Sea-level rise and human migration

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Abstract | Anthropogenic sea-level rise (SLR) is predicted to impact, and, in many cases, displace, a large proportion of the population via inundation and heightened SLR-related hazards. With the global coastal population projected to surpass one billion people this century, SLR might be among the most costly and permanent future consequences of climate change. In this Review, we synthesize the rapidly expanding knowledge of human mobility and migration responses to SLR, providing a coherent roadmap for future SLR research and associated policy. While it is often assumed that direct inundation forces a migration, we discuss how mobility responses are instead driven by a diversity of socioeconomic and demographic factors, which, in some cases, do not result in a migration response. We link SLR hazards with potential mechanisms of migration and the associated governmental or institutional policies that operate as obstacles or facilitators for that migration. Specific examples from the USA, Bangladesh and atoll island nations are used to contextualize these concepts. However, further research is needed on the fundamental mechanisms underlying SLR migration, tipping points, thresholds and feedbacks, risk perception and migration to fully understand migration responses to SLR.

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Global sea levels have risen by approximately 0.2 m since 1900 (REF.[1]), with projections showing continued changes under anthropogenic warming. However, estimates of future global mean sea-level rise (SLR) vary widely; current projections for the year 2100, for example, range from a low of 0.4 m to a high of 2.5 m (REFS[2–4]), depending on assumptions of future greenhouse gas emissions, thermal expansion, melt of glaciers and the Antarctic and Greenland ice sheets, and isostatic adjustment as ice sheets disappear[5]. These SLR projections are likely conservative, and continued improvements in ice-sheet modelling suggest high-end SLR predictions are increasingly likely[6,7]. With global coastal populations totalling more than 600 million (projected to surpass one billion people this century[8]), any level of SLR is expected to impact and potentially displace a large population[9,10]. As a result, SLR is anticipated to be one of the most expensive and irreversible future consequences of global climate change[9,11–13], costing up to 4.5% of global gross domestic product[14].

The implications of SLR on human migration first appeared in the scientific literature during the late 1970s[16], when there was increased recognition that disintegration of the West Antarctic Ice Sheet could lead to major disruption in coastal cities[16], resulting in migration. It is now understood that SLR influences human migration in multiple ways. The most apparent influence involves permanent, irreversible inundation of low-elevation areas, which, under SLR, renders land uninhabitable and unavailable for livelihoods[10,12,17], necessitating relocation. However, various other hazards associated with SLR will also impact migration patterns and, in fact, will exert their influence considerably sooner than complete inundation. Hazards include saltwater intrusion into groundwater and agricultural soils[18–23], coastal flooding[24–26], shifts in sediment regimes[27], coastal erosion[28,29] and increased inland penetration of tropical storm surges[30–33]. These hazards could spur migration by permanently destroying irrigated coastal agriculture and fresh drinking water supplies[34,35], disrupting vital human systems[36–38], reducing property values[39,40] and, ultimately, destroying property and infrastructure[41,42]. SLR also threatens coastal livelihoods such as tourism[43], coastal aquiculture[44], fisheries[45] and silviculture[46], indirectly pressuring migration through adverse impacts on job security.

Since the first studies to quantify population displacement due to SLR[15], our fundamental understanding of SLR and human migration has rapidly advanced with the development of basic theory on climate-change migration[47–50], empirical case studies of historical analogues for future SLR[51–55], integrated economic analysis and modelling of SLR retreat[56–58], explicit models of SLR migration[50,59–61], as well as contentious policy discussions on the need for coastal retreat[62–65]. In some cases, studies even question if SLR will spur widespread migration at all[66,67], as demonstrated by island residents in the Philippines who would rather adapt in place to SLR-related hazards than follow a relocation programme to the mainland[67].

Key points

- A large proportion of the global population presently reside in coastal regions where sea-level rise (SLR) impacts are expected and, in many cases, may influence the migration of millions of people.
- Migration from SLR is multifaceted, influenced by environmental hazards and political, demographic, economic and social factors embedded within policy incentives to encourage or obstruct migration — not just SLR itself.
- Evidence suggests that there are strong economic, social and cultural reasons for households to resist migrating away from areas exposed to SLR until migration is the only remaining option.
- Estimating the number of migrants is difficult because future exposure to SLR is dependent on choices about carbon emissions today, as well as the coastal-adaptation choices we make over time.
- Policies addressing SLR migration via protection and accommodation are well developed but policies addressing relocation are still too abstract and lack guidance on ensuring equity.
- Future research on thresholds related to SLR migration and the interplay between physical and social processes will be critical for informing climate-migration policies.

Globally, however, SLR threatens millions of people[68], and even with strong reductions in carbon emissions, we are committed to SLR that will impact coastal cities[69]. The cost to adapt to such hazards will be hundreds of billions of dollars per year[9,14,70]. Moreover, if SLR forces millions of people further inland, a potential domino effect could result, increasing migration to more distant destinations[48] and significantly altering population distributions[50,59,60,71]. With such a large global population exposed to SLR, there are calls for governments and institutions to facilitate potential migration and protect vulnerable coastal populations[72,73].

Given the societal significance surrounding the topic, this Review synthesizes knowledge of potential human mobility and migration responses to SLR, and, in the process, identifies gaps in the research to help further SLR research and migration-related policymaking. We first discuss predictions of SLR migration, before describing decision-making at the individual and household levels. We then consider the institutional or governmental obstacles and facilitators to SLR migration, illustrating differences across the regional contexts of the USA, Bangladesh and atoll island states. Finally, we provide future directions for SLR and human-migration research.

Defining at-risk populations

Under an assumption that exposure corresponds directly with displacement, numerous studies have sought to identify the numbers and locations of people exposed to SLR[8–11,14,15,26,30,73–78]. However, estimates of SLR displacement are highly divergent, ranging from 88 million[14] to 1.4 billion, the variability driven by competing definitions of who is 'at risk'[11,12,30]. The three most common 'at-risk' definitions are: populations living in the low-elevation coastal zone (LECZ)[8,11,76,79–82], populations living in the 100-year floodplain[9,30,73–75,83–85] and populations living in areas that would be inundated under selected SLR scenarios[10,12,14,15,26,85–90]. All three approaches have associated strengths, weaknesses and implications for understanding the links between SLR and migration.

Assessments using the LECZ approach — typically defined as any area under 10 m in elevation and sometimes within 100 km of a coast[8,9,11,75,79] — employ the most generalized and broadest definition of exposure to SLR. Depending on assumptions of future population growth, global estimates of people residing in the LECZ by 2100 range from 634 million[11] to 1.4 billion[8]. Such studies cast the widest net for identifying exposure to SLR and, thus, provide the largest estimates of who might need to relocate as a result. However, residency in the LECZ alone may not entail exposure to any given SLR hazard, let alone displacement due to SLR.

By considering the extent of extreme water levels expected under SLR, residency within the 100-year floodplain offers more precise estimates of population exposure[9,30,73–75,83–85]. In the floodplain, residents might experience various SLR-associated hazards that influence migration decisions, such as increased severe storm surges[30–33,73,91], occasional or periodic flooding[24,25,92], saltwater intrusion of surface water and soils and groundwater wells[19,20,22,93–95], shifts in sediment regimes[27–29,96] and coastal erosion. In comparison to the LECZ approach, the floodplain metric reduces the exposed population in 2100 by roughly two-thirds, from 1.4 billion to 444 million[8]. However, as with the LECZ, residence in the 100-year floodplain may not necessarily result in migration responses to SLR. Indeed, many low-lying areas in the 100-year floodplain, such as Asia's densely populated 'mega-deltas', possess fertile soil and ample water, which is ideal for farming and fishing. Floodplains thus attract large numbers of migrants from other areas, notwithstanding the presence of coastal hazards[97]. Simple residency in the 100-year floodplain does not, therefore, result in migration; it is only when the costs of increasing exposure to SLR hazards exceed the benefits of coastal environments that migration may occur.

The most conservative definition of populations 'at risk' of relocation due to SLR involves demarcating those living below the future sea level and, thus, projected to be permanently inundated[10,12,14]. This approach directly links exposure to an SLR hazard that will likely spur human migration: permanent inundation. Unlike the 100-year floodplain, which holds millions of residents, virtually no one lives below sea level. However as much as 0.79% (95% credible interval: 0.22–1.60%) of the world's population, approximately 88 million people, could be permanently inundated with a median rise of 0.79 m by 2100 (REF.[14]). While this approach more precisely identifies populations that will have little choice but to relocate under various SLR scenarios, it still only links exposure to a single SLR hazard (permanent inundation), setting aside exposure to salinity, routine flooding and extreme events.

We illustrate the difference in estimates obtained by the three approaches using Bangladesh as an example. By the mid-21st century, Bangladesh is projected to have at least 110 million people living in the 10-m LECZ[8], at least 12 million living in the 100-year floodplain[8] and about 1 million people directly inundated by SLR[10]. The difference between each exposure estimate is about one order of magnitude. Thus, as few as 1 million people could be forced to migrate and as many as 110 million people could experience some SLR-related impact, depending on the selection of temporal horizons, vertical elevation thresholds and SLR forecasts.

In the absence of any adaptive measures, the estimate of populations directly inundated likely underestimates those who will migrate due to SLR impacts[59], whereas the population estimates in the LECZ and 100-year floodplain likely overestimate potential future migrants. However, because exposure to hazard alone is not a valid indicator of migration potential, none of these estimates (alone or in combination with one another) reliably quantify the number of people likely to migrate due to SLR at global, regional or local scales[49,98,99]. Indeed, vulnerable communities have often shown an unwillingness or inability to migrate (BOX 1), even under constant threat[100], influenced by individual and household-level decisions.

Individual and household migration

Decisions by individuals and households to migrate are influenced by more than SLR risk. They instead fall on a multidimensional framework whereby individuals must also weigh up the costs and benefits of a myriad of economic, social, demographic, emotional and political factors[97,101–104], as well as the onset and duration of the environmental hazard itself (FIG. 1). In the case of SLR, people migrate in response to policy incentives, employment opportunities, socioeconomics, and social and kin networks within perceptions of the risk before deciding to migrate. These factors might operate in concert or independently from each other. For instance, property damage from a storm surge alone might not be enough impetus for someone to migrate, but property damage in concert with a policy incentive such as home buyouts might be enough. These factors are then further mediated by individual/household preferences and institutional-level obstacles and facilitators. People make choices about when they move, their destination, who to move with and whether to return[97,105,106] — all embedded within a multidimensional decision-making framework (FIG. 1). In different contexts and increasingly over time, SLR hazards, risk perception, adaptation policies and livelihood changes, in particular, will variably factor into migration decisions.

The perception of climate risk forms a critical bridge between a change in SLR and a potential migration response[107]. Both contextual and cognitive factors influence a person's risk perception, including proximity to a hazard or potential hazard, past experience with a hazard, existence of structural protections against hazards and the individual's ideology, economic resources and demographic characteristics[108,109]. For SLR migration, the perception of flood risk is often paramount[110–112]. Past experience with severe flooding causes people to perceive future flooding events as riskier[113–115], amplifying possible forward-looking migration responses[98,116]. Perceptions of the risks of SLR combine with many other factors to influence the decision to move into or away from coastal areas. Therefore, SLR may marginally increase existing migration out-flows and decrease migration in-flows to coastal areas[76].

Environmental drivers of migration typically operate by negatively affecting natural-resource-based livelihoods, such as farming and fishing, that are sustained by combining different types of capital (for example, natural, social, financial, physical)[117]. A sustainable livelihood allows coastal residents to cope with and recover from stresses and shocks while remaining in place. Soil salinization that lowers agricultural yields is one such threat to the sustainable livelihoods of coastal residents[59]. Other livelihoods threatened by SLR include tourism[43], aquiculture[44], fisheries[45] and silviculture[46]. When livelihoods deteriorate, people diversify their livelihood portfolio by sending household members to work elsewhere temporarily, with the goal of remitting earnings[118–120]. To date, there is little evidence[51] of environmental deterioration leading to complete settlement abandonment[121].

Those who are most likely to move away from SLR hazards are those who can best absorb the emotional and financial costs and extract benefits associated with migrating: healthy, skilled, working-age adults, who can increase lifetime potential earnings by moving to higher-wage labour[119,122–126]. For example, in atoll island nations heavily threatened by SLR, evidence already suggests that SLR hazards translate into reduced housing values[40] and migration of young, working-age people for economic opportunities[127–130].

Tropical cyclones provide important analogues[131] for SLR and human migration, as increased tropical cyclone intensity is associated with SLR. Generally, cyclones and associated flooding produce temporary, short-term mobility, and not permanent out-migration. For example, a study using millions of mobile network subscribers quantified mobility before, during and after Cyclone Mahasen, which struck Bangladesh in May 2013. They found evidence of slight anomalies in temporary mobility around the storm, but virtually no permanent migration[132]. In New Orleans, Louisiana, widespread destruction of housing from Hurricane Katrina produced near complete evacuation of the city

Box 1 | **Inability or unwillingness to migrate**

In the absence of institutional measures to reduce exposure, households adapt according to their perceptions of the risks and the resources available to them[101]. Even in the face of pronounced risks of floods, storms, erosion and other coastal hazards, empirical evidence suggests that households are reluctant to move away from or abandon their homes, livelihood assets and social networks[129].

For example, as a result of land becoming uninhabitable through a combination of sea-level rise (SLR), subsidence and salinization, authorities and non-governmental organizations have attempted to resettle residents of Papua New Guinea's low-lying Carteret Islands. However, the process has been complicated by islanders' reluctance to abandon the islands' resources and fishing opportunities[100], as well as difficulties in finding satisfactory accommodation and livelihood options at the resettlement location.

Similar hesitation to abandon areas highly exposed to coastal flooding, storms and erosion have been described in Fiji[223,224] and Bangladesh[225,226], with affected residents often preferring circular labour migration and temporary relocation over permanently resettling in less exposed areas. In some cases, people even migrate to risky coastal areas for economic[97] or lifestyle reasons[227], further suggesting resistance to migrate away from threatened coastal areas. In the aftermath of Hurricane Katrina, many displaced residents of New Orleans expressed strong desires to return to their destroyed city, with cultural ties and a strong 'sense of place' being important motivations[228–230].

The evidence suggests that there are strong economic, social and cultural reasons for households to resist migrating away from areas exposed to SLR unless and until there are few or no other remaining options. Even then, socioeconomically marginalized households may lack the financial means to relocate, rendering them trapped and vulnerable[47,107,230,231].

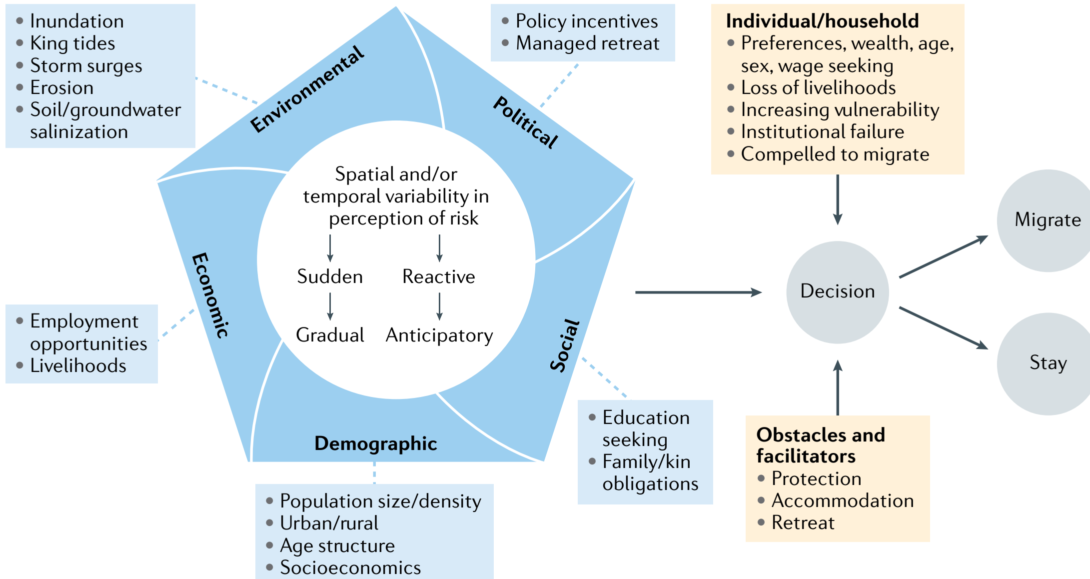

Fig. 1 | **Migration outcomes under conditions of SLR.** A schematic of the numerous factors influencing sea-level rise (SLR)-driven migration. Migration from SLR is multifaceted and is influenced by environmental hazards and political, demographic, economic and social factors embedded within policy incentives to encourage or obstruct migration — not just SLR itself. SLR can gradually pressure migration, such as inundation, or suddenly, such as tropical cyclones, and individuals might migrate in reaction to this change or in anticipation of this change. The decision to migrate is also made in conjunction with individual/household contexts where SLR migration might result from a loss of livelihood or due to institutional failure. Institutions also mediate this decision with obstacles and facilitators designed to either prevent migration by reducing SLR hazards or to accentuate migration through retreat. Adapted from REF.[47], Springer Nature Limited.

and increased residents' mobility over the next several years, but many residents returned after homes and neighbourhoods had been rebuilt[133,134]. Both examples point to a reluctance to permanently relocate to new destinations (BOX 1). Cyclones have yet to produce long-term changes in coastal populations[41,135], but higher-intensity cyclones could compromise economic growth in many regions of the world[136,137] and, in the long term, affect the viability of coastal communities that are unable to adapt[69].

While SLR may displace coastal populations in the future, urbanization and coastal amenities support large coastal populations, and continue to drive pro-coastal migration. For centuries, people have settled in river deltas and coasts for their natural resources and amenities, including fresh water, ecosystem services, transportation and recreational opportunities. These environmental resources and amenities, as well as the disamenities associated with SLR and cyclones, are capitalized in housing prices and wages[138–140]. The processes influencing migration are difficult to incorporate into demographic projections. Instead, those seeking to quantify how SLR will affect future populations identify geographic 'hotspots'[71,141]. The extent of coastal urbanization provides clear motivation for institutions in these 'hotspots' to prevent SLR-related migration or, in the case where prevention is unfeasible, facilitate migration to safer locales.

Institutional influences

Migration is often described as being one of a wide range of potential household-level adaptation choices to reduce exposure[47,142,143]. Yet, in the case of SLR-related hazards, there are relatively few long-term adaptation choices available to households apart from migration[144]. Thus, household-level responses to SLR and other hazards are typically contingent upon or 'downstream' from government and institutional responses[145–147].

Institutional adaptive responses to SLR operate as either obstacles or facilitators to migration (FIG. 1) and fall under three broad categories: protection, accommodation and retreat (FIG. 2). A combination of environmental and socioeconomic conditions influences which response (or mixture of responses) governments employ to cope with, and adapt to, SLR. Protection and accommodation are policy actions designed to prevent migration by either reducing SLR hazards (through protection) or increasing capacity to cope with the hazard (via accommodation). Retreat, by contrast, directly facilitates migration.

Much of the adaptation literature focuses on protection measures designed to hold back the sea, prevent the negative impacts of SLR and, thus, reduce the need for migration[9,30,73,74,148]. These solutions include hard armouring like seawalls, groins and other infrastructure that maintain and expand the current shoreline and, in some cases, provide protection against storm surges. Soft-armouring methods, such as beach nourishment[149–151] or 'living shorelines'[152,153] further replenish lost sediment and encourage more natural defences to SLR. The costs associated with protecting the world's coastal populations via protection are astounding[73,85] and are projected to reach nearly $100 billion by the end of the century[70]. Given both the costs and scale, it is unlikely that governments will armour every coastline in the world[144,154].

Adaptation responses include accommodation of higher water levels, adjusting usage in and of the coastal

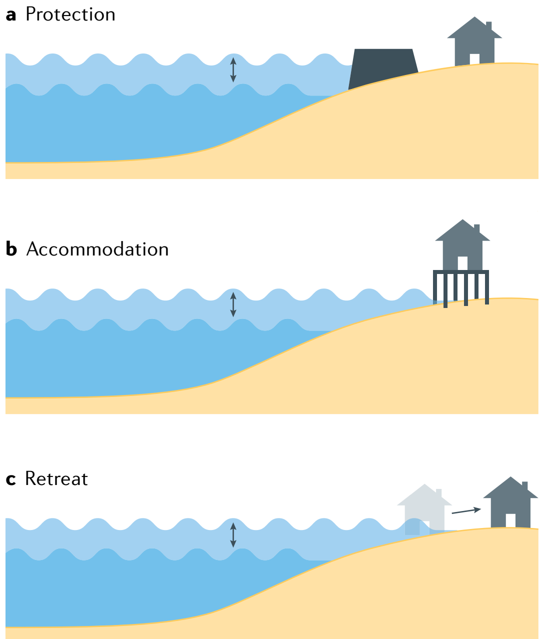

Fig. 2 | **Responses to SLR hazards.** A schematic illustration of the potential responses to sea-level rise (SLR). **a** | Protection, which refers to armouring designed to prevent the hazards. **b** | Accommodation, which refers to adaptation measures designed to facilitate living with the hazards. **c** | Migration or retreat, which refers to the relocation of individuals or communities away from the hazard.

zone[145] to reduce negative SLR-related hazards that drive migration. Accommodation strategies include elevating homes and structures[55,155,156], flood proofing[157], managing land use, deploying flood warnings and pumps[158], changing groundwater-extraction techniques[145] or elevating roads. Many port cities' coastal management plans already contain provisions to accommodate higher water levels[155], such as coastal buffer zones in Ghana[159] or multi-tiered terraces in Mokpo, Korea[160]. Much like costs for protection, those associated with accommodation can be high[157], but remain lower than extensive protection. Thus, accommodation seems to be the most feasible adaptation measure[154], as demonstrated by its already widespread adoption across the world[55,144,161,162].

Retreat includes interventions that aim to facilitate migration out of SLR hazard areas or relocate residents and settlements to safer locations[145]. Although less desirable than protection and accommodation[55,67,163], relocation is already seen as inevitable for a number of 'hotspot' communities[62,164] now or in the future, when protection and accommodation become too costly or ineffective[74]. The Carteret Islands in Papua New Guinea, Vunidogoloa in Fiji and Kivalina in Alaska, USA, are some communities either undergoing relocation or have already relocated due to SLR-associated hazards[62,164]. We identify two types of retreat: planned or managed retreat and unplanned retreat or migration.

Managed retreat. Managed-retreat interventions might include a purposeful and coordinated process of relocation away from the path of eroding coastlines and coastal hazards[62]. Based on past analogues, managed retreat in response to SLR will likely be limited to small populations living in highly exposed areas[49]. Barring a catastrophic storm[63], it is unlikely for many large cities due to the scale and value of infrastructure, or sunk costs. Instead, these cities are likely to commit to protection in the nearterm[165].

Resettlement of a whole community requires centralized planning, where relocation includes considerations for infrastructure and service provisions, such as new roads, schools, markets, clinics and houses[62,164,166–168]. For many countries and areas where most property is privately owned, agreements to resettle are difficult to achieve and the cost is considerable[62,167,169,170]. Governments also lack coherent and coordinated regulatory approaches to address who exactly is vulnerable, what parameters determine habitability, where communities will relocate and when relocation will occur[171]. The success of a centrally planned managed retreat also depends on the availability of safer inland areas to host migrants. In many countries, private land owners can wield property rights and 'institutional muscle' to legally exclude others in a semi-permanent barrier to migrant entry[172]. In contrast, countries with capacity for strong centralized planning, like China, are more able to implement retreat strategies requiring involuntary relocation and large-scale mobilization of resources[172]. Likewise, retreat strategies may be more feasible in countries with large communally owned lands, like the Pacific Island countries of Fiji and Samoa[49]. For example, Fiji successfully relocated 26 households from the village of Vunidogoloa in 2012 (REF.[173]), whereas resettlement has been delayed in highly threatened Alaskan villages[62].

Unplanned retreat. Many countries lack comprehensive federal approaches for planned relocation[174] but have a range of legal mechanisms to support individual and household-level retreat at multiple governmental scales (national, state and local). These policy responses lead to 'unmanaged' or 'unplanned' retreat[175]. These include 'downzoning' flood-prone areas, creating setbacks or buffers, securing easements from developers and protective zoning[176–178]. Market-based interventions, such as small-scale home buyouts[63,112,179,180] may be popular, if not expensive, in higher-income countries with strong private property rights. For example, at least 40,000 voluntary buyouts have occurred in the USA since 1989 (REF.[181]).

Both managed and unmanaged retreat are generally contentious, with deep and persistent equity concerns. Factors of age, class, race, property ownership and historical structural/institutional disadvantage influence the experience of displacement and retreat[180]. Relocation can be perceived as 'thinly veiled forms of social engineering'[169] and those who are relocated might suggest that a government is 'picking sides'[169], deeming some 'victims' and unworthy of protection[65,169]. Relocations that follow 'principles of equitable adaptation'[182,183] and retreat can increase the success of a retreat programme, build social capital, deepen civic engagement and networks, and, ultimately, build resilience[184,185].

Regional contexts

Neumann et al.[8] provide a comprehensive global analysis of the countries with the largest populations in the LECZ and in the 100-year floodplain (FIG. 3a). Countries with more than 50 million people in the LECZ are China (244 million), India (216 million), Bangladesh (109 million), Indonesia (93 million), Vietnam (80 million), Egypt (63 million) and Nigeria (57 million). Countries with more than 10 million people in the 100-year floodplain are China (103 million), India (63 million), Vietnam (50 million), Egypt (20 million), Indonesia (14 million) and Bangladesh (12 million). These countries represent the anticipated 'hotspots' of SLR migration, though neither the LECZ nor the 100-year floodplain metrics guarantee SLR-driven migration.

Some of these countries have few, if any, comprehensive studies on SLR and migration, lacking consideration of the potential destinations of migrations or when migration may occur. In some cases, there is more research on the migration of natural systems in

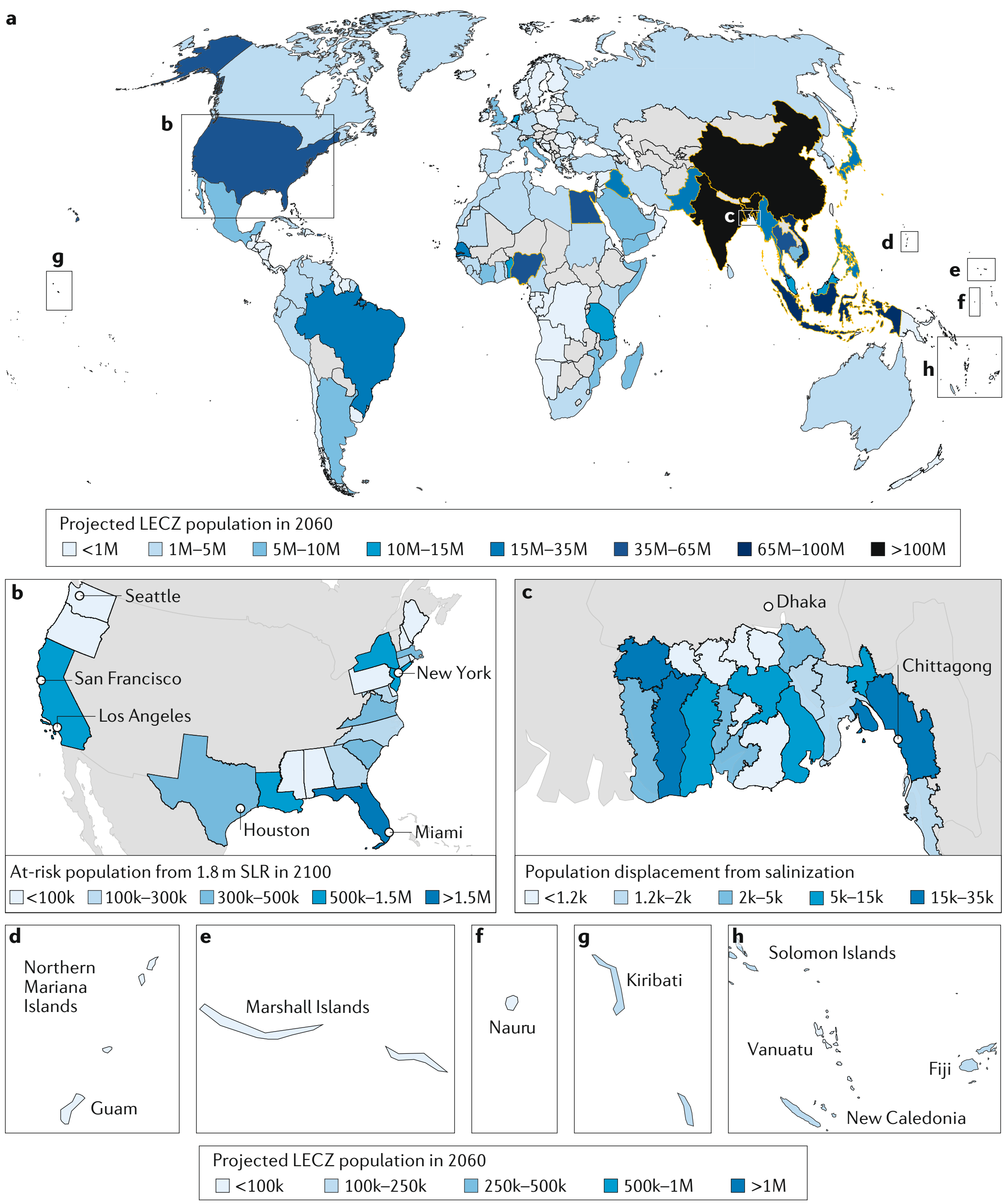

Fig. 3 | **At-risk populations in the LECZ. a** | Population projections in the low-elevation coastal zone (LECZ) for 2060 (REF.[11]); countries with at least 5 million people in the 100-year floodplain but lacking considerable sea-level rise (SLR) and migration research are highlighted with a yellow border. **b** | Projected populations at risk from SLR in the USA under an SLR scenario of 1.8 m by 2100 (REF.[10]). **c** | Projected migrants in coastal Bangladesh due to SLR-induced salinization[59]. **d–h** | Populations in atoll island nations in 2060 (REF.[11]). Grey shading indicates countries/counties where data are unavailable or no coastal region is present. Data for part **a** from REF.[8]. Data for part **b** from REF.[10]. Data for part **c** from REF.[59].

response to SLR than of people[186,187]. Countries with at least 5 million people in the 100-year floodplain but lacking considerable SLR and migration research include China, India, Indonesia, Vietnam, Egypt, Nigeria, Thailand, the Philippines, Japan, Pakistan, Myanmar and Iraq[8]. The behavioural dynamics of SLR migrants needs greater attention, with a focus on the potential destinations of these migrants[50,59,60,71].

Governmental resources and adaptive capacity will combine with local geography to affect how SLR influences migration. Here, we discuss three regional contexts — the USA, Bangladesh and atoll island nations — to highlight similarities and differences in migration signals across contexts (FIG. 3).

USA. Nearly 40% of the US population presently lives in coastal communities[188] that are also predicted to see continued growth and development in the future. As a result, SLR (and its corresponding hazards) are projected to threaten between 3 million and 43 million people by 2100, with as many as 13 million that could face permanent inundation and displacement without protective measures[8,10,12,76] (FIG. 3b). Half of those exposed to SLR reside in Florida and nearly a quarter in Miami, Florida alone[10]. Managed retreats in Alaska, Louisiana, New York and Texas offer a potential glimpse of broader-scale retreat in the USA[63,65,180], including migration into less vulnerable coastal areas as a form of 'climate gentrification'[39,40], sometimes stemming from retreat itself[189].

Numerous historical analyses in the US context[51,52,54,55,190,191] find that SLR can overwhelm resilient coastal residents with strong emotional ties to place[55], leading to abandonment[51]. In particular, the 1918 abandonment of Holland Island in the Chesapeake Bay due to SLR, triggered by population levels falling below a level to support community services, is a powerful analogue for potential future abandonment[51]. Moreover, when people do migrate in response to SLR hazards in the USA, they more often migrate to nearby urban job-growth centres[190], rather than making small, incremental migrations[52]. Accordingly, future migration modelling suggests coastal adjacent, major inland cities, such as Austin, Texas, Orlando, Florida, or Atlanta, Georgia, might become major migration destinations for those migrating in response to SLR inundation[50,76]. For those migrating in response to a short-term risk, however, evidence suggests that people tend to migrate back to their home community once the risk has receded; for example, with Hurricane Katrina in New Orleans and Hurricane Maria in Puerto Rico[42,133].

A wide range of protection and accommodation measures are routinely studied, discussed and deployed in anticipation of SLR in the USA[155,192–194]. Major US cities such as New York and Miami are actively working towards protection and accommodation. How many people these measures will protect from migrating is unknown. Many highly visible and contentious managed retreats are also presently underway in mainly indigenous communities across the USA[65,167,170,195], such as the Isle De Jean Charles relocation in Louisiana or the Kivalina relocation in Alaska, where disagreements between tribal members and government agencies have slowed relocation efforts. No national government agency has the financial resources to coordinate or facilitate widespread adaptation and relocation policies[196], leading to ad hoc policy deployment. With relocation cost estimates ranging between $200,000 and $1 million per capita[62,167,196], widespread managed retreat seems unlikely in the US context, but a number of policy levers may be used to reduce incentives to live on vulnerable coastlines.

Bangladesh. Owing to a long-standing concern for future SLR impacts, Bangladesh has been historically regarded as a major SLR hotspot[197,198] and is the third most at-risk country to SLR, with 2 million to 110 million people at risk to SLR and its associated hazards[8,60] (FIG. 3c).

Episodic tidal inundation and storm surge are major SLR hazards, amplified by riverine flooding associated with cyclones and seasonal monsoons[132]. These hazards threaten subsistence farmers and fishers living in low-lying delta, interrupting access to fresh water, driving soil salinization and eroding human settlements and arable farmland[32,199–201]. As 30% of the total cultivatable land of the country lies along the coast, the impacts of salinization on agriculture could undermine food security far beyond the coast[202] and are estimated to displace more than 200,000 people annually[59]. Permanent inundation could ultimately displace upwards of 2.1 million people primarily towards Dhaka[60]. SLR-related migration in Bangladesh intentionally increases household resilience[203] by migrating short distances[204] towards pre-existing migration destinations[132], spurred by both SLR and socioeconomic vulnerabilities[205]. This migration is likely to be internal, rather than international[206,207].

As in the USA, many climate migrants in Bangladesh gravitate to wage opportunities in urban economic centres[132]. However, unlike the USA, many of these migrant destinations include cities under similar risk of future SLR. SLR-induced migration may, therefore, contribute to the further expansion of the nation's informal settlements[208]. The permanence of these migration patterns has been relatively unexplored due to the paucity of migration data. However, recent work leverages data from millions of mobile network subscribers[132] and existing longitudinal data in one survey site[209] to monitor migration responses to other SLR hazards, such as cyclone incidence and torrential flooding. Although flooding, in these contexts, clearly disrupts livelihoods, these studies contribute to a growing consensus that the observed migration patterns around extreme events are relatively short-lived[132,209–211] (BOX 1). At present, coastal adaptation in Bangladesh almost exclusively consists of accommodation[212]. Without a concerted effort to facilitate retreat from coastlines[98], SLR impacts may intensify the need to migrate, even while reducing people's ability to absorb the losses, transition to urban-wage labour and relocate to urban slums.

Atoll island nations. Unlike the USA and Bangladesh with tens of millions of people threatened by SLR, the sparsely populated atoll island nations contain comparatively far fewer people at risk to SLR. For example, SLR threatens

6,000 people in Nauru, 9,000 in Guam, 25,000 in the Northern Mariana Islands, 31,000 in Vanuatu, 91,000 in the Marshall Islands, 133,000 in Fiji, 190,000 in Kiribati and 234,000 in the Solomon Islands[8] (FIG. 3d–h).

The SLR forecast is so severe for the most low-lying nations that the possibility of deterritorialization has captured much of the discourse on SLR and human migration for many atoll island nations. The United Nations High Commissioner for Refugees noted 10 years ago that early action was needed to prevent statelessness in the low-lying atoll nation states of the Maldives, Tuvalu, Kiribati and the Marshall Islands[213]. Loss of an entire territory or the exile of an entire population is unprecedented[213], introducing unparalleled scenarios of state dissolution and possible statelessness — even if it is unclear that a state would cease to exist if submerged[214]. This anticipated deterritorialization or substantial territorial loss encompasses legal concerns regarding statehood, national identity, refugee status, state responsibility and access to resources, among other things[215] (BOX 2). While inundation is a significant concern, atoll nations are likely to face uninhabitability before complete submersion due to lack of fresh water and increased soil salinization[215].

There is growing consensus that migration should be planned and coordinated[171,182], facilitating movement and admission to other countries for displaced persons[214] but strict migration-eligibility criteria and the lack of financial assistance restricts access to neighbouring countries[216]. The Maldives, Micronesia, the Marshall Island, Kiribati and Fiji have included migration in their national adaptation policies[173,217]. Kiribati's noted 'Migration with Dignity' approach seeks to ensure the best outcome for cross-border migration I-Kiribati people who flee the impacts of climate change[218]. However, the policy only paves the way for those already willing and ready to migrate, possibly excluding those with limited literacy skills or those who rely on agriculture and place-based livelihoods[218,219].

Box 2 | **Climate refugees**

The migration circumstances of people crossing international borders due to climate change falls outside almost all international legal frameworks. Elements of the oft-invoked 1951 Refugee Convention may be fulfilled in certain cases; for example, if authorities deny assistance and protection to certain people because of their race, religion, nationality, membership of a particular social group or political opinion and, as a consequence, expose them to treatment amounting to persecution[214]. The consensus, however, is that climate-induced migration, particularly triggered by relatively slow-moving sea-level rise (SLR), falls outside of the convention's scope and protections.

Nevertheless, international efforts to better understand and manage movements related to climate change have progressed. Three emerging United Nations initiatives are directly relevant: the Global Compact for Safe, Orderly and Regular Migration, the Global Compact on Refugees and the United Nations Framework Convention on Climate Change Task Force on Displacement[232]. By developing recommendations for integrated approaches to avert, minimize and address displacement, the task force seeks to enhance government and organization capacity in managing climate-related migration.

Concerted law and policy initiatives at the nation-state level have been limited, with New Zealand serving as a notable outlier. Though it does not have immigration policies specific to climate-change-related migration, New Zealand does have existing immigration policy, including: the Samoan Quota, the Pacific Access Category, the Recognised Seasonal Employer scheme, a temporary labour mobility policy, and a general visa category that attracts Pacific migrants. New Zealand jurists also conducted a comprehensive analysis on the scope and content of protection for migrants seeking to avoid climate impacts; while sympathetic, the decision makers held that protection under refugee and human rights law was unavailable[233].

Other international agreements that might be relevant are those related to the protection of human rights. To the extent that migration spurred by SLR impacts rights enumerated in the human-rights treaties, protections may be afforded to those on the move[217]. There are also relevant soft-law provisions, such as the Peninsula Principles on Climate Displacement within States and the Sendai Framework for Disaster Risk Reduction. However, these are not binding on any nation state, providing very limited protection for migrants. Some individual nation states also provide temporary or subsidiary protection for disaster-induced, cross-border displaced persons[214].

Conclusion and perspectives

SLR-driven human migration has the potential to alter population distributions at all scales. The work discussed in this Review highlights how hazards associated with SLR might spur human migration and the obstacles and facilitators for this migration. Nonetheless, several significant gaps remain in modelling, measuring and policy development around the implications of SLR for human migration.

First, quantifying the locations and numbers of people 'at risk' to SLR cannot be equated with the numbers of migrants responding to SLR. SLR hazards are highly variable across space and time, and their significance for migration, especially towards the end of this century, will largely be driven by greenhouse gas emissions. There must be more careful consideration of what exactly constitutes exposure to SLR and the time frames associated with these exposures. SLR impacts are often discussed in the far future[5,12], yet impacts such as reduced housing prices, gentrification and migration are documented today where contemporary SLR is already minimal[39,40,59]. Additionally, many people presently reside in highly exposed coastal communities and it is necessary to connect the actual hazards of SLR to human migration on timescales of human decision-making.

Second, as many SLR hazards are still yet to manifest, the empirical linkages between SLR hazards and human migration are still too tenuous. Some commentators continue to erroneously describe a predetermined relationship between the inundation of coastal communities and the resultant waves of migration[6,172]. Research has only begun to turn to the underlying mechanisms that might drive this migration[39,40,59], but it is abundantly clear that more research is critically needed to understand the numbers of future migrants, the decades in which migration may occur and their potential destinations. Human behaviour is complex and scientists should focus on how SLR hazards might translate into migration signals. The work on soil salinization is a start[59] but is limited to agriculturally dominant contexts. Critically, our understanding of thresholds and tipping points beyond which human migration becomes inevitable is severely limited. Further, this Review highlights the dearth of science on SLR and migration for numerous countries highly threatened by SLR, most notably China, India, Indonesia, Vietnam, Egypt and Nigeria.

Third, common non-migration household adaptations to coastal hazards (such as elevating houses and storing valuables above ground) are not sensible if schools, clinics, workplaces or neighbouring households do not take similar actions. Protection — the most effective adaptations to reduce exposure to SLR and coastal hazards — requires resources generally only available through coordinated policy interventions. Policies addressing relocation are still too abstract and lack guidance to ensure equity. Without more concrete policy guidance for relocation across borders and to facilitate integration into destination communities, migrants from atoll island nations may endure a climate-change-related human rights catastrophe and magnified suffering of the most vulnerable populations. Just as with research on the mechanisms associated with SLR migration, research on immobile or trapped populations (those who are unable or unwilling to migrate) is crucially needed. An important priority is to identify the policies that will best alleviate the suffering of those trapped in increasingly flood-prone areas.

Fourth, global population projections from the United Nations show widespread ageing in every country by the century's end[220]. The well-documented relationship between age and migration propensity[221] suggests that youthful populations are more likely to migrate than older populations. What are the implications of an ageing coastal zone if 'migration as adaptation' is the primary adaptation strategy in many developing countries and older people migrate less than younger people? Migrants continue to migrate to the economic engines in coastal cities and mega-deltas[222] but will changing demographics alter this migration dynamic? Relatively little research explores the important implication of ageing on human mobility and migration in the coastal zone.

Rigorous scientific research on SLR and human migration will result from multidisciplinary data, methods and research teams involving oceanographers, anthropologists, geographers, economists, remote sensors, sociologists and geomorphologists, to name a few. Alarmist predictions of 'climate refugees' garner press headlines in the Global North and fuel anti-immigrant sentiments. However, the research reviewed here paints a much more complex picture that allows us to anticipate how SLR migration may unfold in different scenarios to develop informed policies that avert crises and promote more equitable and humane outcomes.

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