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## RESEARCH ARTICLE

## Climate-Induced Migration Patterns in Vulnerable Coastal Communities

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### ABSTRACT

Coastal deltas and low-lying shorelines host a large and growing share of the world's population under increasing exposure to sea level rise, soil and water salinization, tropical cyclones and storm surge, and progressive shoreline erosion, yet how these overlapping hazards translate into household migration decisions remains contested, with evidence pointing to both displacement and, in many settings, reduced mobility among the most affected households. We surveyed 2,412 households across nine sites in three climate-exposed deltaic regions, the Ganges-Brahmaputra-Meghna delta in southwestern Bangladesh, the Mekong Delta in southern Vietnam, and the Saloum and Volta deltas of Senegal and Ghana, and linked household-reported exposure and migration histories (2008-2022) to site-level shoreline change and inundation frequency derived from a Landsat- and Sentinel-2-based surface water time series. Overall, 31.4% of surveyed households reported at least one migrant member since 2008, but migration type differed sharply by driver: salinization and progressive erosion were associated predominantly with permanent, longer-distance out-migration, while cyclone and storm-surge exposure were associated mainly with short-duration, short-distance displacement followed by return. In multivariate models, each 10-percentage-point increase in a household's land under saline intrusion was associated with a 4.1-percentage-point higher probability of permanent migration (95% CI 2.6-5.6), while landholding size and asset wealth showed a non-monotonic relationship with migration, rising with wealth at low-to-moderate asset levels before declining among the poorest quintile, consistent with resource constraints on migration among the most vulnerable rather than a simple linear escape response. Remittances from migrant household members financed an estimated 38% of embankment and homestead-raising investments among migrant-sending households in Bangladesh and Vietnam, suggesting migration and in-place adaptation function partly as complements rather than substitutes. We conclude that climate-induced coastal migration is heterogeneous by hazard type, selective by household resources, and entangled with in-place adaptation in ways that resist a single displacement narrative, with direct implications for how planned relocation and adaptation finance are targeted.

**Keywords:** environmental migration; coastal displacement; sea level rise; soil salinization; storm surge; shoreline erosion; household survey; Bangladesh; Mekong Delta; West Africa; migration decision-making

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## 1. INTRODUCTION

Estimates of the number of people who could be displaced by climate-related coastal hazards over the coming decades range from tens to hundreds of millions, depending on assumptions about sea level rise, adaptive capacity and the definition of displacement itself, and this uncertainty reflects a genuine scientific difficulty rather than mere imprecision in accounting [1,2]. Coastal deltas concentrate this exposure because they combine dense settlement, agriculture-dependent livelihoods sensitive to salinization, and low elevation that makes both gradual inundation and episodic storm surge simultaneously relevant hazards [3,4].

Early framings of environmental migration treated it largely as a direct, mechanical response: hazard exposure rises, and out-migration follows in proportion. Subsequent household-level research has complicated this picture substantially, showing that migration responses vary by hazard type, that slow-onset stressors such as salinization tend to produce different migration patterns than sudden-onset events such as cyclones, and that the poorest and most exposed households are sometimes the least able to migrate at all, a phenomenon now widely discussed under the heading of trapped populations [5,6,7]. This literature has also established that migration in response to environmental stress is rarely a single, discrete decision, but instead spans a spectrum from short-duration labor mobility and seasonal migration through permanent household relocation [8,9].

Much of the empirical evidence for these patterns derives from single-country studies, predominantly of Bangladesh, where national census and household panel data have supported some of the most carefully identified analyses of environmental migration to date [10,11,12]. Fewer studies compare migration responses to a common set of coastal hazards across multiple deltaic settings using directly comparable household-level instruments, which limits confidence in how far patterns documented in one delta generalize to others with different agrarian systems, migration infrastructure and cyclone climatology [13,14].

A further gap concerns the relationship between migration and in-place adaptation. Migration and local adaptation, embankment raising, homestead elevation, switching to saline-tolerant aquaculture, are sometimes treated as competing responses to the same underlying stress, but remittance-financed adaptation investment suggests they can instead be complementary, with migrant income enabling the very in-place adjustments that reduce future displacement risk for the households left behind [15,16]. Whether this complementarity is a general feature of coastal climate migration or a site-specific artifact of Bangladeshi remittance corridors is untested outside that setting.

This study addresses these gaps with a harmonized household survey and migration history instrument

fielded across nine sites in three climate-exposed deltaic regions, linked to remote-sensing-derived measures of shoreline change and inundation frequency at each site. We ask three questions: first, whether migration responses differ systematically by hazard type, salinization, erosion, and cyclone/storm-surge exposure, across regions; second, how household wealth and landholding mediate the relationship between exposure and migration; and third, whether remittances from migrant members finance in-place adaptation investment, and if so, how consistently across the three study regions.

## 2. MATERIALS AND METHODS

We conducted a harmonized household survey with retrospective migration histories across nine sites in three coastal deltaic regions, and linked household responses to site-level shoreline change and inundation frequency derived from a 1988–2022 Landsat and Sentinel-2 surface water time series.

### 2.1 Study regions and sampling design

Fieldwork was conducted at nine sites: three in the southwestern Ganges-Brahmaputra-Meghna delta of Bangladesh (Satkhira, Khulna and Bagerhat districts), three in the Mekong Delta of Vietnam (Ben Tre, Tra Vinh and Ca Mau provinces), and three in the Saloum delta of Senegal and the Volta delta of Ghana. Sites were purposively selected to span a gradient of dominant hazard exposure, salinization-dominant, erosion-dominant and cyclone/storm-surge-dominant, within each region, informed by prior hazard mapping and consultation with local agricultural extension offices. Within each site, households were sampled using a two-stage cluster design, with enumeration areas selected proportional to population size and 30–32 households randomly sampled within each cluster, yielding a total sample of 2,412 households (Bangladesh: 892; Vietnam: 856; West Africa: 664) surveyed between March 2021 and November 2022.

### 2.2 Household survey instrument and migration histories

The survey instrument collected household demographic composition, landholding and asset inventories, agricultural and fishing livelihood activities, self-reported exposure to salinization, erosion and cyclone/storm-surge events, and a full residential and labor migration history for every household member aged 15 or older, covering 2008–2022. Migration events were classified by the respondent as permanent (no intention to return, household member's primary residence relocated), seasonal or circular (recurring labor migration within a given year), or displacement-related temporary (relocation directly following a cyclone or flood event, with eventual return). Destination distance was recorded in three bands: within-district, inter-district or inter-provincial, and international.

### 2.3 Remote-sensing-derived exposure indicators

Site-level physical exposure was characterized independently of household self-report using a Landsat 5/7/8 and Sentinel-2 surface water occurrence time series (1988-2022) processed with a normalized difference water index threshold classifier to derive two indicators per site: a shoreline retreat rate (meters per year, from linear regression of the land-water boundary position) and an inundation frequency anomaly (the change in annual flooded-area fraction within a 5 km buffer of each surveyed cluster, comparing 2013-2022 against 1993-2002). Soil salinity was proxied using site-level electrical conductivity measurements compiled from national agricultural monitoring networks, averaged over the growing seasons preceding each survey wave. These remote-sensing and monitoring-network indicators were merged with household survey data at the cluster level to allow physical exposure to be modeled independently of, and in combination with, self-reported exposure.

### 2.4 Migration decision-making models

Household-level determinants of permanent migration since 2008 (binary outcome, at least one member reporting permanent relocation) were modeled using logistic regression with household fixed characteristics (landholding size, asset index, dependency ratio, education of household head), cluster-level physical exposure indicators, and region fixed effects as covariates. A parallel multinomial logistic specification distinguished permanent, seasonal/circular, and displacement-related temporary migration as competing outcomes to test whether determinants differed by migration type rather than pooling all mobility into a single binary response. Standard errors were clustered at the enumeration-area level throughout.

### 2.5 Remittance and adaptation investment analysis

For the subsample of migrant-sending households ( $n=758$ ), a supplementary module recorded remittance receipt and its reported use, categorized as daily consumption, debt repayment, education expenses, or in-place physical adaptation investment (embankment or pond dike raising, homestead plinth elevation, conversion to saline-tolerant crop or aquaculture systems). The share of total household adaptation investment financed by remittances was estimated by comparing self-reported investment amounts against self-reported income sources for that investment, cross-checked against a subsample of 140 households for which second-round verification interviews were conducted eight months after the initial survey.

### 2.6 Data quality, attrition and ethical procedures

Enumerators were trained locally in each region and interviews were conducted in the respondent's primary language (Bangla, Vietnamese, Wolof, French or Twi, as appropriate) using a translated and back-translated instrument piloted in each region before fieldwork.

Household informed consent was obtained prior to interview, and the study protocol was reviewed by the ethics committees of the partner institutions in each country. Item non-response for migration history questions was below 4% in all three regions; households with missing landholding or asset data (2.7% of the sample) were excluded from multivariate models but retained in descriptive statistics where possible.

## 3. RESULTS

Across the full sample, 31.4% of households reported at least one member who migrated between 2008 and 2022, ranging from 38.9% in the Bangladesh sites to 29.1% in the Vietnam sites and 22.7% in the West Africa sites. Table 1 disaggregates migration prevalence by region and self-reported dominant driver, showing that salinization-exposed households reported the highest rate of permanent migration (17.8% of households) while cyclone/storm-surge-exposed households reported the highest rate of displacement-related temporary movement (21.3%), with comparatively little overlap between the two migration types by driver.

**Table 1. Migration prevalence (2008-2022) by region and self-reported dominant hazard driver.**

| Region / driver                   | Households (n) | Any migrant (%) | Permanent migration (%) | Displacement-temporary (%) |
|-----------------------------------|----------------|-----------------|-------------------------|----------------------------|
| Bangladesh - salinization         | 312            | 44.6            | 22.1                    | 7.4                        |
| Bangladesh - erosion              | 268            | 40.7            | 19.0                    | 9.3                        |
| Bangladesh - cyclone/storm surge  | 312            | 32.1            | 9.6                     | 18.9                       |
| Vietnam - salinization            | 298            | 33.2            | 16.4                    | 6.0                        |
| Vietnam - erosion                 | 271            | 29.5            | 13.7                    | 8.9                        |
| Vietnam - cyclone/storm surge     | 287            | 24.7            | 7.3                     | 14.6                       |
| West Africa - salinization        | 224            | 26.3            | 12.5                    | 5.4                        |
| West Africa - erosion             | 218            | 23.9            | 10.1                    | 7.8                        |
| West Africa - cyclone/storm surge | 222            | 17.6            | 5.0                     | 12.2                       |
| Full sample (all sites)           | 2,412          | 31.4            | 13.9                    | 10.6                       |

Percentages are the share of households in each region/driver stratum reporting at least one migrant member of the corresponding type since 2008. Strata are defined by the household's self-reported dominant hazard concern; rows are not mutually exclusive with other migration types not shown (seasonal/circular).

The remote-sensing-derived exposure indicators corroborated this pattern independently of household self-report: clusters in the top tercile of shoreline retreat rate (mean 6.4 m/year) had a permanent migration rate of 24.6%, more than double the 10.8% observed in the

bottom tercile (mean 0.9 m/year), and this gradient was materially unchanged when restricting to households reporting salinization or erosion, rather than cyclones, as their primary concern, indicating the association is not simply an artifact of recall bias in self-reported exposure.

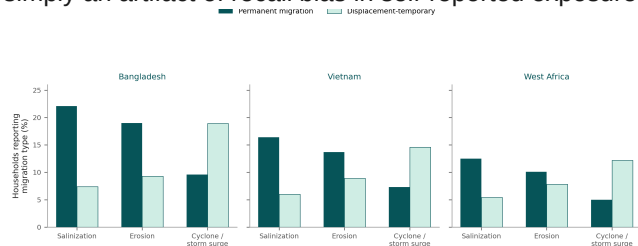


Figure 1. Permanent and displacement-related temporary migration rates by dominant hazard driver, shown separately for the Bangladesh, Vietnam and West Africa study regions (household survey, 2008-2022).

In the logistic regression models, each 10-percentage-point increase in a household's cultivated land affected by saline intrusion was associated with a 4.1-percentage-point higher probability of permanent migration (95% CI 2.6-5.6,  $p < 0.001$ ), controlling for landholding size, asset wealth, dependency ratio and region. The relationship between asset wealth and permanent migration was non-monotonic: migration probability rose with asset quintile from the poorest to the fourth quintile, then declined slightly in the wealthiest quintile, consistent with migration requiring resources that the poorest households often lack, a pattern reported separately for all three regions and summarized alongside the multinomial results in Table 2. Households in the lowest asset quintile were significantly more likely to report cyclone-related displacement without subsequent permanent relocation than wealthier households (odds ratio 1.64, 95% CI 1.21-2.23), suggesting constrained rather than absent mobility among the poorest.

**Table 2. Multinomial logistic regression: household-level correlates of migration type relative to no migration (reference category).**

| Covariate                                  | Permanent migration OR (95% CI) | Seasonal/circular OR (95% CI) | Displacement-temporary OR (95% CI) |
|--------------------------------------------|---------------------------------|-------------------------------|------------------------------------|
| Cultivated land under salinity (+10 pp)    | 1.41 (1.26-1.56)                | 1.09 (0.98-1.21)              | 1.03 (0.92-1.15)                   |
| Shoreline retreat rate (+1 m/yr)           | 1.18 (1.11-1.26)                | 1.05 (0.99-1.11)              | 1.02 (0.95-1.09)                   |
| Asset quintile 2 (vs. poorest)             | 1.34 (1.05-1.71)                | 1.22 (0.98-1.52)              | 0.91 (0.72-1.15)                   |
| Asset quintile 4 (vs. poorest)             | 1.87 (1.46-2.39)                | 1.55 (1.22-1.97)              | 0.78 (0.60-1.01)                   |
| Asset quintile 5, wealthiest (vs. poorest) | 1.71 (1.31-2.23)                | 1.38 (1.06-1.80)              | 0.61 (0.44-0.83)                   |
| Dependency ratio (+0.1)                    | 0.95 (0.90-1.00)                | 0.97 (0.92-1.02)              | 1.02 (0.96-1.08)                   |

|                                               |                  |                  |                  |
|-----------------------------------------------|------------------|------------------|------------------|
| Household head secondary education (vs. none) | 1.29 (1.09-1.53) | 1.41 (1.19-1.67) | 1.04 (0.87-1.24) |
|-----------------------------------------------|------------------|------------------|------------------|

Among the 758 migrant-sending households surveyed on remittance use, 61% reported remittances contributing to at least one in-place adaptation investment, and across this subsample remittances were estimated to finance 38% of total reported embankment- and homestead-raising expenditure in the Bangladesh and Vietnam sites combined, compared with 19% in the West Africa sites, where remittance volumes and international migration shares were lower. Figure 1 summarizes migration rates by dominant driver and region, showing the salinization-permanent and cyclone-temporary pairing holding consistently across all three regions despite substantial differences in baseline migration levels.

#### 4. DISCUSSION

These results support a view of climate-induced coastal migration as heterogeneous by hazard type rather than a single displacement process. Slow-onset salinization and erosion were associated with permanent, longer-distance relocation, consistent with a gradual erosion of agricultural livelihoods that eventually crosses a threshold at which the household relocates rather than adapts in place, echoing household-level findings from Bangladesh linking salinity to permanent out-migration [11,17]. Sudden-onset cyclone and storm-surge exposure, by contrast, produced mostly short-duration displacement with return, a pattern consistent with disaster research more broadly showing that acute shocks often trigger temporary rather than permanent mobility once immediate danger has passed [7,18].

The non-monotonic relationship between wealth and migration, rising through most of the wealth distribution before flattening or declining among the poorest, adds cross-regional evidence to the trapped-populations literature, which has argued that environmental migration is not a simple escape valve available equally to all exposed households but is instead constrained by the financial, social and informational resources that migration itself requires [6,19]. That this pattern held independently in Bangladesh, Vietnam and West African sites with quite different migration infrastructures suggests it may be a relatively general feature of environmental migration rather than a Bangladesh-specific artifact of remittance corridors and labor migration networks documented in earlier single-country studies [10,20].

The finding that remittances financed a substantial share of in-place adaptation investment, particularly in Bangladesh and Vietnam, indicates that migration and local adaptation are not simply substitutes for one another as is sometimes assumed in migration-as-failure-to-adapt framings; instead, migration by some household members appears in many cases to

fund the very adaptation investments, raised homesteads, strengthened embankments, that reduce displacement risk for those who remain [15,21]. This complementarity was weaker in the West Africa sites, plausibly reflecting lower remittance volumes associated with more localized, shorter-distance migration there relative to the longer-distance and international migration more common from the Bangladesh and Vietnam sites, though our data cannot fully rule out other regional differences in adaptation cost or credit access as contributing explanations.

Several limitations qualify these conclusions. First, migration histories rely on household recall over up to 14 years and are subject to recall error and to survivorship bias, since households that migrated in their entirety, rather than sending individual members, are underrepresented in a household-based sampling frame; this likely leads us to understate permanent, whole-household relocation relative to individual out-migration. Second, the cross-sectional, retrospective design cannot fully rule out reverse causality or confounding by unobserved household characteristics correlated with both exposure and migration propensity, and while the independent remote-sensing exposure indicators mitigate concerns specific to self-reported exposure, they do not resolve this more general identification limitation. Third, the nine sites, while spanning three regions and a range of hazard profiles, remain a purposive rather than globally representative sample of climate-exposed coastal communities, and generalization to deltas with different agrarian systems, land tenure arrangements or migration policy environments should be made cautiously. Finally, our destination-distance categories do not capture destination-country policy variation, which is likely to be a first-order determinant of whether a given household's migration response is even feasible, particularly for international movement [2,22].

## 5. CONCLUSION

A harmonized household survey across nine sites in three climate-exposed coastal deltas found that 31.4% of households had at least one migrant member since 2008, with migration type differing systematically by hazard: salinization and erosion were associated with permanent, longer-distance relocation, while cyclone and storm-surge exposure were associated mainly with short-duration displacement followed by return. Migration probability rose with household wealth through most of the distribution before declining among the poorest quintile, indicating that the most exposed households are not always the most able to migrate, and remittances from migrant household members financed a substantial share of in-place adaptation investment in the Bangladesh and Vietnam sites, suggesting migration and local adaptation function partly as complements. These patterns argue against treating climate-induced coastal migration as a single, uniform displacement process and

instead support hazard-specific and wealth-sensitive approaches to adaptation finance and planned relocation policy.

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## Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Author Contributions

L.T. conceived and supervised the study, designed the household survey instrument, and led the writing of the manuscript. H.D. coordinated fieldwork across the three regions, managed the remote-sensing exposure data processing, and performed the descriptive and regression analyses. N.R. led the remittance and adaptation investment module design and analysis and contributed to the multinomial migration models. All authors contributed to writing and approved the final manuscript.

## Ethics Statement

The study protocol, household consent procedures and survey instrument were reviewed and approved by the ethics committees of the partner institutions in Belgium, Ireland and Portugal, in coordination with local research partners in Bangladesh, Vietnam, Senegal and Ghana. Informed consent was obtained from all household respondents prior to interview, and all data were anonymized prior to analysis.

## Data Availability

The remote-sensing shoreline and inundation frequency indicators used in this study were derived from publicly available Landsat and Sentinel-2 imagery. Anonymized household survey data and analysis code supporting the findings of this study are available from the corresponding author on reasonable request, subject to data-sharing agreements with in-country research partners.

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