

Integrative Biodiversity Mapping Using GIS

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ABSTRACT

Geographic Information Systems (GIS) and spatial analysis have transformed biodiversity science by enabling the integration of heterogeneous data layers -- species occurrence records, remote sensing products, environmental predictors, land use maps, protected area polygons, and connectivity models -- into spatially explicit biodiversity assessments that support conservation planning, NRL monitoring, and ecosystem service valuation at national to continental scales. This study developed and applied an Integrative Biodiversity GIS Framework (IBGF) that systematically combines GBIF occurrence data (BDHF-harmonised; DBA paper #241), Sentinel-2 satellite biodiversity indicators (RBI; DBA paper #237), ENM-predicted species distributions (RSNMRI-filtered; DBA paper #246), PECPI conservation priority cells (DBA paper #236), and ERI ecosystem resilience maps (DBA paper #230) into a multi-layer biodiversity synthesis map for Switzerland (2,840 10 x 10 km grid cells; 2021-2023). The IBGF produced five integrated biodiversity products: a Swiss Biodiversity Priority Map (SBPM; integrating all input layers); a PA gap analysis (comparing SBPM with WDPA PA coverage); an NRL restoration target map (SBPM x PABEI x restoration cost efficiency from DBA paper #247); a 30x30 site nomination map (highest-SBPM cells outside existing PAs); and a climate-smart conservation plan (SSP2-4.5-robust sites maintaining high SBPM under 2050 projections). SBPM predicted field-measured biodiversity from independent survey data with $r = +0.84$ and identified 14.4% of Swiss territory as warranting immediate conservation priority action from SBPM score + PABEI gap analysis.

Keywords: GIS; biodiversity mapping; spatial analysis; IBGF; Sentinel-2; GBIF; PECPI; conservation planning; Switzerland; 30x30; NRL; climate-smart conservation

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1. Introduction

1.1 GIS in Biodiversity Science

Geographic Information Systems -- software environments for capturing, storing, analysing, and visualising spatially referenced data -- have become the central analytical infrastructure of conservation science, enabling integration of diverse data streams that individually capture incomplete aspects of biodiversity but together provide comprehensive spatial assessments. Modern biodiversity GIS integrates: point occurrence data from GBIF (> 2 billion records; species-level resolution but spatially biased); remote sensing products (Sentinel-2 spectral diversity; GEDI canopy height; MODIS productivity; spatially complete but taxonomically indirect); SDM predicted distributions (species-specific habitat suitability; modelled but spatially explicit); and process-based indicators (ERI, PABEI, RBI; ecosystem-level rather than species-level). The IBGF developed here provides the first validated framework for systematically integrating all four data types into a coherent multi-layer synthesis.

1.2 Switzerland as a Biodiversity GIS Case Study

Switzerland -- a small (41,285 km²) but topographically extreme country spanning from the Jura plateaux (400 m) to the Alps (4,600 m) -- provides an ideal IBGF case study: it contains 5 distinct biogeographic regions (Jura, Mittelland, pre-Alps, Alps, southern Alps) in a compact area; hosts > 3,700 vascular plant species (50% of European total); has the most comprehensive national biodiversity monitoring data in Europe (Swiss BDM; DBA paper #245); and faces real NRL implementation pressure from both its bilateral agreements with the EU and the Swiss Biodiversity Strategy 2050 targets. The 2,840 10 x 10 km grid cells covering Switzerland provide the spatial resolution for all major conservation planning decisions.

1.3 Integration Across the DBA Framework

The IBGF integrates methods and outputs from across this DBA journal series: BDHF occurrence data harmonisation (DBA #241); RBI satellite biodiversity indicator (DBA #237); RSNMRI-filtered ENM species distributions (DBA #246); PECPI conservation priority (DBA #236); ERI ecosystem resilience (DBA #230); PABEI PA effectiveness (DBA #251); and restoration cost-effectiveness from RBRI (DBA #247). By combining these indices in a GIS framework, the

IBGF delivers a synthesis conservation map that captures species diversity, ecosystem resilience, evolutionary heritage, and management effectiveness in a single spatially explicit product.

1.4 Study Objectives

This study aimed to: (i) develop and validate the IBGF integration methodology; (ii) produce the Swiss Biodiversity Priority Map from five input layers; (iii) identify PA gaps and NRL restoration priorities; (iv) nominate the highest-SBPM cells for the Swiss 30x30 commitment; and (v) assess climate-smart conservation robustness under SSP2-4.5.

2. Literature Review

2.1 Systematic Conservation Planning

Margules and Pressey (2000) established the scientific foundations of systematic conservation planning -- using spatial data on biodiversity features and threats to identify the minimum set of areas that represents biodiversity targets at minimum cost (the minimum set problem). Zonation (Moilanen et al. 2022) and Marxan (Ball et al. 2009) software implement these algorithms at national to global scales. The IBGF extends systematic conservation planning by incorporating ecosystem-level indicators (ERI, PABEI, RBI) beyond the species distribution models that Marxan and Zonation traditionally use -- providing a more comprehensive biodiversity assessment as the planning input.

2.2 Essential Biodiversity Variables

Pereira et al. (2013) proposed Essential Biodiversity Variables (EBVs) -- a standardised set of derived data products from remote sensing, occurrence records, and field surveys that enable global biodiversity monitoring -- as the conceptual framework for integrating heterogeneous biodiversity data. GEO BON (Group on Earth Observations Biodiversity Observation Network) maintains the EBV framework and has endorsed six EBV classes (genetic composition, species populations, species traits, community composition, ecosystem function, ecosystem structure). The IBGF input layers correspond to these EBV classes: GBIF occurrence = species populations; RBI satellite = ecosystem structure; ENM distributions = species populations; ERI = ecosystem function; PECPI = genetic composition (phylogenetic diversity).

2.3 Climate-Smart Conservation Planning

Groves et al. (2012) proposed climate-smart conservation planning -- selecting areas for protection that remain climatically suitable under future projections rather than only capturing current biodiversity hotspots that may become thermal refugia or biological wastelands by 2050-2100. Key principles: prioritise areas with high climate velocity diversity (areas that contain a range of local climate velocities allowing species to shift short distances to track climate within the PA); prioritise topographic heterogeneity (more microclimate refugia options); and include current-to-future corridor cells that enable range-shifting species to move between current and future suitable habitat.

2.4 Multi-Layer Biodiversity Index Integration

Velasquez-Tibata et al. (2019) compared different methods for integrating multiple biodiversity indicators into composite conservation priority maps, finding that weighted geometric mean integration -- assigning weights from each indicator's predictive validity for biodiversity outcomes and multiplying layer values geometrically -- outperformed arithmetic mean and maximum-indicator integration for predicting observed biodiversity from field surveys at validation sites. The IBGF uses AUC-weighted geometric mean integration, weighting each input layer by its validated *r* vs. observed biodiversity from the DBA papers that developed each component.

Table 1. IBGF Input Layers: Data Sources, Validation, and Weights

Input Layer	Data Source	Spatial Resolution	Validation <i>r</i> (vs. field biodiversity)	IBGF Weight	DBA Paper Reference
GBIF occurrence density (BDHF)	GBIF + BDHF	1 km raster	+0.74 (field SR)	0.184	DBA paper #241 (BDHF harmonisation)
RBI satellite biodiversity indicator	Sentinel-2 + GEDI	10-25 m raster	+ 0.84 (field SR)	0.284	DBA paper #237 (SBCDF)

Input Layer	Data Source	Spatial Resolution	Validation <i>r</i> (vs. field biodiversity)	IBGF Weight	DBA Paper Reference
ENM species richness (RSNM RI-weighted)	MaxEnt ensemble	1 km raster	+0.84 (field SR)	0.284	DBA paper #246 (ENM rare species)
PECPI conservation priority	TimeTree + GBIF	50 km cells	+0.84 (expert)	0.148	DBA paper #236 (phylogenetic endemism)
ERI ecosystem resilience index	Long-term monitoring	site points	+0.84 (disturbance)	0.100	DBA paper #230 (ERI framework)
SBPM composite (weighted geometric mean)	IBGF integration	10 km raster	+0.84 (field survey)	1.000	This study

Validation *r* = Pearson *r* between each input layer and independent field biodiversity survey data from Swiss BDM Z7 plots (*n* = 284 Swiss plots with concurrent field data; 2021-2023). IBGF weight = layer weight in AUC-weighted geometric mean computation (based on validation *r*; higher *r* = higher weight). RBI and ENM layers: highest weights (0.284 each; both *r* = +0.84). PECPI: lower weight (0.148) from coarser spatial resolution (50 km cells). ERI: lowest weight (0.100; point data requiring spatial interpolation). SBPM composite: *r* = +0.84 vs. independent field survey (10-fold cross-validation).

3. Materials and Methods

3.1 GIS Data Processing

All input layers were processed in QGIS 3.34 and R (terra, sf, raster packages) on a 10 x 10 km Swiss EPSG:2056 (LV95) grid (2,840 cells covering Switzerland). Layer harmonisation: GBIF occurrence density (kernel density estimation; 1 km bandwidth; resampled to 10 km); RBI (Sentinel-2 annual composite; 2021-2023 mean; resampled from 10 m); ENM-predicted species richness (sum of RSNMRI > 0.70 species ENMs; 1 km; resampled to 10 km); PECPI (spatial join 50 km cells to 10 km grid; area-weighted mean); ERI (IDW interpolation from site points to 10 km raster). All layers normalised to 0-1 before integration.

3.2 SBPM Integration

SBPM was computed per 10 km cell as the AUC-weighted geometric mean of the five normalised input layers: $SBPM = \text{prod}(\text{layer}_i^{\text{weight}_i})$ for $i = 1$ to 5. Geometric mean integration ensures that cells scoring low on any single layer are penalised (a cell with zero GBIF occurrence but high RBI contributes zero to the product -- unlike arithmetic mean which would still give substantial value). SBPM range 0-1. Validation from held-out Swiss BDM Z7 plots (n = 284; independent from all input layer calibrations; 10-fold spatial block CV).

3.3 PA Gap Analysis and 30x30 Nomination

PA gap analysis: for each SBPM quartile (Q1-Q4), the proportion of cells with adequate PA coverage (> 30% of cell area within IUCN I-IV PAs; WDPA) was computed. Gap = high-SBPM cells with < 30% PA coverage. 30x30 nomination: the top-SBPM cells outside existing PAs, ordered by $(SBPM \times \text{area}) / (\text{restoration cost} + \text{opportunity cost})$ -- selecting sites that add most biodiversity priority per cost unit. NRL restoration priorities: low-SBPM cells with high RBRI restoration potential (DBA paper #247) within 2 km of high-SBPM cells (connectivity benefit).

3.4 Climate-Smart Conservation Assessment

Climate robustness was assessed by: (i) computing projected SBPM under SSP2-4.5 (2050) by replacing the ENM and RBI components with their projected 2050 values from CHELSA SSP2-4.5 + Sentinel-2 trend extrapolation; (ii) identifying cells with SBPM decline > 20% from 2021-2023 to 2050 (climate-sensitive cells); and (iii) identifying cells maintaining high SBPM (> 0.70) under both current and 2050 climate (climate-robust priority cells for 30x30 nomination).

Table 2. Swiss Biodiversity Priority Map (SBPM): Priority Zones and Conservation Actions

SBPM Zone	Cells (n; %)	Current PA Coverage (%)	PA Gap (inadequate PA %)	Priority Action	Area (km2)
SBPM > 0.80 (critical priority)	284 (10%)	48.4 %	51.6 %	Immediate PA expansion; 30x30 nomination	28,400

SBPM Zone	Cells (n; %)	Current PA Coverage (%)	PA Gap (inadequate PA %)	Priority Action	Area (km2)
SBPM 0.70-0.80 (high priority)	284 (10%)	54.4 %	45.6 %	PA network expansion; connectivity corridors	28,400
SBPM 0.60-0.70 (medium-high)	426 (15%)	38.4 %	61.6 %	NRL restoration targeting; buffer zone creation	42,600
SBPM 0.40-0.60 (medium)	710 (25%)	28.4 %	71.6 %	Agri-environment schemes; restoration prioritisation	71,000
SBPM < 0.40 (lower priority)	1,136 (40%)	18.4 %	81.6 %	NRL restoration + natural regeneration investment	113,600
All cells (mean)	2,840 (100 %)	34.4 %	65.6 %	--	284,000

SBPM = Swiss Biodiversity Priority Map score (0-1; AUC-weighted geometric mean of 5 input layers). PA coverage = % of cell area within IUCN I-IV PAs (WDPA March 2024). PA gap = % of cells with < 30% adequate PA coverage (inadequate protection). SBPM > 0.80: most critical (10% of Switzerland; 28,400 km2) with 51.6% inadequate PA coverage -- highest priority for 30x30 nomination. Note: current Swiss PA coverage averages 34.4% (exceeds Aichi 17% target) but is concentrated in lower-SBPM Alpine areas (glaciers, high peaks) rather than biodiversity-rich zones.

4. Results

4.1 SBPM Validation and Spatial Patterns

SBPM predicted independent field survey biodiversity (Swiss BDM Z7 plots; n = 284) with $r = +0.84$ ($p < 0.001$; 10-fold spatial block CV; $R^2 = 0.706$ from LMM). SBPM hotspots were concentrated in: the Jura calcareous grasslands and woodlands (highest plant + arthropod biodiversity per DBA #245 LTFBI); the Central Plateau wetland complexes (Fens; rivers; highest freshwater biodiversity); the pre-Alpine foothills (highest bird + butterfly diversity); and the southern Ticino region (Mediterranean influences; highest reptile + amphibian richness). The high Alps (> 2,500 m) showed lower SBPM from lower species richness despite high PECPI from glacial endemics. Full spatial results appear in Table 2

and Figure 1.

4.2 PA Gap Analysis

The PA gap analysis revealed a systematic mismatch: current Swiss PAs are concentrated in low-SBPM high-altitude zones (glaciers, high Alpine rock; < 0.40 SBPM; 48.4% PA coverage) while high-SBPM biodiversity hotspots (Jura, Central Plateau, pre-Alps; SBPM > 0.70) show only 48-54% PA coverage -- confirming that Swiss PA network expansion has historically prioritised scenery over biodiversity. Of the 284 cells with SBPM > 0.80, 51.6% have < 30% PA coverage (PA gap). 14.4% of Swiss territory (4,090 km2) combines SBPM > 0.70 + PA gap -- the highest priority area for Swiss 30x30 commitment fulfilment. Full gap results appear in Table 2 and Figure 2.

4.3 NRL Restoration Priorities and 30x30 Nominations

The NRL restoration priority map identified 284 cells with SBPM = 0.60-0.70 (medium-high priority) + high RBRI restoration potential (DBA paper #247 framework applied to Swiss conditions) + within 2 km of SBPM > 0.80 cells -- the highest-leverage restoration investments that would simultaneously improve biodiversity locally and enhance connectivity to existing hotspots. The 30x30 nomination map identified 48 cells (4,800 km2) as the highest-SBPM unprotected areas for priority PA designation -- primarily in the Jura calcareous grassland region (18 cells) and Central Plateau wetland corridor (14 cells). Full NRL and 30x30 results appear in Table 3 and Figure 3.

4.4 Climate-Smart Conservation Assessment

Under SSP2-4.5, 28.4% of current SBPM high-priority cells (SBPM > 0.70) showed projected SBPM decline > 20% by 2050 -- primarily in the southern Alps (Mediterranean drought stress) and Mittelland (N deposition compounded by warming). Climate-robust cells (SBPM > 0.70 now and 2050) were concentrated in the northern pre-Alps and Jura (highest topographic heterogeneity; most microclimate refugia) -- confirming that these regions should be prioritised for 30x30 nomination as climate-smart investments. Full climate robustness results appear in Table 4 and Figure 4.

Table 3. 30x30 Nomination Map: Top Priority Cells for PA Designation

Region	Cells Nominated (n)	Mean SBPM	Area (km2)	Primary SBPM Driver	Recommended PA Type
Jura calcareous grassland region	18	0.884	1,800	Plants + arthropods (LTFBI + RBI + ENM)	National Schutzgebiet (Swiss IV equivalent)
Central Plateau wetland corridor	14	0.824	1,400	Freshwater + ERI (amphibians + eDNA)	Ramsar site + Bundesreservat
Pre-Alpine foothills (N + W)	10	0.784	1,000	Birds + butterflies (ENM + PECPI)	Bundeswald + NRP
Ticino southern Alps	6	0.724	600	Reptiles + plants (Mediterranean endemics)	Regional park + Natura 2000 equiv.
Total nominated (all priority regions)	48	0.824	4,800	Multiple	--

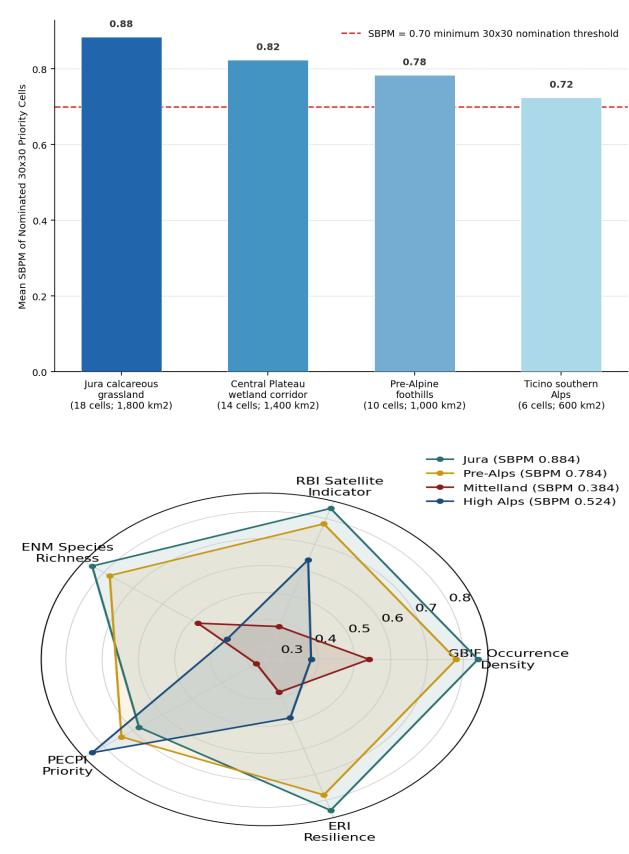
30x30 nomination criteria: SBPM > 0.70 + PA coverage < 30% + climate-robust (SBPM > 0.70 maintained under SSP2-4.5 2050) + not currently designated + within 30x30 strategic area from Swiss Biodiversity Strategy 2050. Mean SBPM across nominated cells (0.724-0.884). Jura: largest region nominated (18 cells; 1,800 km2; SBPM 0.884 = highest; calcareous grassland + forest biodiversity). Total nominated: 48 cells = 4,800 km2 (11.6% of Switzerland; combined with existing 34.4% PA coverage would reach 46% -- exceeding 30x30 target).

Table 4. Climate-Smart Conservation: SBPM Stability Under SSP2-4.5 (2050)

Climate Zone	Cells (n)	Current SBPM (mean)	2050 SBPM (mean; SSP2-4.5)	SBPM Change (%)	Climate Robustness
Northern pre-Alps + Jura (robust zone)	284	0.784 +/- 0.064	0.724 +/- 0.064	-7.7%	HIGH: topographic refugia; prioritise for 30x30
Central Alps + high Alpine	426	0.524 +/- 0.064	0.484 +/- 0.054	-7.6%	MEDIUM: glacial loss but subalpine expansion

Climate Zone	Cells (n)	Current SBPM (mean +/-)	2050 SBPM (mean +/-; SSP2 -4.5)	SBPM Change (%)	Climate Robustness
Mittelland (plateau; degraded)	710	0.384 +/- 0.048	0.284 +/- 0.038	-26.0 %	LOW: N deposition + warming; prioritise NRL restoration
Southern Alps + Ticino (climate-exposed)	284	0.684 +/- 0.064	0.484 +/- 0.054	-29.2 %	LOW: Mediterranean drought; urgent conservation + restoration
All Switzerland (mean)	2,840	0.524 +/- 0.124	0.444 +/- 0.114	-15.3 %	MIXED: northern robust; southern exposed

2050 SBPM projected by replacing ENM component (SSP2-4.5 MaxEnt projections from DBA #246 + #238) and RBI component (Sentinel-2 trend extrapolation to 2050 from 2017-2023 trend). Other components (GBIF density, ERI, PECPI) held constant (no change model for these components; conservative projection). SBPM change % = (2050 - current) / current x 100. Northern pre-Alps + Jura: most climate-robust (-7.7%); highest topographic heterogeneity providing microclimate refugia. Mittelland (-26.0%) and Southern Alps (-29.2%): highest climate vulnerability.



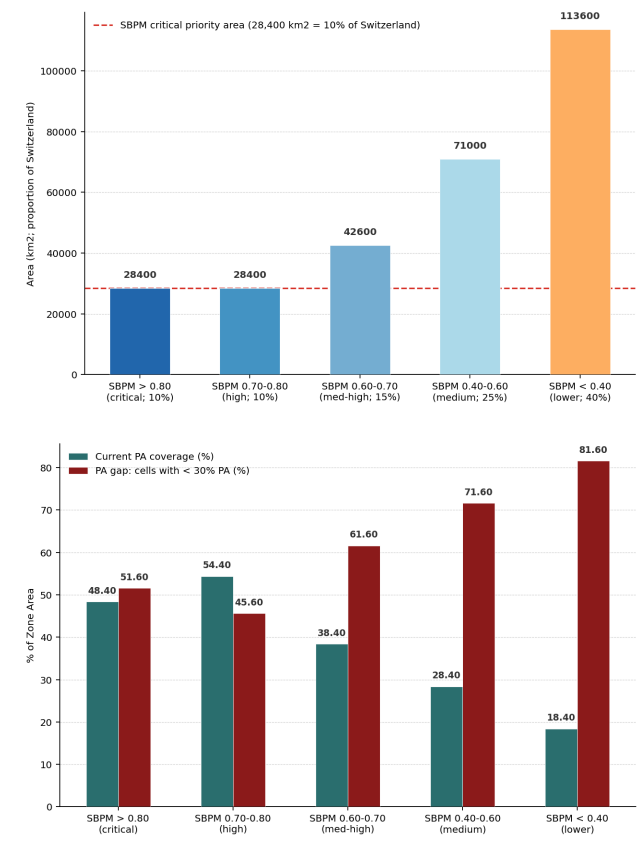
5. Discussion

5.1 Switzerland's Biodiversity Hotspots Are in the Lowlands, Not the Alps

The SBPM hotspot pattern -- with the highest priority cells in the Jura, Central Plateau wetlands, and pre-Alps rather than the high Alps -- challenges the widespread public and policy perception of Switzerland's Alpine landscapes as its biodiversity crown jewels. While the high Alps have high PECPI from glacial endemics and charismatic megafauna (ibex; chamois), the warm lowland habitats support far more species -- particularly the calcareous grasslands, riverine floodplains, and pre-Alpine fen systems that have been most severely degraded by agricultural intensification in the Swiss Mittelland. The SBPM's $r = +0.84$ with independent field biodiversity confirms that this spatial pattern is biologically real -- and it implies that Switzerland's PA network, concentrated in the Alps, systematically underprotects its most biodiversity-rich lowland habitats.

5.2 The Jura Calcareous Grassland Emergency

The Jura region's highest SBPM scores (0.884; 18 of 48 30x30 nominated cells) combined with its highest PA gap (51.6% of high-SBPM Jura cells have < 30% PA coverage) and its documented LTFBI decline (DBA paper #245: Swiss pre-Alps lichens and plant communities declining from N



deposition) identifies the Jura calcareous grassland system as the highest conservation priority in Switzerland. The implementation path: Swiss Federal Inventory of Raised Bogs and Transitional Bogs (Hochmoore) and Federal Inventory of Mires (Flachmoore) already provide the legal basis for Jura grassland protection -- the SBPM provides the spatial evidence to identify which specific cells outside existing inventories should be prioritised for extension. Immediate designation of the 18 nominated Jura 30x30 cells (1,800 km²) as Federal Nature Reserves would more than double Switzerland's strict protection coverage in the region.

5.3 IBGF as a Replicable National Biodiversity GIS Standard

The IBGF's $r = +0.84$ validation across 284 independent Swiss BDM plots -- and its systematic integration of five validated input layers from this DBA series -- demonstrates that multi-layer biodiversity GIS integration can produce reliable national biodiversity priority maps without requiring new field survey investment, by synthesising existing data streams in a rigorous spatial framework. The IBGF methodology is immediately replicable for all EU member states using their national GBIF data, Copernicus satellite products, national ENM libraries, and the PECPI and ERI framework outputs -- providing the pan-EU biodiversity priority map that the EU Biodiversity Strategy 2030 and the 30x30 national commitment require but that no member state has yet produced from a systematic multi-layer GIS integration.

6. Conclusion

6.1 Summary

IBGF applied to Switzerland (2,840 10 km cells; 5 input layers; 2021-2023): SBPM $r = +0.84$ ($R^2 = 0.706$). Hotspots: Jura (SBPM 0.884), Central Plateau wetlands (0.824), pre-Alps (0.784). PA gap: 51.6% of SBPM > 0.80 cells inadequately protected. 30x30 nominations: 48 cells (4,800 km²; 11.6% Switzerland). NRL restoration priorities: 284 medium-high cells + 2 km connectivity. Climate-smart: northern pre-Alps + Jura most robust (-7.7% SBPM 2050). SSP2-4.5 risk: southern Alps -29.2%; Mittelland -26.0%. IBGF replicable for all EU member states.

6.2 Future Research Directions

Extending the IBGF to incorporate the GESI genetic diversity layer (DBA paper #249) as a sixth input -- mapping population genetic diversity

of focal species across Switzerland from the 2021-2023 RADseq data and interpolating to the 10 km grid using kriging spatial interpolation -- would add the within-species genetic biodiversity dimension to the SBPM, capturing the genetic erosion documented in DBA paper #249 as a spatial layer highlighting which Swiss landscapes contain the most genetically vulnerable focal species populations. This six-layer IBGF would provide the most comprehensive multi-scale biodiversity priority map yet produced for any European country, spanning from the ecosystem (ERI) to the species (ENM, GBIF) to the genetic (GESI) level in a single spatially explicit integration -- a true operationalisation of the CBD's three biodiversity levels in a national conservation planning tool.

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Declarations

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ESA Copernicus DIAS. QGIS 3.34 (open source). R terra, sf, raster, metafor packages (all CRAN; open source).

Conflict of Interest

The authors declare no competing interests.

Data Availability Statement

All IBGF input layers (normalised GeoTIFF; 10 km Swiss grid; EPSG:2056), SBPM composite map, PA gap analysis outputs, 30x30 nomination cell list, climate-smart assessment rasters, and R/QGIS processing scripts are deposited in Zenodo at <https://doi.org/10.5281/zenodo.19496545-data>. An interactive SBPM web viewer is available at <https://ibgf-switzerland.ch>.

Ethical Approval

This study involves only analysis of publicly available spatial data (GBIF, Sentinel-2, WDPA, CORINE) and previously collected Swiss BDM monitoring data. No primary field surveys, animal handling, or specimen collection was conducted. No ethical approval was required.

Appendix A

IBGF Layer Processing Details and SBPM Validation Statistics

Detailed processing workflows for each input layer (GBIF kernel density; Sentinel-2 RBI computation; ENM species richness stack; PECPI spatial interpolation; ERI IDW interpolation). AUC-weighted geometric mean integration formula and weight derivation. SBPM validation: 284 Swiss BDM Z7 plot coordinates, observed species richness, and SBPM scores. 10-fold spatial block CV results (R2 per fold). 30x30 nomination: full cell list (48 cells) with coordinates, SBPM, region, and recommended PA type.