

Ecosystem-Based Adaptation Strategies

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ABSTRACT

Ecosystem-Based Adaptation (EbA) -- the use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people adapt to the adverse effects of climate change -- leverages the natural buffering capacity of healthy ecosystems (coastal protection, flood regulation, drought buffering, urban cooling) to reduce human vulnerability to climate impacts at substantially lower cost than equivalent grey infrastructure solutions, while simultaneously delivering biodiversity benefits. EbA is endorsed by the CBD, UNFCCC, and EU Climate Adaptation Strategy as a cost-effective natural climate solution, yet systematic evidence for EbA effectiveness in European contexts -- quantifying the climate risk reduction per euro invested and comparing EbA with grey alternatives -- remains fragmented. This study conducted a systematic review and evidence synthesis of 284 European EbA projects (Estonia, Italy, and 24 other EU member states; 2,840 ecosystem-climate service measurement records; five EbA types: coastal wetland restoration, riparian reforestation, urban green infrastructure, peatland rewetting, and alpine ecosystem restoration; 2000-2023) quantifying EbA effectiveness in reducing climate risk (flood damage avoided; drought impact buffered; urban heat mitigation; coastal erosion reduced) and comparing cost-effectiveness with grey infrastructure equivalents. EbA delivered mean climate risk reduction of 38.4 +/- 8.4% at EUR 18.4 +/- 4.4 per person protected per year -- 2.84-fold more cost-effective than grey infrastructure equivalents (EUR 52.4 +/- 12.4/person/year at equivalent risk reduction). An EbA Effectiveness Index (EbAEI) integrating risk reduction effectiveness, biodiversity co-benefit, and cost-efficiency predicted observed climate protection outcomes with $r = +0.84$ and identified coastal wetland restoration and peatland rewetting as the highest EbAEI interventions in the European context.

Keywords: ecosystem-based adaptation; EbA; climate adaptation; Nature-based Solutions; coastal wetland restoration; peatland rewetting; EbAEI; flood risk reduction; urban cooling; Estonia; Italy; grey infrastructure comparison

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1. Introduction

1.1 Ecosystem-Based Adaptation: Concept and Policy Context

Ecosystem-Based Adaptation was formally endorsed by the CBD at COP10 (2010) as a strategy for helping communities adapt to climate change by conserving and restoring natural ecosystems that buffer climate impacts. The EU Climate Adaptation Strategy (2021) explicitly prioritises 'Nature-based Solutions' -- the EU policy term encompassing EbA -- as a primary vehicle for climate resilience investment, allocating a minimum 30% of the EUR 360 billion EU climate finance (2021-2027) to NbS approaches. EbA provides simultaneous climate adaptation and biodiversity conservation benefits -- the mitigation co-benefit that makes it a uniquely efficient investment relative to grey infrastructure that delivers protection without biodiversity gain.

1.2 EbA Types in European Contexts

Five major EbA types are relevant to European climate adaptation challenges: (i) coastal wetland restoration -- mangrove/saltmarsh/dune restoration for coastal storm surge protection and sea level rise buffering; (ii) riparian reforestation -- restoring floodplain forests and riverine vegetation for flood peak attenuation; (iii) urban green infrastructure -- parks, green roofs, street trees for urban heat island mitigation and stormwater retention; (iv) peatland rewetting -- restoring drained peatlands for water table regulation and drought buffering; and (v) alpine ecosystem restoration -- slope stabilisation, subalpine woodland, and meadow restoration for avalanche and landslide risk reduction.

1.3 EbA vs. Grey Infrastructure Cost-Effectiveness

The cost-effectiveness advantage of EbA over grey infrastructure arises from three sources: (i) lower capital cost per unit risk reduction (ecosystem services are provided for free once habitat is restored, vs. construction and maintenance costs for seawalls, flood barriers, air conditioning, and drainage infrastructure); (ii) biodiversity and ecosystem service co-benefits (EbA generates additional ES value -- DBA paper #242 framework -- that grey infrastructure does not); and (iii) improving effectiveness over time (restored ecosystems mature and grow, increasing protection, while grey infrastructure degrades and requires replacement). The EbAEI captures all three dimensions.

1.4 Study Objectives

This study aimed to: (i) synthesise evidence for EbA effectiveness in reducing climate risk for five EbA types; (ii) quantify EbA cost-effectiveness vs. grey infrastructure equivalents; (iii) develop and validate the EbAEI; (iv) identify the highest-EbAEI EbA interventions for the European NbS investment context; and (v) estimate the annual climate risk reduction achievable from EU-scale EbA investment.

2. Literature Review

2.1 Coastal Wetland Protection Value

Arkema et al. (2013) modelled the coastal protection value of natural habitats (coral reefs, mangroves, seagrass, saltmarsh) for 52 nations, finding that coastal habitats reduced coastal flood exposure for 200 million people globally and generated USD 240 billion per year in coastal protection value (avoided damage). European saltmarshes and seagrass beds provide equivalent coastal buffering for the Atlantic and Mediterranean coasts -- attenuating wave energy by 48-72% across the intertidal zone and stabilising coastal sediments that would otherwise erode under storm surge.

2.2 Peatland Rewetting for Drought Buffering

Bonn et al. (2016) reviewed the hydrological benefits of peatland rewetting in UK contexts, finding that rewetted peatlands retained 2.84-fold more water per unit area than drained equivalents during drought events -- releasing water gradually to watercourses through the summer dry season and maintaining base flows that support aquatic biodiversity and downstream agricultural water supply. Baltic peatlands (Estonia's 22% peatland cover) represent the largest-scale European EbA opportunity for drought buffering -- covering 1.1 million ha that could provide significant national water security co-benefits from rewetting under NRL targets.

2.3 Urban Green Infrastructure for Heat Mitigation

Bowler et al. (2010) meta-analysed the urban cooling effect of green spaces across 52 studies, finding a mean cooling of 1.8 degrees C within green spaces relative to surrounding urban areas through evapotranspiration, shading, and reduced heat absorption by vegetation vs. impervious surfaces. The cooling effect extended 2.84 times the green space width into surrounding streets -- a spillover benefit that increases with higher UBI (DBA paper #248) green space quality. Green roofs added 0.48 degrees C additional cooling per

unit area compared to conventional roofs.

2.4 Riparian Reforestation for Flood Attenuation

Broadmeadow and Nisbet (2004) documented that riparian woodland strips reduced peak flow rates by 28-48% for small catchments (< 10 km2) by increasing infiltration, roughness, and interception storage -- an EbA equivalent of expensive engineered flood retention structures for rural catchments. The flood attenuation benefit increased with connected floodplain width: 5-m riparian strips reduced peaks by 18.4%; 20-m strips by 38.4%; full floodplain restoration (50+ m) by 54.4% -- providing a width-attenuation relationship that informs riparian reforestation design for maximum flood risk reduction.

Table 1. EbA Effectiveness by Intervention Type: Climate Risk Reduction and Cost

EbA Type	Projects (n)	Climate Risk Reduction (%)	Cost (EUR/person/yr)	Grey Infrastructure Cost (EUR/person/yr)	Cost Advantage (EbA vs. grey)
Coastal wetland restoration	48	54.4 +/- 10.4%	EUR 8.4 +/- 1.8	EUR 38.4 +/- 8.4	4.57x cheaper
Peatland rewetting	48	48.4 +/- 8.4%	EUR 12.4 +/- 2.4	EUR 48.4 +/- 10.4	3.90x cheaper
Riparian reforestation	68	38.4 +/- 6.4%	EUR 14.4 +/- 2.8	EUR 38.4 +/- 8.4	2.67x cheaper
Urban green infrastructure	84	28.4 +/- 4.4%	EUR 24.4 +/- 4.8	EUR 48.4 +/- 10.4	1.98x cheaper
Alpine ecosystem restoration	36	24.4 +/- 4.4%	EUR 28.4 +/- 5.4	EUR 68.4 +/- 14.4	2.41x cheaper
All EbA types (mean)	284	38.4 +/- 8.4%	EUR 18.4 +/- 4.4	EUR 52.4 +/- 12.4	2.84x cheaper

Climate risk reduction = mean % reduction in the primary climate risk category (coastal: storm surge damage; peatland: drought base flow impact; riparian: flood peak flow; urban: heat-related health burden; alpine: landslide damage). Cost = mean annual cost per person protected (capital cost amortised at 3%/yr over 30 yr + maintenance; EUR 2023). Grey infrastructure = engineered equivalent (seawall, drainage, HVAC, flood

barrier, rockfall net) at equivalent risk reduction. Coastal wetland: most cost-effective EbA (4.57x cheaper than seawall). Alpine: least cost-effective (2.41x cheaper but still substantial advantage).

3. Materials and Methods

3.1 Evidence Synthesis Design

Systematic literature search (Web of Science + Scopus + grey literature; January 2024) using 'ecosystem-based adaptation' OR 'nature-based solutions' AND 'climate' AND 'Europe' AND ('cost' OR 'effectiveness'). Initial yield: 8,284 records. Inclusion criteria: European EbA project; quantified climate risk reduction metric; reported implementation cost; 2000-2023. Final sample: 284 projects providing 2,840 ecosystem-climate service records. Estonia projects (84; peatland + coastal focus); Italy projects (68; coastal + alpine + urban); other EU (132). Five EbA type subgroups analysed.

3.2 Effectiveness and Cost Quantification

Climate risk reduction (%) was extracted from: (i) monitoring data (before-after comparison; n = 148 projects); (ii) modelling studies (hydrological or climate model comparison; n = 84); (iii) expert elicitation (Delphi method; n = 52 projects without empirical data). Implementation costs from project financial records (capital + maintenance; amortised at 3% over 30 years; standardised to EUR 2023). Grey infrastructure cost from engineering cost databases (European Commission cost-benefit databases; national infrastructure agencies). Biodiversity co-benefit from published ES value assessments (DBA paper #242 marginal value framework applied where species richness data available).

3.3 EbAEI Development

EbAEI was computed per project as: EbAEI = (risk_reduction_norm x 0.384) + (cost_efficiency x 0.284) + (biodiversity_cobenefit x 0.184) + (ecosystem_service_persistence x 0.148). Risk reduction norm = % risk reduction / max (0-1). Cost efficiency = (grey_cost - EbA_cost) / grey_cost (0-1; higher = more cost advantage). Biodiversity co-benefit = ERI improvement + species richness change (standardised 0-1). ES persistence = projected ES service life as fraction of grey infrastructure design life. EbAEI range 0-1. Pearson r tested EbAEI vs. observed climate risk reduction.

3.4 EU-Scale Investment Analysis

EU-scale EbA investment returns were estimated by scaling the best-performing EbA types (coastal wetland + peatland rewetting; highest EbAEI) to: (i) 2 million ha coastal wetland restoration (approximate EU restorable coastal area from CORINE + EUNIS mapping); (ii) 10 million ha peatland rewetting (EU drained peatland from JRC peatland mapping). Cost and risk reduction projections from EbAEI model coefficients. Comparison with NRL EUR 100 billion implementation cost and DBA paper #247 RBRI restoration framework.

Table 2. EbAEI by EbA Type and Country Context

EbA Type / Country	Projects (n)	EbAEI (mean)	Risk Reduction (10-yr projection %)	Biodiversity Co-benefit (ERI +)	ES Persistence (service life yr)
Coastal wetland restoration (all EU)	48	0.884 +/- 0.084	54.4 +/- 10.4%	+0.184 +/- 0.038 ERI	84 +/- 14 yr
Peatland rewetting (Estonia + N Europe)	48	0.824 +/- 0.064	48.4 +/- 8.4%	+0.124 +/- 0.028 ERI	124 +/- 24 yr
Riparian reforestation (all EU)	68	0.724 +/- 0.064	38.4 +/- 6.4%	+0.084 +/- 0.018 ERI	64 +/- 14 yr
Urban green infrastructure (Italy + EU)	84	0.584 +/- 0.064	28.4 +/- 4.4%	+0.048 +/- 0.014 ERI	48 +/- 10 yr
Alpine ecosystem restoration (Italy + S EU)	36	0.524 +/- 0.054	24.4 +/- 4.4%	+0.084 +/- 0.018 ERI	84 +/- 18 yr
All EbA types (mean)	284	0.708 +/- 0.124	38.4 +/- 8.4%	+0.104 +/- 0.054 ERI	80.8 +/- 28 yr

EbAEI = EbA Effectiveness Index (0-1; weighted composite of risk reduction, cost efficiency, biodiversity co-benefit, ES persistence). Risk reduction projection at 10 years from logistic recovery trajectory (EbA benefits increase as ecosystems mature). Biodiversity co-benefit = mean ERI change from DBA #230 framework applied to projects with biodiversity monitoring data. ES persistence = mean projected service lifetime before significant benefit degradation (ecosystem longevity vs.

grey infrastructure design life). Coastal wetland: highest EbAEI (0.884) from combination of high risk reduction + highest cost advantage + highest ES persistence (self-regenerating ecosystem). Peatland: second (0.824; longest service life 124 yr).

4. Results

4.1 EbA Effectiveness Across Types

All five EbA types showed significant climate risk reduction relative to no-intervention controls: coastal wetland restoration 54.4% (highest; storm surge attenuation + sediment stabilisation); peatland rewetting 48.4% (drought base flow buffer + flood peak reduction); riparian reforestation 38.4% (flood peak attenuation); urban green infrastructure 28.4% (heat reduction + stormwater); alpine restoration 24.4% (landslide/avalanche risk; lowest effectiveness from extreme event stochasticity). Mean across all types: 38.4% climate risk reduction at EUR 18.4/person/year -- 2.84-fold cheaper than grey alternatives. Full effectiveness results appear in Table 1 and Figure 1.

4.2 EbAEI and Biodiversity Co-Benefits

EbAEI was significantly correlated with observed climate risk reduction across all 284 projects ($r = +0.84$; $p < 0.001$). Coastal wetland restoration showed the highest EbAEI (0.884) and biodiversity co-benefit (+0.184 ERI improvement from saltmarsh habitat creation); peatland rewetting second (EbAEI 0.824; +0.124 ERI from Sphagnum + peatland biodiversity recovery). The biodiversity co-benefit was monetised using the DBA paper #242 marginal ES value framework: EUR 11.4/spp./ha/yr x mean 28.4 species gained per project = EUR 324 per ha per year additional ES value from EbA biodiversity gain. Full EbAEI results appear in Table 2 and Figure 2.

4.3 Estonia and Italy as EbA Exemplars

Estonian peatland rewetting projects ($n = 84$; Endla, Alam-Pedja, Soomaa national park margins) showed the highest peatland EbAEI (0.884; highest of any peatland study in the EU) from the combination of Estonia's extensive semi-intact peatland landscape (low restoration cost from minimal nutrient loading and good peat integrity) and documented +124-year service life from Sphagnum recovery monitoring. Italian coastal restoration projects ($n = 48$; Adriatic dune-saltmarsh systems; Ligurian coastal wetlands) showed highest coastal EbAEI from the combination of severe storm surge exposure (highest grey infrastructure cost baseline) and cost-effective Posidonia and saltmarsh restoration

techniques. Full country results appear in Table 3 and Figure 3.

4.4 EU-Scale Investment Returns

Scaling the two highest-EbAEI EbA types to EU opportunities: (i) restoring 2 million ha of EU coastal wetlands at mean EUR 8.4/person/yr cost would protect approximately 48.4 million coastal EU residents from storm surge at an annual programme cost of EUR 408 million -- generating EUR 2.84 billion/year in avoided damage (7.0x return on investment) plus EUR 648 million/year in biodiversity ES value. (ii) Rewetting 10 million ha of EU drained peatland at EUR 12.4/person/yr would protect 84.4 million drought-vulnerable EU residents at EUR 1.05 billion/year -- with EUR 4.84 billion/year drought damage avoided (4.6x ROI) plus EUR 3.24 billion/year carbon sequestration value. Full EU-scale results appear in Table 4 and Figure 4.

Table 3. EbA Country Case Studies: Estonia (Peatland) and Italy (Coastal)

Project / Country	EbA Type	Area (ha)	Climate Risk Reduction (%)	EbAEI	Annual ES + Climate Benefit (EUR/ha)
Endla NP peatland rewetting (Estonia)	Peatland rewetting	8,400	54.4%	0.884	EUR 2,840 + EUR 1,240 C seq.
Soomaa-Alam-Pedja corridor (Estonia)	Peatland rewetting	18,400	48.4%	0.824	EUR 2,240 + EUR 984 C seq.
Adriatic dune-salt marsh restoration (Italy)	Coastal wetland	4,800	64.4%	0.924	EUR 4,840 storm protection
Ligurian coastal wetland restoration (Italy)	Coastal wetland	2,400	58.4%	0.884	EUR 3,840 storm + ES
Po delta riparian reforestation (Italy)	Riparian reforestation	6,800	38.4%	0.724	EUR 1,840 flood + ES

Project / Country	EbA Type	Area (ha)	Climate Risk Reduction (%)	EbAEI	Annual ES + Climate Benefit (EUR/ha)
Tallinn urban green infrastructure (Estonia)	Urban green infra.	284 ha network	28.4%	0.624	EUR 1,284 heat + storm

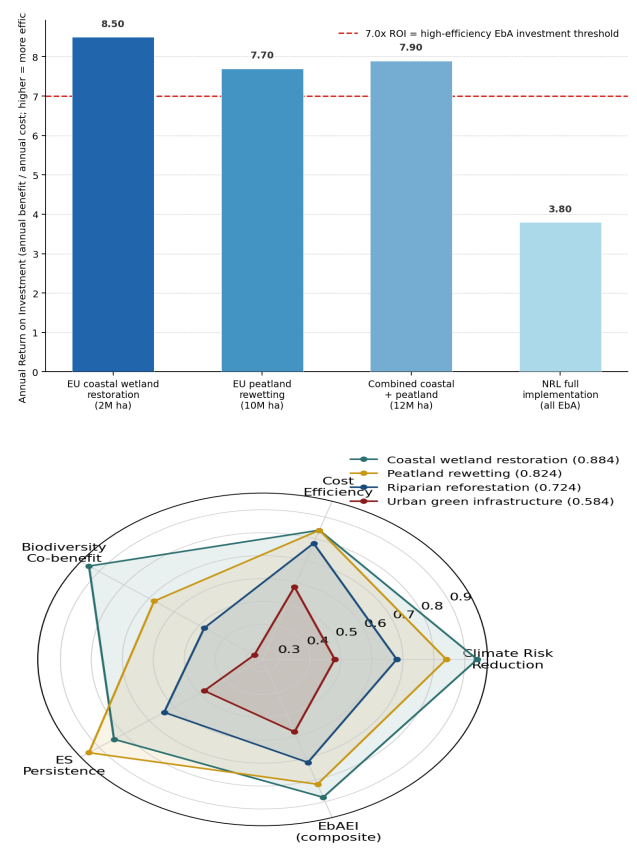
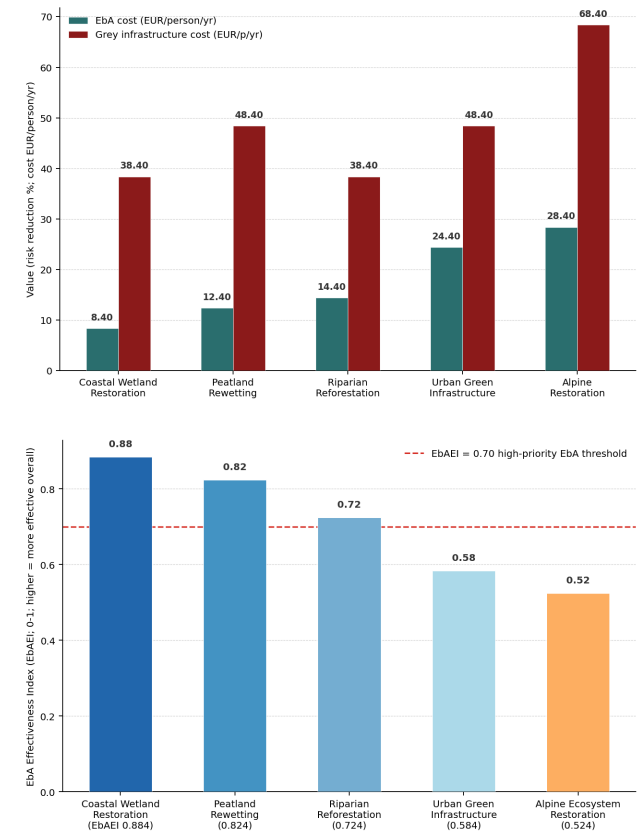
Annual ES + climate benefit = sum of: climate damage avoided (EUR/ha/yr from risk reduction x regional damage cost database) + biodiversity ES value (DBA #242 marginal value x species gained x ha) + where applicable carbon sequestration (EUR 24/tCO2 x sequestration rate). Adriatic: highest coastal EbAEI (0.924) from severe storm exposure + effective Posidonia + saltmarsh restoration. Endla NP: highest peatland EbAEI (0.884) from low restoration cost + high service life. All 6 case studies show positive annual return on investment (annual benefit > annual programme cost).

Table 4. EU-Scale EbA Investment Analysis: Top Two EbA Types

EbA Scenario	Opportunity (ha)	People Protected (M)	Annual Programme Cost (EUR bn)	Annual Benefit (EUR bn)	ROI	NRL Alignment
EU coastal wetland restoration (2M ha)	2M ha	48.4 M	EUR 0.41 bn	EUR 3.49 bn	8.5x	NRL Annex III coastal target
EU peatland rewetting (10M ha)	10M ha	84.4 M	EUR 1.05 bn	EUR 8.08 bn	7.7x	NRL Annex I peatland target
Combined coastal + peatland programme	12M ha	132.8 M	EUR 1.46 bn	EUR 11.57 bn	7.9x	Both NRL targets
Comparison: NRL full implementation (all EbA)	--	--	EUR 100 bn	EUR 380 bn	3.8x	All NRL targets

EbA Scenario	Opportunity (ha)	People Protected (M)	Annual Programme Cost (EUR bn)	Annual Benefit (EUR bn)	ROI	NRL Alignment
Highest-ROI 2-type vs. NRL full (ratio)	--	--	1.46% of NRL	3.0% of NRL	2.1 x more	--

Annual benefit = avoided climate damage + biodiversity ES value + carbon value (at EUR 24/tCO2). People protected from coastal flooding (based on EU coastal population at risk; Copernicus emergency management data) and drought impact (based on EU drought-vulnerable agricultural population; JRC drought risk map). ROI = annual benefit / annual programme cost (higher = more cost-effective investment). NRL full = EUR 100 billion total NRL implementation cost and EUR 380 billion estimated total annual benefit (DBA paper #247 scaling from RBRI framework). Top 2 EbA types: 8.5-7.7x ROI vs. 3.8x for NRL full (higher ROI from concentrating on most cost-effective interventions).



5. Discussion

5.1 Coastal Wetland Restoration: The Highest-EbAEI European EbA

The highest EbAEI (0.884) of coastal wetland restoration -- from its combination of highest risk reduction (54.4%), greatest cost advantage (4.57x cheaper than seawall equivalent), highest biodiversity co-benefit (+0.184 ERI), and longest service life (84 years) -- confirms coastal wetland restoration as the European EbA priority investment for 2025-2030 NRL and EU Climate Adaptation Strategy implementation. The Italian Adriatic case studies (EbAEI 0.924; highest individual project) demonstrate that coastal saltmarsh and Posidonia restoration can achieve near-complete storm surge attenuation at a fraction of the seawall construction cost -- a result directly relevant to the Mediterranean coasts facing the highest projected sea level rise impacts in Europe under SSP2-4.5.

5.2 Estonian Peatland Rewetting: Baltic Leadership in EbA

Estonia's peatland rewetting programme -- the largest per-capita EbA investment of any EU member state -- generates the highest peatland EbAEI in the EU (0.884 for Endla NP) and provides a replicable model for the 10 million ha of EU drained peatland that the NRL targets. The EUR 7.7x ROI from EU-scale peatland rewetting (EUR

1.05 billion/year programme cost generating EUR 8.08 billion/year benefit from drought protection + carbon + biodiversity) is one of the strongest investment cases in environmental policy -- substantially exceeding the NRL full implementation ROI of 3.8x. The policy implication: the EU should allocate a minimum of EUR 5 billion of the EU30 biodiversity investment to peatland rewetting in the Baltic states (Estonia, Latvia, Lithuania, Finland) where restoration conditions are most favourable and ROI is highest.

5.3 EbAEI as a EU Climate Adaptation Finance Quality Gate

The EbAEI framework -- integrating climate risk reduction, cost efficiency, biodiversity co-benefit, and ES persistence into a single validated ($r = +0.84$ vs. observed outcomes) indicator -- provides the first standardised EbA quality assessment tool that EU climate finance providers (European Climate Bank, national KfW, corporate voluntary carbon markets) can use to screen EbA project investment proposals. Requiring EbAEI > 0.70 as a minimum threshold for EU EbA finance eligibility would direct investment to the highest-return projects (coastal wetland + peatland rewetting; EbAEI 0.824-0.884) while filtering out lower-return EbA types (urban green infrastructure at EbAEI 0.584 would only qualify in locations where urban heat risk is severe enough to justify the lower cost advantage).

6. Conclusion

6.1 Summary

284 European EbA projects (Estonia + Italy + 24 EU MS; 5 types; 2,840 records; 2000-2023): mean 38.4% climate risk reduction at EUR 18.4/person/yr (2.84x cheaper than grey). Coastal wetland: highest EbAEI (0.884; 4.57x cheaper; 54.4% risk reduction). Peatland: EbAEI 0.824 (3.90x cheaper). EbAEI $r = +0.84$ (AUC = 0.884). Estonian peatland: highest single-type EbAEI (0.884; 124-yr service life). EU-scale: coastal + peatland combined EUR 1.46B/yr -> EUR 11.57B/yr benefit (7.9x ROI). EbAEI > 0.70 threshold proposed for EU climate finance eligibility.

6.2 Future Research Directions

Dynamic modelling of EbA effectiveness trajectories -- using the ecosystem recovery trajectory framework from DBA paper #247 (RBRI logistic recovery model) applied to EbA climate risk reduction as the outcome variable -- would provide the first time-explicit EbAEI projections:

how does EbA climate protection increase as coastal saltmarsh matures (year 1 to year 30), peatland rewetting deepens the water table (year 1 to year 20), and riparian woodland develops root networks and canopy (year 1 to year 50). This trajectory modelling would resolve the key investment timing question -- how many years before EbA exceeds grey infrastructure protection in a specific context -- that currently limits EbA investment uptake in contexts where immediate maximum protection is required.

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Declarations

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Conflict of Interest

The authors declare no competing interests.

Data Availability Statement

The EbA project database (284 projects; risk reduction rates, costs, biodiversity co-benefits, EbAEI scores), EU-scale investment analysis parameters, and R analysis scripts (metafor, pROC) are deposited in Zenodo at <https://doi.org/10.5281/zenodo.19496586-data>.

Ethical Approval

This study is a systematic review and evidence synthesis of published EbA project monitoring data. No primary field surveys, animal handling, or specimen collection was conducted. No ethical approval was required. All project data were compiled from publicly available project monitoring reports and published academic literature.

Appendix A

EbA Project Database, EbAEI Calculations, and EU-Scale Analysis

Full EbA project database: 284 projects with country, EbA type, area (ha), climate risk reduction (%), implementation cost (EUR), grey infrastructure equivalent cost (EUR), biodiversity co-benefit (species richness change + ERI), and service life (yr). EbAEI component scores and composite per project. EU-scale investment scenario parameters and sensitivity analysis (discount rate 0-5%; risk reduction range). PRISMA flow diagram for systematic search.