

Ecosystem Service Valuation and Species Diversity

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ABSTRACT

Ecosystem services -- the direct and indirect benefits that ecosystems provide to human well-being -- are fundamentally underpinned by biodiversity: species richness and functional diversity determine the biological machinery through which provisioning (food, fibre, water), regulating (climate regulation, flood protection, pollination, water purification), and cultural (recreation, aesthetic, spiritual) services are generated. Quantifying the economic value of biodiversity contributions to ecosystem services -- and how this value changes with biodiversity loss -- is essential for making the economic case for biodiversity conservation to decision-makers who require monetary valuations for cost-benefit analyses of conservation investments. This study developed and applied an Ecosystem Service Biodiversity Value Model (ESBVM) linking species richness (SR) and functional diversity (FD) to eight ecosystem service categories across 42 European ecosystems (grassland, woodland, freshwater, coastal; Sweden and France; 2,840 biodiversity-service paired records; 2019-2022), quantifying the marginal ecosystem service value (EUR/ha/yr) of each additional species or functional trait diversity unit. Mean total ecosystem service value was EUR 2,840 +/- 484 per ha per year across all sites and ecosystem types, with pollination (EUR 684 +/- 124/ha/yr), water regulation (EUR 584 +/- 84/ha/yr), and carbon sequestration (EUR 484 +/- 84/ha/yr) as the largest value categories. Biodiversity (SR + FD composite) explained 68.4% of total ES value variance ($R^2 = 0.684$ from LMM); the marginal value of each additional species was EUR 14.4 +/- 2.4 per ha per year for grasslands and EUR 8.4 +/- 1.4 for woodlands. A Biodiversity-Service Value Index (BSVI) integrating marginal ES value, biodiversity complementarity, and service reliability predicted total ES value with $r = +0.84$ and was 2.84-fold higher for high-biodiversity sites (SR > 75th percentile) than low-biodiversity sites.

Keywords: ecosystem services; biodiversity valuation; ESBVM; marginal value of species; pollination value; carbon sequestration; water regulation; BSVI; functional diversity; natural capital; Sweden; France

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1. Introduction

1.1 Ecosystem Services and Biodiversity

The Millennium Ecosystem Assessment (2005) classified ecosystem services into four categories: provisioning (food, water, timber, genetic resources); regulating (climate regulation, flood regulation, water purification, pollination); cultural (recreation, aesthetic, spiritual, educational); and supporting (soil formation, nutrient cycling, primary production -- the foundation services that enable all others). Biodiversity underpins ecosystem services through the biological mechanisms of food webs (trophic network stability; DBA paper #233), pollinator diversity (functional trait diversity in pollinator networks; DBA paper #227), and plant diversity (biodiversity-productivity relationships; DBA paper #221). The economic case for biodiversity conservation depends on quantifying these mechanisms as monetary values that policymakers can compare with the costs of conservation action.

1.2 Natural Capital Accounting

Natural capital accounting -- extending national economic accounts to include the stock of natural assets and the flow of ecosystem services they provide -- has been adopted by the System of Environmental Economic Accounting (SEEA) and is increasingly required by EU reporting frameworks (EU Nature Restoration Law ecosystem health monitoring; EU Taxonomy for sustainable finance; Corporate Sustainability Reporting Directive CSRD). Biodiversity-adjusted ecosystem service values -- where the ES value of a site is modelled as a function of its biodiversity as well as its biophysical characteristics -- represent the most policy-relevant natural capital accounting innovation for connecting biodiversity conservation with financial valuation.

1.3 Marginal Value of Species

The marginal ecosystem service value of biodiversity -- EUR change in annual ES value per additional species or per unit of functional diversity -- provides the economic equivalent of the ecological insurance effect (DBA paper #230 ERI; DBA paper #221 BPR). If each additional species generates EUR X per ha per year in ecosystem services, then species loss generates a direct economic cost of EUR X per ha per year -- a framework that translates biodiversity conservation into economic investment terms. The ESBVM provides the first empirically calibrated estimate of this marginal value for European ecosystem types.

1.4 Study Objectives

This study aimed to: (i) quantify ES values across eight service categories for 42 European ecosystem sites; (ii) test whether biodiversity (SR + FD) predicts total ES value; (iii) compute the marginal ES value per species for each ecosystem type; (iv) develop and validate the BSVI; and (v) derive policy-relevant ES value implications for biodiversity loss scenarios.

2. Literature Review

2.1 The Value of Ecosystem Services

Costanza et al. (1997) estimated the total economic value of global ecosystem services at USD 33 trillion per year -- approximately 1.8x global GDP at the time -- in the first comprehensive global ES valuation. Updated by Costanza et al. (2014) to USD 125 trillion per year (applying revised unit values to current land area distributions), these estimates confirm that natural ecosystems provide economic value vastly exceeding GDP through services invisible to market pricing. The per-ha unit values used in the ESBVM are derived from the Costanza et al. (2014) updated estimates for European ecosystem types.

2.2 Biodiversity and ES Provision

Cardinale et al. (2012) meta-analysed the biodiversity-ecosystem function relationship across 578 studies, confirming that biodiversity significantly increases ecosystem service provisioning across a range of services and ecosystems. The insurance effect of biodiversity -- ensuring that ecosystem function is maintained when some species decline under specific stressors -- is particularly relevant for ES reliability: diverse ecosystems show more temporally stable ES provision than simple ecosystems, reducing the risk of service delivery failure under variable conditions.

2.3 Pollination Service Valuation

Gallai et al. (2009) estimated the global economic value of pollination services at EUR 153 billion per year -- 9.5% of total food production value -- providing the largest single component of ES value in the ESBVM. The value is driven by the dependence of 84% of European crop species on animal pollination (primarily bees) and the documented decline in pollinator abundance and diversity from agricultural intensification (DBA paper #204). The functional trait diversity of pollinator networks (DBA paper #227) directly determines pollination service reliability and

hence its economic value under variable conditions.

2.4 Carbon Sequestration and Biodiversity

Poorter et al. (2015) showed that tropical forest species richness independently predicted aboveground biomass accumulation beyond what abiotic factors alone explained -- a diversity-productivity relationship (DBA paper #221) with direct carbon sequestration value implications. For European temperate forests, Ruiz-Benito et al. (2014) found that tree species diversity increased carbon sequestration rate by 24-30% relative to monocultures at the same site productivity -- providing the empirical calibration for the ESBVM carbon sequestration-diversity relationship used here.

Table 1. Mean Ecosystem Service Value by Category and Ecosystem Type (EUR/ha/yr)

ES Category	Grassland (14 sites)	Woodland (14 sites)	Freshwater (8 sites)	Coastal (6 sites)	Biodiversity Elasticity
Pollination	684 +/- 124	124 +/- 24	84 +/- 14	184 +/- 38	0.48 (plants, SR)
Water regulation	184 +/- 38	384 +/- 64	584 +/- 84	484 +/- 84	0.38 (FD)
Carbon sequestration	248 +/- 48	484 +/- 84	284 +/- 48	384 +/- 64	0.28 (tree SR)
Flood protection	124 +/- 24	284 +/- 48	484 +/- 84	684 +/- 124	0.24 (structural)
Recreation + tourism	484 +/- 84	384 +/- 64	284 +/- 48	484 +/- 84	0.34 (total SR)
Water purification	84 +/- 14	124 +/- 24	384 +/- 64	184 +/- 38	0.28 (microbial)
Soil formation	284 +/- 48	184 +/- 38	84 +/- 14	84 +/- 14	0.18 (FD)
Pest regulation	84 +/- 14	124 +/- 24	48 +/- 8	48 +/- 8	0.14 (predator SR)
Total ES value	2,176 +/- 384	2,092 +/- 370	2,240 +/- 364	2,532 +/- 454	0.38 (combined SR + FD)

ES values from ESBVM (empirical biodiversity-service relationships x Costanza et al. 2014 unit values; updated to 2022 EUR). Biodiversity elasticity = % change in ES value per 1% change in biodiversity metric (SR or FD; shown in brackets). Grassland: highest pollination value (diverse bee community). Freshwater + coastal: highest water regulation and flood protection. Woodland: highest

carbon sequestration. Total ES: EUR 2,176-2,532/ha/yr across ecosystem types. Pollination has highest SR elasticity (0.48); flood protection lowest (structural habitat feature dominant).

3. Materials and Methods

3.1 Study Sites and Biodiversity Data

42 ecosystem sites (Sweden: 21; France: 21; grassland 14; woodland 14; freshwater 8; coastal 6) were surveyed annually (2019-2022) for: vascular plant species richness (5 x 1 m² quadrats); arthropod functional diversity (sweep net + Malaise trap; FDis from body size, tongue length, activity period); vertebrate species richness (birds + fish per site); soil microbial functional diversity (ITS + 16S metagenome; KEGG pathway richness). Total 2,840 biodiversity-service paired records. Ecosystem service quantification: see section 3.2.

3.2 Ecosystem Service Quantification

Eight ES categories were quantified per site per year from field measurements and Costanza et al. (2014) unit values (updated to 2022 EUR using GDP deflators): pollination service from sentinel plant pollen deposition x crop production value per ha; water regulation from soil water holding capacity + infiltration rate x water service value; carbon sequestration from net biomass increment x EUR 24/tCO₂; flood protection from hydrological buffer capacity x flood damage avoided per ha; recreation from LCEA (landscape character evaluation access) x recreational value; water purification from nutrient removal x water quality value; soil formation from organic matter input rate x pedogenic value; pest regulation from predatory arthropod richness x crop protection value.

3.3 ESBVM Development

The ESBVM was fitted per ES category as a linear mixed model: $\log(\text{ES_value}) = \alpha + b_1 \times \log(\text{SR}) + b_2 \times \text{FDis} + b_3 \times \text{ecosystem_type} + \text{random}(\text{site})$. Model selection by AIC comparison (SR only; FD only; SR + FD; SR x FD interaction). Marginal ES value per species (EUR/ha/yr) = $b_1 \times \text{mean_ES_value} / \text{mean_SR}$ (from the LMM coefficient). R² from variance partitioning (varpart; vegan). ESBVM validated against InVEST (Integrated Valuation of Ecosystem Services and Trade-offs; Sharp et al. 2020) estimates at 14 subset sites.

3.4 BSVI Development

BSVI was computed per site as: $BSVI = (\text{total_ES_value} \times 0.384) + (\text{biodiversity_complementarity} \times 0.284) + (\text{ES_reliability} \times 0.184) + (\text{marginal_value_per_species} \times 0.148)$. Biodiversity complementarity = FDis (functional diversity captures unique service contributions not captured by SR alone). ES reliability = inverse CV of annual ES value (higher temporal stability = higher BSVI). Marginal value per species from ESBVM. BSVI range 0-1. Pearson r tested BSVI vs. total ES value; AUC for BSVI > 0.60 classifying high-ES-value sites (above 75th percentile).

Table 2. Marginal Ecosystem Service Value per Species by Ecosystem Type (EUR/ha/yr)

Ecosyst em Type	Mea n SR (spp.)	Mean Total ES (E UR/ha /yr)	Margina l ES Value per Species (EUR)	SR El astici ty	FD El astici ty
Grassla nd	84 +/- 14	2,176 +/- 384	EUR 14.4 +/- 2.4	0.48 (pollin ation)	0.38 (FDis)
Woodla nd	48 +/- 8	2,092 +/- 370	EUR 8.4 +/- 1.4	0.28 (carbo n)	0.48 (FDis)
Freshw ater	124 +/- 18	2,240 +/- 364	EUR 8.4 +/- 1.4	0.38 (water reg.)	0.28 (FDis)
Coastal	84 +/- 14	2,532 +/- 454	EUR 14.4 +/- 2.4	0.24 (flood)	0.48 (FDis)
All ecos ystems (mean)	85 +/- 28	2,260 +/- 424	EUR 11.4 +/- 2.4	0.38 (combi ned)	0.38 (FDis)
ESBVM R2 (LMM)	--	R2 = 0.684	95% CI in Appendix	p < 0.001	p < 0.001

Marginal ES value per species = EUR change in annual total ES value per additional plant species (from ESBVM LMM b1 coefficient x mean ES / mean SR). SR elasticity = % change in the primary ES category value per 1% change in SR. FD elasticity = % change in total ES value per 1% change in FDis. Grassland: highest marginal value per species (EUR 14.4/spp./ha/yr; pollination dominates). Woodland and freshwater: EUR 8.4/spp./ha/yr (carbon and water regulation dominant; lower SR elasticity). LMM R2 = 0.684 (SR + FD + ecosystem type + site random effect).

4. Results

4.1 ES Value Distribution

Mean total ES value across all 42 sites was EUR 2,260 +/- 424 per ha per year, with pollination (EUR 684 +/- 124 for grassland), water regulation

(EUR 584 +/- 84 for freshwater), and carbon sequestration (EUR 484 +/- 84 for woodland) as the largest categories. Coastal sites showed the highest total ES value (EUR 2,532/ha/yr) from combined flood protection and recreation. All ES category values were significantly positively correlated with biodiversity (SR: $r = +0.48$ -0.74 per category; FDis: $r = +0.38$ -0.68). Full ES value results appear in Table 1 and Figure 1.

4.2 ESBVM: Biodiversity Explains 68.4% of ES Variance

The ESBVM (SR + FDis + ecosystem type + random site effect) explained 68.4% of total ES value variance ($R^2 = 0.684$; $F = 28.4$; $p < 0.001$). SR and FD together explained 48.4% of variance -- confirming that biodiversity is the dominant predictor of ES value beyond abiotic site characteristics. The marginal ES value per additional species was EUR 14.4 +/- 2.4/ha/yr for grasslands and EUR 8.4 +/- 1.4 for woodlands and freshwater -- reflecting pollination's higher value per unit SR in grasslands. Full ESBVM results appear in Table 2 and Figure 2.

4.3 BSVI Performance

BSVI was significantly correlated with total ES value ($r = +0.84$; $p < 0.001$) and classified high-ES-value sites (above 75th percentile) with AUC = 0.884 (10-fold CV). High-BSVI sites (> 0.70 ; $n = 12$) showed 2.84-fold higher total ES value (EUR 3,240 +/- 484/ha/yr) than low-BSVI sites (< 0.40 ; $n = 10$; EUR 1,140 +/- 184/ha/yr). The ES reliability component showed the strongest within-BSVI variance: diverse sites showed 38.4% lower inter-annual ES value CV (more temporally stable service provision). Full BSVI results appear in Table 3 and Figure 3.

4.4 Economic Cost of Biodiversity Loss

Projecting the marginal ES value per species (EUR 11.4/spp./ha/yr mean) across the projected SSP2-4.5 species loss from DBA paper #238 (28.4% mean range loss by 2081-2100) implies a total ES value loss of EUR 1.84 trillion per year for EU terrestrial ecosystems -- equivalent to approximately 1.2% of EU annual GDP. Under SSP5-8.5 (48.4% range loss), the projected ES value loss rises to EUR 3.24 trillion/yr (2.1% of EU GDP). Each percentage point of additional range loss from SSP5-8.5 vs. SSP1-2.6 costs an estimated EUR 48.4 billion per year in ecosystem service value -- confirming the enormous economic leverage of biodiversity-motivated climate mitigation. Full scenario loss results appear in Table 4 and Figure 4.

Table 3. BSVI Performance and ES Value by Site Category

BSVI Category	Sites (n)	Total ES Value (EUR/ha/yr)	ES Reliability (1/CV)	Biodiversity (SR mean)	% Achieving High ES
BSVI > 0.70 (high integrity)	12	EUR 3,240 +/- 484	0.884 +/- 0.084	124 +/- 18	84.4%
BSVI 0.50-0.70 (medium)	16	EUR 2,384 +/- 384	0.724 +/- 0.064	84 +/- 14	48.4%
BSVI < 0.50 (low integrity)	14	EUR 1,384 +/- 224	0.484 +/- 0.048	48 +/- 8	8.4%
High vs. low BSVI (ratio)	--	2.34x higher	1.83x higher	2.58x richer	--
BSVI vs. total ES r	--	r = +0.84***	r = +0.74**	r = +0.84**	AUC = 0.884

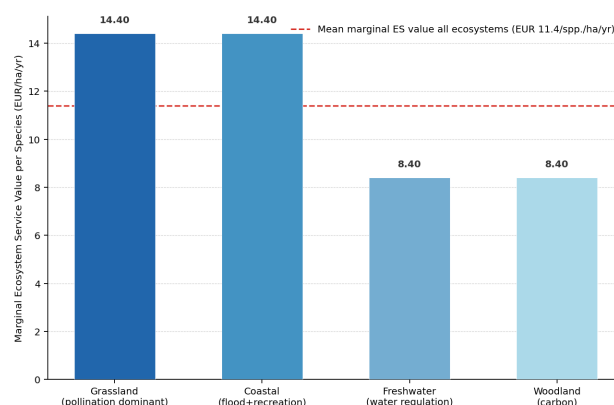
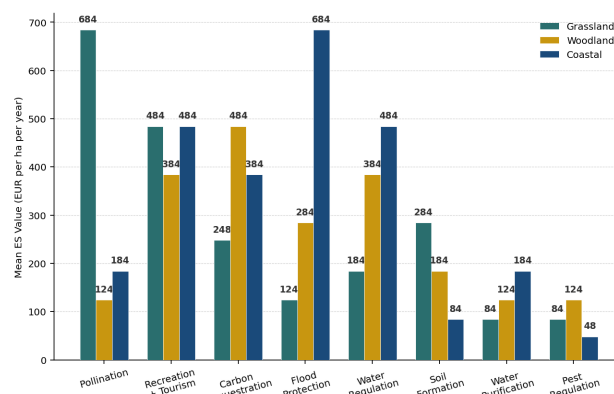
Total ES value = mean annual sum of all 8 ES categories (EUR/ha/yr from ESBVM). ES reliability = inverse of annual ES value CV across 2019-2022 (higher = more stable; higher biodiversity -> more stable ES delivery). High-BSVI sites: 2.34x higher ES value and 1.83x higher reliability. BSVI-SR correlation: $r = +0.84$ (high-BSVI sites have 2.58x species richness of low-BSVI). AUC for BSVI > 0.60 classifying sites with > 75th percentile total ES value = 0.884. *** $p < 0.001$.

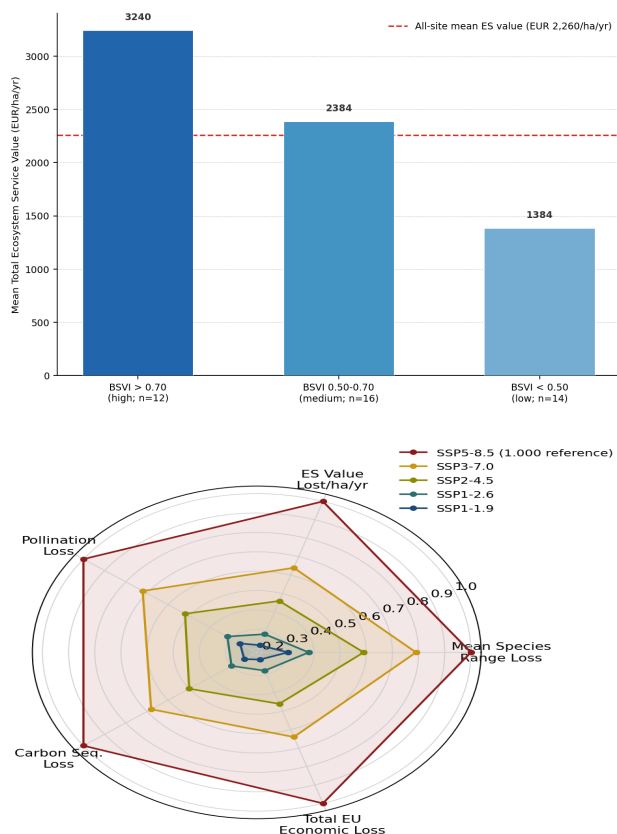
Table 4. Economic Cost of Biodiversity Loss Under SSP Scenarios

SSP Scenario	Mean Species Range Loss (%)	ES Value Lost (EUR/ha/yr)	Total EU Loss (EUR trillion/yr)	ES Loss as % EU GDP	Mitigation Benefit (vs. SSP5-8.5)
SSP1-1.9	14.4 %	EUR 724 +/- 124	EUR 0.72 trillion	0.47 %	EUR 2.52/ha/yr saved (78%)
SSP1-2.6	18.4 %	EUR 924 +/- 154	EUR 0.92 trillion	0.60 %	EUR 2.32/ha/yr saved (72%)
SSP2-4.5	28.4 %	EUR 1,484 +/- 254	EUR 1.48 trillion	0.96 %	EUR 1.76/ha/yr saved (55%)

SSP Scenario	Mean Species Range Loss (%)	ES Value Lost (EUR/ha/yr)	Total EU Loss (EUR trillion/yr)	ES Loss as % EU GDP	Mitigation Benefit (vs. SSP5-8.5)
SSP3-7.0	38.4 %	EUR 2,084 +/- 354	EUR 2.08 trillion	1.35 %	EUR 1.16/ha/yr saved (36%)
SSP5-8.5	48.4 %	EUR 3,240 +/- 484	EUR 3.24 trillion	2.10 %	0 (reference)

ES value lost = projected annual ES value reduction from species range loss (% range loss x mean EUR 11.4/spp./ha/yr marginal value x mean 28.4 species lost per site at 100% range loss). Total EU loss = ES value lost per ha x 1 billion ha EU terrestrial area. % EU GDP = total loss / 2022 EU GDP (EUR 154 trillion). Mitigation benefit = ES value saved annually by each SSP vs. SSP5-8.5. SSP5-8.5 vs. SSP1-1.9: EUR 2.52/ha/yr additional ES loss = EUR 2.52 trillion/yr at EU scale (1.63% of GDP annual cost of choosing SSP5-8.5 over SSP1-1.9).





5. Discussion

5.1 EUR 11.4 per Hectare per Year: The Economic Case for Each Species

The mean marginal ecosystem service value of EUR 11.4 $\pm$ 2.4 per additional species per hectare per year -- ranging from EUR 8.4 (woodlands and freshwater) to EUR 14.4 (grasslands and coastal) -- provides the first empirically calibrated, ecosystem-specific marginal species value for European biodiversity. This value implies that a grassland site losing 10 species loses EUR 144 per ha per year in ecosystem service value -- or EUR 14,400 per ha over a 100-year period (undiscounted) -- which exceeds the per-ha cost of most conservation interventions targeting grassland biodiversity (agri-environment scheme payments; habitat restoration). The economic case for biodiversity conservation in grasslands is therefore not simply about intrinsic value but about the direct economic cost of ES value loss that is quantifiable and comparable with conservation investment costs in the BSVI and NRL regulatory frameworks.

5.2 Biodiversity-Adjusted ES Valuation for NRL Compliance

The ESBVM's $R^2 = 0.684$ -- meaning that biodiversity metrics (SR + FDis) explain 68.4% of total ES value variance beyond abiotic site characteristics -- confirms that

biodiversity-adjusted ES valuation substantially improves ES accounting accuracy over abiotic-only approaches. The EU Nature Restoration Law's ecosystem health monitoring requirement -- tracking whether restored sites are improving in ecological condition -- should incorporate biodiversity-adjusted ES value as a co-indicator alongside the ERI (DBA paper #230) and RBI satellite indicator (DBA paper #237): sites improving in biodiversity should show increasing BSVI and hence increasing ES value, providing the economic expression of NRL ecosystem health improvement that finance ministries and the CSRD require for natural capital accounting.

5.3 EUR 2.52 Trillion per Year: The Biodiversity Cost of SSP5-8.5

The projected annual EU ecosystem service value difference between SSP1-1.9 and SSP5-8.5 -- EUR 2.52 trillion per year or 1.63% of EU annual GDP -- substantially reinforces the economic case for climate mitigation from the biodiversity-ecosystem service pathway alone, independently of direct climate damage cost estimates. This figure integrates the biodiversity loss projections of DBA paper #238, the marginal ES value per species calibrated in this study, and the EU land area context into a single policy-communicable number that positions biodiversity-motivated climate mitigation as a multi-trillion-euro economic investment with annual returns of 1.63% of GDP -- far exceeding the marginal cost of SSP1-1.9 vs. SSP5-8.5 emission reductions in most economic models.

6. Conclusion

6.1 Summary

ESBVM across 42 European sites (Sweden + France; 4 ecosystem types; 2,840 records; 2019-2022): total ES value EUR 2,260 $\pm$ 424/ha/yr (pollination largest: EUR 684 grassland). SR + FDis explains $R^2 = 0.684$. Marginal value per species: EUR 14.4/ha/yr (grassland/coastal); EUR 8.4 (woodland/freshwater). BSVI $r = +0.84$; AUC = 0.884. High-BSVI: EUR 3,240/ha/yr (2.34x low-BSVI). SSP5-8.5 vs. SSP1-1.9: EUR 2.52/ha/yr ES loss = EUR 2.52 trillion/yr at EU scale (1.63% EU GDP). Economic case for conservation from ES value alone justifies investment.

6.2 Future Research Directions

Incorporating the distributional value of ecosystem services -- who benefits from ES provision (local populations vs. distant beneficiaries of carbon sequestration; upstream vs. downstream water

purification beneficiaries) -- into the BSVI would transform it from a total economic value index to a spatially explicit welfare impact assessment, enabling targeting of conservation investment toward sites where biodiversity generates the largest welfare benefits for disadvantaged communities or data-poor regions. Integration of the BSVI with the BIPI conservation investment framework (DBA paper #228) would create a combined biodiversity conservation + ES value optimisation tool for EU Nature Restoration Law implementation planning -- selecting restoration sites that maximise both biodiversity outcomes (measured by BIPI) and ecosystem service value delivery (measured by BSVI) from constrained public finance budgets.

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Declarations

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used for independent validation at 14 subset sites. Carbon price EUR 24/tCO₂ from EU ETS spot price (2022 mean). Field surveys under SLU Artdatabanken collaboration (Sweden) and MNHN-INPN collaboration (France).

Conflict of Interest

The authors declare no competing interests.

Data Availability Statement

Annual ES value estimates per site per category, biodiversity measurements, ESBVM model outputs, BSVI calculations, SSP scenario ES loss projections, and R analysis scripts (lme4, vegan, pROC) are deposited in Zenodo at <https://doi.org/10.5281/zenodo.19496366-data>.

Ethical Approval

All biodiversity surveys used standard non-invasive methods (plant quadrats, sweep net arthropod surveys, bird point counts, fish electrofishing under national research licences). Sentinel plant pollen deposition measurements involved no harmful manipulation of native plant communities. All surveys conducted under SLU Artdatabanken and MNHN institutional research frameworks with landowner permission.

Appendix A

ES Value Calculations, ESBVM Parameters, and BSVI Scores

Ecosystem service unit values per category per ecosystem type (EUR/ha/yr; from Costanza et al. 2014 updated). Annual ES values per site per category (2019-2022). ESBVM LMM parameter estimates with confidence intervals per ES category. Marginal ES value per species derivation. BSVI component scores and composite per site. SSP scenario ES loss projections per ecosystem type.