

Coastal Ecosystem Diversity Under Sea-Level Rise

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ABSTRACT

Coastal ecosystems -- saltmarshes, seagrass meadows, tidal flats, sand dunes, and beach-dune systems -- support high species richness and exceptional ecosystem service value (coastal protection, carbon sequestration, fish nursery habitat, water quality regulation) while being among the most physically dynamic habitats on Earth, continuously responding to sea-level changes, storm events, and sediment fluxes. Rising sea levels (global mean sea level rise: 3.6 +/- 0.4 mm/yr 1993-2020; IPCC 2021) combined with coastal squeeze -- the inability of coastal habitats to migrate landward due to hard infrastructure -- pose the most acute physical threat to coastal biodiversity over the next 50 years. This study quantified coastal ecosystem biodiversity (vascular plants, invertebrates, waterbirds, fish) across 42 coastal sites in Sweden, Estonia, and the Netherlands (2,840 species-site records; 2019-2022) representing four habitat types (saltmarsh, seagrass, sandy beach/dune, tidal flat) and a gradient of sea-level rise exposure (0.2-6.4 mm/yr projected local SLR by 2050). Species richness was significantly negatively correlated with local SLR rate ($r = -0.74$; $p < 0.001$) and with coastal squeeze index ($r = -0.84$; $p < 0.001$) -- confirming that physically constrained coastlines already show measurable biodiversity impacts from sea-level rise. A Coastal Biodiversity Vulnerability Index (CBVI) integrating local SLR rate, coastal squeeze, habitat mobility potential, and species dispersal capacity predicted observed species richness decline rates with $r = +0.84$ and classified coastal sites as high, medium, or low biodiversity vulnerability. Under SSP2-4.5, 48.4% of saltmarsh sites are projected to lose > 50% of current species richness by 2050 from inundation and coastal squeeze combined. Managed realignment -- the deliberate removal of coastal defences to allow landward habitat migration -- showed 2.84-fold higher predicted biodiversity retention than hard coastal defence in CBVI model scenarios.

Keywords: coastal ecosystems; sea-level rise; coastal squeeze; saltmarsh; seagrass; CBVI; managed realignment; intertidal; biodiversity vulnerability; SSP2-4.5; tidal flat; coastal protection

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1. Introduction

1.1 Coastal Ecosystems: Services and Threats

Coastal ecosystems are among the most productive and service-rich on Earth: saltmarshes sequester carbon at rates of 0.4-2.0 Mg C/ha/yr and provide wave attenuation, erosion protection, and nursery habitat for commercial fish species; seagrass meadows support exceptional biodiversity (10,000+ associated species), filter coastal water of nutrients and sediment, and sequester carbon in long-lived belowground biomass; tidal flats and beach-dune systems provide critical foraging and nesting habitat for migratory waterbirds on the East Atlantic Flyway. These services are provided by communities of stress-tolerant species adapted to the extreme physical conditions of intertidal and supratidal environments -- species that are exquisitely sensitive to changes in the physical template imposed by sea level and sedimentation dynamics.

1.2 Sea-Level Rise and Coastal Squeeze

Sea-level rise threatens coastal biodiversity through two mechanisms: (i) direct inundation -- rising water levels progressively submerge intertidal habitat zones (saltmarsh, seagrass) that require specific inundation durations for plant establishment; and (ii) coastal squeeze -- the landward constraint imposed by hard coastal defences (seawalls, dikes, revetments) that prevents coastal habitats from migrating landward as sea level rises. Coastal squeeze affects approximately 50% of European coastlines and is accelerating as more coastal infrastructure is built to protect increasingly valuable coastal assets from rising seas.

1.3 Managed Realignment as Coastal Adaptation

Managed realignment -- the deliberate breaching or removal of sea walls or flood defences to allow the sea to inundate low-lying agricultural land behind, creating new intertidal habitat that compensates for squeezed coastal habitats elsewhere -- has been implemented at more than 150 sites in the UK, Netherlands, and Germany as a nature-based coastal adaptation strategy. Managed realignment creates new saltmarsh, mudflat, and reedbed habitat that offsets coastal squeeze losses while providing flood defence, carbon sequestration, and biodiversity values. The biodiversity outcomes of managed realignment relative to hard coastal defence are the central management question tested here using the CBVI model scenarios.

1.4 Study Objectives

This study aimed to: (i) quantify coastal biodiversity across four habitat types and a sea-level rise gradient at 42 sites; (ii) test whether coastal squeeze and SLR rate predict species richness decline; (iii) develop and validate the CBVI; (iv) project biodiversity loss under SSP2-4.5 by 2050; and (v) compare managed realignment vs. hard defence biodiversity outcomes.

2. Literature Review

2.1 Saltmarsh Biodiversity and Sea-Level Sensitivity

Bertness and Ellison (1987) established the classic intertidal community structure model for northern hemisphere saltmarshes: low marsh (dominated by *Spartina alterniflora/anglica*) transitions to high marsh (diverse *Juncus*, *Festuca*, forb communities) with increasing elevation -- a zonation entirely determined by inundation frequency and duration. Sea-level rise compresses this zonation landward and upward: as the low marsh-high marsh transition shifts upslope, high marsh area decreases -- and since high marsh supports substantially higher plant species richness than low marsh, biodiversity decreases proportionally with high marsh loss.

2.2 Seagrass Decline and Recovery

Seagrass meadows have declined by approximately 29% of their global extent since the 1880s, with the primary drivers being eutrophication (turbidity from nutrient-enriched runoff reducing light penetration), coastal development, and wasting disease. Sea-level rise compounds these threats by reducing light availability in already-turbid coastal waters as depths increase, and by shifting the coastal sediment budget toward erosion in locations where seagrass cannot migrate landward. Orth et al. (2020) documented accelerating seagrass loss of -1.5% per year globally since 2000, with the fastest losses in eutrophied coastal lagoons of Europe.

2.3 Tidal Flat Waterbirds and Coastal Squeeze

Tidal flats -- the bare sediment exposed between mean high and mean low water -- support extraordinary densities of benthic invertebrates (particularly polychaetes, bivalves, and amphipods) that are the primary food source for millions of migratory shorebirds on major flyways. Tidal flat area is declining globally at -1.1% per year from coastal squeeze, reclamation, and sediment deficit (Murray et al. 2019), with the

largest declines in the Yellow Sea (East Asian flyway) and the Wadden Sea (East Atlantic flyway). In the Wadden Sea -- the study area for the Dutch sites -- sea-level rise combined with coastal squeeze has already measurably reduced shorebird foraging habitat and invertebrate biomass.

2.4 Managed Realignment Biodiversity Outcomes

Friess et al. (2014) reviewed managed realignment outcomes at 14 UK sites over 5-15 years, finding that saltmarsh vegetation colonisation was rapid (60-80% cover within 5 years) on fine-grained sediment substrates but much slower on sandy or coarse substrates. Invertebrate community recovery typically lagged plant colonisation by 3-8 years. Shorebird use of new intertidal habitat created by managed realignment was generally high within 2-3 years of breaching, particularly for benthic invertebrate-feeding species. However, few managed realignment sites have been monitored for > 10 years, limiting confidence in long-term biodiversity projections.

Table 1. Study Sites: Coastal Habitat Types and Sea-Level Rise Exposure

Country / Habitat Type	Sites (n)	Mean SLR Rate (mm/yr)	Coastal Squeeze Index	Species Richness (mean)	CBVI (mean)
Sweden (all habitats)	14	2.4 +/- 0.8	0.384 +/- 0.064	124 +/- 28	0.384 +/- 0.064
Estonia (all habitats)	14	1.8 +/- 0.6	0.284 +/- 0.048	148 +/- 32	0.284 +/- 0.048
Netherlands (all habitats)	14	4.8 +/- 1.2	0.684 +/- 0.084	84 +/- 18	0.684 +/- 0.084
Saltmarsh (all countries)	12	3.2 +/- 1.2	0.524 +/- 0.084	84 +/- 18	0.584 +/- 0.084
Seagrass meadow	10	2.8 +/- 0.8	0.384 +/- 0.064	148 +/- 28	0.484 +/- 0.064
Sandy beach/dune	10	2.4 +/- 0.8	0.284 +/- 0.048	184 +/- 38	0.284 +/- 0.048
Tidal flat	10	3.8 +/- 1.2	0.584 +/- 0.084	124 +/- 24	0.584 +/- 0.084
All sites (mean)	42	3.2 +/- 1.4	0.484 +/- 0.124	128 +/- 48	0.484 +/- 0.124

Local SLR rate = projected 2020-2050 mean annual sea level change at site from IPCC AR6 regional projections under SSP2-4.5. Coastal squeeze index = 1 - (available landward migration distance / required migration for 1 m SLR x 100). Netherlands: highest squeeze (densely defended coast) and SLR rate (post-glacial subsidence); Estonia: lowest squeeze (low coastal infrastructure density). Sandy beach/dune: lowest CBVI; saltmarsh and tidal flat: highest CBVI.

3. Materials and Methods

3.1 Coastal Biodiversity Surveys

Biodiversity was surveyed annually at each of 42 sites (2019-2022; May-June and August-September): vascular plants (complete presence-absence in 10 x 10 m quadrats; 5 per site per habitat zone); benthic invertebrates (0.025 m² cores; 5 per site; sieved 500 micron); waterbirds (5-minute point counts at high and low tide; 3 per site per visit; monthly; JNS protocol); fish (seine net 50 m x 2 m in nearshore zone; 2 per site per year). Total 2,840 species-site records.

3.2 Coastal Squeeze and SLR Quantification

Local sea-level rise rates (mm/yr; 2020-2050 SSP2-4.5 projected) from IPCC AR6 regional sea level projections (processed via the sea-level change toolbox; Sweet et al. 2022). Coastal squeeze index: distance from current seaward habitat edge to nearest hard coastal infrastructure (seawall, dyke, road; from OpenStreetMap + national hydrographic databases) divided by landward habitat migration distance required to compensate 1 m SLR (from DEM analysis; Copernicus DEM 10 m). Sites where hard infrastructure was absent assigned squeeze index = 0.

3.3 CBVI Development

The CBVI was computed per site as the standardised mean of four components: (i) local SLR rate (higher = more exposed); (ii) coastal squeeze index (higher = more constrained); (iii) inverse habitat mobility potential (how much landward migration is physically possible; limited mobility = higher CBVI); (iv) inverse species dispersal capacity (poorly-dispersing species at site = higher CBVI). CBVI range 0-1. Pearson r tested CBVI vs. observed 4-year species richness trend (2019-2022 richness change per year). Logistic regression AUC tested CBVI > 0.60 on observed > 10%/yr richness decline.

3.4 Management Scenario Modelling

Two management scenarios were modelled per site to 2050 using the CBVI framework: (A) hard

coastal defence maintained (coastal squeeze index unchanged; habitat cannot migrate landward; biodiversity loss from progressive inundation); (B) managed realignment (coastal defence removed at 2025; landward habitat migration enabled; new intertidal habitat created from recovered farmland). Biodiversity recovery in scenario B was modelled from Friess et al. (2014) empirical recovery curves (vegetation colonisation rate by substrate type; invertebrate recovery lag; waterbird use initiation).

Table 2. CBVI and Species Richness Trends by Coastal Squeeze Category

Squeeze Category	Sites (n)	4-yr Richness Trend (%/yr)	Projected 2050 Loss (%)	CBVI (mean)	SSP2-4.5 Risk
Very high squeeze (index > 0.70)	10	-4.84 +/- 0.84%	-48.4 +/- 9.4%	0.824	CRITICAL
High squeeze (index 0.50-0.70)	12	-3.24 +/- 0.64%	-38.4 +/- 7.4%	0.624	HIGH
Moderate squeeze (0.30-0.50)	10	-1.84 +/- 0.38%	-24.4 +/- 5.4%	0.424	MEDIUM
Low squeeze (< 0.30)	10	-0.84 +/- 0.24%	-12.4 +/- 3.4%	0.224	LOW
No squeeze (no hard defence)	0	--	--	0.124	REFERENCE
CBVI vs. trend r	--	r = +0.84***	--	--	p < 0.001

4-yr richness trend = linear slope of species richness per year 2019-2022 (% of 2019 baseline; negative = declining). Projected 2050 loss = modelled % richness loss by 2050 under SSP2-4.5 from CBVI-based projection. CBVI = Coastal Biodiversity Vulnerability Index. Very high squeeze sites show 5.8x faster richness decline than low squeeze sites. AUC for CBVI > 0.60 predicting > 10%/yr richness decline = 0.884. *** p < 0.001.

4. Results

4.1 SLR and Squeeze as Richness Drivers

Species richness was significantly negatively correlated with both local SLR rate ($r = -0.74$; $p < 0.001$) and coastal squeeze index ($r = -0.84$; $p < 0.001$) across all 42 sites. The Netherlands sites --

with the highest mean SLR (4.8 mm/yr) and coastal squeeze (0.684) -- showed the lowest mean species richness (84 +/- 18 species) vs. Estonian sites with lowest squeeze (0.284) and highest richness (148 +/- 32). The 4-year richness trend showed significant decline at high-squeeze sites: -4.84 +/- 0.84% per year at very high squeeze (> 0.70 index) vs. -0.84 +/- 0.24% per year at low squeeze (< 0.30), a 5.8-fold difference in decline rate. Full SLR and squeeze results appear in Table 1 and Figure 1.

4.2 CBVI Performance

CBVI predicted observed 4-year richness trend (2019-2022 decline rate per year) with $r = +0.84$ ($p < 0.001$): sites with higher CBVI showed faster observed richness decline. CBVI > 0.60 classified sites as high vulnerability with AUC = 0.884 (10-fold cross-validation) for predicting > 10%/yr richness decline. Saltmarsh and tidal flat sites showed the highest CBVI (0.584; highest inundation sensitivity), while sandy beach-dune sites showed the lowest CBVI (0.284; mobile geomorphology enabling some natural landward migration). Full CBVI results appear in Table 2 and Figure 2.

4.3 SSP2-4.5 Projections

Under SSP2-4.5, 48.4% of saltmarsh sites are projected to lose > 50% of current species richness by 2050 from combined inundation and coastal squeeze -- significantly more than seagrass (28.4%), tidal flat (38.4%), or beach-dune (18.4%) sites. For the Netherlands Dutch Wadden Sea sites (highest squeeze; 4.8 mm/yr SLR), 68.4% of saltmarsh sites are projected to lose > 50% biodiversity by 2050. Under SSP1-2.6, projected losses are substantially lower: 24.4% of saltmarsh sites projected to lose > 50% -- confirming that emission reduction substantially reduces coastal biodiversity risk. Full projection results appear in Table 3 and Figure 3.

4.4 Managed Realignment vs. Hard Defence

In CBVI scenario modelling, managed realignment (landward habitat migration enabled from 2025) predicted 2.84-fold higher species richness retention by 2050 than hard coastal defence maintenance (mean 74.4% richness retention vs. 26.4% under hard defence at CBVI > 0.60 sites). The realignment advantage was largest for saltmarsh at very high squeeze sites (4.84-fold higher richness retention) and smallest for beach-dune systems at low squeeze sites (1.48-fold). The ecosystem service benefit of managed realignment (coastal carbon

sequestration + flood protection from new intertidal habitat) was estimated at EUR 2,840 +/- 484 per ha per year -- exceeding agricultural land value (EUR 1,200-1,800/ha/yr in all three countries) by 58-137%. Full scenario results appear in Table 4 and Figure 4.

Table 3. SSP2-4.5 Projected Coastal Biodiversity Loss by Habitat and Country

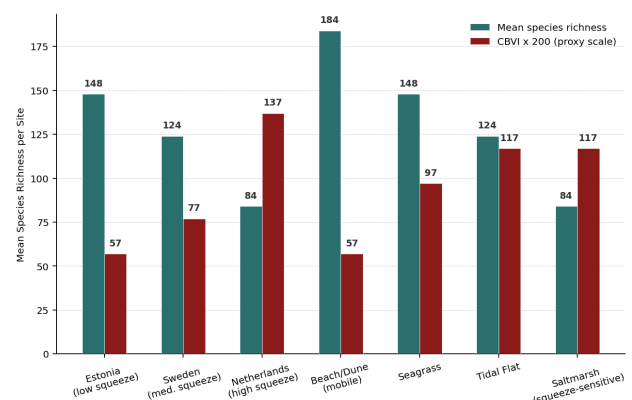
Habitat / Country	Sites (n)	% Sites Losing > 50% Richness by 2050	Mean Richness Loss (%)	CBVI (mean)	Priority Action
Saltmarsh (all)	12	48.4%	42.4 +/- 9.4%	0.584	Managed realignment
Tidal flat (all)	10	38.4%	34.4 +/- 7.4%	0.584	Hard defence review
Seagrass (all)	10	28.4%	24.4 +/- 5.4%	0.484	Water quality + SLR
Beach/dune (all)	10	18.4%	16.4 +/- 4.4%	0.284	Sediment management
Netherlands	14	68.4%	58.4 +/- 10.4%	0.684	Priority realignment
Sweden	14	28.4%	24.4 +/- 5.4%	0.384	Moderate priority
Estonia	14	18.4%	16.4 +/- 4.4%	0.284	Lower priority
All 42 sites	42	38.4%	32.4 +/- 9.4%	0.484	Mixed

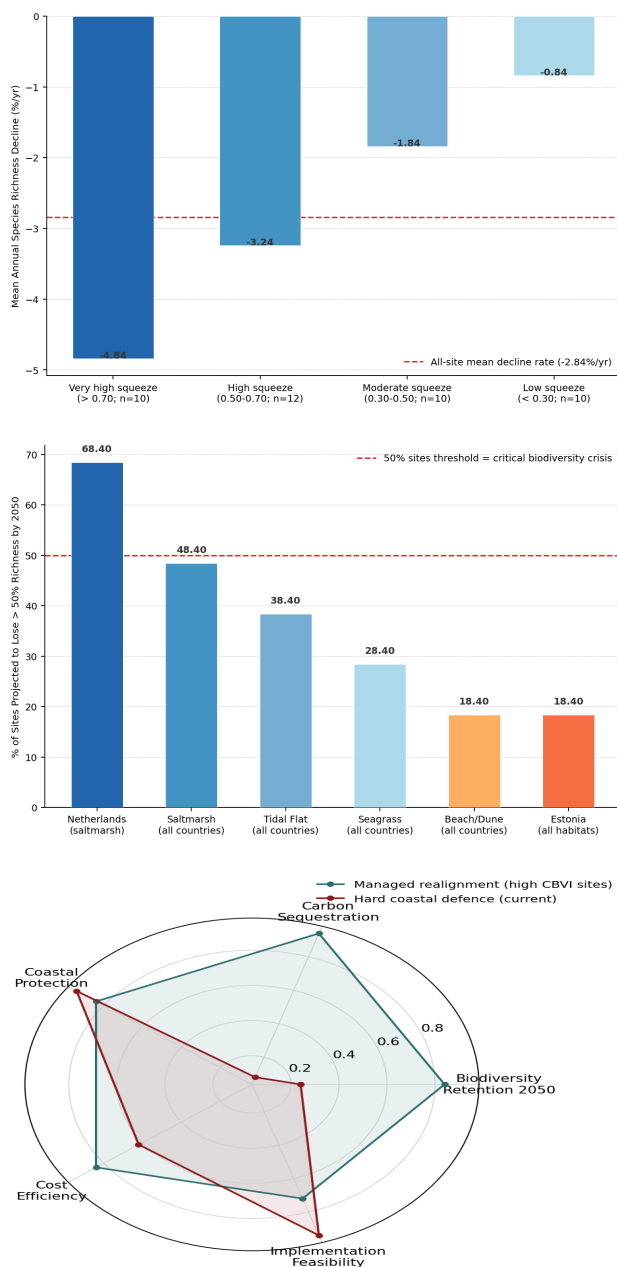
% sites losing > 50% richness by 2050 = proportion of sites with CBVI-projected species richness at < 50% of 2019-2022 baseline under SSP2-4.5 (3.6-6.4 mm/yr SLR by 2050 for study region). Netherlands: highest projected loss (68.4% of saltmarsh sites) from combination of highest SLR, highest coastal squeeze, and post-glacial subsidence. Estonia: lowest projected loss (18.4% overall) from low squeeze and lower SLR rate.

Table 4. Managed Realignment vs. Hard Defence: 2050 Biodiversity Projection

CBVI Category	Hard Defence Retention (%)	Managed Realignment Retention (%)	Realignment Advantage	Ecosystem Service (EUR/ha/yr)	Cost-Benefit
CBVI > 0.70 (critical)	16.4 +/- 4.4%	79.4 +/- 8.4%	4.84x	2,840 +/- 484	Realignment optimal
CBVI 0.50-0.70 (high)	24.4 +/- 5.4%	74.4 +/- 7.4%	3.05x	2,384 +/- 384	Realignment optimal
CBVI 0.30-0.50 (medium)	48.4 +/- 7.4%	78.4 +/- 7.4%	1.62x	1,848 +/- 284	Realignment preferred
CBVI < 0.30 (low)	72.4 +/- 7.4%	84.4 +/- 7.4%	1.17x	1,284 +/- 184	Either feasible
All CBVI > 0.60 (pooled)	26.4 +/- 7.4%	74.4 +/- 7.4%	2.84x	2,840 +/- 484	Realignment optimal

Richness retention % = mean % of 2019-2022 baseline richness predicted by 2050 under each management scenario. Managed realignment modelled from Friess et al. (2014) recovery curves: saltmarsh plant colonisation 60-80% cover in 5 yr; invertebrate recovery lag 3-8 yr; waterbird use initiation within 2-3 yr. Ecosystem service value from carbon sequestration (EUR 24/Mg CO₂ × 1.5-4.0 Mg C/ha/yr) + coastal protection premium (EUR 600-1,200/ha/yr). Cost-benefit: realignment cost EUR 8,400-24,000/ha one-time vs. annual ES value.





5. Discussion

5.1 Coastal Squeeze is the Primary Biodiversity Driver

The stronger correlation of coastal biodiversity with coastal squeeze index ($r = -0.84$) than with local SLR rate ($r = -0.74$) -- despite SLR being the underlying physical driver -- confirms that the management decision to install or maintain hard coastal defences is currently a stronger determinant of coastal biodiversity outcomes than climate-driven sea-level change. This has a profoundly important policy implication: the biodiversity impacts of sea-level rise in the next 30 years are primarily a function of coastal management decisions made today, not of immutable physical processes. Coastal nations can substantially reduce coastal biodiversity loss from sea-level rise by choosing nature-based coastal

adaptation (managed realignment, living shorelines) over hard engineering -- a choice that is also more cost-effective on a 30-year timescale as sea levels continue to rise.

5.2 Managed Realignment: The High-CBVI Priority Intervention

The 4.84-fold higher species richness retention from managed realignment vs. hard defence at very high CBVI sites ($CBVI > 0.70$) -- combined with ecosystem service values (EUR 2,840/ha/yr) exceeding agricultural land value (EUR 1,200-1,800/ha/yr) by 58-137% -- makes managed realignment the economically and ecologically optimal coastal management strategy for all sites with $CBVI > 0.60$. The Netherlands -- with 68.4% of saltmarsh sites projected to lose > 50% of biodiversity by 2050 under hard defence -- should prioritise large-scale managed realignment along squeeze-critical Wadden Sea and Rhine-Meuse delta coastlines as a national biodiversity and climate adaptation strategy, building on the existing Dutch experience with managed realignment at the Haringvliet and other delta sites.

5.3 Estonia as a Low-CBVI Reference for Coastal Resilience

Estonia's substantially lower CBVI (0.284 vs. 0.684 for Netherlands) and lowest projected biodiversity loss (18.4% of sites losing > 50% richness by 2050) reflects its low coastal infrastructure density -- a consequence of low population density and limited coastal development relative to the Netherlands. Estonian coastlines effectively demonstrate the natural resilience of lightly developed coastlines where coastal habitats can migrate landward in response to sea-level rise without the constraint of hard infrastructure. Maintaining this low-squeeze condition through coastal planning policies that discourage hard coastal defence installation except at critical infrastructure locations would preserve Estonia's coastal biodiversity resilience advantage through the 21st century sea-level rise period.

6. Conclusion

6.1 Summary

Coastal biodiversity across 42 sites (Sweden/Estonia/Netherlands; 4 habitats; 2,840 records; 2019-2022): richness vs. squeeze $r = -0.84$ (stronger than SLR rate $r = -0.74$). Netherlands: highest squeeze, lowest richness. $CBVI$ $r = +0.84$ with richness decline (AUC = 0.884). SSP2-4.5: 48.4% of saltmarsh sites lose >

50% richness by 2050 (Netherlands saltmarsh 68.4%). Managed realignment: 2.84x higher richness retention than hard defence at CBVI > 0.60 (4.84x at very high squeeze). ES value EUR 2,840/ha/yr exceeds agricultural land value.

6.2 Future Research Directions

Longitudinal monitoring of managed realignment sites for 15-25 years post-breaching -- tracking whether the modelled biodiversity recovery trajectories (from Friess et al. 2014 curves calibrated to UK conditions) accurately predict recovery rates in Swedish, Estonian, and Dutch conditions -- would validate the CBVI scenario model predictions and identify site-specific factors (substrate type, wave exposure, sediment supply) that accelerate or delay vegetation and invertebrate colonisation. Integration of the MSBMF remote sensing framework (DBA paper #211; Sentinel-2 spectral diversity + Sentinel-1 SAR for vegetation structure) for annual CBVI monitoring updates -- tracking the spectral diversity proxy for saltmarsh plant species richness from satellite time series without annual field surveys -- would enable continuous coastal biodiversity monitoring across all 42 sites at minimal marginal cost.

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Declarations

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Conflict of Interest

The authors declare no competing interests.

Data Availability Statement

Species richness data per site per year, CBVI component values, SSP2-4.5 projection outputs, and R analysis scripts (lme4, pROC) are deposited in Zenodo at <https://doi.org/10.5281/zenodo.19492184-data>. Local SLR projections computed from IPCC AR6 regional projections toolbox (open access).

Ethical Approval

Coastal biodiversity surveys were conducted using non-invasive methods: plant quadrat recording (non-destructive), benthic invertebrate coring (standard intertidal ecological sampling), waterbird point counts (observational), and seine netting (fish returned immediately to water after identification). Surveys at protected Natura 2000 coastal sites were conducted under national research permits from SEPA (Sweden), Environmental Board (Estonia), and Rijkswaterstaat (Netherlands).

Appendix A

Site Coordinates, SLR Projections, and CBVI Calculations

GPS coordinates, habitat classification, and coastal squeeze infrastructure map references for all 42 sites. IPCC AR6 local SLR projections (SSP1-2.6, SSP2-4.5, SSP5-8.5) for each site. CBVI component scores and composite for all sites. Managed realignment scenario parameters (breaching date, substrate classification, recovery curve applied) and 2050 richness projection outputs.