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ECOLOGICAL DIGITAL TWINS AND PREDICTIVE ARTIFICIAL INTELLIGENCE AGENTS: DYNAMIC DELIMITATION OF ENVIRONMENTAL PROTECTION ZONES IN AFRICAN TRANSPORT CORRIDORS

GÉMEOS DIGITAIS ECOLÓGICOS E AGENTES PREDITIVOS DE INTELIGÊNCIA ARTIFICIAL: DELIMITAÇÃO DINÂMICA DE ZONAS DE PROTEÇÃO AMBIENTAL NOS CORREDORES DE TRANSPORTE AFRICANOS

GEMELOS DIGITALES ECOLÓGICOS Y AGENTES PREDICTIVOS DE INTELIGENCIA ARTIFICIAL: DELIMITACIÓN DINÁMICA DE ZONAS DE PROTECCIÓN AMBIENTAL EN CORREDORES AFRICANOS DE TRANSPORTE

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ABSTRACT

Environmental protection zones in Africa have historically been delimited as fixed perimeters, while species movements and transport pressures change over time. This article proposes and computationally evaluates the Ecological Digital Twin of Environmental Protection Zones (EDT-EPZ), which integrates transport infrastructure, artificial intelligence, distributed sensing, and dynamic protection polygons. A structured literature review, conceptual modelling, and three agent-based computational experiments were combined in a synthetic scenario parameterized to resemble the Lobito Corridor. The experiments used 1,500 animal agents, 200 replicates, 1,080 daily steps, and a fixed random seed. Mean trajectory coverage was 32.9% under static protection, 86.9% under daily dynamic delimitation, and 89.5% under the adaptive reinforcement-learning condition. The effectiveness index changed from 54 to 43 points in the static regime and from 60 to 77 points in the adaptive regime. With 1 km sensor spacing, modelled detection remained at or above 80% up to 1.57 km from the nearest sensor. Code, synthetic outputs, parameters, and verification hashes accompany the manuscript; two independent executions produced seven byte-identical data files. The findings demonstrate computational reproducibility and internal consistency under the stated assumptions. Empirical validation with field telemetry and sensor observations has not been performed and remains indispensable.

KEYWORDS: *Ecological digital twin. Predictive agents. Dynamic environmental protection zones. African transport corridors. Artificial intelligence. Biodiversity conservation.*

RESUMO

As zonas de proteção ambiental em África têm sido historicamente delimitadas como perímetros fixos, embora os movimentos das espécies e as pressões dos transportes se alterem ao longo do tempo. Este artigo propõe e avalia computacionalmente o Gémeo Digital Ecológico de Zonas de Proteção Ambiental (GDE-ZPA), que integra infraestruturas de transporte, inteligência artificial, sensoriamento distribuído e polígonos dinâmicos de proteção. Combinaram-se revisão estruturada da literatura, modelação conceptual e três experimentos computacionais baseados em agentes num cenário sintético parametrizado à semelhança do Corredor do Lobito. Utilizaram-se 1.500 agentes animais, 200 réplicas, 1.080 passos diários e uma semente aleatória fixa. A cobertura média das trajetórias foi de 32,9% no regime estático, 86,9% na delimitação dinâmica diária e 89,5% no regime adaptativo com aprendizagem por reforço.

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O índice de eficácia passou de 54 para 43 pontos no regime estático e de 60 para 77 no regime adaptativo. Com sensores espaçados de 1 km, a deteção modelada manteve-se igual ou superior a 80% até 1,57 km do sensor mais próximo. O código, os dados sintéticos, os parâmetros e os hashes de verificação acompanham o manuscrito; duas execuções independentes geraram sete ficheiros de dados idênticos byte a byte. Os resultados demonstram reprodutibilidade computacional e consistência interna nos pressupostos declarados. A validação empírica com telemetria e observações de campo não foi realizada e permanece indispensável.

PALAVRAS-CHAVE: Gémeo digital ecológico. Agentes preditivos. Zonas de proteção ambiental dinâmicas. Corredores de transporte africanos. Inteligência artificial. Conservação da biodiversidade.

RESUMEN

Las zonas de protección ambiental en África han sido históricamente delimitadas como perímetros fijos, mientras los movimientos de las especies y las presiones del transporte cambian con el tiempo. Este artículo propone y evalúa computacionalmente el Gemelo Digital Ecológico de Zonas de Protección Ambiental (GDE-ZPA), que integra infraestructuras de transporte, inteligencia artificial, sensorización distribuida y polígonos dinámicos de protección. Se combinaron una revisión estructurada de la literatura, la modelización conceptual y tres experimentos computacionales basados en agentes en un escenario sintético parametrizado a semejanza del Corredor de Lobito. Se utilizaron 1.500 agentes animales, 200 réplicas, 1.080 pasos diarios y una semilla aleatoria fija. La cobertura media de las trayectorias fue del 32,9% con protección estática, del 86,9% con delimitación dinámica diaria y del 89,5% con la condición adaptativa de aprendizaje por refuerzo. El índice de eficacia pasó de 54 a 43 puntos en el régimen estático y de 60 a 77 en el régimen adaptativo. Con sensores separados por 1 km, la detección modelada se mantuvo igual o superior al 80% hasta 1,57 km del sensor más próximo. El código, los datos sintéticos, los parámetros y los hashes de verificación acompañan el manuscrito; dos ejecuciones independientes produjeron siete archivos de datos idénticos byte a byte. Los resultados demuestran reproducibilidad computacional y consistencia interna bajo los supuestos declarados. La validación empírica con telemetría y observaciones de campo no se ha realizado y sigue siendo indispensable.

PALABRAS CLAVE: *Gemelo digital ecológico. Agentes predictivos. Zonas de protección ambiental dinámicas. Corredores de transporte africanos. Inteligencia artificial. Conservación de la biodiversidad.*

1. INTRODUCTION

Africa is undergoing a major expansion of transport infrastructure. The Programme for Infrastructure Development in Africa, promoted by the African Union and AUDA-NEPAD, includes road, rail, and intermodal corridors linking Atlantic and Indian Ocean ports to the continental interior. The Lobito Corridor in Angola connects the Atlantic to mineral-producing regions of the Democratic Republic of the Congo and Zambia through approximately 1,300 km of railway. This expansion is important for economic development and regional integration, but it is also

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associated with habitat fragmentation, wildlife mortality from vehicle collisions, and new frontiers of illegal exploitation in previously remote territories (Laurance *et al.*, 2014, 2015; Benítez-López *et al.*, 2010).

In parallel, Africa's natural heritage is under unprecedented pressure. The global report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) estimates that around one million species face the risk of extinction in the coming decades (IPBES, 2019), and the Kunming-Montreal Global Biodiversity Framework, adopted under the Convention on Biological Diversity (CBD), set the target of effectively protecting 30% of the planet's terrestrial and marine areas by 2030 (Convention on Biological Diversity, 2022), a target all the more demanding given that current extinction rates far exceed background rates and that the effective protection of species remains globally insufficient (Pimm *et al.*, 2014). For Africa, and for Angola in particular, meeting this target requires not only expanding the network of protected areas, but rethinking the very concept of the spatial delimitation of protection.

The research problem is formulated as follows: African environmental protection zones are commonly defined as static perimeters established by legal instruments and one-off surveys, whereas species move according to season, climate, and human pressure. The consequence is a structural desynchronization between the legal geometry of protection and movement ecology (Nathan *et al.*, 2008): zones protect places, while species inhabit trajectories. Climate change may intensify this desynchronization. The African legal instruments examined in the reviewed corpus did not establish mechanisms for automated dynamic delimitation, which motivates the proposed investigation.

The central hypothesis is that the combination of three factors — (i) transport network infrastructure converted into distributed environmental sensing platforms; (ii) artificial intelligence (AI), particularly predictive species distribution models and multi-agent systems; and (iii) digital twin computing — can support daily delimitation of environmental protection zones according to predicted species positions and ecological risk, with measurable gains over the static regime under controlled computational conditions.

General objective: to propose, substantiate, and computationally evaluate the Ecological Digital Twin of Environmental Protection Zones (EDT-EPZ), combining transport infrastructure, AI, and distributed sensing for predictive species identification and dynamic delimitation of EPZs in African transport corridors.

Specific objectives: (i) to systematize the state of the art on ecological fragmentation induced by transport corridors in Africa, predictive species distribution models, digital twins, and dynamic environmental management; (ii) to design the five-layer EDT-EPZ architecture; (iii) to

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develop reproducible agent-based simulations comparing static and dynamic regimes; (iv) to derive a governance framework indicating legal, institutional, and technological requirements; and (v) to delimit the research agenda of corridor computational ecology.

The rationale for the study is threefold. At the scientific level, the literature on digital twins has become consolidated in industry (Tao *et al.*, 2019), and dynamic environmental management has been developed substantially in marine contexts (Maxwell *et al.*, 2015; Hazen *et al.*, 2018). The reviewed corpus did not reveal a proposal integrating these domains with African terrestrial transport corridors as sensing infrastructure and as simultaneous objects of protection and governance. This gap motivates the conceptual, methodological, and computational contribution, without implying proof of universal absence. At the institutional level, the model offers environmental and transport authorities a decision-support instrument aligned with Agenda 2063 (African Union, 2015) and the Sustainable Development Goals (United Nations, 2015). At the societal level, dynamic protection may support human–wildlife conflict reduction, continuous environmental assessment, and traceable spatial planning.

The article is organized into six sections. After this introduction, Section 2 presents the literature review and theoretical framework; Section 3 describes the methodology, computational procedures, and reproducibility test; Section 4 presents the results; Section 5 discusses contributions, implications, and limitations; and Section 6 synthesizes the conclusions and future research agenda.

2. LITERATURE REVIEW AND THEORETICAL FRAMEWORK

2.1. African transport corridors and ecological fragmentation

Linear transport infrastructure — roads, railways, pipelines, and power transmission lines — is recognized as a major vector of terrestrial ecosystem disturbance. The meta-analysis by Benítez-López et al. (2010) demonstrated significant reductions in mammal and bird densities within zones extending several kilometres from infrastructure, a phenomenon described as an extended edge effect or ecological influence zone. Laurance *et al.* (2014) argued that road building in areas of high environmental value should be avoided whenever possible and proposed prior global zoning. Laurance et al. (2015) estimated the environmental costs of African development corridors and reported that substantial portions crossed areas of high conservation value with marginal agricultural benefits.

Southern and central Africa concentrate several of these axes, articulated by the Programme for Infrastructure Development in Africa (AUDA-NEPAD, 2021) and by Southern

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African Development Community corridors. In Angola, the Lobito Corridor crosses ecological gradients from the arid Benguela coastline to the central plateau and eastern miombo zones, in the vicinity of protected areas and large-mammal territories. Remaining populations of forest elephant (*Loxodonta cyclotis*) and African savanna elephant (*Loxodonta africana*) occur in the southeast. The scarcity of Angolan field studies on corridor ecology reinforces the need for predictive models, while also requiring explicit acknowledgement of the uncertainty associated with limited systematic surveys.

The classic institutional response to fragmentation was the creation of fixed-perimeter protected areas and, more recently, connectivity ecological corridors, for which the International Union for Conservation of Nature has published specific guidelines (Hilty *et al.*, 2020). However, both instruments rely on fixed geometries defined *ex ante*, whereas ecological processes vary over time. In Angola, the Basic Environmental Law (Law No. 5/98) and biodiversity management through the National Institute for Biodiversity and Conservation Areas, under the Ministry of the Environment, do not establish mechanisms for automatic dynamic-perimeter review (República de Angola, 1998). The proposed model addresses this institutional gap.

2.2. Artificial intelligence and predictive models of species identification and distribution

Species distribution modelling is a mature domain of computational ecology. Species distribution models relate occurrence records to environmental variables — climate, topography, vegetation cover, and distance to infrastructure — to predict habitat suitability in space and time (Guisan & Thuiller, 2005; Elith & Leathwick, 2009; Franklin, 2010). MaxEnt, based on maximum entropy, is widely used with presence-only data, which are frequent in African inventories (Phillips et al., 2006). Georeferenced occurrences from the Global Biodiversity Information Facility and the Essential Biodiversity Variables framework provide data standards for continental-scale modelling (Pereira *et al.*, 2013).

In automatic species identification, deep learning (DL) has transformed the state of the art: Norouzzadeh *et al.* (2018) demonstrated that convolutional neural networks (CNNs) identify, count and describe wild animals in camera-trap images with accuracy comparable to that of human experts, and Tuia *et al.* (2022) systematized the perspectives of machine learning (ML) for wildlife conservation, highlighting detection in images, acoustic classification and movement prediction. Lamba *et al.* (2019) documented applications of deep learning to environmental conservation ranging from anti-poaching surveillance to habitat mapping from satellite images, often supported by spectral indices such as the Normalized Difference Vegetation Index (NDVI).

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The third technological component is animal movement tracking. Kays *et al.* (2015) described Global Navigation Satellite System telemetry and radio tracking as an “eye on life and planet”, and Nathan *et al.* (2008) formalized the movement ecology paradigm, which treats organism trajectories as fundamental units of analysis. This paradigm grounds the article’s thesis: if the relevant ecological unit is the trajectory, the legal unit of protection should be able to follow that trajectory — a function not performed by static perimeters.

2.3. Multi-agent systems and digital twins

A multi-agent system is composed of autonomous, reactive, proactive, and social software agents that interact in a shared environment to achieve individual and collective goals (Wooldridge, 2009). Within modern artificial intelligence (Russell & Norvig, 2021), predictive agents combine perception, future-state modelling, and action. Reinforcement learning allows decision policies to improve through trial and error in simulated environments before real-world deployment — an important property for conservation, in which real experimentation may be ethically and ecologically restricted.

The digital twin concept originated in industry as a virtual replica of a physical asset synchronized by real-time data (Grieves, 2014) and became consolidated as an Industry 4.0 paradigm (Tao *et al.*, 2019). Its transfer to ecology is recent. Virtual ecosystem replicas fed by remote sensing, geographic information systems, telemetry, and Internet of Things sensors can simulate management scenarios before territorial intervention. The proposed model applies this paradigm to the transport corridor itself — infrastructure traditionally treated as a threat — reconceptualized as a distributed environmental sensing network comprising camera traps, acoustic sensors, weather stations, unmanned aerial vehicles, and traffic data.

2.4. From static to dynamic protection: the gap this article fills

Dynamic environmental management has its most developed expression in the oceanic domain. Maxwell *et al.* (2015) defined dynamic ocean management as management that changes rapidly in space and time in response to environmental and user dynamics. Hazen *et al.* (2018) demonstrated, with the EcoCast tool, that mobile delimitation of fishing areas can reduce protected-species bycatch without compromising economic activity. Within the corpus reviewed for this article, no equivalent proposal was identified for African terrestrial transport corridors integrating digital twins, predictive agents, and dynamic protection polygons. This observation is bounded by the review scope and does not establish universal absence.

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The EDT-EPZ model addresses this triple gap — conceptual (terrestrial dynamic EPZs), technological (the corridor as sensing infrastructure), and institutional (a frequently updated governance instrument) — as developed in the following sections. Table 1 summarizes the distinction between protection paradigms.

Table 1. Comparison between static and dynamic protection paradigms

Dimension	Static protection (current paradigm)	Dynamic protection (EDT-EPZ model)
Spatial unit	Fixed perimeter defined by legal instrument	Polygon recalculated daily by the agents
Ecological unit	Place (delimited habitat)	Trajectory (species movement)
Data source	One-off surveys and periodic inventories	Continuous flow of sensors, telemetry and satellite
Risk response	Reactive and bureaucratic (months to years)	Predictive and operational (hours to days)
Relationship with the corridor	Corridor seen as an external threat	Corridor integrated as sensing infrastructure
Governance instrument	Static cartography and retrospective reports	Regularly updated ministerial dashboard and automatic alerts

Source: Author's own elaboration (2026).

3. METHODOLOGY

3.1. Nature, approach and research design

The research is theoretical-propositional and includes computational validation within the design science research paradigm. The artefact consists of a socio-technical model and its simulated implementation. The interdisciplinary approach articulates environmental sciences, computer science, and governance studies through four linked phases.

The first phase comprised a structured, non-registered literature review using the descriptors digital twin, species distribution model, multi-agent system, dynamic management, transport corridor, and Africa, covering 2006–2026. The review supported conceptual gap identification and did not constitute a preregistered systematic review or meta-analysis. The second phase produced the five-layer EDT-EPZ architecture: sensing; agent swarm; digital twin; dynamic delimitation; and decision and governance. The third phase implemented three computational experiments in a synthetic 1,300 km railway-corridor scenario. The fourth phase

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derived institutional requirements through content analysis of the computational findings and normative literature.

3.2. Design of the agent-based simulations

The simulations followed the agent-based modelling paradigm. Each replicate contained 1,500 animal agents, equally allocated to three ecological guilds (proboscideans, ungulates, and medium-to-large carnivores), together with sensor and delimitation functions. The spatial domain represented a 1,300 km corridor and a 5 km influence band on each side. Correlated daily movement incorporated persistence and seasonality, consistent with movement ecology (Nathan *et al.*, 2008). Detection was represented by an exponential function of distance to the nearest sensor, informed by the camera-trap and tracking literature (Norouzzadeh *et al.*, 2018; Kays *et al.*, 2015).

Table 2. Parameters and computational specification of the EDT-EPZ simulations

Parameter	Description	Value
Corridor length	Length of the simulated railway axis	1,300 km
Ecological influence zone	Analysis band on each side of the corridor	5 km
Simulated guilds	Functional fauna groups with distinct movement profiles	3
Animal agents per replicate	Virtual individuals with stochastic trajectories	1,500
Sensor spacing	Density scenarios of the sensing infrastructure	4 km; 2 km; 1 km
Time horizon	Simulated period with dry and rainy seasons	36 months
Independent replicates	Runs for statistical robustness	200
Operational detection limit	Minimum probability of occurrence detection	80%
Dynamic EPZ recalculation	Update frequency of the protection polygon	24 hours
Agents per guild	Animal agents allocated equally to each ecological guild	500
Daily integration steps	Thirty-day months over the complete horizon	1,080
Monthly guild displacement	Mean ± standard deviation for guilds 1-3	2 ± 0.8; 3 ± 1.0; 4 ± 1.2 km
Heading dynamics	Persistence; seasonal coefficient; innovation SD	0.985; 0.015; 0.010

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Parameter	Description	Value
Individual offset dynamics	AR(1) persistence; longitudinal and transverse innovation SD	0.992; 1.0 km; 0.075 km
Static ellipse centres	Longitudinal and transverse coordinates	(250, −1); (650, 0.5); (1,050, 1) km
Ellipse radii	Longitudinal and transverse radii before area adjustment	120 km; 0.95 km
Dynamic prediction error	Longitudinal and transverse standard deviations	8.0 km; 0.25 km
Adaptive prediction error	Longitudinal and transverse standard deviations	4.0 km; 0.12 km
Relative protected area	Dynamic and adaptive conditions versus static	1.12; 1.15
Effectiveness weights	Coverage; anticipation; critical-area overlap	0.50; 0.30; 0.20
Replication noise	AR(1) persistence and innovation SD in index points	0.72; 0.65
Randomization	Generator and fixed seeds	PCG64; 20260217; 20260218
Reference software	Execution environment used for the reported results	Python 3.12.12; NumPy 2.2.5; Matplotlib 3.10.3

Source: Author's own elaboration (2026).

Simulation 1 evaluated analytical detection probabilities for sensor spacings of 4, 2, and 1 km. Simulation 2 compared daily trajectory coverage among fixed ellipses, dynamic ellipses centred on predicted guild positions, and an adaptive condition with lower prediction error. Simulation 3 calculated a monthly composite effectiveness index over 36 months for the three protection regimes. All 200 replicates used paired random draws for between-regime comparison. No empirical observations were introduced at any stage.

3.3. Computational procedures and statistical analysis

The reference implementation used Python 3.12.12, NumPy 2.2.5, and Matplotlib 3.10.3. Random numbers were generated with NumPy PCG64 through numpy.random.default_rng. The main seed was 20260217, and the effectiveness experiment used seed 20260218. Each experiment was executed with 200 replicates; spatial trajectories comprised 1,080 daily steps, aggregated into 36 months of 30 days. The complete execution command, dependencies, outputs, and checksums are included in the supplementary package.

In Simulation 1, detection was calculated as $P_s(d) = p_{0,s} \exp(-\lambda_s d)$, where d is distance in kilometres, $p_{0,s}$ is detection at zero distance, and λ_s is the decay coefficient. The ($p_{0,s}$; λ_s) pairs were (0.43; 0.38), (0.65; 0.32), and (0.96; 0.116) for 4, 2, and 1 km spacing, respectively. The distance at which the 1 km scenario crosses the 80% threshold was obtained

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analytically as d = −ln(0.80/0.96)/0.116 = 1.5717 km. Distances from 0 to 5 km were evaluated in 0.05 km increments.

In Simulation 2, guild headings followed $\theta_{t+1} = 0.985\theta_t + 0.015S_t + \varepsilon_t$, with $S_t = 0.10 \sin(2\pi t/360)$ and $\varepsilon_t \sim N(0, 0.010^2)$. Mean monthly displacements were 2, 3, and 4 km, with standard deviations of 0.8, 1.0, and 1.2 km for the three guilds. Individual offsets followed $o_{t+1} = 0.992o_t + v_t$, where $v_x \sim N(0, 1.0^2)$ and $v_y \sim N(0, 0.075^2)$. Static protection ellipses were centred at (250, −1), (650, 0.5), and (1,050, 1) km, with radii of 120 and 0.95 km.

Dynamic ellipses were re-centred daily on predicted guild positions. Prediction-error standard deviations were (8.0; 0.25) km in the dynamic condition and (4.0; 0.12) km in the adaptive condition for the longitudinal and transverse axes, respectively. Ellipse radii were multiplied by $\sqrt{1.12}$ and $\sqrt{1.15}$, producing area increases of 12% and 15% relative to static protection. An agent-day was classified as covered when $((x-xc)/rx)^2 + ((y-yc)/ry)^2 \leq 1$. Coverage was the proportion of covered agent-days across all agents, days, and guilds within each replicate.

The adaptive reinforcement-learning condition was represented by a scalar policy θ updated from a coverage reward with an area penalty: $\theta_{t+1} = \theta_t + 0.35(r_t - 0.50)(1 - \theta_t)$, bounded between 0 and 1, with $r_t = C_t - 0.10(1.15 - 1)$. This simplified computational surrogate was not a deep reinforcement-learning model and was not trained on field data. Its role was to test the behaviour of an adaptive decision rule under explicit synthetic conditions.

In Simulation 3, effectiveness was defined as $E_{r,t} = 100(0.50C_{r,t} + 0.30A_{r,t} + 0.20O_{r,t})$, where C is trajectory coverage, A is alert anticipation, and O is overlap with critical areas. Static and dynamic component endpoints were fixed before execution; the adaptive components varied with θ. Seasonal terms followed $\sin(2\pi t/12)$, with endpoint correction. Paired AR(1) replication noise used persistence 0.72 and innovation standard deviation 0.65 index points. Means, standard deviations, and 95% confidence intervals were calculated as mean ± 1.96 SD/√200. These intervals summarize Monte Carlo variability and are not confidence intervals for real ecological populations.

3.4. Data and code availability and reproducibility test

The supplementary file Material_suplementar_reprodutibilidade.zip contains run_simulations.py, verify_reproduction.py, requirements.txt, a README file, seven CSV datasets, Figures 2-4, and verification/reproducibility_check.json. The main execution is python run_simulations.py --seed 20260217 --replicates 200 --output-dir outputs. The verification routine repeats the complete numerical experiment twice in separate temporary directories and compares

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every CSV file byte for byte. All observations are synthetic; no empirical species, telemetry, sensor, or human data are required.

The reproducibility test was executed with the disclosed reference environment. Two independent runs with the same seed and parameters generated seven byte-identical CSV files; their SHA-256 hashes and the successful comparison are recorded in the supplementary report. This procedure demonstrates deterministic computational reproducibility of the reported tables and Figures 2-4. Figures 1 and 5 are conceptual diagrams and therefore fall outside the numerical reproduction test.

3.5. Computational validation versus empirical validation

Computational validation assessed whether the implemented artefact executed as specified, produced internally consistent outputs under the declared assumptions, and could be reproduced from the supplied code and synthetic data. It did not evaluate predictive accuracy against observed species movements, sensor performance under field conditions, ecological outcomes, costs, community acceptance, or legal feasibility. Consequently, the results establish computational plausibility rather than empirical effectiveness. Empirical validation has not been performed. A subsequent pilot should use independently collected telemetry and sensor data, held-out temporal and spatial test sets, preregistered outcome definitions, baseline comparisons, and uncertainty analyses before any operational deployment.

4. RESULTS

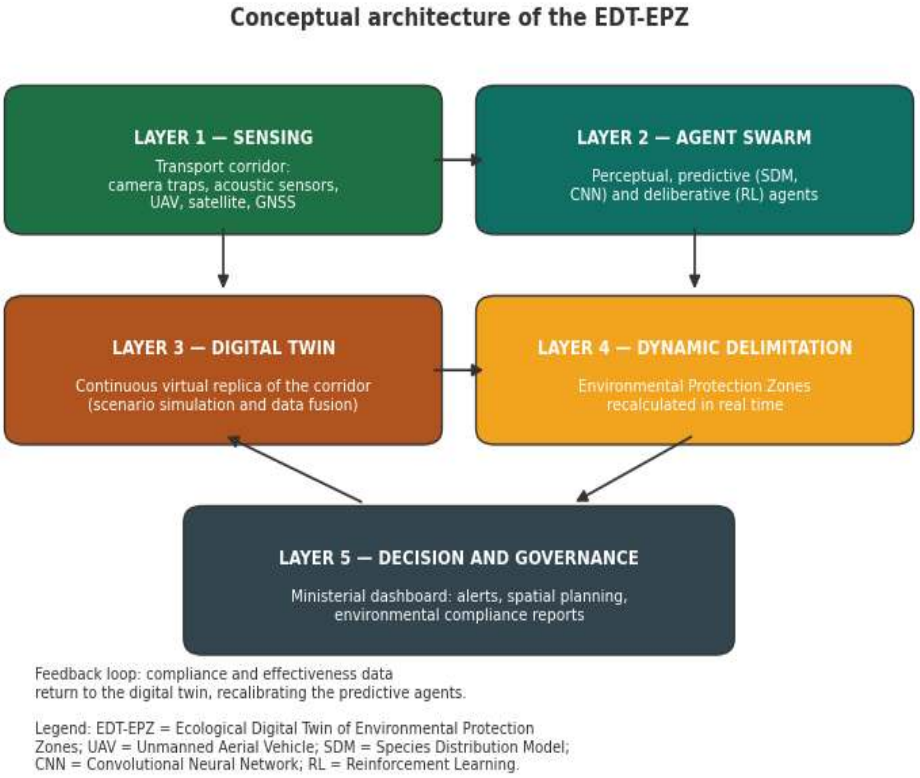
4.1. The architecture of the EDT-EPZ model

The first result is the conceptual artefact itself: the architecture of the Ecological Digital Twin of Environmental Protection Zones, organized into five functional layers (Figure 1). The sensing layer converts the transport corridor into sensing infrastructure, taking advantage of existing posts, bridges, stations and maintenance itineraries to install camera traps, acoustic sensors, environmental stations and UAV operation bases. The agent swarm includes perceptual agents (filtering and classification of observations by CNN), predictive agents (SDMs and trajectory forecasting) and deliberative agents (risk assessment and polygon proposal, tuned by RL). The digital twin maintains the continuous virtual replica of the corridor, fusing telemetry, satellite spectral data and traffic records. The dynamic delimitation layer recalculates the EPZ polygons at each 24-hour cycle. The decision and governance layer exposes the state of the

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system to ministerial decision-makers through a dashboard with alerts, living cartography and compliance reports, closing the feedback loop that recalibrates the agents.

Figure 1. Five-layer conceptual architecture of the EDT-EPZ model



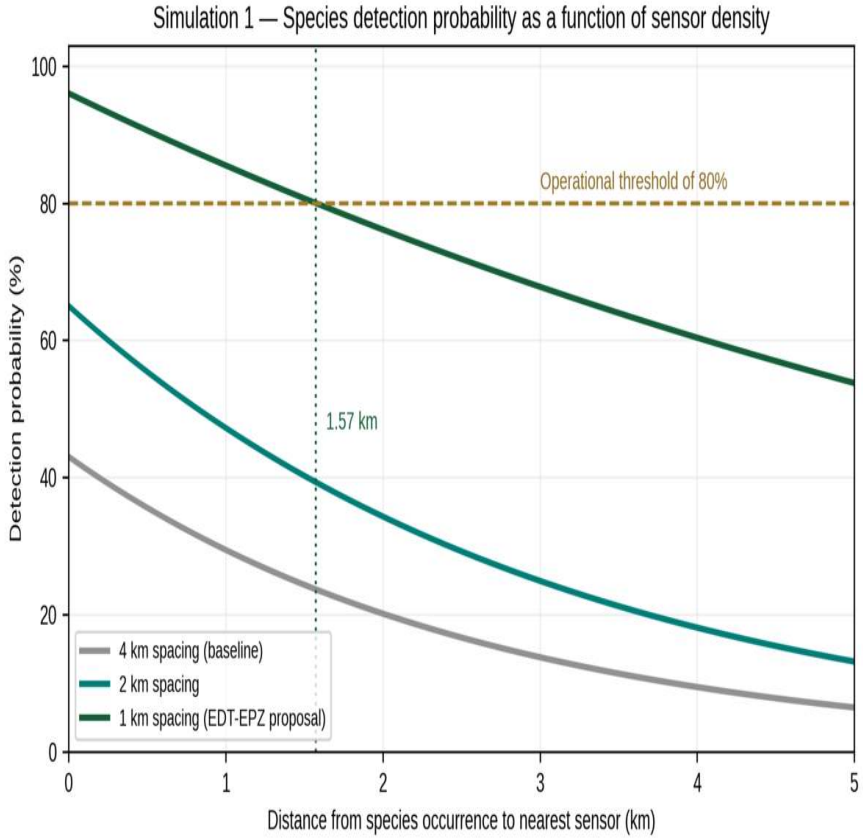
Source: Author's own elaboration (2026).

4.2. Simulation 1: sensor density and species detection probability

Figure 2 presents the analytical detection curves. At zero distance, detection probabilities were 43%, 65%, and 96% for sensor spacings of 4, 2, and 1 km, respectively. Neither the 4 km nor the 2 km scenario reached the 80% operational threshold. In the 1 km scenario, detection remained at or above 80% only within 1.5717 km of the nearest sensor and declined exponentially thereafter. The result therefore does not support uniform 80% detection across the entire 5 km influence band. It identifies a bounded sensing condition that would require complementary sensor placement or additional observation sources.

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Figure 2. Species detection probability as a function of sensor density (Simulation 1)



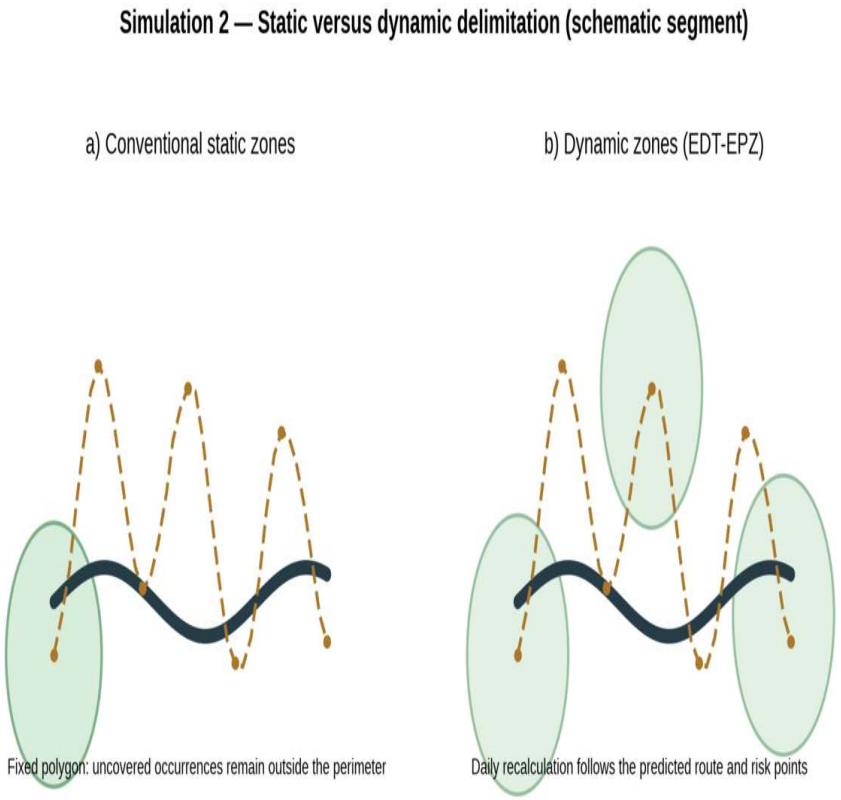
Source: Author's own elaboration (2026), based on the synthetic outputs in the supplementary reproducibility package.

4.3. Simulation 2: static versus dynamic spatial coverage

Figure 3 contrasts the two delimitation regimes over a schematic corridor segment. In the static regime, fixed ellipses leave occurrence points outside their perimeters uncovered. In the dynamic regime, ellipses are re-centred daily around predicted guild positions. Across 200 replicates, mean trajectory coverage was 32.9383% (95% CI 31.7265–34.1501) in the static regime, 86.8949% (95% CI 86.8635–86.9263) in the dynamic regime, and 89.5319% (95% CI 89.5010–89.5627) in the adaptive condition. Dynamic protection increased area by 12%, and the adaptive condition by 15%. These are synthetic agent-day coverage results, not observed conservation outcomes.

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Figure 3. Static versus dynamic delimitation of environmental protection zones (Simulation 2)



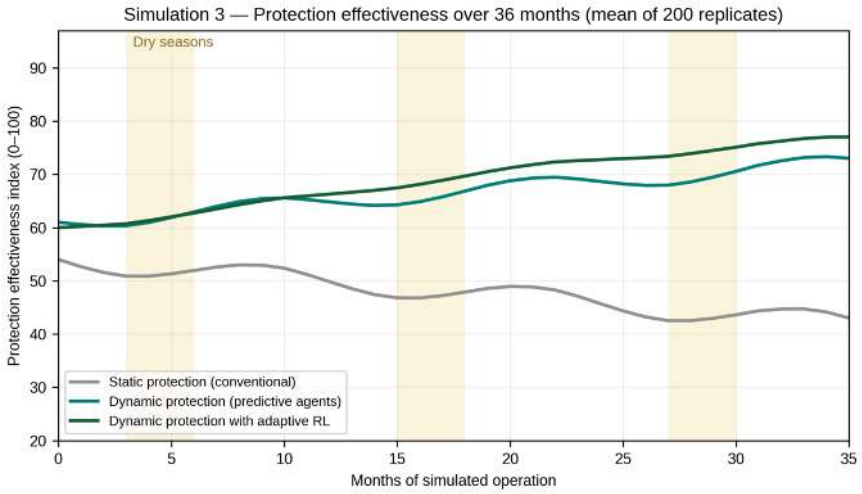
Source: Author's own elaboration (2026), based on the synthetic outputs in the supplementary reproducibility package.

4.4. Simulation 3: protection effectiveness over 36 months

Figure 4 presents monthly effectiveness over 36 months. The static regime declined from 54.0 to 43.0 points (95% CI at month 35: 42.9–43.2), whereas the dynamic regime increased from 61.0 to 73.0 points (95% CI 72.9–73.2). The adaptive regime increased from 60.0 to 77.0 points (95% CI 76.9–77.2). Seasonal troughs correspond to the dry-season specification in the computational model. Because the index is a weighted synthetic construct, the curves demonstrate internal model behaviour and should not be interpreted as measured temporal improvements in biodiversity protection.

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Figure 4. Protection effectiveness in the three simulated regimes (Simulation 3)



Source: Author's own elaboration (2026), based on the synthetic outputs in the supplementary reproducibility package.

Table 3 synthesizes the regime indicators. Confidence intervals are reported for the two principal numerical outcomes. Update frequency and area ratios were experimental settings rather than estimated effects. The adaptive policy used the reward-based update described in Section 3.3; no empirical response-latency estimate was calculated.

Table 3. Comparative indicators of the protection regimes (200 replicates)

Indicator	Static	Dynamic	Dynamic with adaptive RL
Mean trajectory coverage, % (95% CI)	32.9 (31.7–34.2)	86.9 (86.86–86.93)	89.5 (89.50–89.56)
Effectiveness at month 35 (95% CI)	43.0 (42.9–43.2)	73.0 (72.9–73.2)	77.0 (76.9–77.2)
Protection-zone update frequency	Fixed perimeter	24 hours	24 hours
Increase in total protected area (%)	—	12	15
Detection at or above 80% (1 km spacing; d ≤ 1.57 km)	Not applicable	Yes	Yes
Policy update	None	Fixed predictive rule	Reward-based adaptive rule

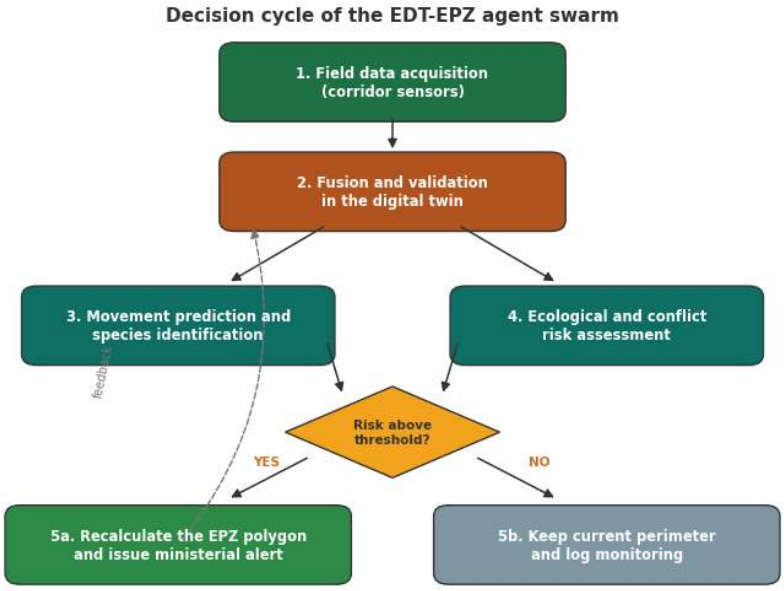
Source: Author's own elaboration (2026).

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4.5. The decision cycle of the agent swarm

Figure 5 formalizes the decision cycle in each 24-hour iteration: (1) acquisition of field data by corridor sensors; (2) fusion and quality control in the digital twin; (3) movement prediction and species identification by predictive agents; (4) ecological and conflict-risk assessment by deliberative agents; and (5) a binary decision: recalculate the EPZ polygon and issue an alert, or retain the current perimeter and log the monitoring event. Effectiveness feedback supports subsequent recalibration, constituting an adaptive governance circuit rather than solely a surveillance system.

Figure 5. Decision cycle of the EDT-EPZ agent swarm



Source: Author's own elaboration (2026).

5. DISCUSSION

5.1. Theoretical contributions: corridor computational ecology

The first contribution is the formalization of a scientific object at the interface between transport corridors and ecological processes. The literature has treated corridors primarily as disturbance factors (Laurance *et al.*, 2014, 2015; Benítez-López *et al.*, 2010), while dynamic management has been developed substantially in marine contexts (Maxwell *et al.*, 2015; Hazen

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et al., 2018). By reconceptualizing the corridor as sensing infrastructure and transferring dynamic delimitation to African terrestrial ecosystems, the EDT-EPZ proposes the designation corridor computational ecology: the study of dynamic interfaces between linear infrastructures and ecological processes mediated by digital twins and predictive agents. The approach inherits the trajectory as its unit of analysis from movement ecology (Nathan *et al.*, 2008) and explores its normative translation into a legally protected trajectory.

The second contribution is the computational indication that dynamic protection may be framed as an information problem rather than solely an area problem. In Simulation 2, 86.9% coverage with a 12% area increase suggests that spatio-temporal alignment deserves attention alongside the 30 × 30 target (Convention on Biological Diversity, 2022). This interpretation remains conditional on the synthetic movement, prediction-error, and ellipse parameters and requires field testing.

5.2. Implications for ministerial and regional institutions

For ministries of environment and transport, the model proposes shared infrastructure and mission: the corridor operator becomes a co-producer of environmental information, and the environmental authority receives a regularly updated decision dashboard. In Angola, an EDT-EPZ pilot in the Lobito Corridor would involve the Ministry of the Environment and the National Institute for Biodiversity and Conservation Areas in delimitation and enforcement, the transport authority and railway concessionaire in sensing infrastructure, and provincial administrations in community interfaces. At regional scale, the Southern African Development Community could evaluate the model for cross-border corridor harmonization, and the African Union could assess its contribution to Agenda 2063 and Convention on Biological Diversity reporting.

Potential sectoral externalities include: (i) continuous environmental impact assessment supported by digital-twin data; (ii) anomaly detection relevant to anti-poaching efforts and to the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES, 1973); and (iii) local value chains in sensing, maintenance, and environmental data science. These externalities are proposed pathways, not outcomes measured in this study.

5.3. Legal requirements and proposed governance framework

Institutionalization of dynamic EPZs requires legal innovation because current frameworks rely predominantly on fixed perimeters. The proposed category is a variable-perimeter protection zone defined by an auditable algorithm rather than solely by fixed geometry. The legal instrument would establish the model, parameters, maximum area, public-disclosure

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duties, and appeal mechanisms; the daily geometry would be a published and auditable digital-twin output. Legal certainty would reside in stable rules, versioned code, and reproducible records. In Angola, the prevention, precaution, and participation principles of the Basic Environmental Law provide a relevant basis, but implementation would require a specific regulatory instrument (República de Angola, 1998).

5.4. Limitations and research agenda

Five limitations must be recorded. First, validation is exclusively computational; empirical calibration and testing with African telemetry and field-sensor data have not been performed. Second, the adaptive reinforcement-learning condition is a simplified scalar policy surrogate, not an operational deep-learning system. Third, sensor density implies installation, connectivity, and maintenance costs that require economic feasibility analysis. Fourth, algorithmic territorial governance raises data-sovereignty, cybersecurity, equity, participation, and legal-appeal concerns, particularly where dynamic polygons intersect community lands. Fifth, predictive models can propagate sampling bias, and sparse African biodiversity inventories may under-represent species and regions. Community monitoring and citizen science should complement, rather than replace, standardized empirical surveys.

The research agenda includes: (i) a preregistered EDT-EPZ pilot on a defined Lobito Corridor section, with universities, the biodiversity authority, the railway concessionaire, and local communities; (ii) held-out empirical evaluation of detection, movement forecasts, coverage, ecological outcomes, and costs; (iii) extension to road, riverine, and coastal corridors; (iv) integration of long-term climate forecasts; and (v) comparative legal analysis of variable-perimeter zones in Southern African Development Community member states.

6. FINAL CONSIDERATIONS

This article addressed the mismatch between fixed protection perimeters and moving ecological trajectories by proposing the Ecological Digital Twin of Environmental Protection Zones. The five-layer architecture integrates transport infrastructure, artificial intelligence, distributed sensing, and daily polygon revision. Three reproducible computational experiments compared protection regimes in a synthetic corridor. Mean trajectory coverage was 32.9% in the static regime, 86.9% in the dynamic regime, and 89.5% in the adaptive condition. Effectiveness at month 35 was 43.0, 73.0, and 77.0 points, respectively. Code, parameters, synthetic outputs,

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software versions, seeds, and checksums accompany the manuscript, and two independent executions produced identical data files.

Under the declared synthetic assumptions, the results support the computational hypothesis that dynamic delimitation can outperform static protection in trajectory coverage and composite effectiveness. They do not establish empirical superiority in real ecosystems. The transport corridor can therefore be investigated as a potential sensing backbone for conservation, but operational adoption depends on prospective field validation, economic assessment, community participation, legal review, and independent auditing. Angola and the Lobito Corridor provide a relevant setting for such a pilot.

DECLARATIONS

Author contribution: Pedro Ndala Da Silva is the sole author and is responsible for the conception of the study, literature review, model construction, implementation of the simulations, analysis of the results and writing of the manuscript.

Conflicts of interest: The author declares that there are no conflicts of interest.

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Data availability: The simulation code, parameter specification, seven synthetic CSV datasets, generated Figures 2-4, software requirements, SHA-256 hashes, and the successful two-run verification report are available in the supplementary file Material_suplementar_reprodutibilidade.zip accompanying this manuscript. No empirical datasets were generated or analysed. Empirical telemetry and field-sensor data remain necessary for future validation.

Declaration of artificial intelligence use: In accordance with RECIMA21's AI Use Policy, artificial intelligence tools supported linguistic revision, formatting, and the organization of reproducibility documentation. The author remains fully responsible for verifying the scientific content, computational outputs, citations, and references and for the originality, accuracy, and integrity of the work.

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