Optimal Life-Cycle Adaptation of Coastal Infrastructure under Climate Change

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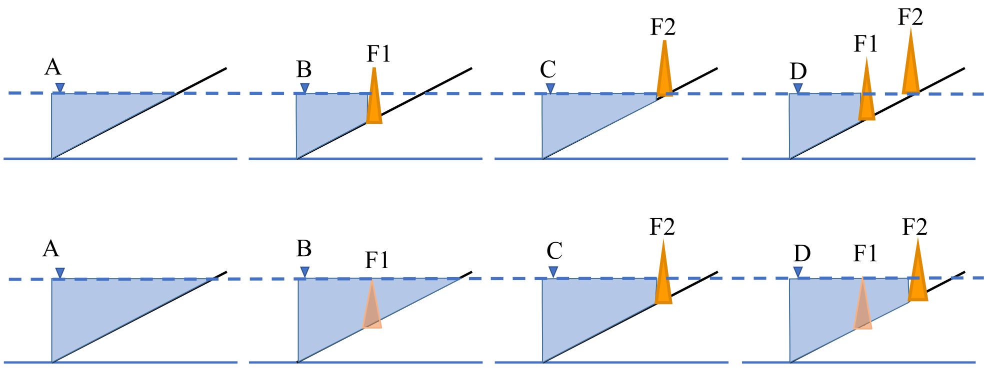
Supplementary Materials

MDP Formulation Additional Insights

1.1 States

With two possible interventions, the two floodwalls *F1* and *F2*, as shown in Supplementary Fig. 1, there can overall be 4 possible system configurations; configuration A where none of the measures have been implemented yet, B where only the lower floodwall *F1* is constructed, C where only the higher floodwall *F2* is constructed, and lastly the terminal system D where both floodwalls have been built. Among these possible systems, in the terminal system D, all possible flood measures have been implemented, leaving the agent with no alternative actions to modify the system thereafter. Thus, once the agent reaches the terminal system, the decision-making process essentially terminates, with the agent receiving a terminal reward for remaining in the terminal system until the end of the planning horizon. The terminal reward can be calculated as the expected flooding, maintenance, carbon, and any other relevant costs/metrics over the future planning horizon from the time of transition into the terminal system.



Supplementary Fig. 1 : Representative flood levels to show the dependence on the current system configuration. It can be seen that the flooded regions vary across the 4 considered systems: *A* (system with no floodwalls), *B* (system with only the lower floodwall *F1*), *C* (system with only the higher floodwall *F2*) and *D* (system with both floodwalls).

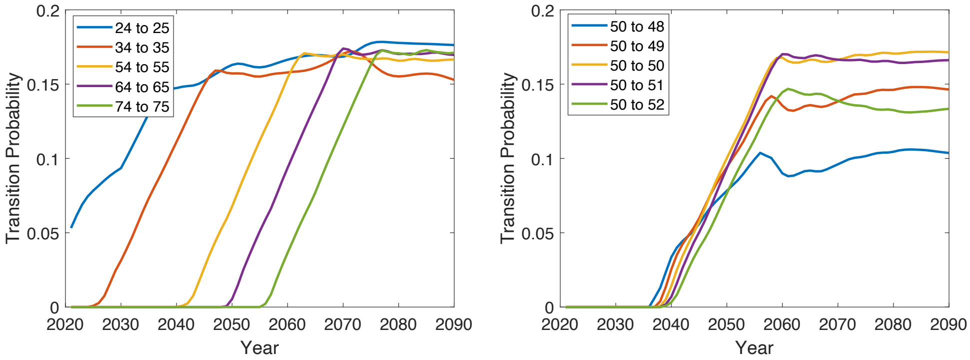
Hence, the state space of the control problem can be potentially reduced to include only the states belonging to the controllable systems. However, it is to be noted here that in this case, the terminal reward for each state in the terminal system needs to be pre-calculated, which can often be computationally very expensive and therefore has been avoided here for the purposes of this study, and instead, the 221,760 states of the terminal system have been also fully integrated in the MDP setting.

A related note here is that with a stationary storm surge model, the pertinent MDP surge states can be eliminated from the problem formulation and instead represented by expected relevant costs at each SLR state, considerably reducing the dimensionality of the state space. We have not implemented this option in our work, though, in order to describe the more general formulation, as explained in the manuscript, that can also support non-stationary storm surge models without any limitations.

1.2 Transition Probabilities

To obtain the transition probabilities for the SLR states under a given SSP, Monte Carlo sampling is performed to generate 100 million SLR trajectories using the SLR model described in the manuscript. The continuous SLR values are then discretized with a step size of 2 cm, with the maximum SLR value being 150 cm, resulting in a total number of 77 discrete SLR states (S_{SLR}). The probability of transitioning from a given discrete SLR state s to another SLR state s' for any year t is then estimated by counting the number of jumps from s to s' and normalizing this count by the total number of data in SLR state s. These computed transition probabilities are finally smoothened over a time window of 5 years, and some representative probabilities are shown in Supplementary Fig. 2.

The transition probability matrix structures for do-nothing and constructing the first floodwall actions are provided in the main manuscript. The transition matrices for the actions of constructing the second floodwall and constructing both floodwalls are provided below.



Supplementary Fig. 2 : Non-stationary transition probabilities for sea level rise states. Transition probabilities are smoothened with a moving average over a window of 5 years.

Action a_{F_2}: This action corresponds to the implementation of the higher floodwall F_2. Thus, this action will result in transitioning from system A to system C, and from system B to system D, respectively. However, if the environment is already in system C or D, it naturally remains there, respectively. Thus, the a_{F_2} transition matrix is defined as:

$$\mathbf{T}^{Full}\left(a_{F_2}\right) = \begin{bmatrix} \mathbf{0} & \mathbf{0} & \mathbf{T}^{time}_{(A\to C)} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{T}^{time}_{(B\to D)} \\ \mathbf{0} & \mathbf{0} & \mathbf{T}^{time}_{(C\to C)} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{T}^{time}_{(D\to D)} \end{bmatrix} \tag{1}$$

Action a_{F_1,F_2}: This action corresponds to the implementation of both flood preventive measures at the same time. Thus, this action will result in transitioning from any system it may be to the terminal system D. The a_{F_1,F_2} transition matrix is then defined as:

$$\mathbf{T}^{Full}\left(a_{F_1,F_2}\right) = \begin{bmatrix} \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{T}^{time}_{(A\to D)} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{T}^{time}_{(B\to D)} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{T}^{time}_{(C\to D)} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{T}^{time}_{(D\to D)} \end{bmatrix} \tag{2}$$

POMDP Formulation Additional Insights

2.1 States

We consider two different climate scenario models, SSP2-4.5 and SSP5-8.5. The previously defined MDP state space is expanded to include all relevant states within each of the climate scenario models under consideration. The decisions are assumed to be taken at 5-year intervals now, instead of on an annual basis, as is done in the MDP solutions, and we still consider a 40-years horizon. The state space under each system configuration consists of 77 primary SLR states (S_{SLR}), considered for 8 different decision epochs, resulting in a total of 6,167 SLR states (S'_{SLR}), combined with 72 surge states (S_{surge}), resulting in a total of 44,352 states, as $S_t = S'_{SLR} \times S_{surge}$. Including the states under all the four system configurations and a terminal state, the state space under each climate model scemario consists of $44,352 \times 4 + 1 = 177,409$ states. Therefore, the total POMDP state space characterizing two climate scenario models consists of $177,409 \times 2 = 354,818$ states.

2.2 Transition Probabilities

The transition matrix $\mathbf{T}_M^{Full}(s'|s,a)$ for each of the considered climate models is obtained following the same steps as those used for deriving the full MDP transition matrix based on one climate model. The $\mathbf{T}^{time}(s'|s,a)$, under each model, is constructed now as follows:

$$\mathbf{T}^{time}_{(44,352\times 44,352)} = \begin{bmatrix} \ddots & \vdots & \iddots \\ \cdots & \mathbf{T}\,(i \to j) & \cdots \\ \iddots & \vdots & \ddots \end{bmatrix} \tag{3}$$

$$\mathbf{T}(i \to j)_{(11,088\times 11,088)} = \begin{bmatrix} \mathbf{0}^{ii}_{(5,544\times 5,544)} & \mathbf{T}^{ij}_{(5,544\times 5,544)} \\ \mathbf{0}^{ji}_{(5,544\times 5,544)} & \mathbf{0}^{jj}_{(5,544\times 5,544)} \end{bmatrix} \tag{4}$$

where i and j represent arbitrary, consecutive decision-steps with $j = i + 5$. The sub-matrix $\mathbf{T}(i \to j)$ represents the fact that the only non-zero probabilities are the ones corresponding to the transition from step i to the subsequent step j. The matrix $\mathbf{T}^{ij}$ over 5,544 states is the 5-step Markov transition matrix obtained from the yearly transition matrices for each climate model:

$$\mathbf{T}^{ij} = \mathbf{T}^{i\to i+5} = \mathbf{T}^{i\to i+1} \times \mathbf{T}^{i+1\to i+2} ... \times \mathbf{T}^{i+4\to i+5} \tag{5}$$

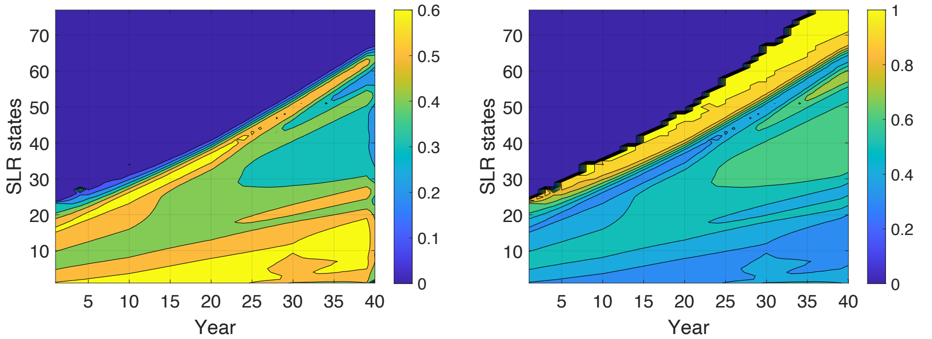
where $\mathbf{T}^{i+(k-1)\to i+k}$ for $k = 1,..,5$ represents the non-stationary transition matrix from year $i + (k-1)$ to year $i + k$.

2.3 Observation Likelihoods

To obtain the likelihood of observing different SLR states under different climate model scenarios, 100 million SLR trajectories are simulated, using the SLR model described in the manuscript, utilizing both SSP model scenarios. The counts of different SLR states for each year are computed for each model using the respective simulated ensemble of SLR trajectories. These counts for each SLR state in each year are then proportioned across the two models to obtain the likelihood of observing each SLR state under the two models. The likelihood contours for the different SLR states over the next 40 years are shown in Supplementary Fig. 3.

2.4 Costs

Since in the POMDP formulation decisions are taken once every 5 years, the costs incurred at any decision time-step should include the sum of average annual costs that can be accumulated over the next 5 years starting from the current decision time-step. The annual costs that should be accumulated over the next 5 years include the



Supplementary Fig. 3 : The observation likelihoods under different climate models. The likelihood of observing the 77 SLR states over the 40 years horizon under climate model scenarios of SSP2-4.5 (left) and SSP5-8.5 (right).

annual maintenance costs of the existing flood measures and the annual flood risks. The costs associated with average/expected annual flood risk are calculated based on n-step Markov transitions, where n represents the year after the current time-step. Therefore, the expected flood risk C_f from state s at time-step $t+1$ is calculated as:

$$C_f(s, t+1) = \sum_{s' \in S} p_1(s'|s, a) R_f(s') \tag{6}$$

where $p_1(s'|s, a)$ is the state transition probabilities corresponding to the 1-step Markov transition matrix from the current time-step. Similarly, the expected flood risk C_f from state s at time-step $t+2$ is calculated as:

$$C_f(s, t+2) = \sum_{s' \in S} p_2(s'|s, a) R_f(s') \tag{7}$$

where $p_2(s'|s, a)$ is the state transition probabilities corresponding to the 2-step Markov transition matrix from the current time-step.

The annual expected flood risks are then calculated for every consecutive year starting from the current year using the respective year's step transition matrix. The annual costs of the five years are suitably discounted and added to obtain the sum of average flood-risk related costs over the next 5 years from the current time-step, as:

$$C_f(s, t \to t+5) = \sum_{k=1}^{5} \gamma^k C_f(s, t+k) \tag{8}$$

Additional Figures and Tables

The effect of the social cost of carbon on the total costs and carbon costs is illustrated in Supplementary Fig. 4. The comparison of monetary costs and carbon costs between salt marshes and oyster reefs is shown in Supplementary Fig. 5. Illustrative probability distributions of being in a state starting from the current state, derived from Monte-Carlo simulations and discrete-state Markov chains, based on the estimated transition probabilities, are shown in Supplementary Fig. 6. The solution process of the Focused Real-Time Dynamic Programming (FRTDP) solver used in this work is illustrated in Supplementary Fig. 7. The system boundary of the construction section in the EIO-LCA tool used in this work is shown in Supplementary Fig. 8.

3.1 Coastal City Model Parameters

The general parameters used to characterize the idealized coastal city are shown in Supplementary Table 1.

3.2 Coastal Community Model Parameters

The general parameters used to characterize the idealized coastal community are shown in Supplementary Table 2.

3.3 Summary of Results

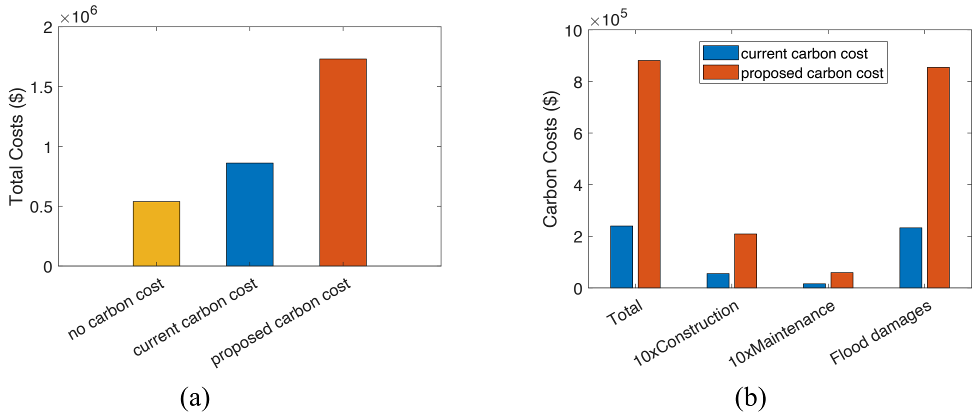
The results in each scenario in coastal city and community settings are provided in Supplementary Table 3.

3.4 Floodwall Cost and Flood Damage Parameters

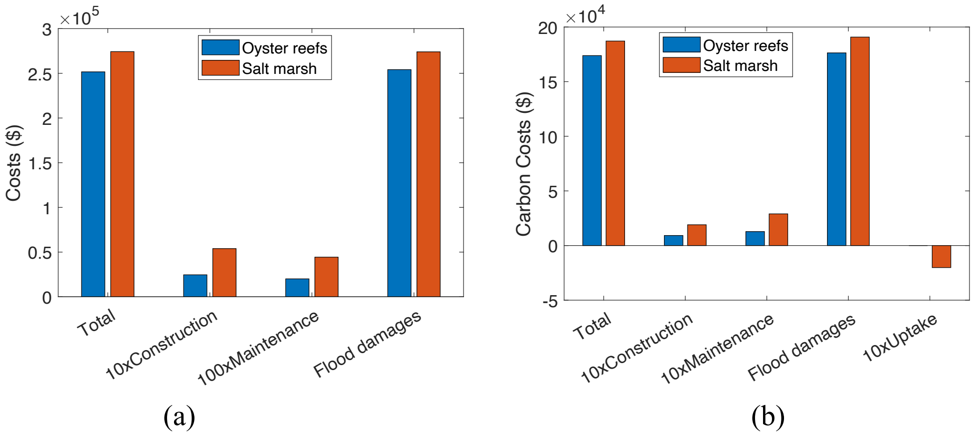
The parameters related to costs of floodwalls and flood-induced damages are listed in Supplementary Table 4. The land-use distribution of buildings destroyed by Hurricane Sandy is reported in Supplementary Table 5.

3.5 Nature-based Infrastructure

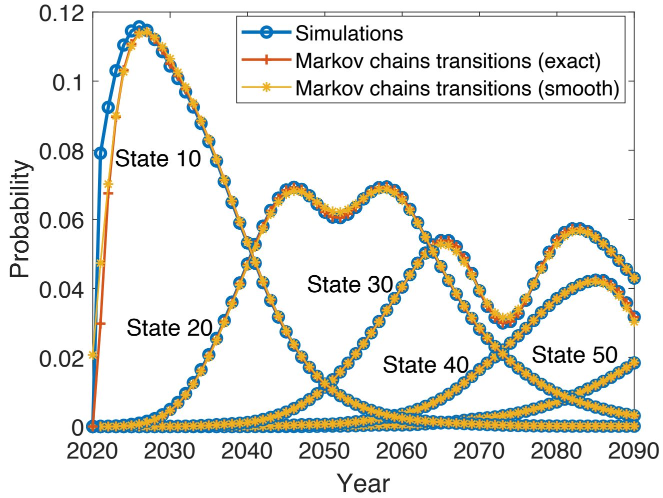
The monetary construction and maintenance costs and respective carbon costs of the different nature-based solutions are listed in Supplementary Tables 6 and 7. The wave attenuation properties and the biological carbon sequestration of the nature-based solutions considered in this work are shown in Supplementary Tables 8 and 9.



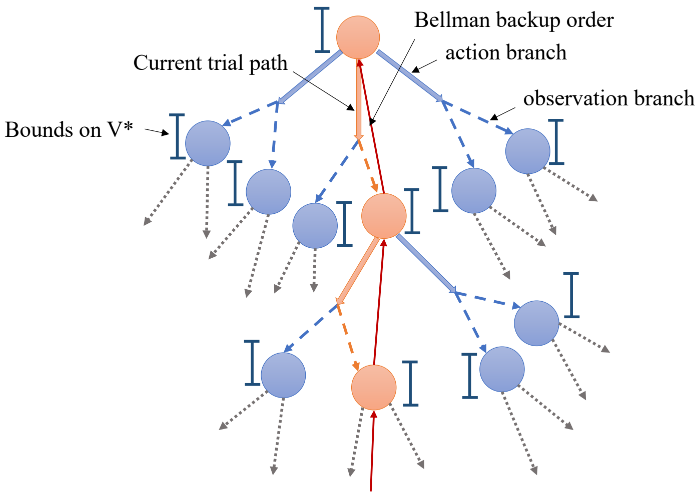
Supplementary Fig. 4 : Effect of social cost of carbon on (a) the total overall (monetary + carbon) costs and (b) the total carbon costs decomposed into categories of construction, maintenance and flood-induced damages.



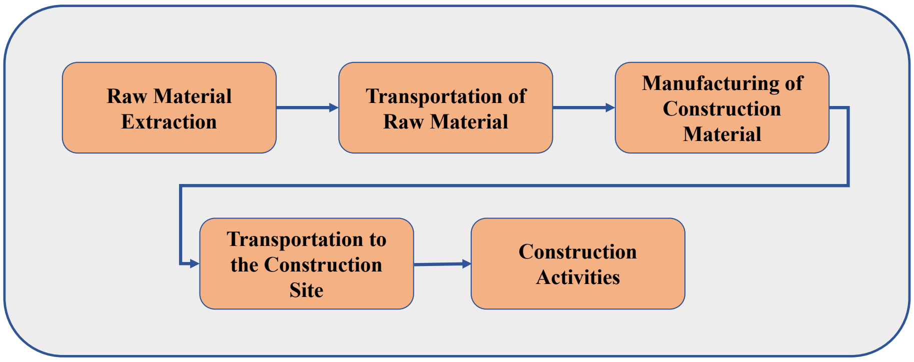
Supplementary Fig. 5 : Comparison of (a) monetary costs and (b) carbon costs (associated with construction, maintenance, flood-induced damages, and uptake processes (rewards)). Oyster reefs are more effective against floods here, thus resulting in a reduction of overall costs.



Supplementary Fig. 6 : Probability of being in a state starting from the initial state. Comparison of Markov chain simulation results based on estimated discrete-state transition probabilities with that obtained from continuous Monte-Carlo simulations. Smoothened transitions are obtained by moving average over a window of 5 years.



Supplementary Fig. 7 : Search and updating process in FRTDP.



Supplementary Fig. 8 : The cradle-to-gate system boundary of the construction sector in the Economic Input-Output Life-Cycle Assessment (EIO-LCA).

Supplementary Table 1 : List of coastal city model parameters

Parameter	Value	Units	Description
L_Z	1	m	Length of the city under study
Val_Z	15	\$ million	Exposure value of the city
f_{damage}	0.07	-	Vulnerability of the city to flooding
Vol_Z	4,250	m^3	Volume of the city = $\frac{1}{2}H_Z D_Z L_Z$
H_Z	8.5	m	Height of the city
D_Z	1	km	Depth of the city
$H_{seawall}$	1.2	m	Height of the seawall
H_{fw}	1.5	m	Height of the floodwall
$b1_{fw}$	0.5	m	Height of the base of the first floodwall
$b2_{fw}$	2.5	m	Height of the base of the second floodwall
W_{gr}	150	m	Width of green resistance zone along the wedge

Note: The city value is uniformly distributed among its zones.

Supplementary Table 2 : List of coastal community model parameters

Parameter	Value	Units	Description
L_Z	1	m	Length of the community under study
Val_Z	5	\$ million	Exposure value of the community
f_{damage}	0.10	-	Vulnerability of the community to flooding
Vol_Z	8,500	m^3	Volume of the zone = $\frac{1}{2}H_Z D_Z L_Z$
H_Z	8.5	m	Height of the community
D_Z	2	km	Depth of the community
H_{fw}	1.5	m	Height of the floodwall
b_{fw}	1.5	m	Height of the base of the floodwall
W_{gr}	100	m	Width of nature-based solution before the wedge starts

Note: The community value is uniformly distributed among its zones.

Supplementary Table 3 : Simulation-based comparison between MDP and optimal static policies in coastal city and community settings. $\boldsymbol{E}[C_T]$ is the expected total (monetary + carbon) costs in \$ million per meter coastline. 95% confidence intervals are provided on the expected costs, assuming Gaussian estimators, based on 1,000 Monte Carlo simulations

Setting	Flood Protections	$\boldsymbol{E}[C_T]$ (95% C.I) MDP	$\boldsymbol{E}[C_T]$ (95% C.I) Best static policy
Coastal city	Two floodwalls (no pre-existing seawall)	0.5632 ±0.0105	0.5925 ±0.0109($F1$)
	Green resistance zone and a floodwall (with pre-existing seawall)	0.0937 ±0.0040	0.0992 ±0.0038(GR)
Coastal community	Salt marsh and a floodwall	0.4473 ±0.0042	0.4664 ±0.0045(SM)
	Oyster reef and a floodwall	0.4215 ±0.0047	0.4316 ±0.0049(OR)

Note: *F1*, *GR*, *SM*, and *OR* represent the best static policy, as reported in the manuscript.

Supplementary Table 4 : List of the cost and damage parameters

Parameter	**Value**	**Units**	**Reference**
City value	15	\$ million per meter coastline	Hazus 5.1 inventory [1]
Discount factor (γ)	0.97	-	[2]
Floodwall construction cost (C_{cfw})	13,848	\$ per meter coastline	[3]
Floodwall annual maintenance cost (C_{mfw})	115.4	\$ per meter coastline	[3]
Flood damage GHG emission intensity ($GHGI_f$)	311.3	ton CO2-equivalent per \$ million	EIO LCA tool [4]
Floodwall construction GHG emission intensity ($GHGI_{cfw}$)	169.9	ton CO2-equivalent per \$ million	EIO LCA tool [4]
Floodwall maintenance GHG emission intensity ($GHGI_{mfw}$)	269.2	ton CO2-equivalent per \$ million	EIO LCA tool [4]

Note: Construction and annual maintenance costs of floodwall listed here are for the coastal city setting. The costs for the coastal community setting are obtained by reducing the respective costs by 20 %.

Supplementary Table 5 : Hurricane Sandy's damaged buildings as a percentage of land use (from [5] and corresponding EIO-LCA sector)

Land Use	Damaged Building Share	EIO-LCA Construction Sector
One & two family	88.0%	Single family homes
Multi-family walk up	1.0%	Multi-family homes
Mixed residential & commercial	6.0%	Commercial structures
Commercial & office	2.0%	Commercial structures
Vacant	1.0%	Other non-residential structures
Open space & recreation	1.0%	Other non-residential structures
Industrial & manufacturing	0.2%	Manufacturing buildings
Multi-family elevator	0.2%	Multi-family homes
Transportation & utility	0.2%	Utilities buildings and infrastructure
Parking	0.2%	Utilities buildings and infrastructure
Public facility & institution	0.2%	Schools and vocational buildings
Total	100%	All sectors

Supplementary Table 6 : Construction and maintenance cost of nature-based infrastruture

Solution	Cost	Reference
Multi-functional green space	$\$25/m^2$ (capital cost) (calculated as area-weighted average of $\$10/m^2$ (turfgrass), $\$10/m^2$ (meadow), $\$50/m^2$ (trees), $\$88/m^2$ (rain garden/swale) and $\$50/m^2$ (path)) $\$2.7/m^2/yr$ (maintenance) (calculated as area-weighted average of $\$1/m^2/yr$ (turfgrass), $\$0.1/m^2/yr$ (meadow), $\$9/m^2/yr$ (trees), $\$1.6/m^2/yr$ (rain garden/swale), and $\$5/m^2/yr$ (path))	[6]
Salt marshes	$50,000-$250,000/ha Assume $100,000/ha for the first 100m width, then $1,000/m length along shore	[7]; [8]
Constructed oyster reefs	$8,000-$386,000/ha Assume $50,000/ha for the first 5m, then $5/m length along shore	[9]

Supplementary Table 7 : Construction and maintenance carbon cost of nature-based infrastructure

Solution	Carbon Cost	Reference
Multi-functional green space	1.6 kg C/m^2 (construction) (calculated as area-weighted average of 0.7 kg C/m^2 (turf-grass), 0.5 kg C/m^2 (meadow), 0.48 kg C/m^2 (trees), 5 kg C/m^2 (rain garden/swale) and 10 kg C/m^2 (path)) 0.09 kg C/m^2/yr (maintenance) (calculated as area-weighted average of 0.05 kg/m^2/yr (turf-grass), 0 (meadow), 0.15 kg C/m^2/yr (trees), 0.3 kg C/m^2/yr (rain garden/swale), and 0.3 kg C/m^2/yr (path))	[10]; [11]
Salt marshes	1 kg C/m^2 (construction). If we assume 100 m width, then 100 kg/m (along shore)	
Constructed oyster reefs	0.5 kg C/m^2 (construction)	

Note: Assuming no maintenance carbon cost for salt marsh and oyster reef. The construction carbon costs for salt marshes and oyster reefs have been assumed based on authors' experience in this study, due to insufficient available information.

Supplementary Table 8 : Wave attenuation function of nature-based infrastructure

Solution	Wave Attenuation	Reference
Multi-functional green space	0.1% wave height attenuation per meter along the wedge	[12]
Salt marshes	60% for $h \leq 0.1$ m; $6.34h^{-0.974}$, otherwise (where h is the total water depth in meters)	[13]
Constructed oyster reefs	40% for total water depth of 0.5–1.0 m; 10% for water depth of 1.0–1.5 m; assume 5% for > 1.5 m depth.	[14]; [15]

Note: Since water level reduction should not exceed wave height: if water level reduction $>$ wave height, then water level reduction $=$ wave height.

Supplementary Table 9 : Biological carbon sequestration of nature-based infrastructure

Solution	**C Accumulation**	**Reference**
Multi-functional green space	0.17 kg C/m^2/yr (calculated as area-weighted average of 0.15 kg/m^2/yr (turfgrass), 0.2 kg/m^2/yr (meadow), 0.21 kg/m^2/yr (trees), 0.3 kg/m^2/yr (rain garden/bioswale))	[6], [11]
Salt marshes	440 g C/m^2/yr If we assume 100 m width salt marsh, then 44 kg C/m (along shore) /yr	[16]
Constructed oyster reefs	0.0003-0.0027 g C/ha/yr (3 E-8 to 3 E-7 g C/m^2/yr) If we assume 5 m width reef, then 1.5 E-6 g C/m (along shore)/yr	[17]

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