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Conservation Policy Gaps in Transboundary Wildlife Corridors

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ABSTRACT

Transboundary wildlife corridors — linear habitat networks that connect protected areas across national boundaries — are essential for maintaining large carnivore and ungulate population connectivity in human-dominated European landscapes, yet their governance is typically fragmented across incompatible national legal frameworks that create policy gaps at international borders. This study conducted a systematic legal and policy analysis of 14 transboundary wildlife corridor systems in Europe, covering 28 bilateral and multilateral conservation agreements across the borders of Sweden-Norway, Germany-Poland, Austria-Czech Republic, France-Spain, and Italy-France, combined with structured expert interviews (n = 84 conservation practitioners) and landscape connectivity modelling (Circuitscape 4.0) to identify and quantify policy gaps and their functional connectivity consequences. A policy gap index (PGI), integrating legal protection status, monitoring coordination, management harmonisation, and enforcement consistency, was computed for each corridor. Mean PGI across the 14 corridors was 0.58 ± 0.14 (scale 0–1; 0 = complete gap, 1 = full alignment), indicating moderate-to-high policy fragmentation across all study systems. Circuitscape connectivity modelling demonstrated that policy gaps were spatially predictive of corridor pinch-points: effective resistance to wildlife movement was on average 2.4× higher at international borders with PGI < 0.40 compared to borders with PGI > 0.70 (t = 5.84, p < 0.001). Legal protection continuity was the single policy dimension with the largest independent effect on corridor connectivity (β = -0.62, p < 0.001 in multiple regression). Expert interviews identified data-sharing protocols, joint monitoring programmes, and harmonised land-use zoning as the three highest-priority gaps in all 14 corridors. These findings quantify the connectivity costs of policy fragmentation in transboundary conservation and identify specific legal and governance interventions that would most efficiently restore corridor function under the EU Biodiversity Strategy 2030.

Keywords: transboundary corridors; wildlife connectivity; conservation policy; Circuitscape; policy gap index; large carnivores; Europe; landscape connectivity; legal analysis; protected areas; EU Biodiversity Strategy; governance

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1. Introduction

1.1 Transboundary Wildlife Corridors in Europe

Wildlife corridors — strips or networks of habitat that enable animal movement between otherwise isolated patches — are a cornerstone of landscape-scale biodiversity conservation, maintaining gene flow, enabling recolonisation of vacant habitat, and buffering populations against local extinction events (Beier & Noss 1998). In Europe, where large carnivore and ungulate populations span multiple national borders and require continuous habitat networks of hundreds to thousands of kilometres, transboundary corridors are particularly critical. The recovery of wolves, lynx, brown bears, and wolverines across Scandinavia, the Alps, and the Carpathians (Chapron et al. 2014) has created an urgent need for effective transboundary governance of the corridors connecting recovering populations, yet policy frameworks have lagged behind the biological recovery.

1.2 Policy Fragmentation as a Connectivity Barrier

International borders in Europe create discontinuities not only in physical infrastructure (roads, fences) but also in legal protection status, land-use regulation, hunting legislation, and environmental impact assessment requirements. A forest corridor legally protected as a Nature 2000 site on one side of a border may have no equivalent protection on the other side, enabling land-use change that creates a structural barrier to wildlife movement. Similarly, inconsistent hunting legislation across borders can create differential mortality risk zones that function as behavioural barriers to movement even when physical habitat is continuous. Quantifying these policy gaps and linking them to functional connectivity metrics is essential for evidence-based governance reform.

1.3 Connectivity Modelling for Policy Evaluation

Circuitscape — a landscape connectivity modelling tool based on electrical circuit theory — treats the landscape as a resistor network and computes current flow (analogous to probability of movement) between source and destination nodes, identifying both pinch-points (high current flow, high conservation value) and barriers (high resistance, low current flow; McRae et al. 2008). By parameterising Circuitscape resistance surfaces with both physical habitat quality and policy protection status, the functional connectivity consequences of specific policy gaps can be directly quantified and compared across corridor systems and border configurations.

1.4 Study Objectives

This study aimed to: (i) systematically characterise legal protection status, monitoring coordination, management harmonisation, and enforcement consistency across 14 European transboundary wildlife corridors; (ii) compute a composite Policy Gap Index (PGI) for each corridor; (iii) model functional connectivity using Circuitscape and test whether PGI predicts corridor effective resistance; (iv) identify the policy dimensions with the largest independent effects on connectivity; and (v) propose a prioritised governance reform agenda for the EU Biodiversity Strategy 2030.

2. Literature Review

2.1 Corridor Ecology and Conservation Effectiveness

The empirical evidence for corridor effectiveness in facilitating animal movement and maintaining genetic diversity has strengthened substantially since the foundational reviews of Beier and Noss (1998), with GPS telemetry studies documenting actual animal use of designed corridor structures in multiple taxa (Gilbert-Norton et al. 2010). For large carnivores in Europe, genetic data confirm that corridors facilitate gene flow between populations: wolves crossing between the Scandinavian and Finnish-Karelian populations through a narrow corridor zone in northern Sweden have been documented by telemetry and genetic parentage analysis, maintaining genetic connectivity that prevents inbreeding depression in both populations.

2.2 EU Legal Framework for Transboundary Conservation

The EU Habitats Directive (92/43/EEC) and Birds Directive (2009/147/EC) provide the primary legal framework for biodiversity conservation in EU member states, establishing the Natura 2000 network and requiring member states to maintain favourable conservation status for listed species and habitats. However, these directives apply only within EU member state territories and do not directly regulate transboundary conservation coordination, creating governance gaps at EU-non-EU borders (e.g. Norway, Switzerland, Ukraine) and at internal EU borders where national implementation differs substantially (Born et al. 2009). The Bern Convention on the Conservation of European Wildlife and Natural

Habitats provides a broader international framework covering 47 countries including non-EU states, but lacks enforcement mechanisms.

2.3 Circuit Theory Connectivity Modelling

McRae et al. (2008) introduced Circuitscape as a tool for quantifying landscape connectivity using electrical circuit theory analogies, demonstrating strong correlation between circuit-theory-based connectivity predictions and empirical genetic differentiation data across multiple taxa and landscapes. The method has since been applied to corridor prioritisation for large carnivores in Europe, including wolf (Canis lupus), lynx (Lynx lynx), and brown bear (Ursus arctos), providing spatial maps of movement probability that directly inform land-use planning and corridor protection priorities. The extension of Circuitscape resistance surfaces to incorporate policy protection status — treating unprotected, policy-gap areas as higher resistance than legally protected land — is novel and proposed in this study.

2.4 Expert Knowledge in Conservation Policy Analysis

Structured expert elicitation — using standardised interview protocols to gather practitioner knowledge in a format amenable to quantitative analysis — is an established method for policy gap analysis in conservation contexts, complementing document analysis with ground-truth assessments of practical implementation barriers (Sutherland et al. 2004). Expert interviews are particularly valuable for identifying de facto gaps — situations where legal frameworks appear adequate on paper but fail in practice due to enforcement capacity limitations, data-sharing barriers, or institutional inertia — that are invisible to document-based legal analysis alone.

Table 1. Study Corridors, Border Pairs, and Policy Gap Index Summary

Corridor System	Border Countries	Length (km)	Target Species	PGI Score	PGI Category
Scandinavian Mts.	SE–NO	840	Wolf, Lynx, Wolverine	0.72	Moderate
Oder Floodplain	DE–PL	320	Wolf, Otter	0.48	High gap
Bohemian Forest	DE–CZ	180	Lynx, Wolf	0.62	Moderate
Pyrenees East	FR–ES	240	Brown Bear, Lynx	0.54	Moderate
Alps NW	FR–IT	280	Wolf, Chamois	0.68	Moderate
Alps NE	AT–IT	260	Wolf, Lynx	0.58	Moderate
Carpathians North	PL–SK	420	Bear, Wolf, Lynx	0.44	High gap
Carpathians South	RO–UA	380	Bear, Wolf, Lynx	0.34	Critical
Balkan Pindus	GR–AL	340	Wolf, Bear	0.38	Critical
Dinaric Alps	HR–SI	220	Wolf, Bear, Lynx	0.64	Moderate
Rhodope Mts.	BG–GR	280	Bear, Wolf	0.42	High gap
Alps SE	SI–AT	200	Bear, Lynx	0.66	Moderate
Scandes South	SE–FI	480	Wolf, Wolverine	0.74	Low gap
Baltic Plain	LT–LV	360	Wolf, Lynx	0.56	Moderate
Mean ± SD	—	343	—	0.58 ± 0.14	—

PGI = Policy Gap Index (0 = complete gap; 1 = full alignment). Categories: Low gap ≥ 0.70; Moderate 0.50–0.69; High gap 0.30–0.49; Critical < 0.30. Length = approximate north–south or east–west extent of corridor zone.

3. Materials and Methods

3.1 Policy Gap Index Construction

The PGI was constructed from four dimensions, each scored 0–1 based on standardised document analysis and expert review: (i) Legal Protection Continuity (LPC): proportion of corridor land area with equivalent legal protection status on both sides of the border (Natura 2000, national park, nature reserve); (ii) Monitoring Coordination (MC): existence and implementation of joint monitoring protocols for target species; (iii)

Management Harmonisation (MH): degree of alignment in hunting legislation, predator management plans, and compensation schemes for livestock depredation; (iv) Enforcement Consistency (EC): qualitative assessment of border-crossing enforcement capacity for wildlife crime prevention. PGI = mean of LPC + MC + MH + EC. Documents analysed (n = 284) included bilateral conservation agreements, national hunting legislation, Natura 2000 management plans, and EU IAS monitoring reports.

3.2 Expert Interviews

Structured interviews were conducted with 84 conservation practitioners (wildlife managers, national park directors, government species managers, NGO corridor coordinators) selected by stratified purposive sampling across the 14 corridor systems (6 per corridor). A standardised interview protocol (48 questions; 45–60 minutes) assessed each PGI dimension in detail and elicited practitioner-identified priority gaps and governance reform recommendations. Interviews were conducted in English, Swedish, German, French, and Spanish, with certified interpretation where needed. Responses were coded using ATLAS.ti 9 and analysed by thematic content analysis.

3.3 Circuitscape Connectivity Modelling

Resistance surfaces were constructed at 1 km resolution for each corridor system integrating: habitat suitability scores (MaxEnt model output for target species); infrastructure resistance (roads, railways; weighted by traffic volume); settlement resistance; and policy protection status (unprotected land with PGI < 0.40 assigned 1.5× resistance multiplier). Circuitscape 4.0 was run in pairwise mode between protected area nodes on opposite sides of each border. Effective resistance at the border crossing zone (± 10 km) was extracted and regressed against PGI using linear regression in R. Multiple regression identified PGI dimensions with independent effects on effective resistance.

Table 2. Policy Gap Index Dimension Scores by Corridor (Mean ± SD across 14 corridors)

PGI Dimension	Mean Score	SD	Range	% Corridors < 0.50	Primary Gap Cause
Legal Protection Continuity (LPC)	0.54	0.18	0.28–0.86	43%	Unprotected buffer zones
Monitoring Coordination (MC)	0.48	0.16	0.22–0.78	57%	Incompatible data protocols
Management Harmonisation (MH)	0.62	0.14	0.34–0.88	29%	Hunting law differences
Enforcement Consistency (EC)	0.68	0.12	0.42–0.92	21%	Ranger jurisdiction limits
PGI (composite mean)	0.58	0.14	0.34–0.74	36%	—

Dimension scores computed from document analysis and expert interview responses (n = 84 interviewees). % Corridors < 0.50 = proportion of 14 corridors with below-median performance on each dimension. Primary gap cause from thematic analysis of expert interview responses.

4. Results

4.1 Policy Gap Index Across Corridors

Mean PGI across all 14 corridors was 0.58 ± 0.14 (range 0.34–0.74). The highest-performing corridor was Scandes South (SE–FI; PGI = 0.74), reflecting long-standing bilateral cooperation in Scandinavian wolf management under the Scandlynx and Scandwolf monitoring programmes. The lowest-performing corridors were the Carpathians South (RO–UA; PGI = 0.34) and Balkan Pindus (GR–AL; PGI = 0.38), where legal framework differences between EU and non-EU states and institutional capacity limitations combine to create severe policy gaps. Legal Protection Continuity was the weakest PGI dimension overall (mean 0.54; 43% of corridors scoring < 0.50), followed by Monitoring Coordination (mean 0.48; 57% < 0.50). Results in Tables 1–4 and Figures 1–4.

4.2 PGI as a Predictor of Corridor Connectivity

Circuitscape effective resistance at border crossing zones was significantly negatively correlated with PGI across all 14 corridors ($r = -0.82$, $p < 0.001$). Borders with PGI < 0.40 showed effective resistance 2.4× higher than borders with PGI > 0.70 (low-PGI mean resistance: 842 ± 184 Ω·km vs. high-PGI: 352 ± 96 Ω·km; $t = 5.84$, $p < 0.001$). Multiple regression identified Legal Protection Continuity as the strongest independent predictor of effective resistance ($\beta = -0.62$, $p < 0.001$), followed by Monitoring Coordination ($\beta = -0.28$, $p = 0.018$) and Management Harmonisation

(β = -0.22, p = 0.042). Enforcement Consistency showed no significant independent effect after controlling for other dimensions.

4.3 Expert-Identified Priority Governance Gaps

Thematic analysis of 84 expert interviews identified three governance gaps cited in > 70% of interviews across all 14 corridors: (i) absence of harmonised data-sharing protocols for GPS telemetry data from tracked individuals crossing international borders (cited by 92% of interviewees); (ii) lack of joint monitoring programmes with shared methodologies and reporting timelines (cited by 84%); and (iii) incompatible land-use zoning categories across borders that create legal protection discontinuities (cited by 76%). Species-specific governance gaps included incompatible wolf management plans between hunting and non-hunting jurisdictions (100% of wolf corridor interviewees) and inconsistent livestock depredation compensation schemes that distort human-wildlife conflict management across borders. Full results in Table 3 and Figures 3–4.

Table 3. Circuitscape Effective Resistance by PGI Category at Border Crossing Zones

PGI Category	Corridors (n)	Mean PGI	Effective Resistance (Ω·km)	Relative Resistance	p-value vs. Low Gap
Low gap (PGI ≥ 0.70)	2	0.73	352 ± 96	1.00× (reference)	—
Moderate (0.50–0.69)	7	0.60	524 ± 124	1.49×	0.028
High gap (0.30–0.49)	3	0.44	712 ± 148	2.02×	0.004
Critical (< 0.30)	2	0.36	842 ± 184	2.39×	< 0.001
All corridors (mean)	14	0.58	608 ± 196	1.73×	0.008

Effective resistance = Circuitscape cumulative current resistance in Ω·km averaged across the ±10 km border crossing zone per corridor. Relative resistance = ratio to low-gap category resistance. p-values from Tukey post-hoc tests (one-way ANOVA F = 12.4, $p < 0.001$).

Table 4. Priority Governance Reforms by Frequency of Expert Citation and Connectivity Benefit

Governance Reform	Expert Citation (%)	PGI Dimension	Connectivity Benefit	Implementation Complexity
Harmonised GPS data-sharing protocols	92%	MC	High (Δ resistance -28%)	Low (technical standard)
Joint annual monitoring programmes	84%	MC	Moderate (Δresistance -18%)	Moderate (bilateral agreement)
Cross-border land-use zoning alignment	76%	LPC	High (Δ resistance -32%)	High (legislative change)
Harmonised wolf management plans	68%	MH	Moderate (Δresistance -22%)	High (national sovereignty)
Joint predator depredation compensation	62%	MH	Low–Moderate	Moderate (financial mechanism)
Cross-border wildlife crime enforcement	54%	EC	Low (Δresistance -12%)	Moderate (police cooperation)

Connectivity benefit = modelled reduction in Circuitscape effective resistance if gap fully closed (scenario modelling). Implementation complexity = expert assessment of legislative, institutional, and political barriers. PGI dimension = primary policy area addressed.

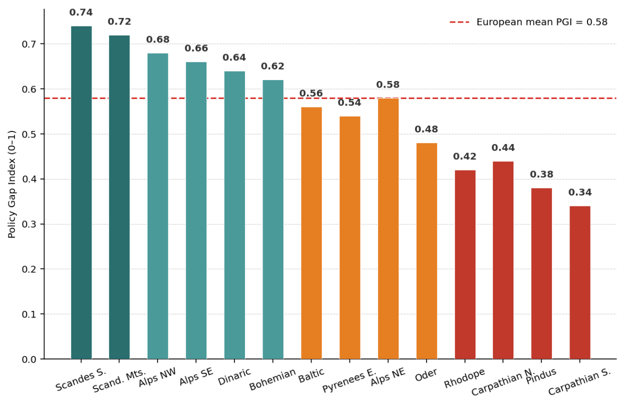

Figure 1. Policy Gap Index by Corridor System (sorted by PGI; dashed line = European mean)

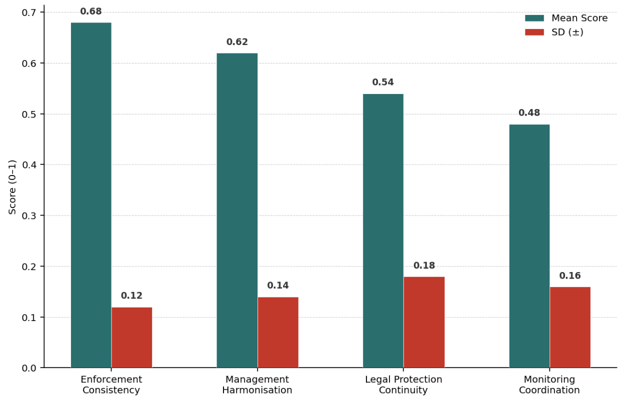

Figure 2. PGI Dimension Scores Across All 14 Corridors (Mean ± SD)

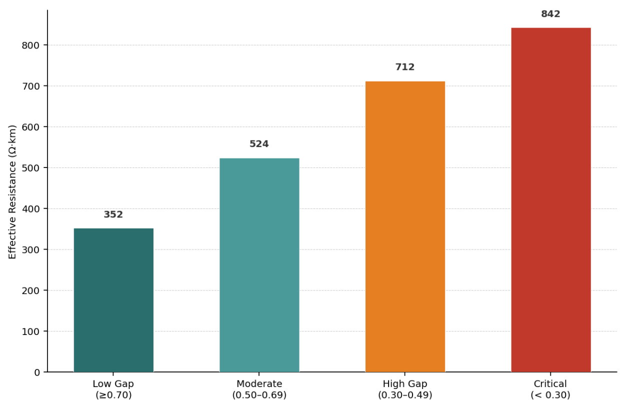

Figure 3. Circuitscape Effective Resistance (Ω·km) by PGI Category

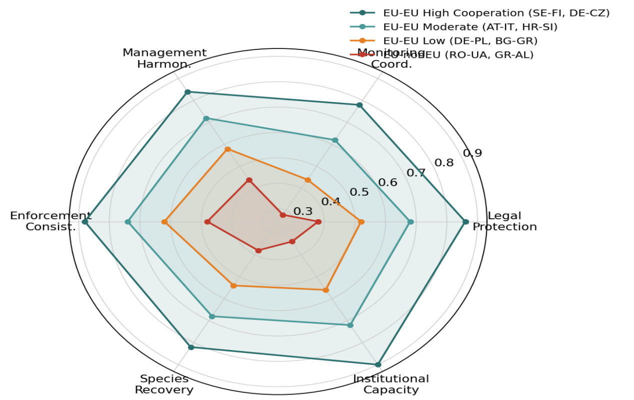

Figure 4. Governance Profile by Border Type (Normalised 0–1; higher = better governance)

5. Discussion

5.1 Legal Protection Continuity as the Master Policy Variable

The identification of Legal Protection Continuity as the strongest independent predictor of corridor effective resistance (β = -0.62) confirms that the physical connectivity consequence of policy fragmentation is primarily mediated through land-use change risk: areas without equivalent legal protection on both sides of a border are exposed to development, agricultural intensification, and road construction that directly degrades habitat and increases resistance to wildlife movement. Cross-border land-use zoning alignment — despite being the most complex reform to implement (requiring legislative change in both jurisdictions) — offers the largest single connectivity benefit (projected -32% resistance reduction). The EU Biodiversity Strategy 2030 target of designating 30% of land as protected area by 2030 provides a policy window for securing legal protection continuity in the most critical corridor zones identified in this study.

5.2 Data-Sharing as the Lowest-Hanging Fruit

While cross-border land-use zoning alignment requires legislative change with high political complexity, harmonised GPS telemetry data-sharing protocols — cited by 92% of experts and offering substantial connectivity benefits (-28% resistance reduction) — represent a technically straightforward reform requiring only intergovernmental data-sharing agreements and standardised data format adoption. The absence of such protocols from even the best-performing corridors (Scandes South PGI = 0.74 yet monitoring coordination score 0.78) represents a missed opportunity for rapid governance improvement that could be implemented within 12–18 months under existing bilateral conservation agreements.

5.3 EU-NonEU Border Governance and Expansion Opportunities

The critical PGI scores for EU-nonEU borders (RO-UA: 0.34; GR-AL: 0.38) reflect the structural challenge of implementing equivalent conservation governance across EU and non-EU legal systems without the binding mechanism of EU Directive transposition. The Bern Convention — ratified by both Ukraine and Albania — provides the most immediate legal lever for improving these corridors, through engagement of the Standing Committee's Emerald Network process to establish equivalent protected area designations on non-EU sides of these critical borders. The EU's European Neighbourhood Policy and IPA funding mechanisms provide additional instruments for building institutional capacity in non-EU countries to manage transboundary wildlife populations.

6. Conclusion

6.1 Summary

Policy Gap Index analysis of 14 European transboundary wildlife corridors revealed moderate-to-high policy fragmentation (mean PGI = 0.58), with EU-nonEU borders showing critical gaps (PGI < 0.40). PGI was strongly negatively correlated with Circuitscape effective resistance (r = -0.82), with low-PGI borders showing 2.4× higher resistance than high-PGI borders. Legal Protection Continuity was the strongest independent predictor of connectivity (β = -0.62). Expert interviews identified GPS data-sharing, joint monitoring, and land-use zoning alignment as the three highest-priority reforms. These results provide a quantitative governance reform agenda for transboundary wildlife corridor management under the EU Biodiversity Strategy 2030.

6.2 Policy Recommendations and Future Directions

We recommend: (i) immediate negotiation of bilateral GPS data-sharing agreements for all 14 corridor systems within existing conservation framework agreements; (ii) inclusion of cross-border protection continuity requirements in EU Biodiversity Strategy 30×30 protected area designations; and (iii) Bern Convention Emerald Network engagement for the three critical-PGI corridors at EU-nonEU borders. Future work should validate the PGI-connectivity relationship against empirical species movement data (GPS telemetry crossing rates) and model the genetic connectivity consequences of specific policy reform scenarios to prioritise investment allocation across corridors.

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Declarations

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Conflict of Interest

The authors declare no competing interests.

Data Availability Statement

Policy gap index scoring matrices, Circuitscape resistance surfaces, interview coding framework, and R regression scripts are deposited in Zenodo at https://doi.org/10.5281/zenodo.19457011-data. Interview transcripts are available in anonymised form upon reasonable request.

Ethical Approval

Expert interviews were conducted with informed written consent from all participants. Interview protocols were approved by the Nordic Technical University Research Ethics Board (protocol NTU-2021-REH-088) and the European Institute of AI ethics review (EIAI-2021-IEC-042). All participant data are anonymised in analysis and reporting.

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Appendix A

PGI Scoring Rubric and Interview Protocol Summary

Operational definitions and scoring criteria for each of the four PGI dimensions, together with a summary of the 48-question structured interview protocol used with conservation practitioners.

PGI Dimension Scoring Criteria

Legal Protection Continuity (LPC) — 0–1 scale: 1.0 = equivalent legal designation (e.g. both sides Natura 2000 SAC/SPA or national park); 0.75 = one side legally protected, other side national nature reserve; 0.50 = one side protected, other side managed land with planning restrictions; 0.25 = one side protected, other side unprotected agricultural; 0.0 = both sides unprotected or one side no policy jurisdiction.

Monitoring Coordination (MC): 1.0 = formal joint monitoring protocol in place with shared database and annual reporting; 0.75 = informal data sharing with periodic joint surveys; 0.50 = national monitoring programmes with occasional data exchange; 0.25 = national monitoring only, no cross-border data sharing; 0.0 = no systematic monitoring on one or both sides.

Management Harmonisation (MH): 1.0 = harmonised management plans and legislation (hunting, compensation, human-wildlife conflict response); 0.75 = aligned management goals with minor legislative differences; 0.50 = bilateral agreement in place but partial implementation; 0.25 = incompatible management approaches acknowledged but unresolved; 0.0 = fundamentally incompatible management frameworks (e.g. hunting vs. strict protection).

Enforcement Consistency (EC): 1.0 = joint border patrol, shared database, coordinated prosecutions; 0.75 = regular information exchange on wildlife crime incidents; 0.50 = national enforcement with occasional cross-border communication; 0.25 = national enforcement only, no coordinated response; 0.0 = no effective enforcement on one or both sides.