Supplementary Information

Supplementary Notes 1

List of cost and benefit items reported in literature.

Supplementary Table 1: Seawall heightening costs reported in literature[1–4].

Item	Value	Units
	(Linham et al., 2010)(1)	
Dutch raising low sea dikes in rural	0.7	M$2009USD /km /m
Dutch raising high sea dikes in rural	1.4	M$2009USD /km /m
Dutch raising sea dikes in urban	14.04	M$2009USD /km /m
USA New Orleans Vertical seawall, concrete floodwall	5.0 – 6.1	M$2009USD /km /m
	(Jonkman et al., 2013)	
T-wall floodwall construction cost	4.9 – 11.8	M€2009EUROS /km /m
Netherlands raising of low sea dikes (rural)	4.5 – 12.4	M€2009EUROS /km /m
Netherlands raising of sea dikes (urban)	15.5 – 22.4	M€2009EUROS /km /m
USA (California) Dike raising	0.6 – 2.7	M€2009EUROS /km /m
Maintenance of flood defense	0.1	M€2009EUROS /km /m
	(USACE, 2015)	
Floodwall construction first cost	5,335	$2015USD /foot (for 10 foot high floodwall)
	(Oppenheimer et al., 2019)	
Seawall capital cost(2)	0.4 – 27.5	/km /m
Seawall maintenance cost(3)	1 – 2%	per annum
Sand unit cost	3 – 21	$2019USD /$m^3$

(1) Values from (Linham et al., 2010) were used in economic analysis.
(2) Originally reported in (Linham et al., 2010).
(3) Originally reported in (Jonkman et al., 2013).

Supplementary Table 2: Environmental services value from literature[5,6].

Item	Value	Units
(FEMA, 2022)		
Coastal wetland	8,955	$2021USD /acre /year
Breakdown:		
Aesthetic value	1,648	$2021USD /acre /year
Climate regulation	125	$2021USD /acre /year
Flood and storm hazard reduction	1,035	$2021USD /acre /year
Habitat	2,420	$2021USD /acre /year
Recreation	1,624	$2021USD /acre /year
Water filtration	1,558	$2021USD /acre /year
Water supply	544	$2021USD /acre /year
(Jin et al., 2018)		
Ecosystem services – Lower bound	12,127	$2016USD /acre /year
Carbon storage asset value – Lower bound	12,312	$2016USD /acre /year
Carbon storage asset value – Higher bound	13,050	$2016USD /acre /year

Supplementary Table 3: Capital costs of salt marsh installation and restoration[2–4,7].

Item	Value	Units
(USACE, 2015)		
Planting cost	2	$2015USD /planting
(Narayan et al., 2016)		
Salt marsh restoration cost (median)	1.1	$2016USD /m^2
(Oppenheimer et al., 2019)		
Salt marsh capital cost	67,000	$2016USD /ha
(Linham et al., 2010)		
Marshland creation	4.1	$2009USD /m^2
Marshland stabilization	1.9	$2009USD /m^2

Supplementary Table 4: Maintenance costs of marshes[2,4].

Item	Value	Units
(USACE, 2015)		
Maintenance cost	0.5	% of capital cost
(Linham et al., 2010)		
Marshland stabilization maintenance	0.09	\$2009USD /m^2

Supplementary Table 5: Other engineering costs for marsh creation and restoration[2].

Item	Value	Units
(USACE, 2015)		
Contingency	25	% of capital cost
Engineering and Design	12	% of capital cost
Construction management	10	% of capital cost

Supplementary Notes 2

Vegetation parameters used for the model validation reported in Fig. 2 in the *Results*.

Supplementary Table 6: Vegetation parameters used to model marsh species at Bath and Hellegat, with specific values used for each vegetation section between sensors.

Site	**Bath**	**Hellegat**
Species name	*Scirpus maritimus*	*Spartina anglica*
l_l **(m)**	0.2[(1)]	0.2[(1)]
C_s	0.4[(2)]	0.4[(2)]
N_l	0, 2, 4[(1)]	0, 2 ,5[(1)]
b **(m)**	0.002[(1)]	0.006[(1)]
d **(m)**	0.0002[(1)]	0.0002[(1)]
E_l **(GPa)**	3[(2)]	3[(2)]
E_s **(GPa)**	0.4[(1)]	0.1[(1)]

Section	l_s **(m)**	N_s **(shoots per m^2)**	D **(m)**	λ_p
Bath S1-S2	0.17	144	0.0087	$1.5(10^{-3})$
Bath S2-S3	0.15	372	0.0080	$2.8(10^{-3})$
Bath S3-S4	0.35	1072	0.0049	$7.1(10^{-3})$
Hellegat S1-S2	0.20	944	0.0030	$1.3(10^{-3})$
Hellegat S2-S3	0.29	1136	0.0034	$3.0(10^{-3})$
Hellegat S3-S4	0.27	1520	0.0027	$2.3(10^{-3})$

[(1)] Lower bound values from Zhang et al., 2021[8] used to reflect the winter state of the plants.

[(2)] Standard reference values from Zhang et al., 2021[8] used.

Supplementary Notes 3

Vegetation parameters used to compare wave attenuation achieved by six different marsh species in Fig. 3 in the *Results*.

Supplementary Table 7: Salt marsh parameters of six species[8].

Vegetation parameters	*Scirpus mariqueter*	*Spartina alterniflora*	*Phragmites australis*	*Scirpus maritimus*	*Scirpus tabernaemontani*	*Spartina anglica*
l_l (m)	0.2	0.35[(1)]	0.3[(1)]	0.3[(1)]	-	0.3[(1)]
l_s (m)	0.38	1.3[(1)]	2[(1)]	0.85[(1)]	1.5[(1)]	0.65[(1)]
N_s (shoots/m^2)	2352	295[(1)]	340[(1)]	550[(1)]	550[(1)]	655[(1)]
C_s	0.4	0.4	0.4	0.4	0.4	0.4
N_l	1	9[(1)]	13[(1)]	6[(1)]	-	8[(1)]
b (m)	0.006	0.011[(1)]	0.02[(1)]	0.007[(1)]	-	0.011[(1)]
d (m)	0.0003	0.00046[(1)]	0.000285[(1)]	0.0003[(1)]	-	0.000335[(1)]
D (m)	0.0022	0.007[(1)]	0.009[(1)]	0.006[(1)]	0.012[(1)]	0.005[(1)]
E_l (GPa)	0.06	3	3	3	3	3
E_s (GPa)	0.12	0.74[(1)]	7.5[(1)]	0.8[(1)]	0.125[(1)]	0.4[(1)]
$E_l I_l$	$8.1(10^{-7})$	$2.7(10^{-4})$	$1.2(10^{-4})$	$4.7(10^{-5})$	-	$1.0(10^{-4})$
$E_s I_s$	$1.4(10^{-4})$	$8.7(10^{-2})$	2.4	$5.1(10^{-2})$	$1.3(10^{-1})$	$1.2(10^{-2})$

[(1)] Mean values from Zhang et al., 2021[8] used to reflect the average plant conditions.

Supplementary Notes 4

Example breakdown of benefits and costs associated with the marsh-fronted seawall in Fig. 1.

Supplementary Table 8: Example breakdown of benefits and costs associated with the marsh-fronted seawall (Fig. 1) using wave period $T = 5.0$ s, offshore wave height $H_0 = 1.5$ m, water depth at the toe of seawall $h_t = 3$ m, and 20-m wide *Spartina alterniflora* marsh with 5 plants/m^2 (plants spaced 18 inches apart)[9]. The marsh attenuated waves sufficiently to reduce the required seawall height by 1.03 m. The estimate assumed a 50 year useful project life and 2.5% discount rate[10]. Monetary values given in low, medium and high ranges.

	Low	**Medium**	**High**
Benefits			
Reduced seawall heightening subtotal ($)	1163	8306	23323
Annualized at 2.5% rate ($/year)	41	293	822
Environmental services			
Annual environmental services value ($/year)	51	84	90
Total annual benefits ($/year)	**92**	**377**	**912**
Costs			
Construction costs subtotal ($)	312	469	475
Other costs			
Contingency ($)	78	117	119
Engineering and Design ($)	37	56	57
Construction management ($)	31	47	48
Total first construction cost	**459**	**689**	**699**
Annualized capital cost at 2.5% ($/year)	**16**	**24**	**25**
Marsh maintenance			
Stabilization maintenance ($/year)	2.9	2.9	2.9
Maintenance proportion ($/year)	2.3	3.4	3.5
Annual maintenance cost subtotal ($/year)	**5.2**	**6.4**	**6.4**
Total equivalent annual cost ($/year)	**21**	**31**	**31**
BCR	**4.3**	**12.3**	**29.4**

Supplementary Notes 5

Example breakdown of benefits and costs for the Juniper Cove case study with service life of 50 years and at 2% discount rate.

Supplementary Table 9: BCR at 2% discount rate for 100-year storm event, with healthy plants that achieve an avoided seawall heightening of 1.08 m, all in $2023USD.

	Quantity	**Units**	**Unit price**	**Units**	**Subtotal**
Costs					
High Marsh Plantings – *S. patens*	1000	PLUGS	1.9	$/PLUG	1896
Low Marsh Plantings – *S. alterniflora*	4500	PLUGS	1.9	$/PLUG	8530
Salt Marsh Sand	153	m^3	132	$\$/m^3$	20219
Sill Construction	68	m	415	$/m	28054
Salt Marsh Maintenance	1	LS	3791	$/LS	3791
Marsh restoration subtotal					62490
Contingency cost			15%		9374
Engineering construction + closeout services			15%		9374
Total cost					**81237**
Annualized total cost ($/year)					**2585**
Benefits					
Avoided seawall construction cost	52	m^3	989	$\$/m^3$	
Annualized avoided seawall construction cost ($/year)					**1637**
Annual environmental services	1600	m^2	2.25	$\$/m^2$	**4076**
Annualized total benefits ($/year)					**5713**
BCR					**2.21**

Supplementary Notes 6

Vegetation parameters used for the Juniper Cove case study in Fig. 5 in the *Results*.

Supplementary Table 10: Vegetation parameters for the Juniper Cove case study.

Vegetation parameters	*Spartina alterniflora*		*Spartina patens*	
	Healthy	Dormant	Healthy	Dormant
λ_p	0.006[3]	0.006[3]	0.006[3]	0.006[3]
l_l (m)	0.35[1]	0.2[2]	0.44[4]	0.25[5]
l_s (m)	1.3[1]	0.3[2]	0.76[4]	0.34[5]
N_s (stems/m^2)	295[1]	170[2]	752[6]	563[6]
C_s	0.4[3]	0.4[3]	0.4[3]	0.4[3]
N_l	9[1]	5[2]	5.4[4]	4.0[5]
b (m)	0.011[1]	0.005[2]	0.0043[4]	0.0030[5]
d (m)	0.00046[1]	0.00025[2]	0.00046[3]	0.00046[3]
D (m)	0.007[1]	0.003[2]	0.0016[4]	0.0011[5]
E_l (GPa)	3[3]	3[3]	3[3]	3[3]
E_s (GPa)	0.74[1]	0.08[2]	1.5[7]	0.13[7]
$E_l I_l$ (Nm^2)	$2.7(10^{-4})$	$2.0(10^{-5})$	$1.0(10^{-4})$	$7.3(10^{-5})$
$E_s I_s$ (Nm^2)	$8.7(10^{-2})$	$3.2(10^{-4})$	$4.2(10^{-4})$	$9.3(10^{-6})$

[1] Mean values from Zhang et al., 2021[8] used to reflect healthy plant parameters.
[2] Lower bound values from Zhang et al., 2021[8] used to reflect dormant plant parameters.
[3] Standard representative values from Zhang et al., 2021[8] used.
[4] Mean values from Hester et al., 1996[11] used to reflect healthy plant parameters.
[5] Lower bound values from Hester et al., 1996[11] used to reflect dormant plant parameters.
[6] Values from Castillo et. al., 2017[12] used.
[7] Instron experimental values measured by Garber, 2024[13].

Supplementary References

1. Jonkman, S. N., Hillen, M. M., Nicholls, R. J., Kanning, W. & Van Ledden, M. Costs of adapting coastal defences to sea-level rise - New estimates and their implications. *J Coast Res* **29**, 1212–1226 (2013).
2. U.S. Army Corps of Engineers (USACE). *Appendix C-Planning Analyses North Atlantic Coast Comprehensive Study (NACCS) United States Army Corps of Engineers ® APPENDIX C: PLANNING ANALYSES NORTH ATLANTIC COAST COMPREHENSIVE STUDY: RESILIENT ADAPTATION TO INCREASING RISK Appendix C-Planning Analyses-i*. (2015).
3. Oppenheimer, M. *et al. Sönke Dangendorf (Germany), Petra Döll (Germany)*. (2019).
4. Linham, M. M., Green, C. H. & Nicholls, R. J. *Costs of Adaptation to the Effects of Climate Change in the World's Large Port Cities*. (2010).
5. Federal Emergency Management Agency (FEMA). *FEMA Ecosystem Service Value Updates*. (2022).
6. Jin, D., Watson, C., Kite-Powell, H. & Kirshen, P. Evaluating Boston Harbor Cleanup: An ecosystem valuation approach. *Front Mar Sci* **5**, (2018).
7. Narayan, S. *et al.* The effectiveness, costs and coastal protection benefits of natural and nature-based defences. *PLoS One* **11**, (2016).
8. Zhang, X., Lin, P. & Nepf, H. A simple-wave damping model for flexible marsh plants. *Limnol. Oceanogr* **66**, 4182–4196 (2021).
9. Taylor, L. & Smith, D. A. *Preliminary Design Summary Letter - October 2020. Https://Www.Salem.Com/Sites/g/Files/Vyhlif12836/f/Uploads/Columbus_ave_wall_-_design_summary_letter_with_attachments_-_10-21-20.Pdf.* https://www.salem.com/sites/g/files/vyhlif12836/f/uploads/columbus_ave_wall_-_design_summary_letter_with_attachments_-_10-21-20.pdf (2020).
10. Office of Information and Regulatory Affairs (OIRA). *GUIDANCE FOR ASSESSING CHANGES IN ENVIRONMENTAL AND ECOSYSTEM SERVICES IN BENEFIT-COST ANALYSIS Office of Information and Regulatory Affairs Office of Management and Budget*. https://www.whitehouse.gov/wp-content/uploads/2024/02/ESGuidance.pdf (2024).
11. Hester, M. W., Mendelssohn, I. A. & Mckee, K. L. Intraspecific variation in salt tolerance and morphology in the coastal grass Spartina patens (Poaceae). *Am J Bot* **83**, 1521–1527 (1996).
12. Castillo, J. M., Leira-Doce, P. & Figueroa, E. Biomass and clonal architecture of the cordgrass Spartina patens (Poaceae) as an invasive species in two contrasted coastal habitats on the Atlantic coast of the Iberian Peninsula. *Plant Ecol Evol* **150**, 129–138 (2017).
13. Garber, S. C. *Analyzing Remote Sensing-Derived Normal Difference Vegetation Index to Predict Coastal Protection by Spartina Alterniflora*. (2024).