



Global asymmetric mangrove-edge shifts reveal coastal squeeze under sea-level rise

Dongjie Fu, Xichen Xu , Fenzhen Su, Zhijun Dai , Vincent Lyne , Jiasheng Tang, Lu Kang & Hao Yu

To cite this article: Dongjie Fu, Xichen Xu , Fenzhen Su, Zhijun Dai , Vincent Lyne , Jiasheng Tang, Lu Kang & Hao Yu (2026) Global asymmetric mangrove-edge shifts reveal coastal squeeze under sea-level rise, GIScience & Remote Sensing, 63:1, 2741774, DOI: [10.1080/15481603.2026.2741774](https://doi.org/10.1080/15481603.2026.2741774)

To link to this article: <https://doi.org/10.1080/15481603.2026.2741774>



© 2026 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group.



[View supplementary material](#)



Published online: 01 Oct 2026.



[Submit your article to this journal](#)



Article views: 220

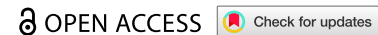


[View related articles](#)



[View Crossmark data](#)

RESEARCH ARTICLE



Global asymmetric mangrove-edge shifts reveal coastal squeeze under sea-level rise

Dongjie Fu^{a,b} , Xichen Xu^{a,b}, Fenzhen Su^{a,b,c} , Zhijun Dai^{d,e}, Vincent Lyne^f, Jiasheng Tang^{a,b} ,
Lu Kang^g and Hao Yu^{a,b} 

^aState Key Laboratory of Resources and Environmental Information System, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, People's Republic of China; ^bCollege of Resources and Environment, University of Chinese Academy of Sciences, Beijing, People's Republic of China; ^cCollaborative Innovation Center for the South China Sea Studies, Nanjing University, Nanjing, People's Republic of China; ^dState Key Laboratory of Estuarine and Coastal Research, East China Normal University, Shanghai, People's Republic of China; ^eLaboratory for Marine Geology, Qingdao Marine Science and Technology Center, Qingdao, People's Republic of China; ^fRetired Scientist, Hobart, Tasmania, Australia; ^gChina Land Surveying and Planning Institute, Beijing, People's Republic of China

ABSTRACT

Changes at the land–sea interface reveal whether mangrove systems advance seaward, retreat landward, or undergo coastal squeeze as their seaward and landward boundaries converge. Yet global assessments have largely relied on area change, with less focus on these directional processes. This study applies a global coastline-normal transect framework to Global Mangrove Watch data for 1996, 2008, and 2020. By quantifying the seaward and landward edges together with width and centroid position, we distinguish expansion, directional migration, and contraction across multiple spatial scales. Globally, mangroves lost an average width of 77.2 m: the seaward edge retreated landward by 47.5 m, a pattern consistent with marine forcing including relative sea-level rise and coastal erosion, while the landward edge shifted seaward by 53.7 m, compatible with restricted accommodation space. Together, these opposing movements reveal widespread asymmetric contraction. Among regions exhibiting clear directional migration, 65.2% shifted seaward, including advances of up to 2.5 km in Marajó Bay, Brazil, whereas less frequent landward migration reached 5.6 km in the northern Gulf of Mexico. After 2008, the prevalence of landward migration increased, particularly across Asia and Africa. The edge trajectories constrain the set of plausible controls but do not uniquely attribute change to sea-level rise, sediment supply, topography, land use, or restoration. Conservation should therefore protect potential landward migration pathways while accounting for uncertainty in the mechanisms producing individual local trajectories.

ARTICLE HISTORY

Received 27 May 2026
Accepted 27 September 2026

KEYWORDS

Mangrove migration;
mangrove boundary; spatio-
temporal evolution; coastal
squeeze

1. Introduction

Occupying the transition between terrestrial and marine domains, mangrove forests continually adjust their cross-shore position as sedimentation, inundation, erosion, and human land use alter the available intertidal space. Satellite remote sensing has progressively resolved mangrove extent, structure, and multi-decadal change, but most global products remain area based and therefore do not explicitly distinguish movement of the seaward and landward boundaries (Lu and Wang 2021; Lucas et al. 2020; Lymburner et al. 2020; Wang et al. 2019).

Mangroves are among the most productive coastal ecosystems, providing critical services including carbon sequestration, shoreline stabilisation, and protection from storm surges (Alongi 2002; Giri et al. 2011; Jia et al. 2023; Spalding 2010; Sunkur et al. 2023). Their persistence under climate change depends on their capacity to adjust to relative sea-level rise through vertical accretion, lateral migration, or both (Lovelock et al. 2015; Schuerch et al. 2018; Wen, Glasby, and Hughes 2023). Process-based studies show that this adjustment is

CONTACT Hao Yu  yuh@reis.ac.cn

 Supplemental data for this article can be accessed online at <https://doi.org/10.1080/15481603.2026.2741774>.

© 2026 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group.

This is an Open Access article distributed under the terms of the Creative Commons Attribution-NonCommercial License (<http://creativecommons.org/licenses/by-nc/4.0/>), which permits unrestricted non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited. The terms on which this article has been published allow the posting of the Accepted Manuscript in a repository by the author(s) or with their consent.

governed by the interaction of sediment supply, elevation dynamics, and accommodation space, with thresholds beyond which mangroves cannot maintain their position relative to rising sea levels (Krauss et al. 2014; Saintilan et al. 2020; Woodroffe et al. 2016). Where sediment supply is sufficient, mangroves may expand seaward; where accommodation space exists, they may migrate landward; and where both pathways are constrained, coastal squeeze leads to contraction of width and area (Phan, de Vries, and Stive 2015; Rogers 2021). These processes are further modified by coastal geomorphology, tidal range, and hydrodynamic conditions, producing spatially heterogeneous responses across regions and scales (Xie et al. 2022).

Despite this mechanistic understanding, a fundamental conflict persists in the interpretation of mangrove change. At the process level, rising sea levels are expected to drive landward retreat, while sediment accumulation may promote seaward expansion. At the observational level, however, global analyses frequently report net-areal loss or gain without resolving directionality, leading to apparently contradictory evidence of simultaneous landward retreat and seaward advance (Giri et al. 2011; Goldberg et al. 2020; Hagger et al. 2022; Thomas et al. 2017). This inconsistency reflects a mismatch between process-based expectations and the metrics used to quantify change. Area-based assessments integrate multiple processes into a single scalar measure, obscuring whether mangroves are adapting through migration, expanding through sedimentation, or being compressed by coastal squeeze. As a result, identical net-area changes may arise from fundamentally different underlying dynamics, limiting the ability to diagnose mechanisms or predict future responses.

This interpretive problem is compounded by scale. Landsat and Sentinel-2 time series, multi-source observations, interpretable classification, and border-focused training have substantially improved national and regional mangrove mapping (Tian et al. 2025; Yang et al. 2024; Ye and Weng 2025; Zhao and Qin 2020; Zhao et al. 2023;). Local studies can also contextualise change using sediment, storm, or land-use evidence (Liang et al. 2025; Sun and Jiang, 2024). Conversely, global products provide consistent coverage but usually lack an explicit coast-normal representation of both boundaries. A standardised framework for quantifying edge movement across scales is therefore needed, while recognising that directional geometry alone cannot identify a unique driver.

Accordingly, this study addresses five objectives that move from global edge measurement to classification, multi-scale comparison, interpretive reconciliation, and robustness assessment.

The objectives concern observed edge geometry and its robustness across sampling densities and spatial scales; they do not treat spatial patterns as causal driver identification.

Specifically, this study aims to: (1) quantify global changes in mangrove seaward and landward boundaries from 1996 to 2020; (2) distinguish expansion, directional migration, and contraction using edge-based indicators; (3) assess how migration patterns vary across spatial scales and regions; (4) reconcile the apparent coexistence of landward retreat and seaward expansion; and (5) evaluate whether the principal categorical results are sensitive to reduced transect-sampling density.

To address these objectives, we use Global Mangrove Watch data for 1996, 2008, and 2020 (Bunting et al. 2022; Xu et al. 2024) and a global coastline-normal transect framework that separately measures the seaward (nearest) and landward (farthest) boundaries. Nearest Distance Change (NDC), Farthest Distance Change (FDC), Width Change (WC), Centroid Distance Change (CDC), and Extreme Distance Change (EDC) are combined to distinguish expansion, directional migration, and contraction across grid, national, and continental scales.

By explicitly resolving change direction, the framework moves beyond a single area statistic and identifies where opposing edge movements warrant closer examination of accommodation space, sediment supply, or anthropogenic constraints. These controls are treated as hypotheses requiring independent contextual evidence rather than as drivers diagnosed from edge movement alone.

2. Materials and methods

2.1. Analytical framework and study design

This study quantifies global mangrove land–sea migration by explicitly resolving the movement of both seaward and landward mangrove boundaries. The analysis is designed to distinguish between three fundamental outcomes—seaward expansion, landward retreat, and coastal squeeze—by separating the behaviour of each edge and their combined effect on mangrove width. To achieve this, we implement a

coastline-normal transect framework to extract directional metrics from multi-temporal mangrove distribution data, followed by classification and multi-scale statistical analysis.

The workflow comprises four stages: (1) construction of a global coastal baseline and generation of coastline-normal transects; (2) extraction of edge-based and spatial indicators describing mangrove position and width; (3) calculation of temporal changes between 1996, 2008, and 2020; (4) classification of migration patterns and analysis across grid, national, and regional scales.

This framework ensures that mangrove change is interpreted in terms of directional processes rather than net area alone.

2.2. Data sources and transect generation

Mangrove distribution data were obtained from the Global Mangrove Watch (GMW) dataset (Bunting et al. 2022), using three benchmark years: 1996, 2008, and 2020. These time points define two analysis periods (1996–2008 and 2008–2020), enabling decadal-scale assessment of migration dynamics.

A static global coastal baseline was derived from the Natural Earth 1:110 million coastline dataset (version 4.1.0, released May 2018; <https://www.naturalearthdata.com/>) and manually checked to maintain a consistent seaward geometric reference for measuring land–sea distances. The baseline was not interpreted as the observed shoreline in 1996, 2008, or 2020. Because the same origin and transect orientation were used for all epochs, a constant positional offset cancels in temporal distance differences.

From this baseline, equally spaced transects were generated perpendicular to the coastline at 3 km intervals using the Google Earth Engine (GEE) platform. A sensitivity test for the choice of 3 km is attached in the supplementary material. Transects were extended landward across mangrove zones, with lengths defined according to regional mangrove extent using Marine Ecoregions of the World (MEOW) classifications (Spalding et al. 2007). This ensured that transects captured the full cross-shore distribution of mangroves in each region.

2.3. Extraction of edge-based indicators

For each transect and time point, mangrove patches were identified and analysed using a 50 m buffer to isolate intersecting mangrove areas. From these, two key boundary points were extracted: the seaward (nearest) edge and the landward (farthest) edge relative to the coastal baseline (Figure 1). These points form the basis for all directional metrics.

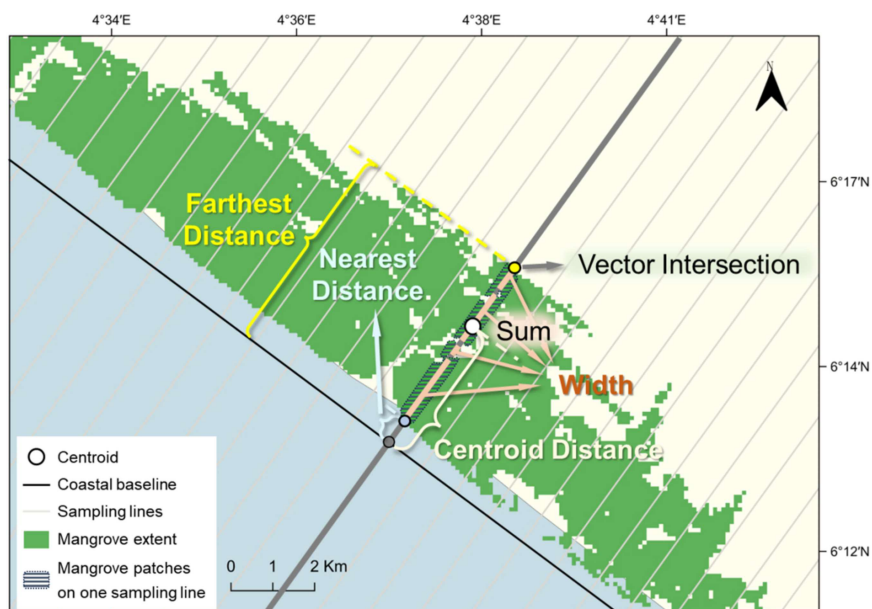


Figure 1. Extraction method of mangrove land-sea migration indicators.

2.3.1. Mangrove width

Mangrove width was calculated as the total number of mangrove pixels intersecting each transect multiplied by the spatial resolution ($K = 25$ m) (Xu et al. 2024). For a given region k , the average mangrove width was calculated as the arithmetic mean of all transect-based width measurements within that region. As a scalar indicator, mangrove Width Change (WC_k) reflects overall expansion or contraction trends. It was calculated as follows:

$$W_k = \frac{1}{m} \sum_{i=1}^m K \times N_{i,k} \quad (1)$$

$$WC_k = W_{kb} - W_{ka} \quad (2)$$

where, W_k represents the average mangrove width for the k^{th} region; $K (= 25$ m) denotes the sampling distance. For k^{th} region, $N_{i,k}$ is number of mangrove pixels for the i^{th} sampling line, and m is total number of sampling lines; W_{kb} and W_{ka} denote mangrove width, with subscripts a and b denoting initial and final time periods, respectively.

2.3.2. Extreme distance change

We calculated extreme distance for both the nearest and farthest distances to the coastal baseline. First, to isolate mangrove patches along the transect, a 50-m buffer was used to clip the mangrove extent. These patches were then intersected with the sampling line to identify two boundary points: the sea-facing and land-facing edge points. The distances from these two points to the coastal baseline along the transect were recorded as the Nearest Distance (ND) and Farthest Distance (FD) to the sea, respectively (Figure 1).

Nearest Distance represents the distance between the sea-facing edge of mangroves and the sea. Therefore, the Nearest Distance Change (NDC_k) reflects the movement of the sea-facing edge of mangroves and was calculated as follows:

$$ND_k = \frac{1}{m} \sum_{i=1}^m ND_{i,k} \quad (3)$$

$$NDC_k = ND_{kb} - ND_{ka} \quad (4)$$

where, ND_k represents the average nearest distance to the sea for k^{th} region, $ND_{i,k}$ is the nearest distance to the sea of mangrove patches for i^{th} sampling line, and m is total number of sampling lines; ND_{kb} and ND_{ka} denote nearest distance at final (b) and initial (a) periods. NDC_k is a directional variable, with positive values indicating landward migration and negative values indicating seaward migration.

The farthest distance represents the distance between the land-facing edge of mangroves and the sea. Therefore, the Farthest Distance Change (FDC_k) reflects the movement of the land-facing edge of mangroves and was calculated as follows:

$$FD_k = \frac{1}{m} \sum_{i=1}^m FD_{i,k} \quad (5)$$

$$FDC_k = FD_{kb} - FD_{ka} \quad (6)$$

where, FD_k represents the average farthest distance to the sea for k^{th} region, $FD_{i,k}$ is the farthest distance to the sea of mangrove patches for i^{th} sampling line, and m is total number of sampling lines; FD_{kb} and FD_{ka} denote farthest distance at final (b) and initial (a) periods. FDC_k is a directional variable, with positive values indicating landward migration and negative values indicating seaward migration.

By summing the changes in the nearest and farthest distances, the total migration distance was obtained, reflecting the extreme land-sea displacement of mangroves. The Extreme Distance Change (EDC_k) was calculated as follows:

$$EDC_k = NDC_k + FDC_k \quad (7)$$

where, NDC_k and FDC_k represent nearest distance change and farthest distance change for k^{th} region, respectively. The sign of EDC_k indicates the predominant migration direction, with positive values denoting landward movement and negative values denoting seaward movement.

2.3.3. Centroid distance change

Centroid Distance (CD) was used to characterise the overall distance of mangrove patches from the sea. A 50 m buffer was applied to each transect and used to clip the mangrove extent, extracting the mangrove patches along the transect (Figure 1). The centroid of each extracted patch (x_c , y_c) was then calculated using the following formula (Jia et al. 2016):

$$x_c = \frac{\sum_{i=1}^n x_i a_i}{\sum_{i=1}^n a_i} \quad (8)$$

$$y_c = \frac{\sum_{i=1}^n y_i a_i}{\sum_{i=1}^n a_i} \quad (9)$$

where, (x_i , y_i) represents the centroid coordinates for each basic shape, a_i is the area of each basic shape.

By calculating the distance between the centroid and the coastal baseline, the centroid distance of mangroves along the transect was obtained. The Centroid Distance Change (CDC_k) was used to reflect the overall land-sea migration of mangrove patches and was calculated as follows:

$$CD_k = \frac{1}{m} \sum_{i=1}^m CD_{i,k} \quad (10)$$

$$CDC_k = CD_{kb} - CD_{ka} \quad (11)$$

where, CD_k represents the average centroid distance to the sea for k^{th} region, $CD_{i,k}$ is the centroid distance to the sea of mangrove patches for i^{th} sampling line, and m is total number of sampling lines; CD_{kb} and CD_{ka} denote centroid distance at final (b) and initial (a) periods. CDC_k is also a directional variable, with positive values indicating landward migration and negative values indicating seaward migration.

For all directional indicators, positive values denote landward displacement and negative values denote seaward displacement; $WC > 0$ denotes expansion and $WC < 0$ denotes contraction. At $1^\circ \times 1^\circ$ grid scale for 1996–2020, the observed ranges were NDC: –1034.4 to 5629.1 m; FDC: –2468.3 to 3402.0 m; EDC: –1724.9 to 5622.2 m; CDC: –1350.5 to 2135.4 m; and WC: –5732.5 to 694.7 m. Display limits in the figures are used only to reveal distributional detail and do not filter the data.

2.4. Classification of migration patterns

Mangrove migration patterns were classified based on the combined behaviour of Width Change (WC), Nearest Distance Change (NDC), and Farthest Distance Change (FDC). This classification distinguishes six categories representing expansion, contraction, and directional migration (Table 1; Figure 2): **Categories 1 and 4**: Landward Migration; **Categories 2 and 5**: Seaward Migrations; **Categories 3 and 6**: No Dominant Directional Change.

This classification explicitly captures the geometric squeeze configuration: contraction ($WC < 0$) accompanied by landward retreat of the seaward edge ($NDC \geq 0$) and seaward movement of the landward edge ($FDC \leq 0$). The convergence of the two mapped edges is directly observed, whereas the environmental or anthropogenic causes of that convergence require independent evidence.

Table 1. Classification of mangrove land-sea migration patterns.

WC	NDC-FDC condition	Mangrove change status	Migration pattern categories
>0	$NDC \geq 0 \wedge FDC > 0$	Mangrove expansion with landward movement	1
	$NDC < 0 \wedge FDC \leq 0$	Mangrove expansion with seaward movement	2
	$\neg D$	Mangrove expansion with no overall directional change	3
<0	$NDC \geq 0 \wedge FDC > 0$	Mangrove contraction with landward movement	4
	$NDC < 0 \wedge FDC \leq 0$	Mangrove contraction with seaward movement	5
	$\neg D$	Mangrove contraction with no overall directional change	6

Note: $D = (NDC \geq 0 \wedge FDC > 0) \vee (NDC < 0 \wedge FDC \leq 0)$; therefore, $\neg D$ is the mathematical complement of the two directional NDC–FDC conditions.

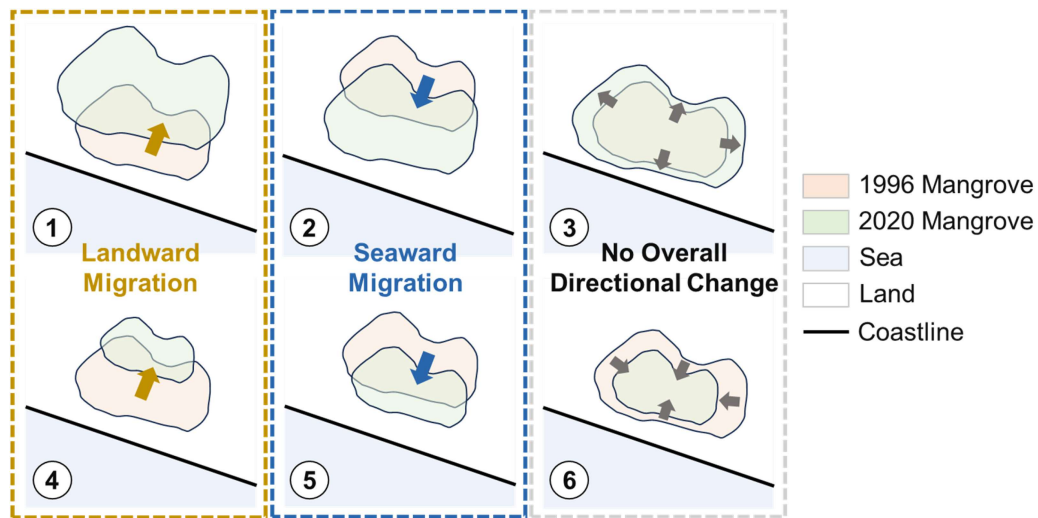


Figure 2. Schematic diagram of six mangrove land-sea migration patterns.

2.5. Multi-scale statistical analysis

All indicators were aggregated to a $1^\circ \times 1^\circ$ grid to analyse global spatial patterns while retaining local variability. Results were also summarised at national and continental scales to assess scale-dependent behaviour.

Temporal changes were evaluated across two periods (1996–2008 and 2008–2020) to identify shifts in migration dynamics. Statistical summaries, including mean, median, and distributional properties, were computed for all indicators, and spatial clustering of migration types was analysed across regions.

The multi-scale analysis evaluates whether local edge configurations persist, cancel, or become concentrated when aggregated to grid, national, and continental units. Differences among scales describe the spatial organisation of change and generate hypotheses about potential controls; they are not treated as statistical attribution of drivers.

3. Results

This section quantifies mangrove land–sea migration from 1996 to 2020 using the edge-based indicators defined in the Methods. The analysis proceeds from global patterns to temporal and regional variation, and then to scale-dependent interpretation across national and $1^\circ \times 1^\circ$ grid units. This structure is necessary because mangrove migration is not expressed uniformly across scales: global averages reveal the dominant contraction signal, regional distributions show where that signal is strongest or weakening, and grid- and country-level analyses reveal how local seaward and landward shifts aggregate into broader patterns. Results are interpreted using Width Change (WC), Nearest Distance Change (NDC), Farthest Distance Change (FDC), Extreme Distance Change (EDC), and Centroid Distance Change (CDC), which together distinguish expansion, contraction, directional migration, and coastal squeeze at the land–sea interface.

3.1. Overall global trends in mangrove-edge change

Based on the sampling lines, change indicators were extracted and aggregated into $1^\circ \times 1^\circ$ grids. Because extreme values affected the overall data display, the box plots were stretched to show distributional detail while outliers were hidden for clarity (Figure 3; Table 2). From 1996 to 2020, global mangroves declined in average width by 77.2 m, indicating a substantial reduction in cross-shore extent. This reduction reflects opposing movements of the mangrove edges: the sea-facing edge retreated landward, with a mean Nearest Distance Change (NDC) of 47.5 m, while the land-facing edge shifted seaward, with a mean Farthest Distance Change (FDC) of -53.7 m. Together, these changes produced a weak net seaward signal,

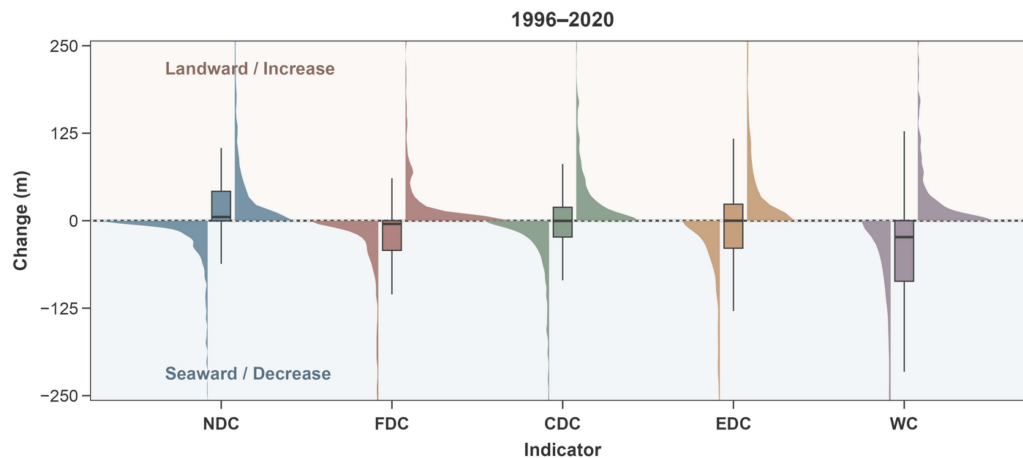


Figure 3. Split half-violin and box plots of the five 1996–2020 indicators at $1^{\circ} \times 1^{\circ}$ grid scale. NDC and FDC describe displacement of the seaward and landward mangrove edges, respectively; EDC is their summed displacement, CDC describes centroid displacement, and WC describes width change. Positive values are shown on the right half of each distribution and denote landward movement, or expansion for WC; negative values are shown on the left and denote seaward movement, or contraction for WC. The display is limited to -250 to 250 m only to reveal distributional detail; density estimation and summary statistics use the complete data, whose full ranges are reported in [Section 2.3](#) and [Table 2](#).

Table 2. Key statistics for each indicator from 1996 to 2020.

Measure	Nearest distance change (m)	Farthest distance change (m)	Extreme distance change (m)	Centroid distance change (m)	Width change (m)
Minimum	−1034.4	−2468.3	−1724.9	−1350.5	−5732.5
1 st Qu.	−0.2	−42.7	−39.2	−23.3	−86.7
Median	5.3	−4.7	0.0	−0.3	−23.4
Mean	47.5	−53.7	−6.2	−3.9	−77.2
3rd Qu.	42.2	0.0	23.8	19.1	0.0
Maximum	5629.1	3402.0	5622.2	2135.4	694.7

with an average Extreme Distance Change (EDC) of -6.2 m and an average Centroid Distance Change (CDC) of -3.9 m.

This combination of positive NDC, negative FDC, and negative WC indicates that the global signal is not simple directional migration but contraction from both boundaries. Near-zero EDC and CDC values therefore do not imply stability. Rather, they reflect compensating edge movements that mask a systematic loss of mangrove width. The global pattern is consistent with widespread coastal squeeze, in which mangroves are compressed between retreat of the seaward edge and constraints acting on the landward edge.

The spatial distribution of global mangrove land–sea migration patterns from 1996 to 2020 was analysed at both grid and country scales ([Figure 4](#)). Grid-based classification showed that mangrove areas experiencing width reduction (Categories 4, 5, and 6) accounted for 74.2% of the total, while expansion (Categories 1, 2, and 3) accounted for 25.8%. Areas exhibiting clear directional migration (Categories 1, 2, 4, and 5) accounted for 32.2% of the total. Within these, seaward migration was more prevalent than landward migration, with proportions of 65.2% and 34.8%, respectively.

Seaward migration was globally distributed, with regional concentrations in the Philippines, Sulawesi, and the eastern coast of Myanmar. The most extreme seaward case occurred in Marajó Bay, Brazil, where displacement reached 2468.2 m. Nine countries showed an overall seaward pattern, including Myanmar and Venezuela. Landward migration had less distinct regional concentration, but nine countries also displayed an overall landward pattern; the largest displacement occurred in the northern Gulf of Mexico (5629.1 m). Only South Africa, Timor-Leste, and Bangladesh combined landward migration with increased mangrove width, whereas the remaining six countries combined landward movement with width loss.

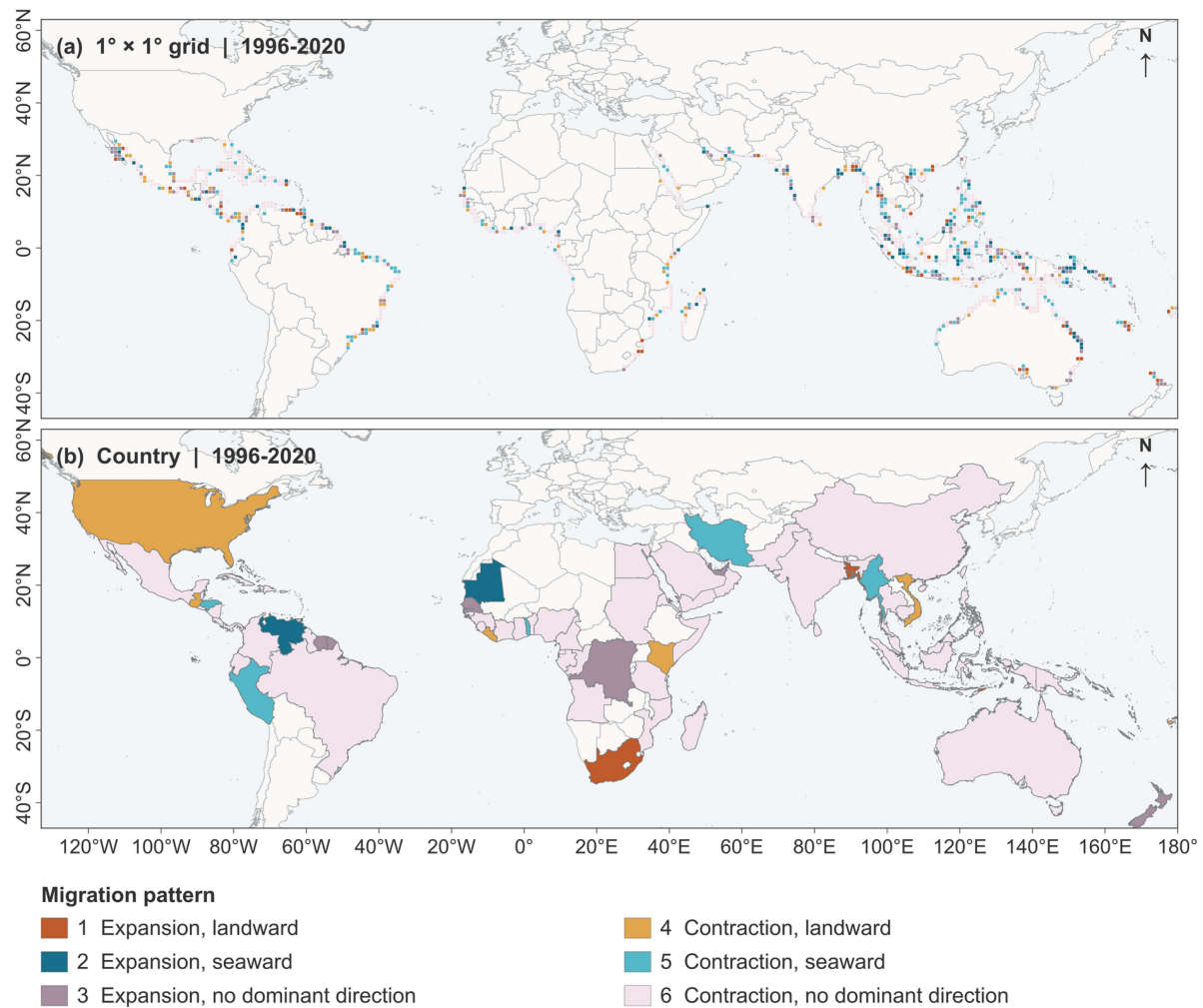


Figure 4. Global distribution of mangrove migration patterns during 1996–2020 at (a) $1^\circ \times 1^\circ$ grid and (b) national scales. Categories 1 and 4 indicate landward expansion and contraction, respectively; Categories 2 and 5 indicate seaward expansion and contraction; and Categories 3 and 6 indicate expansion and contraction without a dominant migration direction. The complete NDC–FDC–WC conditions are given in Table 1.

3.2. Temporal, national, and regional change patterns

Mangrove migration patterns were extracted using national boundaries and $1^\circ \times 1^\circ$ grids for the three time points 1996, 2008, and 2020, producing two study phases: 1996–2008 and 2008–2020 (Figures 5 and 7). Comparison between these phases shows a clear temporal shift in migration dynamics.

In Phase 1 (1996–2008), directional migration was relatively limited. Most regions exhibited near-zero EDC and CDC values, reflecting balanced edge movements rather than stability. In Phase 2 (2008–2020), landward migration became more prominent. At the national scale, the number of countries exhibiting landward migration increased from 5 (6.3%) in Phase 1 to 17 (21.3%) in Phase 2 (Figure 5), indicating a substantial increase in inland displacement.

To further examine these patterns, countries with dominant migration in each phase were ranked by EDC (Figure 6). For Phase 2 landward-migrating countries, CDC generally aligned with EDC, except in Oman and Madagascar. Bangladesh showed the strongest landward migration, driven primarily by landward boundary displacement and accompanied by increased width. Ghana also showed strong centroid migration despite relatively small EDC values.

In contrast, Phase 1 seaward-migrating countries showed greater divergence between CDC and EDC, including Myanmar, the United Arab Emirates, Indonesia, and Fiji. Myanmar exhibited the strongest seaward migration, driven primarily by changes in the land-facing boundary and associated with width

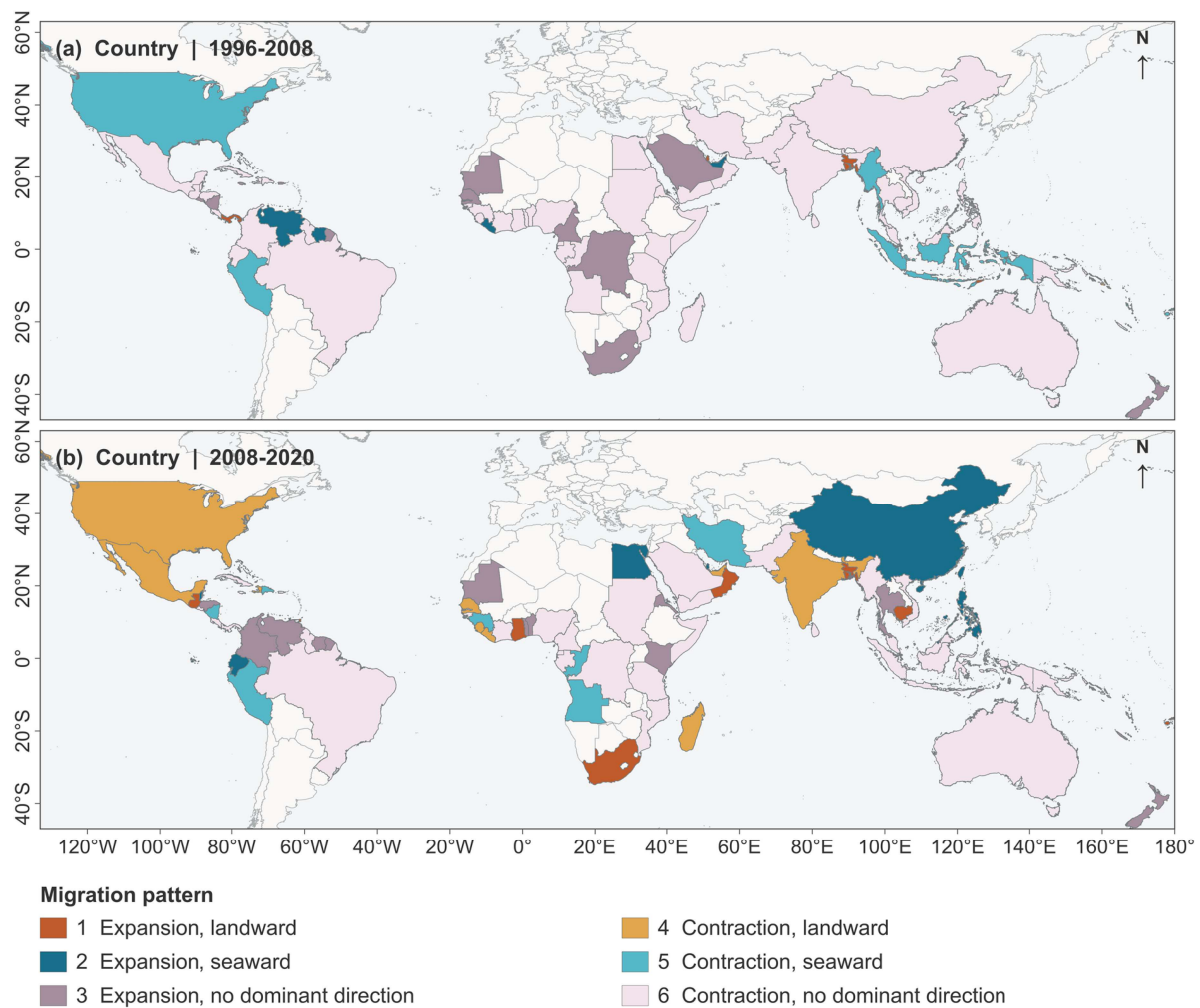


Figure 5. National-scale mangrove migration patterns during (a) 1996–2008 and (b) 2008–2020. Categories 1 and 4 indicate landward expansion and contraction, respectively; Categories 2 and 5 indicate seaward expansion and contraction; and Categories 3 and 6 indicate expansion and contraction without a dominant migration direction. The complete NDC–FDC–WC conditions are given in [Table 1](#).

reduction. Venezuela showed a low CDC value that did not correspond to its EDC ranking, highlighting differences between centroid and edge-based metrics.

Several countries, including the United States and Fiji, showed reversals in migration direction between phases. More than half of all countries (41, or 51.3%) showed no clear directional migration trend in either phase. For example, Pakistan experienced a width reduction of 886.4 m without a clear directional trend, indicating balanced contraction from both boundaries.

At the grid scale, seaward migration was more prevalent than landward migration in both phases ([Figure 7](#)). In Phase 1, seaward migration occurred 1.89 times more frequently than landward migration, while in Phase 2 this ratio decreased to 1.45. Both migration types increased in Phase 2, but landward migration increased more rapidly, with landward grids increasing by 46.9% compared with 12.6% for seaward grids.

3.2.1. Regional analysis

Regional distributions further clarify the spatial and temporal dynamics of mangrove migration across the four major geographies ([Figures 8 and 9](#)). During Phase 1 (1996–2008), the statistical distributions of CDC and EDC across all regions were tightly centred around zero, initially showing no clear directional trend in overall mangrove migration ([Figure 8](#)).

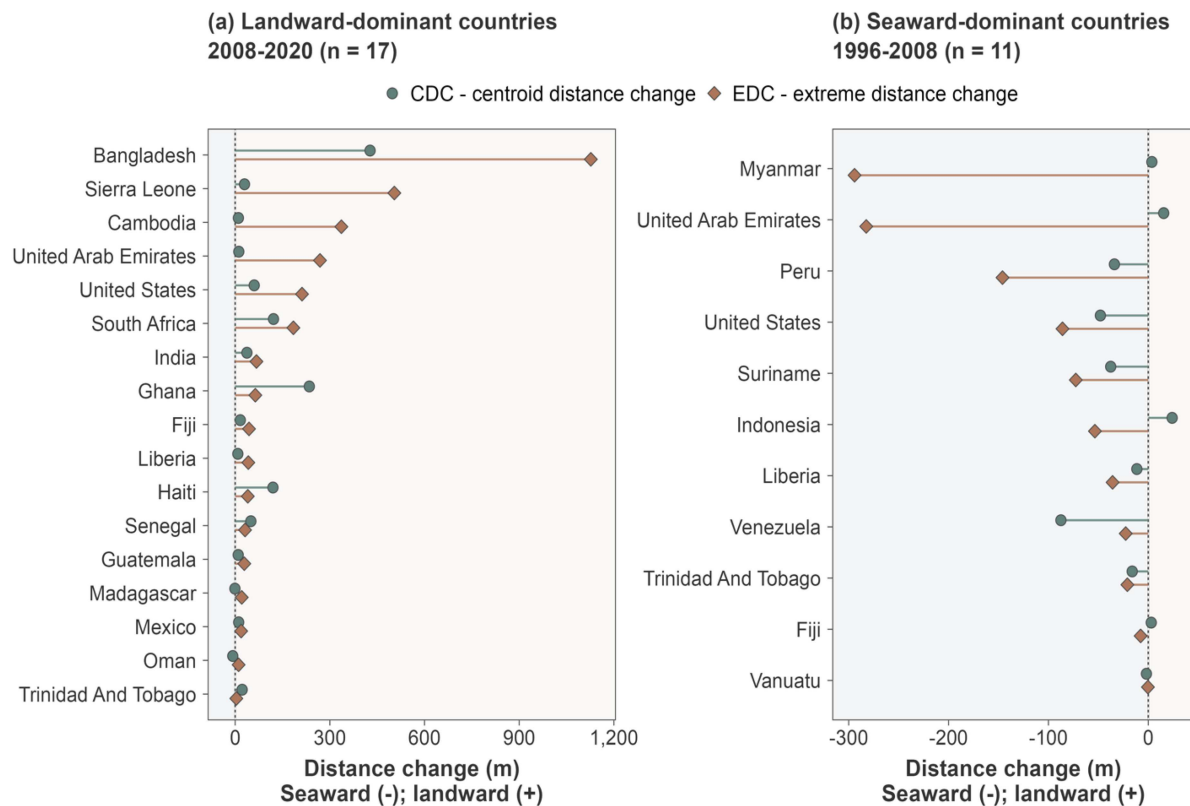


Figure 6. Centroid Distance Change (CDC) and Extreme Distance Change (EDC), in metres, for countries classified by dominant national migration direction. (a) All 17 countries classified as landward-dominant during 2008–2020, ordered by decreasing EDC; (b) all 11 countries classified as seaward-dominant during 1996–2008, ordered by increasing EDC. Positive values denote landward displacement and negative values denote seaward displacement. CDC tracks movement of the mangrove centroid, whereas EDC sums displacement of the seaward and landward edges.

However, this apparent stability masked significant internal boundary dynamics. As illustrated in Figure 9, the near-zero CDC and EDC values resulted from strongly opposing migration directions at the two margins. During Phase 1, NDC values were predominantly positive, indicating a landward migration of the seaward edge. Simultaneously, FDC values were overwhelmingly negative, indicating a seaward migration of the landward edge. This opposing directional trend—where both boundaries migrate toward each other—highlights a severe bilateral coastal squeeze across most regions. This contraction was most pronounced in Asia, which exhibited the widest deviations in both the landward-shifting NDC and the seaward-shifting FDC, reflecting substantial mangrove shrinkage. In contrast, changes in Oceania were relatively modest, suggesting highly stable boundary conditions.

In Phase 2 (2008–2020), CDC and EDC values remained approximately centred around zero but became more dispersed, indicating greater local variability (Figure 8). NDC and FDC distributions moved closer to zero than in Phase 1, while the prevalence of grids and countries classified as landward migration increased, particularly in Asia and Africa (Figure 9). With only two 12-year intervals, these results demonstrate a change in the frequency and distribution of migration classes, not a statistically resolved acceleration or a discrete post-2008 climatic or policy trigger.

4. Discussion

The results reveal a dominant global signal of contraction alongside regionally variable and locally expressed migration patterns. Opposing movements of the seaward and landward edges are directly observed, whereas sea-level rise, sediment supply, topography, land use, and restoration remain potential controls whose contributions cannot be separated by edge geometry alone. Interpretation therefore

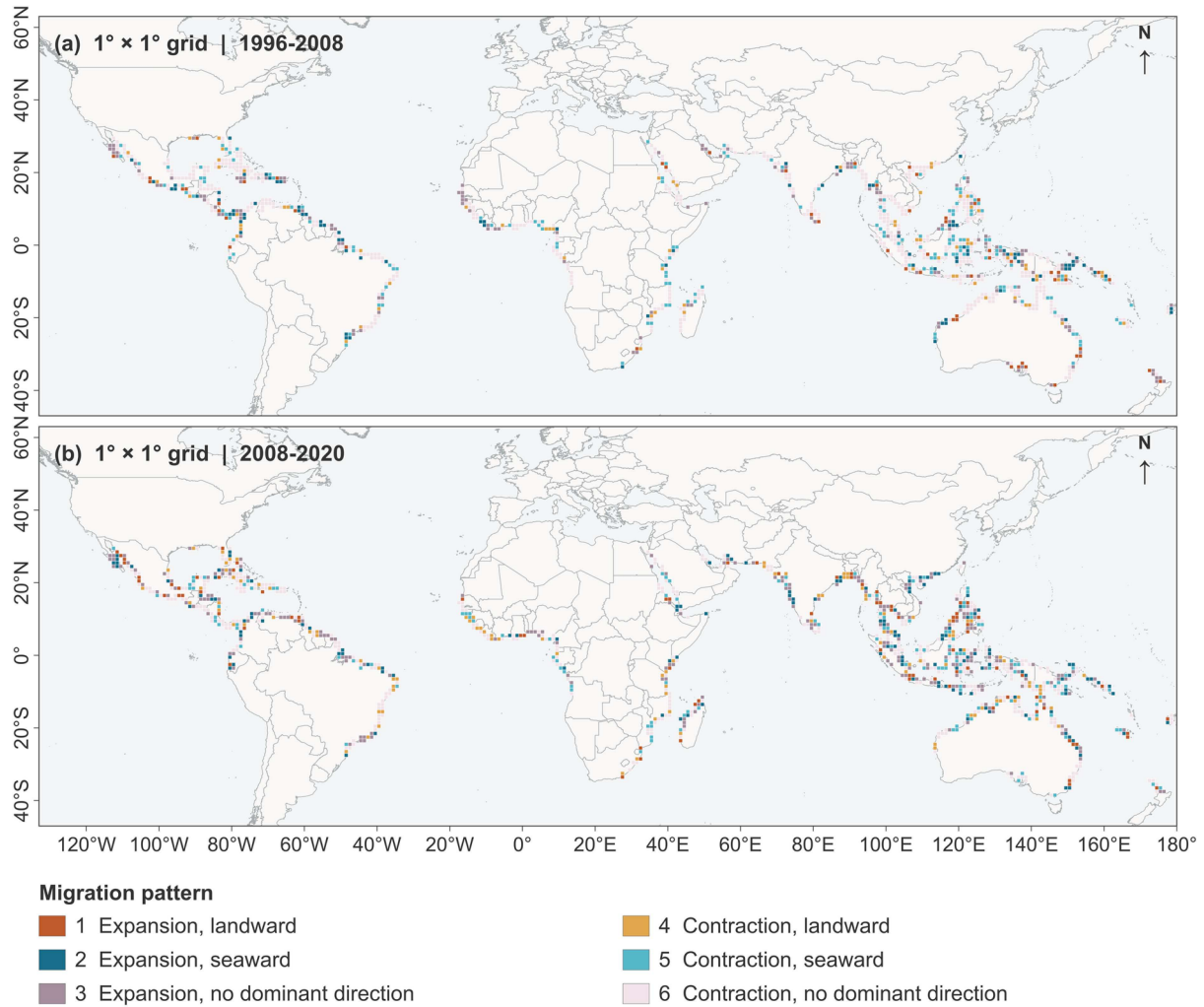


Figure 7. Grid-scale mangrove migration patterns during (a) 1996–2008 and (b) 2008–2020. Each unit is a $1^\circ \times 1^\circ$ grid. Categories 1 and 4 indicate landward expansion and contraction, respectively; Categories 2 and 5 indicate seaward expansion and contraction; and Categories 3 and 6 indicate expansion and contraction without a dominant migration direction. The complete NDC–FDC–WC conditions are given in Table 1.

proceeds from observed indicators, to configurations consistent with particular mechanisms, and only then to locally supported contextual evidence.

4.1. Validation of extracted land–sea migration patterns using representative regions

To validate the reliability of the extracted land–sea migration patterns, several representative regions of change were selected and visually examined using high-resolution remote sensing imagery. One of the most illustrative examples is Maheshkhali Island, located in the northeastern Bay of Bengal, which exhibited significant seaward and landward mangrove shifts during different phases of the study period (Figure 10).

In Phase 1, pronounced seaward migration was observed, with mean centroid displacement up to 655.3 m (Figure 10b,c). The mapped expansion coincided with local sediment trapping and land-building activities that may have favoured colonisation of newly accreted intertidal zones (Jupin et al. 2023). This contextual correspondence is compatible with a sediment-related contribution but does not isolate it from hydrodynamic or management effects.

In Phase 2 (2008–2020), mangroves along the adjacent Maheshkhali Channel exhibited landward migration (Figure 10c,d). Changes in sediment supply, hydrodynamics, erosion, or intervention are plausible

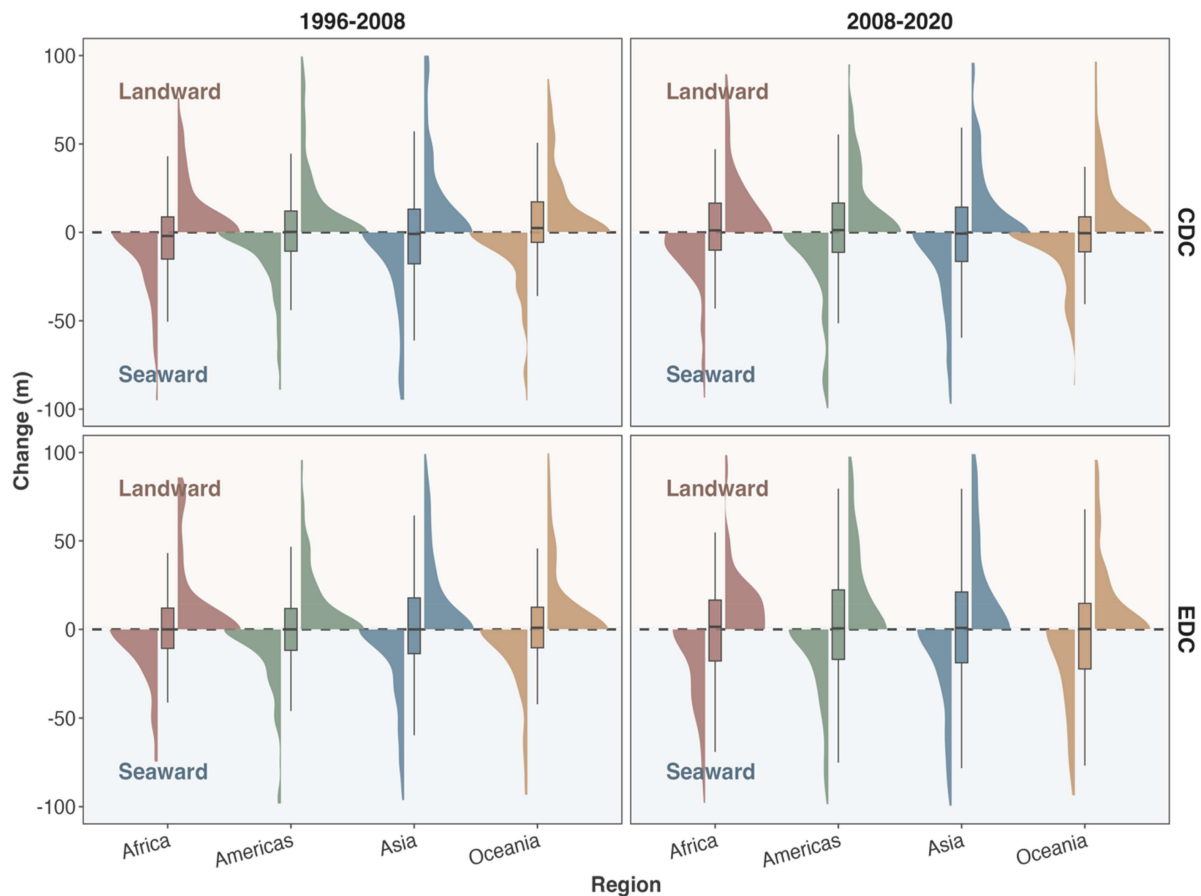


Figure 8. Regional distributions of Centroid Distance Change (CDC) and Extreme Distance Change (EDC), in metres, during 1996–2008 and 2008–2020. Positive values denote landward movement and negative values denote seaward movement. Violins and box plots summarise $1^\circ \times 1^\circ$ grid values within Africa, the Americas, Asia, and Oceania. The display is limited to -100 to 100 m only to reveal distributional detail; the underlying data were not filtered.

explanations, but they cannot be separated by the available observations. The agreement between mapped edge trajectories and high-resolution imagery supports the reliability of the directional indicators without establishing a specific cause.

4.2. Relationship between mangrove migration and broader tidal wetland dynamics

To further explore the relationship between mangrove migration and broader intertidal ecosystem dynamics, we compared the extracted migration patterns with tidal wetland changes using the global dataset provided by Murray et al. (2022), applying the same methodological framework described in Section 2.2 (Table 3).

As mangroves represent a key component of tidal wetlands, their spatial dynamics are closely linked. Mangrove migration can be viewed as a subset of broader tidal wetland migration, while the extent of other tidal wetland types, including tidal flats and saltmarshes, may create spatial opportunities for mangrove expansion (Waycott et al. 2011).

At Maheshkhali Island, tidal wetlands migrated landward during both phases. Mangrove movement aligned with this trend in Phase 2 but showed the opposite pattern in Phase 1. This mismatch may result from slight differences in the timeframes used for mangrove and tidal wetland analyses, or it may reflect genuine differences in migration behaviour. The shift in mangrove migration type between phases suggests that earlier landward movement of tidal wetlands may have created suitable substrate for subsequent mangrove expansion.

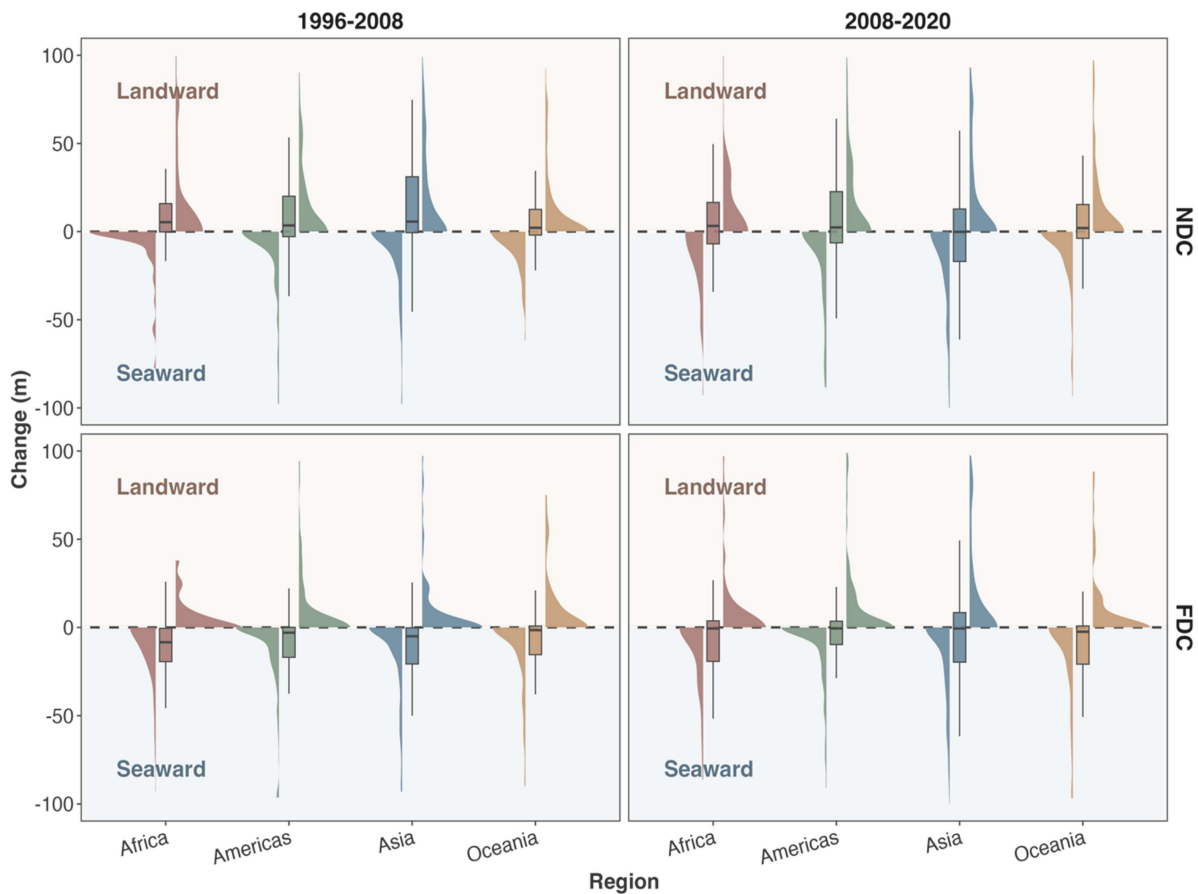


Figure 9. Regional distributions of Nearest Distance Change (NDC) and Farthest Distance Change (FDC), in metres, during 1996–2008 and 2008–2020. NDC describes the seaward edge and FDC the landward edge; positive values denote landward movement and negative values denote seaward movement. Violins and box plots summarise $1^\circ \times 1^\circ$ grid values within Africa, the Americas, Asia, and Oceania. The display is limited to -100 to 100 m only to reveal distributional detail; the underlying data were not filtered.

A contrasting pattern is observed at the Amazon River mouth. In both phases, tidal wetlands expanded and exhibited consistent seaward migration, primarily driven by strong expansion of the sea-facing edge. In contrast, mangroves experienced contraction in Phase 1 followed by expansion in Phase 2, with notable landward migration during Phase 1. These differences highlight the complexity of intertidal ecosystem interactions and demonstrate that mangroves, while linked to broader wetland systems, respond to drivers in distinct and sometimes asynchronous ways.

4.3. Potential controls on mangrove land-sea migration and limits of attribution

Interpreting potential controls on mangrove land-sea migration requires linking the observed edge configurations to independent environmental and land-use evidence. Relative sea-level rise, sediment dynamics, storms, topography, aquaculture, infrastructure, and restoration can each influence boundary position, but the present global edge dataset does not estimate their independent causal contributions.

Because the 2018 Natural Earth coastline was held fixed across the three observation years, the reported edge displacements represent changes relative to a common geometric baseline rather than movement relative to the contemporaneous shoreline. Although this fixed reference improves temporal comparability and causes a constant baseline offset to cancel in temporal differences, coastline migration and generalisation may locally alter transect orientation and mangrove-patch intersections, particularly in rapidly changing deltas and fragmented archipelagos. Accordingly, local displacement estimates in such settings

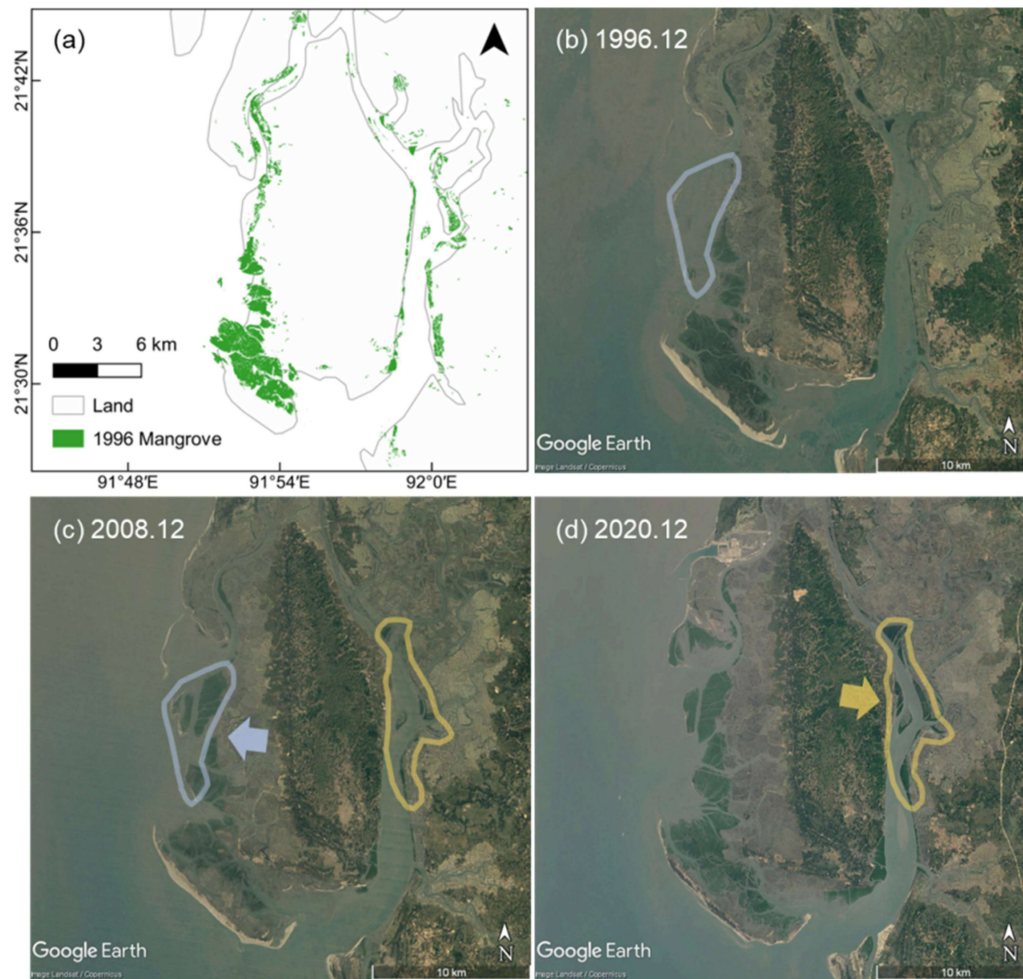


Figure 10. High-resolution temporal remote sensing imagery (from Google Earth Pro) of mangrove migration in a representative region: Maheshkhali Island, located in the northeastern Bay of Bengal, Bangladesh. The blue and yellow outlined areas highlight mangroves undergoing seaward and landward migration, respectively.

Table 3. Key parameters for the extraction of tidal wetland and mangrove migration in representative regions.

Typical area	Type	Time period	NDC (m)	FDC (m)	EDC (m)	CDC (m)	WC (m)
Maheshkhali	Tidal wetland	1999–2010	71.0	44.8	115.9	288.4	94.5
		2010–2019	–173.9	188.6	14.7	451.0	383.3
	Mangrove	1996–2008	543.7	–1150.8	–607.1	–1234.8	–447.5
		2008–2020	–1455.2	1266.1	–189.1	1033.4	1257.2
Amazon	Tidal wetland	1999–2010	–1401.0	–79.6	–1480.6	–523.3	242.2
		2010–2019	–1445.2	–1.7	–1446.9	–771.4	397.0
	Mangrove	1996–2008	306.6	–293.8	12.8	–34.2	–22.7
		2008–2020	–1964.8	–605.3	–2570.1	–1638.3	1568.0

should be interpreted with caution, while the fixed baseline preserves a consistent temporal reference for regional and global comparisons.

At the global scale, the Results show a mean width loss of 77.2 m accompanied by opposing movements of the seaward and landward edges (NDC = 47.5 m; FDC = –53.7 m; Table 2). This observed configuration is consistent with compression between marine-side retreat and restricted landward accommodation, but it does not by itself identify the processes responsible for either edge movement.

Figure 11 places the observed squeeze configuration within an idealised tidal-estuary framework. Panel (a) shows three non-exclusive landscape contexts: river–sediment input supporting seaward expansion, open low-gradient accommodation space allowing landward migration, and local topographic or infrastructure restriction producing edge convergence. Mangroves form a dense seaward intertidal belt and

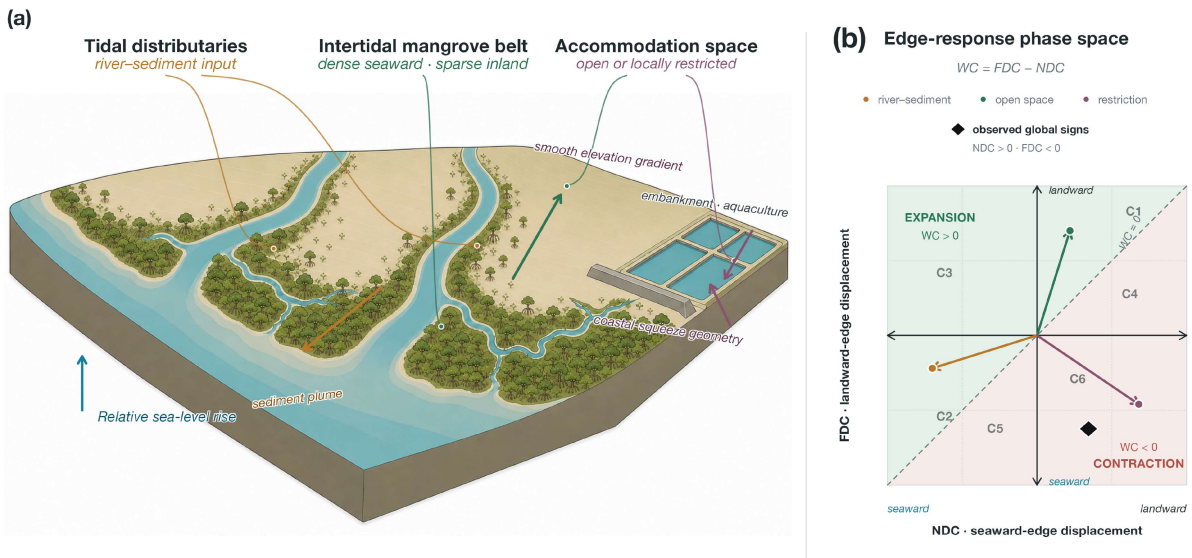


Figure 11. Conceptual mangrove edge-response pathways. (a) An idealised tidal estuary showing sediment-supported seaward expansion, landward migration where accommodation space remains open, and edge convergence where space is restricted. Mangroves form a dense seaward intertidal belt and become sparser inland along tidal distributaries. (b) Corresponding NDC–FDC phase space. $WC = FDC - NDC = 0$ separates expansion from contraction; C1–C6 denote the six classes in Table 1. Coloured arrows are illustrative pathways, and the black diamond records the observed global sign combination ($NDC > 0$; $FDC < 0$). The pathways do not identify causal drivers.

become progressively sparser inland along tidal distributaries. Panel (b) maps these pathways into NDC–FDC phase space: $WC = FDC - NDC = 0$ separates expansion from contraction, C1–C6 correspond to Table 1, and the black diamond records only the observed global mean sign combination ($NDC > 0$ and $FDC < 0$). The coloured vectors are illustrative, non-exclusive pathways rather than fitted driver effects.

At the regional scale, variability in sediment supply and accommodation space modulates this global signal. Regions with high sediment supply can sustain seaward expansion, as illustrated by the Marajó Bay example in Brazil (up to 2468.2 m), while regions with available accommodation space allow substantial landward migration, as observed in the northern Gulf of Mexico (up to 5629.1 m). However, in many regions, anthropogenic pressures limit inland migration pathways. Activities such as river damming, dredging, aquaculture expansion, and coastal infrastructure development restrict sediment delivery and reduce available accommodation space, thereby constraining adaptive capacity (Schuerch et al. 2018; Di Nitto et al. 2014; Jankowski, Törnqvist, and Fernandes 2017).

To add locally contextualised quantitative evidence, we assessed southern Mekong Delta (Figure 12). The grid intersected 47 transects, of which 44 supported valid 2-km landward assessment corridors. Within these corridors, Copernicus DEM GLO-30 elevation had a median of 1.8 m (interquartile range 0.5–2.6 m), and 98.8% of cells were at or below 5 m. Mapped 2020 aquaculture occupied 28.6% of corridor area (Jiang et al., 2024). Together with $NDC = 284.7$ m, $FDC = -57.2$ m, and $WC = -637.3$ m during 1996–2020, these observations show that low-lying accommodation space coincides locally with substantial aquaculture occupation. Aquaculture is interpreted as a potential land-use constraint, not as proof that it caused the observed contraction.

At the local scale, diverse edge combinations produce the patterns observed in Figures 6 and 7. Seaward migration was 1.89 and 1.45 times more frequent than landward migration at grid scale in the two periods, whereas the number of countries classified as landward migration increased from 5 (6.3%) to 17 (21.3%). These are descriptive differences in frequency and regional concentration; they do not demonstrate sediment-driven processes or reduced constraints without independent local evidence.

These scale-dependent patterns explain how global contraction can coexist with local seaward migration and a post-2008 increase in the prevalence of landward migration. The mapped geometry is compatible with multiple interacting controls, but the relative effects of sea-level rise, sediment dynamics, land use, and restoration require temporally matched driver data.

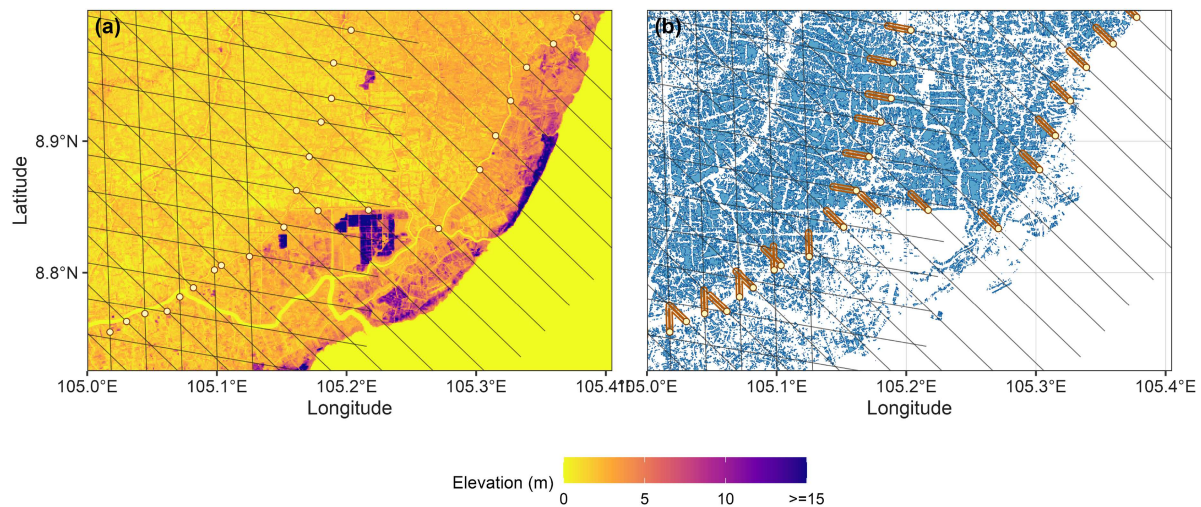


Figure 12. Representative topographic and anthropogenic context for grid N09E105 in the southern Mekong Delta/Ca Mau coastal setting. (a) Copernicus DEM GLO-30 elevation and coast-normal transects; yellow circles locate the mapped 2020 landward mangrove edges. (b) Mapped 2020 coastal aquaculture ponds (blue) and 2-km landward assessment corridors (orange). Within the corridor, median surface elevation was 1.8 m (interquartile range 0.5–2.6 m), 98.8% of DEM cells were ≤ 5 m, and aquaculture occupied 28.6% of corridor area. The grid exhibited $NDC = 284.7$ m, $FDC = -57.2$ m, and $WC = -637.3$ m during 1996–2020. This local correspondence is not treated as causal attribution. Aquaculture data: Jiang et al. (2024); DEM: Copernicus GLO-30 (2021 release).

The 2008 epoch is an observation boundary rather than a statistically detected changepoint. The 2008–2020 interval overlaps continued global mean sea-level rise and the expansion of restoration, protected-area, and climate-adaptation initiatives, any of which could alter mapped edge gains or available accommodation space (Arifanti 2020; Lovelock et al. 2015; Worthington et al. 2020). Because these environmental and policy changes were gradual, regionally asynchronous, and not encoded as temporally matched covariates, the observed increase in landward-migration prevalence is contextualised as coincident with—not attributed to—global climate or policy shifts.

4.4. Coastal squeeze, ecosystem services, and management implications

The significance of monitoring mangrove migration lies in the essential ecosystem services these forests provide (Lee et al. 2014). Regions exhibiting positive NDC, negative FDC, and width loss have an edge configuration consistent with coastal squeeze. Continued loss of mangrove width can reduce ecosystem function, although the consequences at individual sites depend on forest structure and local setting (Barbier 2016; Gedan et al. 2011).

Restoration provides an additional anthropogenic explanation for some apparent edge gains. Planting or assisted natural regeneration on abandoned landward aquaculture or agricultural land can appear as landward migration, whereas planting on accreting tidal flats can produce seaward expansion. Because Global Mangrove Watch does not encode whether new cover arose from natural recruitment or intervention, the post-2008 increase in landward-migration prevalence cannot be attributed solely to sea-level rise or changing accommodation space.

The Results show that 74.2% of analysed mangrove units experienced contraction, indicating that squeeze-consistent edge configurations are widespread rather than localised. Width loss can affect shore-line protection, carbon storage, and habitat provision, but these ecological consequences were not measured directly in the present analysis.

By identifying areas where opposing edge movements lead to contraction, the analysis provides a spatially explicit basis for prioritising restoration and conservation efforts. Incorporating mangrove migration patterns into coastal zone management enables more adaptive strategies that anticipate ecological responses to sea-level rise, erosion, and infrastructure development (Walters et al. 2008).

Effective management therefore requires moving beyond static conservation boundaries toward dynamic approaches that preserve landward migration pathways and maintain sediment supply.

4.5. Future research and policy directions

Future research should prioritise the integration of high-resolution spatial and temporal data to refine understanding of regional variation in mangrove migration. This includes incorporating sediment transport modelling, hydrological data, and socioeconomic indicators to disentangle the complex drivers of change (He et al. 2024).

Advances in Earth observation technologies, coupled with long-term ecological monitoring, will be critical for developing early-warning systems and adaptive management frameworks (Worthington et al. 2020). Policymakers are encouraged to embed migration-informed zoning and restoration strategies into broader coastal development agendas (Arifanti 2020), ensuring that mangrove systems retain the spatial flexibility needed to respond to environmental change while continuing to deliver essential ecosystem services.

5. Conclusion

This study shows that global mangrove dynamics are dominated by contraction rather than simple directional migration. From 1996 to 2020, mangrove width declined by an average of 77.2 m alongside opposing movements of the seaward and landward edges. Although 32.2% of analysed units exhibited clear directional migration, approximately two-thirds shifted seaward. These edge trajectories describe the geometry of change but do not, by themselves, identify a causal driver.

After 2008, the prevalence of landward migration increased, especially across Asia and Africa, but often alongside continued width loss. The coexistence of landward and seaward shifts is consistent with spatially variable sediment dynamics and accommodation space; their relative contributions, together with restoration and land-use change, cannot be separated by the present design.

Effective management must therefore prioritise dynamic coastal space, particularly the protection of landward migration pathways under accelerating sea-level rise.

Acknowledgements

This work is supported by the Strategic Priority Research Program of Chinese Academy of Sciences (Grant No. XDB0740300).

Author contributions

CRediT: **Dongjie Fu**: Conceptualization, Methodology, Project administration, Resources, Supervision, Writing – review & editing; **Xichen Xu**: Conceptualization, Data curation, Formal analysis, Methodology, Software, Validation, Writing – original draft, Writing – review & editing; **Fenzhen Su**: Conceptualization, Methodology, Project administration, Resources, Supervision, Writing – review & editing; **Zhijun Dai**: Conceptualization, Methodology, Supervision, Writing – original draft; **Vincent Lyne**: Conceptualization, Investigation, Supervision, Visualization, Writing – original draft, Writing – review & editing; **Jiasheng Tang**: Formal analysis, Investigation, Writing – review & editing; **Lu Kang**: Formal analysis, Writing – review & editing; **Hao Yu**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing.

Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

Dongjie Fu  <http://orcid.org/0000-0003-3062-2727>

Fenzhen Su  <http://orcid.org/0000-0003-4972-3595>

Jiasheng Tang  <http://orcid.org/0009-0003-3812-4711>

Hao Yu  <http://orcid.org/0000-0002-7647-1162>

Data availability statement

The data supporting the findings of this study are derived from the public domain. This study utilized the mangrove distribution data provided by the Global Mangrove Watch Version 3.0 downloaded from <https://zenodo.org/record/6894273#.YyMn4tXMKdw>. The coastline data was sourced from Natural Earth 1:110 million vector boundaries of coastline, downloaded from <https://www.naturalearthdata.com/>. Ecoregion data was from Marine Ecoregions of the World (MEOW) provided by World Wildlife Fund (WWF), downloaded from <https://www.worldwildlife.org/publications/marine-ecoregions-of-the-world-a-bioregionalization-of-coastal-and-shelf-areas>. The representative N09E105 assessment used Copernicus DEM GLO-30 (<https://registry.opendata.aws/copernicus-dem/>) and the 2020 Vietnam coastal aquaculture dataset archived at <https://zenodo.org/records/8344132> (Jiang et al., 2024). All data could be found in the repository "Global Mangrove Land-Sea Migration Patterns", (Fu, D., Xu, X., Hao, Y. (2025). Global Mangrove Land-Sea Migration Patterns [Data set]. Zenodo. <https://doi.org/10.5281/zenodo.15412114>).

References

- Alongi, D. M. 2002. "Present State and Future of the World's Mangrove Forests." *Environmental Conservation* 29 (3): 331–349. <https://doi.org/10.1017/S0376892902000231>.
- Arifanti, V. B. 2020. "Mangrove Management and Climate Change: A Review in Indonesia." *IOP Conference Series: Earth and Environmental Science* 487 (1): 012022. <https://doi.org/10.1088/1755-1315/487/1/012022>.
- Barbier, E. B. 2016. "The Protective Service of Mangrove Ecosystems: A Review of Valuation Methods." *Marine Pollution Bulletin* 109 (2): 676–681. <https://doi.org/10.1016/j.marpolbul.2016.01.033>.
- Bunting, P., A. Rosenqvist, L. Hilarides, R. M. Lucas, N. Thomas, T. Tadono, T. A. Worthington, M. Spalding, N. J. Murray, and L.-M. Rebelo. 2022. "Global Mangrove Extent Change 1996–2020: Global Mangrove Watch Version 3.0." *Remote Sensing* 14 (15): 3657. <https://doi.org/10.3390/rs14153657>.
- Di Nitto, D., G. Neukermans, N. Koedam, H. Defever, F. Pattyn, J. G. Kairo, and F. Dahdouh-Guebas. 2014. "Mangroves Facing Climate Change: Landward Migration Potential in Response to Projected Scenarios of Sea Level Rise." *Biogeosciences* 11 (3): 857–871. <https://doi.org/10.5194/bg-11-857-2014>.
- Gedan, K. B., M. L. Kirwan, E. Wolanski, E. B. Barbier, and B. R. Silliman. 2011. "The Present and Future Role of Coastal Wetland Vegetation in Protecting Shorelines: Answering Recent Challenges to the Paradigm." *Climatic Change* 106 (1): 7–29. <https://doi.org/10.1007/s10584-010-0003-7>.
- Giri, C., E. Ochieng, L. L. Tieszen, Z. Zhu, A. Singh, T. Loveland, J. Masek, and N. Duke. 2011. "Status and Distribution of Mangrove Forests of the World Using Earth Observation Satellite Data." *Global Ecology and Biogeography* 20 (1): 154–159. <https://doi.org/10.1111/j.1466-8238.2010.00584.x>.
- Goldberg, L., D. Lagomasino, N. Thomas, and T. Fatoyinbo. 2020. "Global Declines in Human-Driven Mangrove Loss." *Global Change Biology* 26 (10): 5844–5855. <https://doi.org/10.1111/gcb.15275>.
- Hagger, V., T. A. Worthington, C. E. Lovelock, M. F. Adame, T. Amano, B. M. Brown, D. A. Friess, et al. 2022. "Drivers of Global Mangrove Loss and Gain in Social-Ecological Systems." *Nature Communications* 13 (1): 6373. <https://doi.org/10.1038/s41467-022-33962-x>.
- He, C. Q., J. Braun, H. Tang, X. P. Yuan, E. Acevedo-Trejos, R. F. Ott, and G. S. de Quay. 2024. "Drainage Divide Migration and Implications for Climate and Biodiversity." *Nature Reviews Earth & Environment* 5 (3): 177–192. <https://doi.org/10.1038/s43017-023-00511-z>.
- Jankowski, K. L., T. E. Törnqvist, and A. M. Fernandes. 2017. "Vulnerability of Louisiana's Coastal Wetlands to Present-Day Rates of Relative Sea-Level Rise." *Nature Communications* 8(1): Article 1. <https://doi.org/10.1038/ncomms14792>.
- Jia, M., Z. Wang, L. Luo, R. Zhang, and H. Zhang. 2023. "Global Status of Mangrove Forests in Resisting Cyclone and Tsunami." *The Innovation Geoscience* 1 (2): 100024. <https://doi.org/10.59717/j.xinn-geo.2023.100024>.
- Jia, M., M. Liu, Z. Wang, D. Mao, C. Ren, and H. Cui. 2016. "Evaluating the Effectiveness of Conservation on Mangroves: A Remote Sensing-Based Comparison for Two Adjacent Protected Areas in Shenzhen and Hong Kong, China." *Remote Sensing* 8(8): 627. Article 8. <https://doi.org/10.3390/rs8080627>.
- Jiang, Yufeng, Jing Li, Zhen Zhang, and Yi Li. 2024. "Dynamics of coastal land-based aquaculture pond in China and Southeast Asia from 1990 to 2020." *International Journal of Applied Earth Observation and Geoinformation* 127: 103654. <https://doi.org/10.1016/j.jag.2024.103654>.
- Jupin, J. L. J., A. C. Ruiz-Fernández, A. Sifeddine, J. A. Sanchez-Cabeza, L. H. Pérez-Bernal, J. G. Cardoso-Mohedano, M. A. Gómez-Ponce, and J. G. Flores-Trujillo. 2023. "Anthropogenic Drivers of Increasing Sediment Accumulation in Contrasting Mexican Mangrove Ecosystems." *CATENA* 226: 107037. <https://doi.org/10.1016/j.catena.2023.107037>.
- Krauss, K. W., K. L. McKee, C. E. Lovelock, D. R. Cahoon, N. Saintilan, R. Reef, and L. Chen. 2014. "How Mangrove Forests Adjust to Rising Sea Level." *New Phytologist* 202: 19–34. <https://doi.org/10.1111/nph.12605>.

- Lee, S. Y., J. H. Primavera, F. Dahdouh-Guebas, K. McKee, J. O. Bosire, S. Cannicci, K. Diele, et al. 2014. "Ecological Role and Services of Tropical Mangrove Ecosystems: A Reassessment: Reassessment of Mangrove Ecosystem Services." *Global Ecology and Biogeography* 23 (7): 726–743. <https://doi.org/10.1111/geb.12155>.
- Liang, X., Z. Dai, X. Mei, R. Wang, W. Zeng, and S. Fagherazzi. 2025. "Hurricanes Induced Irreversible Large-Scale Loss of Mangrove Forests." *Geophysical Research Letters* 52 (9): e2025GL115692. <https://doi.org/10.1029/2025GL115692>.
- Lovelock, C. E., D. R. Cahoon, D. A. Friess, G. R. Guntenspergen, K. W. Krauss, R. Reef, K. Rogers, et al. 2015. "The Vulnerability of Indo-Pacific Mangrove Forests to Sea-Level Rise." *Nature* 526 (7574): 559–563. <https://doi.org/10.1038/nature15538>.
- Lu, Y., and L. Wang. 2021. "How to Automate Timely Large-Scale Mangrove Mapping with Remote Sensing." *Remote Sensing of Environment* 264: 112584. <https://doi.org/10.1016/j.rse.2021.112584>.
- Lucas, R., R. Van De Kerchove, V. Otero, D. Lagomasino, L. Fatoyinbo, H. Omar, B. Satyanarayana, and F. Dahdouh-Guebas. 2020. "Structural Characterisation of Mangrove Forests Achieved through Combining Multiple Sources of Remote Sensing Data." *Remote Sensing of Environment* 237: 111543. <https://doi.org/10.1016/j.rse.2019.111543>.
- Lymburner, L., P. Bunting, R. Lucas, P. Scarth, I. Alam, C. Phillips, C. Ticehurst, and A. Held. 2020. "Mapping the Multi-Decadal Mangrove Dynamics of The Australian Coastline." *Remote Sensing of Environment* 238: 111185. <https://doi.org/10.1016/j.rse.2019.05.004>.
- Murray, N. J., T. A. Worthington, P. Bunting, S. Duce, V. Hagger, C. E. Lovelock, R. Lucas, et al. 2022. "High-Resolution Mapping of Losses and Gains of Earth's Tidal Wetlands." *Science* 376: 744–749. <https://doi.org/10.1126/science.abm9583>.
- Phan, L. K., J. S. V. T. de Vries, and M. J. Stive. 2015. "Coastal Mangrove Squeeze in the Mekong Delta." *Journal of Coastal Research* 31 (2): 233–243. <https://doi.org/10.2112/JCOASTRES-D-14-00049.1>.
- Rogers, K. 2021. "Accommodation Space as a Framework for Assessing Mangrove Response to Relative Sea-Level Rise." *Singapore Journal of Tropical Geography* 42: 163–183. <https://doi.org/10.1111/sjtg.12357>.
- Saintilan, N., N. S. Khan, E. Ashe, J. J. Kelleway, K. Rogers, C. D. Woodroffe, and B. P. Horton. 2020. "Thresholds of Mangrove Survival under Rapid Sea Level Rise." *Science* 368 (6495): 1118–1121. <https://doi.org/10.1126/science.aba265>.
- Schuerch, M., T. Spencer, S. Temmerman, M. L. Kirwan, C. Wolff, D. Lincke, C. J. McOwen, et al. 2018. "Future Response of Global Coastal Wetlands to Sea-Level Rise." *Nature* 561(7722): 231–234. Article 7722. <https://doi.org/10.1038/s41586-018-0476-5>.
- Spalding, M. 2010. *World atlas of mangroves*. Routledge. <https://www.taylorfrancis.com/books/mono/10.4324/9781849776608/world-atlas-mangroves-mark-spalding>.
- Spalding, M. D., H. E. Fox, G. R. Allen, N. Davidson, Z. A. Ferdaña, M. A. X. Finlayson, B. S. Halpern, M. A. Jorge, A. L. Lombana, and S. A. Lourie. 2007. "Marine Ecoregions of the World: A Bioregionalization of Coastal and Shelf Areas." *BioScience* 57 (7): 573–583. <https://doi.org/10.1641/B570707>.
- Sun, Z., W. Jiang, Z. Ling, J. Sun, Z. Zhang, S. Huang, and Q. Li. 2024. "Rapid Expansion of Coastal Mangrove Forest in Guangxi Beibu Gulf: Patterns, Drivers and Impacts." *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 18: 1–13. <https://doi.org/10.1109/JSTARS.2024.3454976>.
- Sunkur, R., K. Kantamaneni, C. Bokhoree, and S. Ravan. 2023. "Mangroves' Role in Supporting Ecosystem-Based Techniques to Reduce Disaster Risk and Adapt to Climate Change: A Review." *Journal of Sea Research* 196: 102449. <https://doi.org/10.1016/j.seares.2023.102449>.
- Thomas, N., R. Lucas, P. Bunting, A. Hardy, A. Rosenqvist, and M. Simard. 2017. "Distribution and Drivers of Global Mangrove Forest Change, 1996–2010." *PLoS One* 12 (6): e0179302. <https://doi.org/10.1371/journal.pone.0179302>.
- Tian, J., L. Wang, C. Diao, Y. Zhang, M. Jia, L. Zhu, M. Xu, X. Li, and H. Gong. 2025. "National Scale Sub-Meter Mangrove Mapping Using an Augmented Border Training Sample Method." *ISPRS Journal of Photogrammetry and Remote Sensing* 220: 156–171. <https://doi.org/10.1016/j.isprsjprs.2024.12.009>.
- Walters, B. B., P. Rönnbäck, J. M. Kovacs, B. Crona, S. A. Hussain, R. Badola, J. H. Primavera, E. Barbier, and F. Dahdouh-Guebas. 2008. "Ethnobiology, Socio-Economics and Management of Mangrove Forests: A Review." *Aquatic Botany* 89 (2): 220–236. <https://doi.org/10.1016/j.aquabot.2008.02.009>.
- Wang, L., M. Jia, D. Yin, and J. Tian. 2019. "A Review of Remote Sensing for Mangrove Forests: 1956–2018." *Remote Sensing of Environment* 231: 111223. <https://doi.org/10.1016/j.rse.2019.111223>.
- Waycott, M., McKenzie, L., Mellors, J. E., Ellison, J. C., Sheaves, M. T., Collier, C., Schwarz, A.-M., Webb, A., Johnson, J. E., and Payri, C. E. 2011. Vulnerability of mangroves, seagrasses and intertidal flats in the tropical Pacific to climate change (J. D. Bell, J. E. Johnson, & A. J. Hobday, Eds.; pp. 297–368). Secretariat of the Pacific Community <http://www.spc.int/climate-change/fisheries/assessment/>
- Wen, L., T. M. Glasby, and M. G. Hughes. 2023. "The Race for Space: Modelling the Landward Migration of Coastal Wetlands under Sea Level Rise at Regional Scale." *Science of The Total Environment* 859: 160483. <https://doi.org/10.1016/j.scitotenv.2022.160483>.
- Woodroffe, C. D., K. Rogers, K. McKee, C. Lovelock, I. Mendelssohn, and N. Saintilan. 2016. "Mangrove Sedimentation and Response to Relative Sea-Level Rise." *Annual Review of Marine Science* 8: 243–266. <https://doi.org/10.1146/annurev-marine-122414-034025>.
- Worthington, T. A., D. A. Andradi-Brown, R. Bhargava, C. Buelow, P. Bunting, C. Duncan, L. Fatoyinbo, et al. 2020. "Harnessing Big Data to Support the Conservation and Rehabilitation of Mangrove Forests Globally." *One Earth* 2 (5): 429–443. <https://doi.org/10.1016/j.oneear.2020.04.018>.

- Xie, D., C. Schwarz, M. G. Kleinhans, Z. Zhou, and B. van Maanen. 2022. "Implications of Coastal Conditions and Sea-Level Rise on Mangrove Vulnerability: A Bio-Morphodynamic Modeling Study." *Journal of Geophysical Research: Earth Surface* 127 (3): e2021JF006301. <https://doi.org/10.1029/2021JF006301>.
- Xu, X., D. Fu, F. Su, V. Lyne, H. Yu, J. Tang, X. Hong, and J. Wang. 2024. "Global Distribution and Decline of Mangrove Coastal Protection Extends Far Beyond Area Loss." *Nature Communications* 15 (1): 10267. <https://doi.org/10.1038/s41467-024-54349-0>.
- Yang, X., Z. Zhu, K. D. Kroeger, S. Qiu, S. Covington, J. R. Conrad, and Z. Zhu. 2024. "Tracking Mangrove Condition Changes Using Dense Landsat Time Series." *Remote Sensing of Environment* 315: 114461. <https://doi.org/10.1016/j.rse.2024.114461>.
- Ye, L., and Q. Weng. 2025. "A Hybrid Neural Network for Mangrove Mapping Considering Tide States Using Sentinel-2 Imagery." *Remote Sensing of Environment* 329: 114917. <https://doi.org/10.1016/j.rse.2025.114917>.
- Zhao, C., and C.-Z. Qin. 2020. "10-m-resolution Mangrove Maps of China Derived from Multi-Source and Multi-Temporal Satellite Observations." *ISPRS Journal of Photogrammetry and Remote Sensing* 169: 389–405. <https://doi.org/10.1016/j.isprsjprs.2020.10.001>.
- Zhao, C., M. Jia, Z. Wang, D.-H. Mao, and Y. Wang. 2023. "Identifying Mangroves through Knowledge Extracted from Trained Random Forest Models: An Interpretable Mangrove Mapping Approach (Imma)." *ISPRS Journal of Photogrammetry and Remote Sensing* 201: 209–225. <https://doi.org/10.1016/j.isprsjprs.2023.05.025>.