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The Global Economic Case for Immediate and Continuous Coastal Adaptation

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Abstract

Despite growing evidence of a global coastal adaptation gap under accelerating sea-level rise, global economic evidence on when and how to close this gap remains scarce. Here, we identify economically optimal adaptation pathways for floodplains worldwide, enabling flexible timing and switching between adaptation options over time. We find that immediate adaptation is economically optimal for 28% of the global coastline, irrespective of the climate change scenario, reflecting that many floodplains are under-adapted today. By 2150, adaptation is economically warranted along 31% of the global coastline, with 20% optimally managed through retreat, 7% through coastal protection, less than 1% through accommodation, and 4% through combined retreat and inland protection. Relative future cost burdens of adaptation investments and flood damages are highest in the Global South, exacerbating inequities embedded in today's adaptation gap.

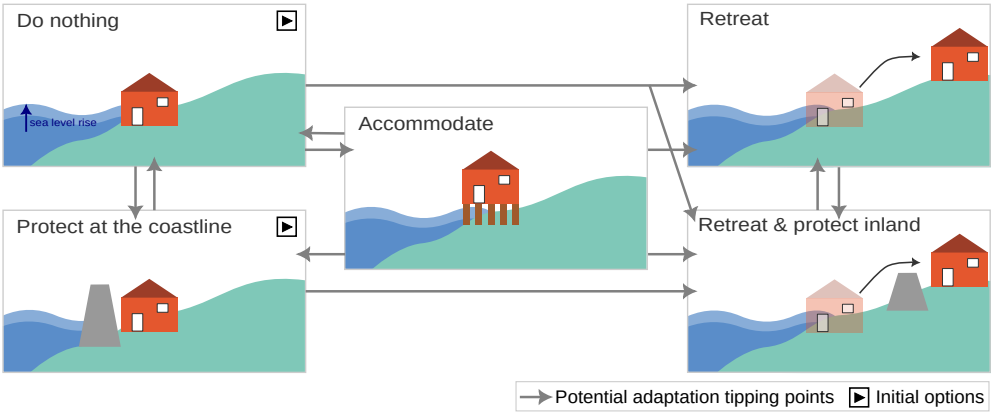


Fig. 1: Coastal adaptation options assessed in this study.

The world is facing substantial future investments in coastal adaptation. Already today, more than 10% of the world's population lives in low-elevation coastal zones [1], where they are exposed to flooding and are at increasing risk from future sea-level rise (SLR). SLR is projected to accelerate over the course of this century and continue for centuries [2]. Current projections indicate that approximately 50 cm of SLR will be reached during the second half of the 21st century, largely independent of the extent to which greenhouse gas (GHG) emissions are reduced [3].

Although the Intergovernmental Panel on Climate Change (IPCC) has identified a range of coastal adaptation options for managing future SLR [4], their implementation at the global scale remains limited [5]. These options include protection, through hard infrastructure (e.g., dikes or storm surge barriers); accommodation, by reducing vulnerability to coastal hazards (e.g., flood-proofing buildings); and retreat, which reduces coastal risk by relocating people and assets (Figure 1). They may be implemented immediately or at a later point in time, combined, and sequenced into adaptation pathways that account for local characteristics. Points in time or conditions under which it becomes necessary to shift from one adaptation option to another, e.g. such as from protection to retreat [6], are referred to as adaptation tipping points (ATPs). While ATPs are most commonly defined by risk-based thresholds, they may also be determined by economic limits [7], as applied in this study.

Globally, projected coastal flood damages and economically optimal adaptation investments in protection and retreat are estimated to amount to USD 1.5–11 trillion over the 21st century, depending on the magnitude of climate change and associated SLR [8, 9]. Such investments in coastal adaptation are often publicly funded, and economically optimal investment strategies are therefore sought [10]. Consequently, the use of economic decision-making tools, such as cost–benefit analysis, is widespread and in some cases legally mandated, as governments have a fiduciary duty to allocate taxpayers' money efficiently [11, 12].

Global economic assessments of coastal adaptation typically assume immediate and static implementation, overlooking the flexibility inherent in timing decisions and switching between adaptation options over time, leaving the economic case for timely

action unresolved [8, 13–27]. In contrast, global non-economic studies that examine dynamic shifts in coastal risk consistently highlight the need for timely adaptation over the coming decades [28, 29]. Although some economic models [8, 9] implicitly account for today's adaptation gap through an initial "spin-up" phase to implement cost-optimal adaptation, they do not allow for delayed adaptation actions or dynamic switching between options. Instead, these studies primarily focus on the benefits of climate mitigation for reducing costs [9] or on the magnitude of land loss and migration [8], rather than addressing when and how coastal adaptation should be initiated and implemented. Only one recent European-scale study has explicitly considered multiple adaptation options, flexible timing, and the possibility to switch between options by applying a multi-stage cost–benefit optimization framework [30].

In this study we provide global economic evidence supporting immediate and continuous coastal adaptation to manage flood risk and future SLR, independent of the climate change scenario. Building on a recent European-scale study [30], we extend the analysis globally and identify economically optimal adaptation pathways for 61,828 coastal floodplains worldwide that contain exposed people and assets. The analysis spans a time horizon from 2020 to 2150, using a 3% discount rate, and considers three greenhouse gas emission scenarios: low (SSP1-2.6), medium (SSP2-4.5), and very high emissions (SSP5-8.5). We explicitly account for flexibility in the timing of adaptation actions and the possibility of switching between options once ATPs are reached. Four distinct adaptation options are considered: accommodation, protection at the coastline, retreat, and retreat combined with protecting the inland (Figure 1). Protection involves implementing hard defensive infrastructure to an appropriate height; retreat entails relocating people and assets from the floodplain, and accommodation involves flood-proofing buildings up to one meter. Here, *economically optimal* refers to adaptation pathways that minimize the combined costs of expected residual flood damages and adaptation investments from a public economic perspective.

1 Results

1.1 Economically optimal adaptation pathways

To illustrate the resulting adaptation pathways from our model, we first present six economically optimal adaptation pathways from floodplains across the globe, namely New York, Varna, Lima, Cape Town, Jakarta and Sydney (Figure 2). The highlighted floodplains in New York, Varna, Cape Town, and Jakarta require immediate action to upgrade or adjust their adaptation strategies, whereas the floodplain in Lima requires no intervention, and Sydney can defer action until the next century. The New York floodplain combines a high concentration of assets with extreme sea-level exposure, necessitating protection height upgrades of up to six meters by the end of this century. In contrast, Varna can rely on accommodation measures to remain economically optimal throughout the entire model horizon. Jakarta demonstrates the combination of protection and retreat, accommodating the city for one more decade before retreating all assets and people below one meter elevation and building an inland protection line.

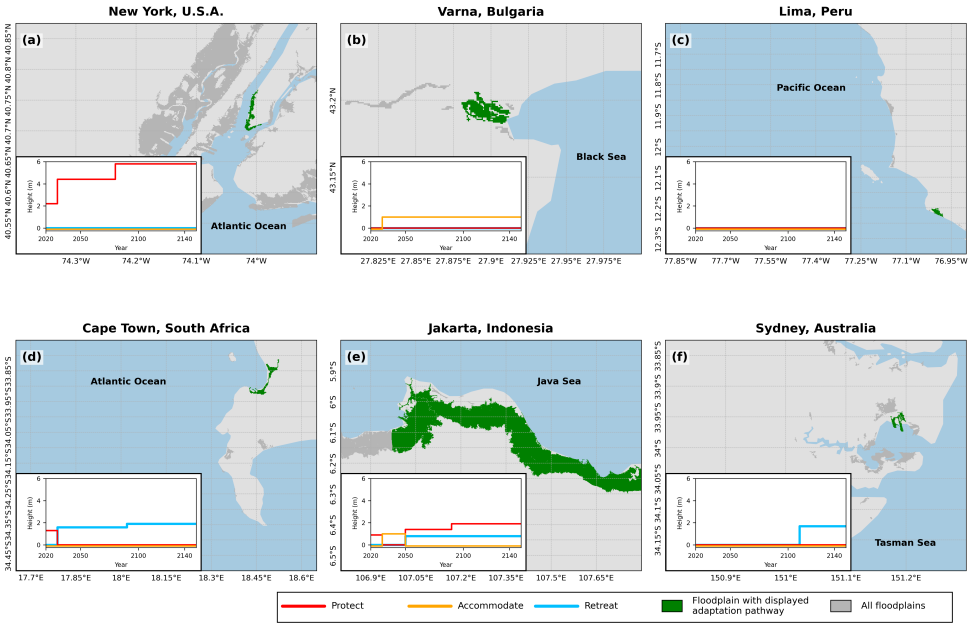


Fig. 2: **Economically optimal adaptation pathways for selected floodplains.** Each subfigure shows the models' floodplains in the city of (**a**) New York, (**b**) Varna, (**c**) Lima, (**d**) Cape Town, (**e**) Jakarta and (**f**) Sydney and one economically optimal adaptation pathway for the floodplain highlighted in green under SSP2-4.5. Here, the height of retreat refers to the height above sea level below which assets and people are removed.

1.2 Coastal under-adaptation today requires immediate action

Immediate adaptation action is required for 28% of the global coastline due to current under-adaptation from an economic perspective (Figure 3). About two-thirds of the global coastline do not require any adaptation throughout the model's entire time horizon, while retreat is applied most frequently on 20% of the coastline in 2150 (Figure 3, Table 1). The largest adaptation investments occur in the first model time step, and although retreat is implemented along more than three times the length of the global coastline compared to protection, the investment costs for protection outweigh the costs of retreat (Figure S1). Switching from doing nothing to one of the adaptation options occurs in the earliest time step (2030) for 94% of the coastline that experience such a switch at any point (Figure 4a). The urgency of immediate adaptation remains robust even under a low-emissions scenario and a counterfactual scenario without SLR, highlighting the economic necessity of early action (Figure S3 and S8).

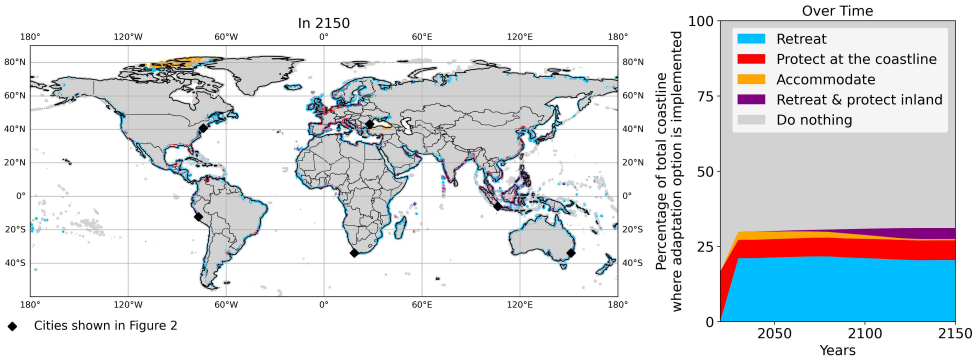


Fig. 3: **Implemented adaptation options across floodplains and over time.** A map (left) showing the final adaptation option implemented per floodplain in 2150 and a graph (right) showing the percentage of the entire coastline where each adaptation option is implemented over time under SSP2-4.5.

Table 1: Proportion of the coastline for which different adaptation options are implemented in 2150, together with the net present value of adaptation investments and residual expected flood damages, discounted at 3% over the 2020–2150 time horizon and reported in absolute terms and as a percentage of 2023 GDP. Results are shown for the five countries with the highest absolute and relative costs under the SSP2-4.5 climate scenario, together with the global average.

Country	Protect at the coastline (%)	Retreat (%)	Accommodate (%)	Retreat & protect inland (%)	Do nothing (%)	Total costs (bil. US$)	Relative costs (% of GDP)
Netherlands	79.0	9.8	0.0	2.3	8.9	2664.6	238.3
U.S.A.	15.0	22.7	0.1	2.0	60.2	1121.1	4.1
China	27.3	28.0	0.0	4.4	40.3	985.4	5.5
Belgium	96.4	0.7	0.0	0.0	2.8	675.7	106.9
India	16.2	30.0	0.0	20.7	33.1	426.5	12.0
Suriname	11.9	23.4	0.0	33.7	31.0	35.2	929.5
Myanmar	3.0	54.6	0.0	13.7	28.7	249.2	384.4
Guyana	25.3	48.3	0.0	0.2	26.2	60.6	361.1
Netherlands	79.0	9.8	0.0	2.3	8.9	2664.6	238.3
Belize	0.0	57.9	0.0	17.1	25.0	5.5	166.8
Global	6.6	20.4	0.4	3.7	68.9	12579.8	12.0

1.3 Continuous actions required under all climate scenarios

Continuous coastal adaptation action is required to maintain protection levels under SLR and to switch adaptation options where ATPs occur (Figures 4b, S1), regardless of the climate change scenario (Figures S3, S5). Over time, several regions of the global coastline will encounter ATPs, where an implemented adaptation option becomes economically insufficient. Specifically, the Atlantic coasts of North and Central America, the Mediterranean, and the Sea of Japan are projected to require transitions from accommodation to retreat, while the majority of the coastline in Southeast Asia will need to combine retreat and inland protection. Some ATPs emerge as early as 2040, with most occurring during the next century under SSP2-4.5 (Figure 4b), and in the

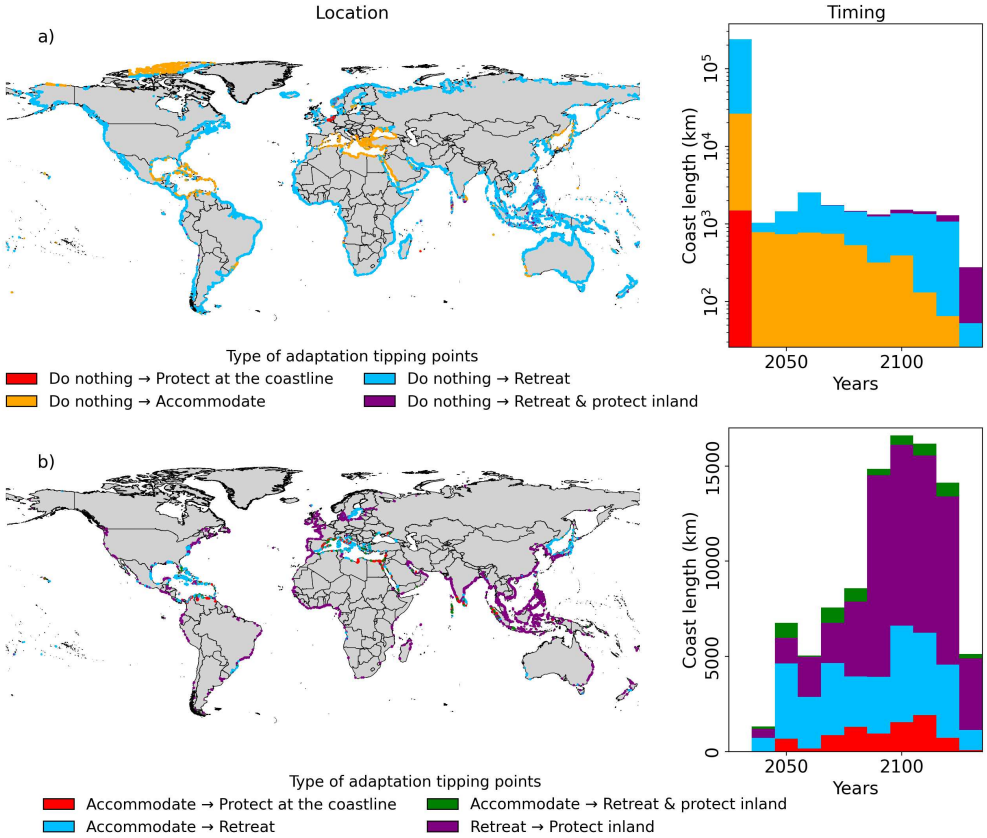


Fig. 4: **The geographic location and timing of adaptation tipping points.** For adaptation tipping points where (**a**) doing nothing becomes insufficient and (**b**) another option becomes insufficient, a map (left) shows the geographic location and a stacked bar chart (right) illustrates the timing (x-axis) for the accumulated length of coastline (y-axis) for all floodplains under SSP2-4.5.

end of this century under SSP5-8.5 (Figure S5). In a counterfactual scenario without SLR, the vast majority of these ATPs do not occur (Figure S8). However, even under the low-emissions scenario SSP1-2.6, ATPs emerge at similar times and still affect roughly half of the coastline compared to SSP2-4.5 (Figure S3), highlighting the need for continuous adaptation efforts regardless of the climate change scenario.

1.4 Most vulnerable Nations and Regions

Africa, Southeast Asia and South America are the regions most vulnerable in terms of adaptation investments and expected flood damages relative to GDP (Figure 5). Among countries, Suriname, Myanmar and Guyana experience the highest relative cost burdens, whereas the Netherlands, the U.S.A. and China face the largest absolute costs (Table 1). Southeast Asia is notable for encountering multiple ATPs over the

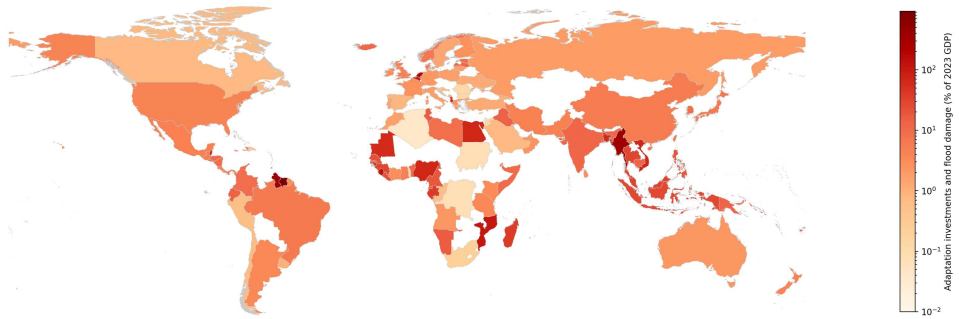


Fig. 5: **Relative cost burden per country.** A map showing the discounted adaptation investments and expected residual flood damages over the entire time horizon relative to each countries GDP in 2023 under SSP2-4.5.

next century, where retreat must be combined with inland protection (Figure 4b). Small island states also appear among the top 20 vulnerable countries by relative cost, including Seychelles and Kiribati (Table S1). Under high-emissions scenarios, these patterns persist, with an increasing number of floodplains worldwide projected to encounter future ATPs that require retreat to be combined with inland protection (Figure S5).

2 Discussion

While previous global studies emphasized the timely need to maintain coastal protection levels from a hazard perspective and highlighted the current gaps in coastal adaptation, this study provides economic evidence for immediate adaptation actions. Recent tracking of global coastal adaptation [5] concluded that adaptation efforts remain too narrow in scope, long-term pathways are limited, and rural areas lag behind urban ones. A previous global study [28] quantified the timing of decreasing coastal flood protection due to SLR, finding that, if no action is taken, current protection levels will be exceeded ten times more frequently over the next 30 years at 26–32% of locations. Our results strengthen the economic case for immediate coastal adaptation, showing that even without considering future SLR, current protection levels should be either raised or replaced by retreat from an economic perspective at 28% of the global coastline.

Our estimates of global adaptation investment and flood damage costs are of the same order of magnitude as those reported in recent global assessments, though slightly higher and spanning a narrower range, reflecting higher assumed retreat costs and the exclusive use of median SLR projections. Lincke and Hinkel [23] estimate undiscounted global costs over the 21st century of 7–17 trillion USD (2024; reported as USD 2014 5–13 trillion) under RCP2.6–RCP8.5 when considering high-end SLR percentiles and economically optimal protection strategies; incorporating both protection and proactive retreat yields comparable costs of 7–14 trillion USD (2024; reported as USD 2014 5–11 trillion) [8]. Wong et al. [9] project cumulative costs of 2.1–3.6 trillion USD (2024;

reported as USD 2010 1.5–2.6 trillion) up to 2150 under 2 °C–3.5 °C global warming, with lower estimates compared to Lincke et al. largely attributable to the application of a 4% discount rate. By contrast, this study estimates cumulative costs of 12.6–13.4 trillion USD (2024) under SSP2-4.5 and SSP5-8.5 up to 2150 using a 3% discount rate (Table S1). The higher estimates are driven by retreat cost assumptions consistent with Völz et al. [30], which are twice as high as those adopted in earlier studies [8, 9]. The narrower cost range across climate change scenarios in this study arises from the exclusive consideration of median SLR projections, whereas previous assessments also incorporated high-end SLR percentiles.

This study finds that, when multiple adaptation options are considered, only 7% of the global coastline is optimally managed through coastal protection and 4% through retreat and inland protection, slightly deviating from values reported in previous studies. When only protection at the coastline is considered as an adaptation option, Lincke and Hinkel [23] estimate that 13% of the global coastline would be protected, whereas allowing retreat as an additional option reduces the share of protected coastline to 7% worldwide [8]. The same share of protected coastline identified in this study, combined with another 4% applying the combination of inland protection and retreat, can be attributed to its more diverse adaptation state space and substantially higher spatial resolution, which evaluates 144,361 coastal floodplains compared to 12,148 in Lincke and Hinkel [8]. This finer resolution enables a more precise identification of rural and sparsely populated floodplains that are economically better suited for inland protection and retreat, rather than protection at the coastline or retreat.

Although retreat is identified as the economically optimal adaptation option for the majority of the coastline requiring adaptation, empirical evidence of retreat in response to SLR remains limited, whereas coastal protection through hard engineering measures is widespread globally [4]. Case studies of coastal adaptation practices suggest that responses have often involved continued advancement toward the sea rather than retreat [31], with a rather small but growing number of documented retreat cases worldwide [4, 32]. By contrast, a recent global analysis of settlement proximity to coastlines using satellite-derived nighttime light data from 1992–2019 offers a more nuanced perspective, showing that more than half of subnational regions exhibit a relative withdrawal from the coast, as measured by the concentration of human activity within 10 km of the shoreline [33]. These findings underscore the growing relevance of managed retreat and highlight the need for coordinated efforts among government agencies, communities, scientists, and other stakeholders [33], a conclusion that is strongly supported by the economic case for retreat presented in this study.

Our results need to be considered in the context of the following limitations. First, the optimal timing of adaptation actions depends on currently implemented adaptation options. We account for existing coastal protection but do not explicitly consider current accommodation measures or nature-based solutions, owing to the absence of global empirical data, a key limitation also identified in previous work [28]. Consistent with earlier global assessments [8, 23], we infer current protection levels worldwide using decision rules based on GDP and population density (Methods, Section 3.3). For Europe, we instead rely on protection levels derived from an expert survey [34], following an approach similar to [30]. Despite these fundamentally different data sources

and assumptions, both approaches consistently indicate widespread under-adaptation, supporting the conclusion that immediate adaptation is economically justified. Second, the set of adaptation options considered could be expanded. We do not account for land reclamation or accommodation options exceeding one metre, which could alter the optimal allocation among adaptation strategies. Finally, this analysis focuses on a single hazard, i.e. coastal flooding, while other climate-related hazards, such as riverine flooding and extreme precipitation, may interact with coastal flood risk through compound events and thereby influence optimal adaptation decisions.

Our findings indicate that the Global South will bear the highest relative future cost burden from coastal adaptation investments and flood damages, consistent with previous studies identifying these regions as among the most vulnerable, despite their historically minimal contribution to greenhouse gas emissions and climate change [35]. Other economic assessments support our results, showing that Sub-Saharan Africa, Latin America and the Caribbean, and East Asia and the Pacific experience disproportionately high damages [9]. Beyond facing elevated future costs, the current status of coastal adaptation in the Global South remains characterized by low to moderate levels of implementation, especially in Africa and Small Island regions, whereas high levels of adaptation effort are observed predominantly in Europe and North America [5]. In Africa and Southeast Asia, adaptation actions are most frequently undertaken by individuals and households rather than public institutions [36], and low-income populations tend to live closest to the coast and, in some cases, are moving even nearer, increasing their vulnerability and exposure to coastal hazards [33]. These disparities in coastal adaptation suggest that future cost burdens are likely to exacerbate the inequities already persisting today.

3 Methods

We expand the dynamic cost–benefit optimisation framework from Völz et al. [30] from European to Global scale. The framework integrates several components: a hazard module to simulate extreme sea levels; an exposure module to quantify populations and assets at risk; a vulnerability module to assess asset susceptibility to flooding; an adaptation state space defining feasible adaptation pathways; and cost functions estimating the costs of adaptation actions. The optimisation is conducted independently for each of the 144,361 coastal floodplains worldwide, with the hazard, exposure, and adaptation state-space components specified at the individual floodplain level.

3.1 Adaptation state space

We consider four coastal adaptation options to reduce flood risk: (i) protection at the coastline through hard infrastructure such as dikes; (ii) accommodation through flood-proofing buildings; (iii) planned retreat from the coast; and (iv) planned retreat combined with inland protection (Figure 1). Let $d_t = (d_t^p, d_t^r, d_t^a)$ denote the adaptation state space over time, where d_t^p represents protection height, d_t^r retreat height, and d_t^a accommodation. Protection is expressed as absolute protection heights above mean sea level (10 values ranging from the 1-year extreme event height to the 1-in-10,000-year extreme event height plus sea-level rise in 2150). Retreat is defined as absolute

elevation thresholds below which all assets and people relocate (5 values over the same range). Accommodation is binary ($d_t^a \in \{0, 1\}$), indicating whether buildings within the one-meter floodplain are flood-proofed up to one meter. The adaptation action $u = (u^p, u^r, u^a)$ independently adjusts each adaptation option:

$$d_{t+1} = d_t + u = (d_t^p + u^p, d_t^r + u^r, d_t^a + u^a),\ u^r \geqq 0, \tag{1}$$

where protection and accommodation are reversible and may decrease to zero. The state space allows for the simultaneous activation of protection d_t^p and retreat d_t^r, corresponding to planned retreat combined with inland protection. Overall, the adaptation state space allows for multiple switches between the four adaptation options and a doing nothing, representing potential ATPs (Figure 1).

3.2 Costs of adaptation options

For protection, we assume a linear cost function with a fixed cost component, which makes small upgrades relatively more expensive than large upgrades, consistent with previous studies [37, 38]:

$$I(d, u) = 0.3 * c * 1 * l + 0.7 * c * u * l, \tag{2}$$

where u is the height upgrade, l the length of the protection action and c the unit cost factor. Unit cost factors are derived from dike construction costs reported in case studies from the Netherlands [39]. These costs are converted and adjusted using country-specific cost factors that account for national differences in construction costs, following [40]. To approximate dike unit costs for other countries, we use the median of the lower- and upper-rural cost estimates (Table S2). This choice reflects the fact that the Netherlands represents a special case, characterized by comparatively high investment levels and safety standards. Following earlier work [41–43], we assume annual maintenance costs for coastal protection infrastructure equal to 1% of the initial investment costs.

We use the same retreat cost assumptions as in [30] and estimate retreat costs at six times the local GDP per capita per migrant, assuming no maintenance costs for the retreat.

For accommodation, we derive country-specific unit cost factors for flood-proofing buildings based on reported costs from U.S. case studies [44]. We use the cost values converted to a per-person, per-meter basis based on the average U.S. household size in 2009 [30]. This yields an estimated average unit cost of US$6,585 (2009) per person per meter for flood-proofing buildings in the United States. Following the approach used for dike unit costs, we adjust this average value for each country using country-specific cost factors [40] (Table S2). Maintenance costs for accommodation are assumed to be zero.

We convert all costs from US$2009 or US$2011 to US$2024 using GDP deflator values from the World Bank [45].

3.3 Current protection levels

We estimate coastal protection levels using a combination of expert survey data, GDP, and the population density of each floodplain (people per square kilometre). Floodplains are classified as uninhabited (<30 people/km^2), sparsely populated (30–1,500 people/km^2), or densely populated (>1,500 people km^2).

For Europe, current coastal flood protection levels are specified at the NUTS2 scale according to population density, based on a recent European expert survey [34]. Following [30], missing survey data are supplemented with modeled estimates [26].

Outside Europe, we follow previous global assessments [8, 23] and assign protection levels based on local population density and GDP per capita. In sparsely populated areas, protection corresponds to a 1-in-20-year return period in lower-middle- to upper-middle-income regions and a 1-in-50-year return period in high-income regions. In densely populated areas, assumed protection levels increase with income, ranging from 1-in-10 years in low-income regions to 1-in-25 years in lower-middle-income regions, 1-in-100 years in upper-middle-income regions, and 1-in-200 years in high-income regions. Floodplains outside these categories, including uninhabited areas, are assumed to have no coastal flood protection by default.

3.4 Exposure and vulnerability using DIVACoast

We build on the DIVACoast framework, which has been widely used to assess coastal flood damages at continental and global scales [8, 13, 16–19, 22, 23, 30]. Extending this prior work, we substantially increase the spatial resolution of the analysis by subdividing the global coastal zone into 144,361 coastal floodplains [46], compared to 12,148 segments in the original DIVA model.

The floodplains are defined as hydrologically connected areas lying below the 1-in-100-year flood level, with an additional 2-m allowance for SLR. They are delineated using a digital elevation model (DEM) [47] in combination with extreme water level estimates from COAST-RP [48].

For each coastal floodplain, we generate a hypsometric profile H by overlaying elevation data from the DEM [47] with population data from the Global Human Settlement Layer (GHSL) [49]. This approach is consistent with established methods for linking elevation and population distributions [50]. In order to correct for different vertical datums all digital elevation data is converted to be referenced to GOCO06s. To do so, conversion grids from GFZ have been used (https://icgem.gfz.de/calcgrid). In order to align the digital elevation data with the surge data, mean dynamic topography data has been used [51]. Asset exposure is estimated by multiplying local GDP per capita [52] with population counts and an asset-to-GDP scaling factor of 2.8, reflecting the empirical near-linear relationship between produced capital and GDP [15]. Future asset exposure is projected by applying SSP-based population and GDP growth rates [53] to current exposure values up to 2100, with linear extrapolation used beyond 2100. Under retreat scenarios, the hypsometric profile is modified by removing all population and assets located below a retreat elevation threshold d_t^r, resulting in $H_t^{d_t^r}$.

Flood damage $\phi_t(H_t, x, d)$ is computed on the hypsometric profile H_t under extreme water level x and adaptation state d. We apply a bathtub-style inundation

model in combination with a logarithmic depth–damage function for inundation depth w, defined as $\frac{w}{w+1}$, following established coastal flood damage modeling approaches [16].

3.5 Hazards

We use regional mean sea-level projections l_t^p from the IPCC Sixth Assessment Report [54]. Specifically, we consider the median quantile ($p = 0.5$) of the medium-confidence projections for the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios.

Extreme water level distributions are constructed by fitting Generalized Extreme Value (GEV) or Generalized Pareto (GPD) models to the return period estimates provided by COAST-RP [48]. Model selection is based on a least-squares criterion, and the best-performing distribution is retained for each location. The underlying return period data are available at a spatial resolution of 1.25 km along the coastline. Each coastal floodplain is linked to an extreme water level return period via nearest-neighbour matching, using the midpoint of the associated coastline segment. This yields a location-specific extreme value distribution with probability density function $f(x)$. Temporal changes due to SLR l_t^p are incorporated by vertically shifting the location parameter μ of the distribution such that $\mu \rightarrow \mu + l_t^p$, resulting in a time-dependent probability density function $f_t(x)$.

3.6 Cost-benefit optimisation

We apply the time-dependent cost–benefit optimisation framework of [30] to each coastal floodplain separately. The objective is to minimise the expected total discounted sum of adaptation investments and residual flood damages by selecting an optimal adaptation pathway π. The pathway specifies the adaptation action u undertaken in adaptation state d_t,

$$\min_{\pi \in \Pi} \sum_{t_0}^{T} \beta^t C(d_t, \pi_t(d_t)), \tag{3}$$

where β is the discount rate and $C(d, u)$ is the cost function. Let $I(d, u)$ be the investment cost function and $m(d)$ the annual maintenance cost function (see section 3.2 for details). Using the flood damage function $\phi_t(H_t, x, d)$ (section 3.4) we can then rewrite our objective function 3 as

$$\min_{\pi \in \Pi} \sum_{t_0}^{T} \beta^t \Big[I\left(d_t, \pi_t(d_t)\right) + m(d_t)\Delta t + \int_{max(d_t^p, d_t^a)}^{\infty} \phi_t \left(H_t^{d_t^r}, x, d_t \right) f_t(x)\, dx \Delta t \Big], \tag{4}$$

where the integral represents expected annual flood damages, obtained by weighting flood damages by the probability density function of extreme water levels $f_t(x)$ (section 3.5). The expected annual flood damages are scaled by the number of years between successive time steps, Δt. The lower integration bound is given by $\max(d_t^p, d_t^a)$, reflecting the assumption that no flood damage occurs for extreme water levels below the

maximum of the protection or accommodation height. Once this threshold is exceeded, flood damages are assumed to occur as if no adaptation measure were in place, corresponding to a complete failure of coastal protection or accommodation.

We consider a planning horizon defined by $(t_0, \Delta t, T) = (2020, 10, 2150)$ and solve the optimisation problem in Eq. 4. As the problem can be formulated as a Bellman equation [55], it is addressed using dynamic programming techniques [56]. A discount rate of 3% is applied, which lies within the range commonly adopted in related literature [8, 24, 30].

3.7 Climate and Counterfactual Scenarios

In total, we run four simulations using different model configurations. The baseline results presented in the main text rely on the SSP2-4.5 climate scenario. To explore climate uncertainty, we conduct two additional simulations under SSP1-2.6 and SSP5-8.5, which represent low and very high greenhouse gas emission pathways, respectively, thereby covering a broad range of plausible future conditions. In addition, we carry out one counterfactual experiment using the baseline parameter set in which SLR is set to zero, to isolate its contribution to the results.

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Declarations

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Conflict of interest/Competing interests

There are no conflicts of interests to declare.

Data, material and code availability

Additional results of this study are provided in the Supplementary Information. The applied code for the DIVACoast model is available under https://gitlab.com/globalclimateforum/DIVACoast.jl and for the dynamic programming of

the multi-stage cost-benefit analysis under https://gitlab.com/globalclimateforum/AdaptiveDM. The code and data that was used to conduct the results of this research can be found under https://doi.org/10.5281/zenodo.20445806.

Author contribution

V.V.: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Visualization. J.H.: Conceptualization, Methodology, Software, Resources, Data Curation, Writing - Review & Editing, Supervision, Project administration, Funding acquisition. D.L.: Methodology, Software, Validation, Resources, Data Curation, Project administration. L.H.: Methodology, Software. N.V.: Writing - Review & Editing, Supervision. S.B.: Methodology, Data Curation, Writing - Review & Editing.

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