions and are influenced by substrate availability, root activity, and sediment mineralogy. (10) demonstrated that mineralisation below the surface can be missed by surface respiration measurements, while (13) identified DIC derived from organic matter buried more than a century earlier. (17) further provided experimental evidence that simulated root-derived organic substrates can increase bicarbonate in mangrove sediment incubations. These processes need not contribute equally in every mangrove setting.

The third component is hydrological transport between sediments, mangrove creeks, estuaries, and coastal waters. Rivers deliver DIC formed upstream, whereas porewater exchange and groundwater discharge transfer DIC associated with subsurface processes. (20) documented tide-dependent groundwater and DIC export in the Sundarbans, and (7) traced bicarbonate transport from mangrove-influenced waters toward the continental shelf. DIC can accumulate when exchange is restricted and be exported more rapidly when water exchange intensifies. An increase in transport therefore need not indicate a simultaneous increase in the rate of internal DIC production.

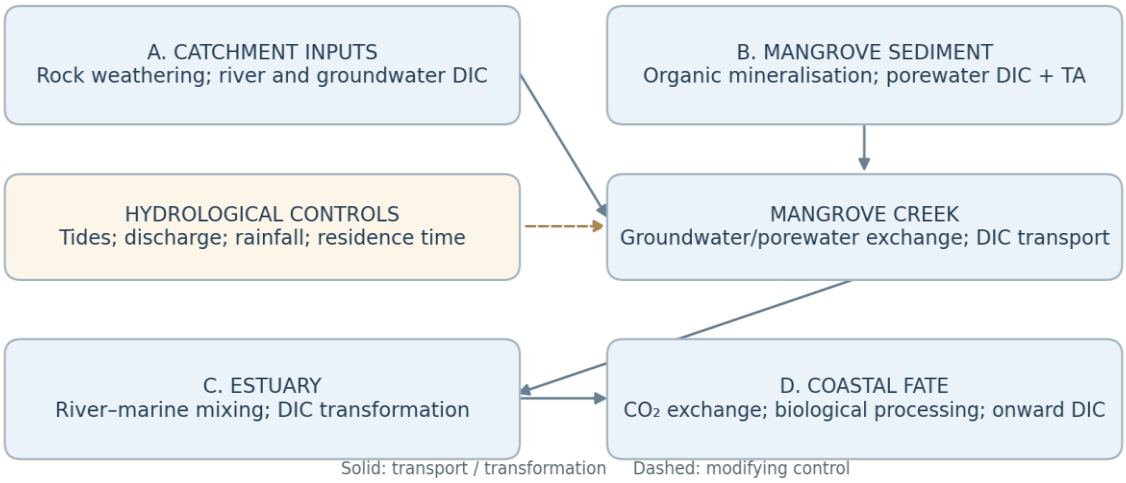


Figure 1. Integrated conceptual framework of DIC sources, biogeochemical processes, hydrological transport, and coastal fate.

Boundary consistency also prevents double counting. DIC formed in sediment may pass from porewater into a creek, from the creek into an estuary, and from the estuary into coastal waters. These are successive transfers potentially involving the same carbon rather than three independent new sources. Moreover, groundwater tracers estimate water movement but do not establish that all exported DIC was produced under mangroves: groundwater may carry terrestrial carbon or recirculated seawater. The distinction between origin and pathway must therefore be maintained when adding transport terms to a carbon budget.

The fourth component addresses the transformation and fate of DIC in estuaries and coastal waters. (7) observed CO_2 release from mangrove creeks alongside net CO_2 uptake in adjacent coastal waters. (8) found that much of the DIC leaving a subtropical mangrove reached the estuary without immediate atmospheric CO_2 loss. These cases show that the carbonate-system response of receiving waters cannot be inferred solely from creek chemistry. Mixing, biological metabolism, air–water

exchange, and further transport influence subsequent carbon behaviour.

The main contribution of the framework is therefore to separate three questions often conflated in mangrove carbon research: where DIC originates, how much passes through an ecosystem boundary, and what happens after it enters receiving waters. A consistent carbon budget needs more than a concentration measurement or a single estimate of groundwater discharge. The framework offers a guide to evidence requirements rather than a universal quantitative model, and the relative importance of its pathways must be established with site-specific observations. This distinction provides the basis for identifying research priorities in tropical mangrove systems.

5. Knowledge Gaps and Future Research Priorities

Research has established several important pathways for DIC production and export in mangroves, including organic matter mineralisation, carbonate dissolution, porewater exchange, groundwater discharge, and tidal-creek transport. The principal remaining challenge is not a complete absence of knowledge about these mechanisms, but limited comparability and integration across sites and study boundaries. Carbon sources, hydrological settings, observation periods, and analytical methods differ substantially among studies. Four related areas warrant particular attention: source attribution, temporal coverage, cross-site comparability, and downstream DIC fate.

The first priority concerns separating catchment inputs, groundwater contributions, and internal mangrove DIC production. (5) demonstrated a catchment weathering contribution to estuarine DIC in the Philippines, whereas (6) estimated source contributions to porewater DIC in Qinglan Bay. These studies do not address identical budget terms, and their reported percentages are consequently not directly comparable. Future studies would benefit from source-resolved carbon budgets linking riverine water, groundwater, porewater, tidal creeks, and estuarine outflow over consistent boundaries and observation periods.

A second gap concerns the temporal representativeness of DIC observations. (20) documented changing groundwater-associated DIC export across neap–spring tides, and (21) measured carbonate-system variability across tidal, diel, and longer short-term scales. (26) reported seasonal shifts in the factors associated with alkalinity in the Sundarbans. A short tidal campaign may not represent seasonal export, while monthly sampling may miss rapid exchanges associated with tides or rainfall events. Multi-timescale designs are required where annual or seasonal carbon budgets are the goal.

Third, cross-site extrapolation should explicitly account for mangrove geomorphology, sediment properties, and hydrological connectivity. A cross-site synthesis did not identify a simple universal relationship between dissolved carbon export and several environmental descriptors (1). In contrast, nearby mangrove creeks in Palau exhibited markedly different carbon export rates (22), while porewater carbon variability was associated with morphometric characteristics and tidal-flow properties in the Pearl River Delta (23). These findings suggest that geographical proximity or climatic similarity alone is insufficient to establish comparability among mangrove systems. Harmonised flux definitions and explicit consideration of hydrological and geomorphological settings would improve cross-site interpretation.

The fourth gap concerns DIC fate beyond the creek and estuary. (7,27) traced carbon and bicarbonate transport toward or beyond continental shelf waters, while (8) found that much of the DIC exported from one mangrove reached an estuary without immediate CO_2 release. These results demonstrate progress in documenting downstream transfer. They do not consistently resolve the duration of carbon retention or its longer-term exchanges with

the atmosphere. Coastal observations combining DIC, TA, pCO_2, discharge, and biological processes would help narrow this uncertainty.

The central gap emerging from the available literature is the absence of consistently linked evidence for DIC provenance, hydrological mass transport, and coastal fate across many of the systems examined. The proposed framework does not replace empirical process models or assign universal fractions to individual pathways. Instead, it clarifies the questions, system boundaries, and evidence needed to interpret DIC observations without conflating sources, transport, and storage. Future work can thereby establish not only how much DIC leaves mangroves, but where it originated, which pathways conveyed it, and how it changes after reaching coastal waters.

CONCLUSION

This review shows that DIC dynamics in tropical mangrove ecosystems emerge from interactions among carbon sources, sediment biogeochemical processes, hydrological transport, and exchange with adjacent coastal waters. In addition to mineralisation of mangrove organic matter, DIC may originate in terrestrial groundwater, catchment carbonate weathering, and surrounding aquatic environments. The relative contribution of these sources varies with geology, sediment characteristics, biogeochemical conditions, and hydrological connectivity. Consequently, high DIC concentrations or substantial creek export cannot be interpreted directly as evidence of a comparably large rate of internal mangrove DIC production.

Connectivity determines how carbon from different sources mixes, changes chemical form, and moves toward coastal waters. Net DIC exchange is not invariably seaward: some systems import DIC or exhibit contrasting directions for inorganic and organic carbon fractions. Once exported, DIC may exchange CO_2 with the atmosphere, undergo biological or carbonate-system transformations, or remain dissolved during onward transport. Evidence of export to an estuary or continental shelf does not by itself demonstrate long-term marine carbon storage.

The review proposes a four-component conceptual framework linking carbon provenance, internal DIC formation and transformation, hydrological transport, and fate in receiving waters. The framework distinguishes external sources from carbon generated within mangroves and separates biogeochemical production from transfer across a boundary. Such distinctions reduce the risk of counting the same carbon repeatedly as it moves through porewater, tidal creeks, estuaries, and coastal waters. This is an evidence-based interpretative framework, not a quantitative model validated for all tropical mangrove systems.

Future studies should adopt consistent system boundaries and flux definitions to distinguish mangrove-derived DIC from riverine and groundwater inputs across contrasting geomorphological and hydrological settings. Coordinated measurements of DIC, total alkalinity, water discharge, porewater exchange, and carbon-source indicators across connected compartments would improve estimates of carbon transport. Observations spanning tidal cycles, seasonal variability, and extreme hydrological events are needed to capture changes in DIC export, while measurements of carbonate chemistry and air–water CO_2 exchange in receiving waters would help clarify its downstream fate. These approaches would strengthen coastal carbon budgets without assuming that lateral DIC export represents long-term carbon sequestration.

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