Journal of Economics and Development

Lemur Bond and biodiversity finance in Madagascar: pricing, impact dynamics and stochastic resilience

Hoby Nirina Rasoloarimanana
Doctoral School of Natural Resources Management and Development, University of Antananarivo, Antananarivo, Madagascar, and
Ambinintsoa Ramanambonona
Department of Economics, Faculty of Economics, Management and Sociology, University of Antananarivo, Antananarivo, Madagascar

Received 22 April 2026
Revised 5 July 2026
24 July 2026
Accepted 7 August 2026

Abstract

Purpose – This study develops an evaluation framework for the Lemur Bond, an outcome-based biodiversity finance instrument under preparation in Madagascar. It examines how sovereign pricing, ecological performance, ecosystem-service valuation and evidence governance interact under uncertainty.

Design/methodology/approach – The paper combines three analytical blocks: a bond-pricing module incorporating greenium, compliance costs and default risk, an ecological production function linking mobilized resources to a composite biodiversity index and a discounted valuation of ecosystem services. Monte Carlo simulations propagate uncertainty in key parameters, while stochastic impulse response analysis evaluates resilience to shocks such as cyclones, wildfires and institutional disruptions.

Findings – The results show that the expected environmental value of the instrument is highly sensitive to ecological depreciation, allocation efficiency and the credibility-driven greenium. They also indicate that financial viability depends not only on coupon design but also on monitoring quality, independent verification and the capacity to maintain conservation outcomes after shocks.

Research limitations/implications – The analysis relies on illustrative calibration rather than fully estimated empirical parameters. It therefore provides a simulation-based framework that can be updated as official monitoring and financial data become available.

Originality/value – The paper contributes to sustainable finance, biodiversity economics and sovereign debt literature by linking pricing, ecological production, KPI governance and resilience within a single framework adapted to Madagascar.

Keywords Biodiversity finance, Sovereign bond, Greenium, Ecosystem services, Stochastic resilience, Madagascar

Paper type Research article

1. Introduction

Sustainable finance is moving toward objectives that were long handled through grants, projects and conventional budgetary instruments. Biodiversity is now part of this movement. This shift responds to two simultaneous constraints. On the one hand, the accelerated erosion of ecosystems requires costly, continuous actions that are exposed to climate shocks. On the other hand, states with limited fiscal capacity face a durable budget constraint that weakens recurrent financing for protected areas, which is often procyclical and sensitive to political trade-offs. Madagascar crystallizes this tension. The country concentrates natural capital of exceptional value and high endemism, yet it remains highly vulnerable to crises and shocks

Disclosure statement: No potential conflict of interest was reported by the authors.

Journal of Economics and Development
Emerald Publishing Limited
e-ISSN: 2632-5330
p-ISSN: 1859-0020
DOI 10.1108/JED-04-2026-0453

(Cooke *et al.*, 2022; World Bank, 2013). Lemurs play the role of a flagship species. They draw international attention and signal the state of habitats. Their conservation nevertheless depends on a broader socio-ecological system in which local governance, livelihood strategies, social norms and law enforcement intersect (Corson, 2012; Gardner *et al.*, 2013; Jones *et al.*, 2008).

For the purpose of this study, the *Lemur Bond* is treated as an official instrument under preparation, not as a security already issued on the market. This status is important for interpretation. In November 2024, Madagascar's Country Platform for Climate Finance identified a Lemur Bond among the initiatives considered by the World Bank Group and the Global Environment Facility to raise funds for nature conservation and climate resilience. In June 2025, the GEF Council approved the Science-based Management of Biodiversity and Natural Resources for Economic Development Project (GEF ID 11694), which supports the planned launch of a Lemur Bond as an outcome-based mechanism for mobilizing capital markets to protect endangered species, strengthen livelihoods and improve climate resilience around protected areas. The World Bank/IDA preparation grant for the Landscape Seascape Management and Lemur Bond Operations Project further confirms that preparation activities cover legal and institutional arrangements, baseline data, target protected areas, lemur populations, conservation actions, participatory fire-management plans, income-generating activities and project monitoring systems (Global Environment Facility, 2025c; International Development Association, 2025; International Monetary Fund, 2024). The singular spelling "Lemur Bond" refers to the financial instrument and to lemurs as flagship species; it does not imply that the instrument targets a single species or a single protected area.

In this context, a sovereign bond linked to biodiversity indicators, here designated the "Lemur Bond", fits within a logic of contracting on outcomes. The final legal structure remains a matter of project design, but the institutional perimeter is no longer purely speculative. Official documentation identifies Madagascar as the recipient of preparation support, the World Bank as the implementing agency for GEF ID 11694, the Ministry of Environment and Sustainable Development as the executing agency and the Ministry of Economy and Finance as the authority signing the IDA preparation grant and collaborating technically in the inter-ministerial steering arrangements (Global Environment Facility, 2025c; International Development Association, 2025; Minamata Convention on Mercury, 2025). For analytical clarity, the reference architecture models the instrument as a sovereign transaction in which the Republic of Madagascar, acting through the ministry responsible for finance and public debt, remains the reference obligor. A special-purpose vehicle or ring-fenced conservation account may be used to track proceeds, structure payments or administer outcome payments, but it does not replace the sovereign character of the obligation unless the final legal documentation assigns the issuance to that vehicle. Multilateral partners enter the structure as concessional financiers, risk-sharing actors, technical-assistance providers, data-governance supporters or independent verification sponsors.

The repayment source is also specified in sovereign terms. Coupon and principal payments would come from the national debt-service budget, supported by general public revenues and, where relevant, by a reserve account or concessional support. Ecosystem-service benefits, tourism spillovers or protected-area revenues can strengthen the economic justification of the instrument, but they are not assumed to be pledged collateral or the sole cash-flow source. The cost of financing reflects the credibility of the environmental commitment through a green premium, reporting requirements and a verification architecture. The proceeds support a trajectory of outcomes that is measured, published and audited (Flammer, 2020; Ntsama *et al.*, 2021; Weber and Saravade, 2019). This type of instrument belongs to the family of green bonds, sustainability-linked bonds and indicator-indexed structures, but it places at the centre a difficulty specific to biodiversity: the production of observable outcomes remains more complex than that of standardized energy or climate assets because the benefits are heterogeneous, often non-excludable, spatially specific and spread over time (Margules and Pressey, 2000).

The literature on green bonds provides a first foundation. It documents the rapid expansion of the market and discusses the existence of a greenium, which reduces the return required by investors for credible and traceable instruments (Demski *et al.*, 2025; Ntsama *et al.*, 2021). It also examines the real effects of issuances on environmental indicators, with measurable results in some contexts but strong heterogeneity across institutions and verification rules (Ahmed *et al.*, 2023; Flammer, 2020). A critical line of work has consolidated around additionality. The label may coexist with projects similar to those financed by ordinary bonds, which weakens the causal argument when traceability remains incomplete (Lam and Wurgler, 2024). This controversy is decisive for a biodiversity bond because credibility does not rest only on narrative. It rests on evidence and therefore on the quality of indicators, methodological transparency and data governance.

The literature on Madagascar illuminates this requirement from a more concrete angle. Conservation outcomes vary widely across institutional arrangements, local perceptions and the quality of consultation (Corson, 2012; Gardner *et al.*, 2013). Pressures on wildlife and forests are rooted in subsistence constraints and incentive structures. Hunting and bushmeat consumption illustrate this reality, with sometimes extensive exploitation of protected species and measurement difficulties related to rare and seasonal events (Golden, 2009; Golden *et al.*, 2013; Jenkins *et al.*, 2011). Social norms and taboos can support conservation, but their stability depends on social cohesion, economic transformations and the legitimacy of local authorities (Jones *et al.*, 2008; Keller, 2009). The legal framework completes this picture. Rules and sanctions lose effectiveness when use rights remain ambiguous and monitoring capacities are insufficient, which creates gaps between norm and practice (Rakotoarivelo *et al.*, 2011). An outcomes-based bond cannot ignore these determinants because they enter the ecological production function itself.

A second foundation concerns measurement. Contracting on outcomes requires a robust monitoring system. Classical analyses insist on the role of ecological monitoring in integrated programs because, without monitoring, arrangements become non-falsifiable and learning is reduced (Kremen *et al.*, 1994). Participatory monitoring experiences in Madagascar show the potential to lower collection costs and increase legitimacy, provided there is training, minimal standardization and coordination (Andrianandrasana *et al.*, 2005). These elements become central as soon as the cost of capital depends on the credibility of the indicators. In this framework, reporting is no longer merely a communication exercise. It becomes a macro-fiscal component because it conditions the greenium and, as a result, the cost of debt service.

This paper proposes a coherent articulation between finance, ecology and outcome governance. The objective is not a definitive calibration. The objective is an analytical template that clarifies the mechanisms and then organizes the robustness analysis. The model relies on three connected blocks. The first block describes bond pricing, with a discount rate adjusted by a green premium and with compliance costs taken into account. The second block formalizes an ecological production technology that transforms effectively mobilized resources into an outcome index. This index aggregates biological, habitat and socioeconomic dimensions because a mono-indicator approach increases the risk of substitution across objectives. The third block economically values outcomes through a net present value of ecosystem services over a horizon consistent with the maturity of the instrument (Cooke *et al.*, 2022; Golden *et al.*, 2014). This scheme allows a clear economic reading: social value comes from a discounted flow of impacts, while the sustainability constraint depends on expected payments, compliance costs and default risk.

Two robustness building blocks then structure the empirical analysis. First, a Monte Carlo simulation propagates parameter uncertainty in key parameters such as allocation efficiency, the elasticity of ecological production, ecological depreciation and the green premium. This approach reflects a simple fact: in biodiversity, knowledge of parameters remains imperfect even when the theory of change is clear. Second, a stochastic impulse-response analysis characterizes the resilience of outcomes to exogenous shocks. Climate shocks, wildfires and episodes of instability can create temporary breaks. The dynamics of returning to trend matter as much as the level of the trend itself because they condition the period of vulnerability and the design of contingency clauses, a point consistent with public GEF documentation on the Lemur Bond operation and Madagascar's resilience needs (Global Environment Facility, 2025a, b). The logic connects with conservation concerns in a context of political crises and a possible relaxation of rule enforcement (Schwitzer *et al.*, 2014; World Bank, 2013).

This contribution is distinguished by its emphasis on the interface between evidence and sustainability. A strictly financial reading ignores field-level determinants and therefore overestimates the contract's capacity to produce outcomes. A purely ecological reading ignores market access and the role of institutional credibility in the cost of capital. The proposed framework makes this cross-dependence explicit. It highlights a point often underestimated in operational discussions: the green premium is an endogenous variable of the governance system. It depends on data quality, verification architecture and the capacity to publish information on a predictable schedule (Lam and Wurgler, 2024; Weber and Saravade, 2019). As a result, improving outcome governance can lower the cost of capital, which creates an incentive to invest in measurement and audit systems. The incentive remains fragile if compliance costs exceed administrative capacity or if institutional trust deteriorates (Ntsama *et al.*, 2021).

This article is also part of a public-policy perspective. Protected areas contribute to employment, tourism and regulatory services that remain largely invisible in national accounts (Cooke *et al.*, 2022). They also support subsistence extraction that plays a food-security safety-net role, which makes restrictions on use politically sensitive (Golden *et al.*, 2014). A biodiversity bond cannot reduce the social dimension to a co-benefit. It must incorporate benefit-sharing mechanisms and credible economic alternatives; otherwise pressure shifts toward other spaces and other species (Gardner *et al.*, 2013; Kaimowitz and Sheil, 2007). The very notion of an outcome must therefore reflect an explicit theory of change, with verifiable indicators, floor rules and transparency regarding trade-offs.

Finally, the "Lemur Bond" is part of an international dynamic of mobilizing financing for biodiversity and resilience objectives, with a blended-finance architecture supported by the GEF Trust Fund, the LDCF, World Bank implementation and substantial co-financing (Global Environment Facility, 2025c; Minamata Convention on Mercury, 2025). This architecture opens space for contractual innovation, but it also exposes a risk of complexity. The more the contract accumulates indicators, clauses and verification mechanisms, the more it requires administrative and statistical capacities. The proposed model seeks precisely to clarify this trade-off: it helps isolate the parameters that dominate expected social value and then identify the points at which governance reduces uncertainty and improves credibility.

The theoretical contribution lies in combining four strands that are often discussed separately. From sustainable-finance theory, the paper takes the pricing role of labelled credibility and the greenium. From outcome-based contracting, it takes the idea that a measurable indicator can allocate incentives and risks across the issuer and investors. From conservation economics, it takes the transformation of financing into ecological and ecosystem-service value under diminishing returns. From institutional and law-and-economics reasoning, it treats monitoring, auditing, community legitimacy and rule enforcement as productive inputs rather than as peripheral implementation details. The framework therefore complements generic green-bond models by making the evidence chain endogenous: stronger governance can reduce perceived risk and financing costs, while weaker governance can lower additionality, reduce the greenium and weaken ecological persistence.

The remainder of this article is organized as follows. The next section synthesizes the established findings in the literature on the pricing of sustainable bonds, additionality, evidence governance and the socio-ecological determinants of conservation in Madagascar. The methodology then formalizes the model, specifies the assumptions and describes the simulation devices. The results present orders of magnitude, sensitivity analyses, Monte Carlo distributions and resilience properties derived from the impulse-response analysis. The discussion draws implications for contractual design, the choice of indicators and the verification architecture, and the conclusion summarizes the contributions and limitations while identifying empirical extensions based on monitoring data and public-finance data.

2. Literature review

The literature mobilized here is organized around a common issue: reducing the biodiversity financing gap in a context of budgetary constraint and high risk, without sacrificing the credibility of outcomes. It covers, on the one hand, the contributions of sustainable bond markets and sovereign instruments based on performance indicators and, on the other hand, the socio-ecological and institutional determinants that condition the effectiveness of an arrangement such as a *Lemur Bond* in Madagascar. Two guiding threads dominate. The first concerns additionality and real impact: raising capital is not enough; the key issue is the transformation of financial resources into verifiable ecological outcomes (Ahmed *et al.*, 2023; Flammer, 2020; Lam and Wurgler, 2024). The second concerns evidence governance: the more the instrument depends on indicators, the more the quality of data, audits and transparency mechanisms becomes an economic variable in its own right because it influences the cost of capital and the sustainability of the contract (International Capital Market Association, 2025; Ntsama *et al.*, 2021; Weber and Saravade, 2019).

2.1 Analytical foundations of biodiversity-linked finance

Biodiversity-linked finance differs from conventional green finance because the object of contracting is not only the use of proceeds but also the verified production of ecological outcomes. Three analytical conditions follow. First, the financial label must be credible enough to affect the investor's required return through a greenium. Second, mobilized resources must be transformed into conservation effort after transaction, monitoring and verification costs. Third, ecological performance must be observable through indicators that are robust to substitution, local pressure and climate shocks. This subsection therefore connects sustainable-bond pricing, outcome-based contracting and conservation economics before turning to the Malagasy institutional setting.

2.2 Conservation finance and Madagascar's biodiversity financing gap

Protected areas produce economic and social benefits that exceed directly observable budgetary revenues. They support regulatory services, subsistence uses, tourism activities and local spillovers. In the Malagasy case, the economic argument draws on syntheses documenting the contribution of protected areas to the national economy and the diversity of the channels involved (Cooke *et al.*, 2022). Yet financing stability remains fragile. Dominant mechanisms, whether based on grants, projects, trust funds or budget lines, often expose conservation to political cycles and external shocks. Crises can rapidly degrade implementation capacity, weaken communities and intensify pressures on natural resources (World Bank, 2013). In Madagascar, the literature also underscores the importance of the political context in extinction risks and the possible deterioration of conservation enforcement (Schwitzer *et al.*, 2014).

These observations support a gradual shift toward instruments that seek temporal continuity and result-based discipline. In this context, biodiversity is a particularly demanding case. The benefits are heterogeneous and often diffuse, and the horizon over which they materialize frequently exceeds budgetary timeframes. This structure makes commitments difficult to verify and increases the value of an architecture that transforms ecological objectives into observable indicators and then into contractual clauses (Kremen *et al.*, 1994; Margules and Pressey, 2000). A *Lemur Bond* fits within this logic: it targets a trajectory of outcomes rather than a spending program. It nevertheless inherits a central problem: the production of outcomes relies on social and institutional mechanisms that cannot be reduced to a budget, which requires grounding in work on protected-area governance and local behaviours (Corson, 2012; Gardner *et al.*, 2013).

2.3 Sustainable bond markets and sovereign nature-linked instruments

The market for sustainable bonds has been structured around families of instruments whose contractual logics differ. Green bonds are based on the allocation of proceeds to defined uses, with ex ante traceability and ex post reporting. Sustainability-linked bonds shift attention toward measurable objectives: the financial characteristics of the security may vary depending on whether predefined targets are met, which gives indicators the function of contractual triggers (International Capital Market Association, 2023; Organisation for Economic Co-operation and Development, 2024). This distinction matters for biodiversity. Biodiversity projects lend themselves poorly to a fully standardized use-of-proceeds approach, whereas well-designed KPIs can translate a performance commitment, subject to methodological robustness and independent auditing (International Capital Market Association, 2025).

Recent literature stresses the broadening of reference frameworks toward sovereign issuers and nature-related themes. Professional guides highlight the integration of nature indicators into sustainable structures, along with the need for coherence between national strategy, monitoring systems and data transparency (International Capital Market Association, 2023, 2025). At the same time, market reports describe the expansion of sustainable issuance volumes and the gradual entry of sovereigns into issuance clubs, indicating a progressive normalization of labelling and reporting practices (Climate Bonds Initiative, 2024). This dynamic opens space for biodiversity instruments, but it also raises the credibility requirement. Investors arbitrate among return, sovereign risk, liquidity and confidence in the evidence architecture. A sovereign biodiversity instrument must therefore articulate explicitly the environmental logic and the credit-risk logic (Ntsama *et al.*, 2021; Organisation for Economic Co-operation and Development, 2024).

The literature on sovereign debt-for-nature instruments complements this panorama. Debt-conversion operations associated with conservation commitments, often referred to as *debt-for-nature swaps*, have regained interest, notably through blue structures linked to marine protection. The Belize case illustrates this architecture: it combines refinancing, debt-service relief and conservation commitments, with complex contractual and institutional engineering (Fontana-Raina and Grund, 2024; The Nature Conservancy, n.d.). These experiences are not biodiversity bonds in the strict sense, but they show a common principle: conservation can become an explicit condition of a debt trajectory through formalized commitments and monitoring mechanisms.

Finally, an emerging strand proposes valuation frameworks specific to *biodiversity-linked bonds*. A recent contribution advances an option-based pricing approach, formalizing the idea that biodiversity performance introduces a nonlinear payment structure and a distinct risk profile (Chan-Lau, 2025). This literature remains young, but it points in one direction: the instrument cannot be reduced to a labelled bond; it integrates an interaction among ecological trajectory, financial clauses and available information.

2.4 Greenium, credibility and additionality

The question of the *greenium* occupies an important place because it reflects a potential gain in financing cost for the issuer. Analyses devoted to low- and middle-income countries show that the premium depends not only on investor preferences but also on sovereign risk, market depth and above all on the quality of reporting and verification frameworks (Ntsama *et al.*, 2021). In this reading, transparency becomes a financial asset: it can reduce perceived uncertainty, improve demand and influence pricing.

Empirical work nevertheless discusses the existence and size of the greenium depending on periods, sectors and labelling rules. Part of the literature highlights climate effects and positive associations between green issuances and environmental indicators, which strengthens the argument that the instrument is useful for public policy (Ahmed *et al.*, 2023; Flammer, 2020). Another part stresses identification limits and the difficulty of distinguishing the effect of the instrument from the effect of selection. The most virtuous issuers may be more inclined to issue sustainable bonds, which biases simple comparisons (Flammer, 2020).

The debate on additionality thus structures a major critical line. An influential analysis concludes that, in many cases, green bonds finance projects that would have existed without the label, or refinance expenditures already incurred, thereby reducing the marginal impact of the green-bond market on genuinely new investments (Lam and Wurgler, 2024). This critique does not disqualify the instrument, but it does impose safeguards. It reinforces the role of traceability, precise project definition, auditing and disclosure. It also shows that a KPI-based instrument can, in theory, limit some biases, provided indicators do not become targets that are easily manipulated. At this stage, the literature converges on one point: credibility depends on rules of evidence, not only on narrative.

Macro-environmental work adds a complementary dimension. An analysis dealing with the growth of the green-bond market and greenhouse gas emissions discusses the possible links between market expansion and emission trajectories, which highlights the importance of an impact reading at an aggregate scale (Demski *et al.*, 2025). For biodiversity, this perspective implies an adaptation: aggregate impact cannot be reduced to a single variable comparable to emissions. It requires composite indicators or sets of indicators, hence the need for a theory of aggregation and objective prioritization.

2.5 Evidence governance and KPI measurement

Contracting on outcomes rests on a simple principle: the indicator becomes the bridge between ecology and finance. The conservation literature nevertheless warns against weak measurement. Integrated conservation and development programs require credible ecological monitoring to distinguish real effects, natural fluctuations and contextual effects (Kremen *et al.*, 1994). Without robust monitoring, arrangements become non-falsifiable, which prevents learning and weakens policy discipline.

Participatory monitoring experiences in Madagascar reinforce this argument. They show that participatory collection can improve spatial coverage, reduce some costs and strengthen local ownership, provided there is training, standardization and institutional coordination (Andrianandrasana *et al.*, 2005). This literature naturally connects with sustainable finance: when debt service and the cost of capital depend on a KPI, the quality of data collection is no longer only a scientific question; it becomes a contractual variable. The audit system, data publication and conflict-of-interest management then shape overall credibility (International Capital Market Association, 2025; Weber and Saravade, 2019).

Systematic conservation-planning work provides a useful framework for constructing indicators. It reminds us that effective conservation requires coherence among ecological priorities, budget constraints and spatial trade-offs (Margules and Pressey, 2000). In a biodiversity bond, this coherence translates into the choice of measurement units and the management of substitutions. A single indicator may induce opportunistic maximization, whereas a basket of indicators may limit substitutions, but at the cost of increased verification complexity. Recent professional literature oriented toward nature bonds emphasizes precisely this trade-off: the closer the indicator gets to the final outcome, the more difficult verification becomes, but the greater the credibility of impact will be, provided the evidence chain holds (International Capital Market Association, 2025).

Finally, biodiversity implies an additional methodological challenge: the measurement of rare and seasonal events. Work devoted to wildlife consumption shows that recall-based surveys can suffer from substantial errors when the event is rare or strongly seasonal, which requires adapted collection protocols and caution in interpretation (Golden *et al.*, 2013). This limitation does not concern academic research alone. It affects the definition of a KPI if the indicator is based on declarations or on indirect measures that are difficult to audit.

2.6 Socio-ecological determinants in Madagascar

Protected areas lie at the heart of tensions between conservation objectives and human needs. The literature on Madagascar insists that conservation cannot succeed durably without taking livelihoods, access to resources and compensation or alternative economic mechanisms into account (Gardner *et al.*, 2013; Kaimowitz and Sheil, 2007). This logic becomes central in a *Lemur Bond*. If the contract rewards outcomes, it must support trajectories of change compatible with local realities; otherwise pressures are displaced and gains become temporary.

Work on hunting and bushmeat use provides a direct illustration. It shows extensive exploitation of protected species and complex interactions among food constraints, local markets and economic opportunities (Golden, 2009; Jenkins *et al.*, 2011). An economic valuation of these subsistence extractions also highlights the importance of these resources for food security and well-being, which makes any unaccompanied restriction on use politically sensitive (Golden *et al.*, 2014). These results suggest a key point for indicator design: a KPI focused only on the status of a species may ignore the social mechanisms that determine that status. An indicator of livelihoods or pressure reduction may play a complementary role, provided it is verifiably defined.

Social norms and taboos constitute another determinant. Work on Madagascar shows that social prohibitions can support conservation, but their stability depends on cultural, economic and institutional factors (Jones *et al.*, 2008; Keller, 2009). This dimension reinforces the value of an approach that recognizes informal institutions and seeks robust arrangements rather than a strictly coercive model. It also recalls a risk: a strictly quantitative measure may miss qualitative breaks, for example a loss of local legitimacy that precedes a rapid rise in pressures.

The governance of protected areas is finally a decisive constraint. Analyses underline that highly visible conservation policies may fail to establish effective community consultation, which weakens acceptability and implementation (Corson, 2012). In an outcomes-based bond, this issue does not remain peripheral. It influences the capacity to transform mobilized resources into verifiable impacts, and therefore the performance trajectory itself. Work focused on wildlife legal frameworks in Madagascar complements this finding. It describes progress, but also persistent needs, particularly in terms of rule coherence, monitoring capacity and articulation with local practices (Rakotoarivelo *et al.*, 2011). Here, the literature meets the contractual logic: when the contract rewards outcomes, legal effectiveness and enforcement capacity become parameters of the ecological production function.

2.7 Resilience and shock-sensitive contract design

Uncertainty dominates conservation in Madagascar because ecological trajectories depend on climate shocks, anthropogenic pressures and institutional factors. Project documents related to the national system for the scientific management of biodiversity and natural resources emphasize the need for greater resilience in and around protected areas, as well as the country's exposure to recurrent hazards (Global Environment Facility, 2025b). The political crisis and its effects on conservation also remind us that institutional ruptures can amplify risks for species and habitats (Schwitzer *et al.*, 2014; World Bank, 2013).

In the sustainable-finance literature, this uncertainty translates into a requirement for robust indicators and a reflection on contractual clauses. Contemporary frameworks dedicated to nature bonds emphasize consistency among strategy, KPIs and reporting mechanisms, which makes it easier to integrate adjustments and control mechanisms in the event of shocks (International Capital Market Association, 2025). Recent approaches to the pricing of biodiversity-linked bonds also introduce structures that recognize the asymmetry of risks and the nonlinearity of payments associated with performance (Chan-Lau, 2025). In this context, a biodiversity bond should not only aim at a level of performance; it should aim at a capacity to return to trajectory after a shock, because that property conditions the intertemporal credibility of the arrangement.

2.8 Synthesis and research gap

The literature provides four useful lessons. First, sustainable bond instruments can create a financing channel and a discipline of transparency, but impact credibility does not follow from the label (Flammer, 2020; Weber and Saravade, 2019). Second, additionality remains a central condition, and critical findings on green bonds invite the design of safeguards, notably through more demanding indicators and audits (Lam and Wurgler, 2024). Third, biodiversity requires a more complex measurement effort than standardized climate themes, which justifies the attention paid to monitoring systems, protocols and data governance (Andrianandrasana *et al.*, 2005; International Capital Market Association, 2025; Kremen *et al.*, 1994). Fourth, in Madagascar, conservation trajectories depend strongly on local incentives, social norms, poverty and rule-enforcement capacity, which places social and institutional dimensions at the centre of any ecological production function (Corson, 2012; Gardner *et al.*, 2013; Golden *et al.*, 2014; Rakotoarivelo *et al.*, 2011).

These findings reveal a structural gap that motivates the model proposed in the methodology. The literature separately describes the pricing of sustainable bonds, controversies over additionality and the socio-ecological determinants of conservation in Madagascar. It offers fewer integrated frameworks that explicitly connect, within the same system, the cost of capital, ecological production technology, information quality and resilience to shocks. Yet it is precisely this articulation that determines the economic coherence of a *Lemur Bond*: the credibility of evidence influences pricing, pricing influences fiscal space, fiscal space influences action and action influences the ecological trajectory under uncertainty (Chan-Lau, 2025; Global Environment Facility, 2025b; Ntsama *et al.*, 2021). The methodological section takes up this point and formalizes a framework that makes these dependencies observable and testable.

3. Methodology

This section presents an integrated framework that links (1) the pricing of a sovereign instrument indexed to biodiversity indicators, (2) a production function for ecological outcomes financed by the issuance and (3) an economic valuation of environmental benefits. The whole aims at a direct economic interpretation and transparent computational implementation while taking into account the uncertainty that characterizes ecological trajectories in Madagascar (Global Environment Facility, 2025a, b; Schwitzer *et al.*, 2014).

The *Lemur Bond* is treated as a KPI-linked sovereign bond: part of its financial conditions depends on a biodiversity-related performance index. This approach differs from purely *use-of-proceeds* green bonds because of the structuring role of indicators and the increased importance of independent verification (International Capital Market Association, 2023, 2025). The model deliberately retains a parsimonious form in order to make the essential mechanisms visible, and then organizes robustness analysis through Monte Carlo simulations and a stochastic impulse response.

3.1 Theoretical framework: governance, financing, outcomes and value

The theoretical structure can be summarized as a sequence of linked mechanisms. Let G denote the quality of governance and evidence, including additionality, monitoring capacity, audit independence, reporting timeliness, dispute-resolution rules and community legitimacy. Governance affects the greenium so that

$$\eta = \eta(G), \qquad \eta'(G) > 0, \tag{1}$$

where a more credible evidence architecture lowers the return required by investors. Because the relevant discount rate is $r - \eta(G)$, stronger governance raises the issue price P_0 for a given coupon or permits the sovereign to lower the coupon for a target level of proceeds.

The second mechanism links net financing to conservation action. Let M denote resources effectively available for field implementation after compliance and transaction costs. A parsimonious representation is

$$M = \max\{\alpha P_0 - \kappa F + \Gamma, 0\}, \quad (2)$$

where α is the share of proceeds allocated to conservation and resilience activities, κF is the cost of certification, monitoring and verification and Γ represents concessional co-financing, reserve funding, a liquidity facility, or partial support from international partners. This specification is used directly in the ecological production function, the Monte Carlo simulation and the scenario appendix. Therefore, κ is not only a fiscal-cost parameter: a higher compliance burden reduces the resources reaching field implementation. Conversely, a positive Γ increases the implementation scale, especially in the multilateral-support scenario.

The third mechanism transforms implementation resources into outcomes through M, not through gross proceeds alone. Biodiversity performance is modelled as a composite index because a species-only measure may ignore habitat loss or local pressure, whereas a purely socioeconomic indicator may obscure biological deterioration. The final mechanism values outcomes through discounted ecosystem services. In compact form, the causal chain is therefore

$$G \rightarrow \eta(G) \rightarrow P_0 \rightarrow M \rightarrow I(t) \rightarrow V_{\text{env}}. \quad (3)$$

This chain clarifies the theoretical contribution of the paper. Evidence governance is not a residual implementation condition; it is a pricing variable, a fiscal-space variable and a determinant of ecological persistence. The model complements green-bond pricing studies by embedding the cost of capital in a conservation-production and verification system.

3.2 Institutional perimeter, repayment source and partner roles

The baseline structure assumes a sovereign reference obligor because official preparation documents identify the Republic of Madagascar as the recipient of preparation support and the Ministry of Economy and Finance as the signatory authority, while the Ministry of Environment and Sustainable Development leads implementation arrangements for the preparation activities (International Development Association, 2025). The final market structure may still choose among direct sovereign issuance, a sovereign-authorized special-purpose vehicle, or an outcome-payment structure supported by donors. The modelling choice is therefore explicit: coupon and principal obligations are treated as sovereign obligations serviced through the debt-service budget, whereas conservation expenditures and outcome payments are tracked through a ring-fenced biodiversity account or equivalent financial-management mechanism.

International partners may support the instrument through four channels. First, they may provide partial guarantees or liquidity facilities that reduce perceived default risk p. Second, they may provide concessional co-financing Γ for monitoring, protected-area operations, or post-shock recovery. Third, they may finance technical assistance for remote sensing, biodiversity inventories and community monitoring. Fourth, they may support independent verification, without replacing the verifier's independence. These roles are separated in the model because guarantees affect financial sustainability, while technical and verification support affect G, η, α and δ.

3.3 Financial structure of the Lemur Bond *and primary pricing*

Let F denote face value (principal), T the maturity (in years), c the annual coupon rate and r a reference discount rate interpreted either as a risk-free rate or as a social discount rate depending on the chosen reading. The sustainable character of the instrument is reflected in a green premium (greenium) $\eta \geq 0$ that reduces the return required by investors when the environmental commitment is credible and traceable (Climate Bonds Initiative, 2024; Ntsama *et al.*, 2021). The relevant discount rate for primary pricing then becomes $r - \eta$.

The issue price P_0 corresponds to the present value of contractual cash flows:

$$P_0 = \sum_{t=1}^{T} \frac{cF}{(1+r-\eta)^t} + \frac{F}{(1+r-\eta)^T}. \tag{4}$$

Equation (4) captures a central point: environmental credibility affects the cost of capital. When η increases, the discount rate falls, which raises P_0 for a given pair (F, c). Two interpretations coexist. The first emphasizes the budgetary advantage: for a targeted amount of net resources, the issuer can reduce c or reduce F for an equivalent debt service. The second emphasizes the conservation effort: with financial structure unchanged, an increase in P_0 expands the space of effective financing available for field actions, subject to compliance costs.

3.4 Expected fiscal cost, compliance costs and default risk

A transparency-based instrument requires certification, monitoring and auditing arrangements. Let κ denote the proportional compliance and verification cost (as a percentage of face value), assumed to be borne by the issuer. The literature stresses that these costs are not a simple administrative friction: they condition investor confidence and therefore the green premium (International Capital Market Association, 2025; Weber and Saravade, 2019). They therefore enter the intertemporal budget constraint of the arrangement.

We then introduce a probability of default $p \in [0, 1)$, cautiously interpreted as a risk of partial non-payment associated with macro-budgetary shocks, liquidity tensions, or an incomplete guarantee architecture. The issuer's expected discounted cost, denoted C_{tot}, is defined by

$$C_{tot} = \sum_{t=1}^{T} (cF + \kappa F)(1-p)^t e^{-rt} + F(1-p)^T e^{-rT}. \tag{5}$$

Equation (5) distinguishes two channels. The first channel is contractual: debt service (cF and F) depends on the financial terms. The second channel is institutional: the compliance cost κF reflects the effort of proof. The term $(1-p)^t$ formalizes an expected payment discount; it does not represent a default strategy, but summarizes a risk that is imposed on the issuer in an uncertain environment. This structure remains compatible with extensions in which p depends on climate shocks or revenue trajectories, as discussed in the Discussion section.

3.5 Ecological block: production of outcomes and definition of the performance index

The ecological block links net implementation resources to an outcome index $I(t)$, defined in continuous time and discretized in annual steps. The index aggregates outcomes that are verifiable and comparable over time, and then serves as the basis for the KPI mechanism. We retain a decreasing-returns technology in which net field resources are given by M in Equation (2). To avoid unit dependence, the implementation scale is measured in millions of dollars, $m = M/10^6$. The production function takes the form:

$$I(t) = A m^{\beta} e^{-\delta t}, \qquad m = \frac{M}{10^6}. \tag{6}$$

where $A > 0$ represents organizational efficiency (implementation capacity, coordination and partnership quality), $\beta \in (0, 1)$ captures decreasing returns to funded effort and $\delta > 0$ summarizes ecological depreciation in a broad sense (return of pressures, habitat degradation, maintenance costs of protection, losses related to shocks) (Global Environment Facility, 2025a, b; Kremen *et al.*, 1994).

Expression (6) fulfills three functions. First, it imposes a monotonic relationship between net implementation resources and outcomes, which is indispensable for economic interpretation. Second, it makes compliance costs and concessional co-financing operational in the outcome trajectory: higher κ reduces M, whereas higher Γ raises it. Third, it introduces a simple temporal dynamic: at constant effort, performance declines at rate δ, which reflects the idea that durable conservation requires recurrent expenditures and continuous vigilance.

The productivity scale is calibrated once at the reference scenario rather than re-normalized in each simulation draw. Let $M^{\star}$ denote the reference value of Equation (2), $m^{\star} = M^{\star}/10^6$ and $\beta^{\star}$ the reference elasticity. The calibration is

$$A = \frac{I^{\star}}{(m^{\star})^{\beta^{\star}}}. \tag{7}$$

This calibration keeps the reference case interpretable while allowing α, κ, Γ, η and β to affect the level of $I(t)$ whenever they modify the implementation scale or its productivity.

The index $I(t)$ must also reflect the plurality of objectives associated with credible conservation. A robust approach defines a composite index from three families of indicators: (1) a biological indicator $L(t)$ related to lemur populations (abundance, probability of persistence, reproduction), (2) a habitat indicator $H(t)$ (quality, fragmentation and deforestation rate) and (3) a socioeconomic indicator $S(t)$ (alternative income, food security, resilience of livelihoods). We then define

$$I(t) = \omega_L L(t) + \omega_H H(t) + \omega_S S(t), \qquad \omega_L + \omega_H + \omega_S = 1, \quad \omega_i \geq 0. \tag{8}$$

Structure (8) reduces the risk of substitution across objectives. An improvement in $S(t)$ should not mask a deterioration in $L(t)$ or $H(t)$, which justifies the introduction of floor rules that can be built into the contract:

$$L(t) \geq \underline{L}, \qquad H(t) \geq \underline{H}. \tag{9}$$

This choice responds to an empirical constraint documented in the ecological-monitoring literature: combining heterogeneous information sources improves learning and reduces dependence on a single potentially manipulable indicator (Andrianandrasana *et al.*, 2005; Kremen *et al.*, 1994). Habitat indicators can be estimated through remote sensing, biological indicators rely on inventories and targeted monitoring, while socioeconomic indicators come from household surveys and administrative data. This triangulation supports the credibility of the instrument in an outcome-based logic (International Capital Market Association, 2025).

3.6 Economic valuation: present value of ecosystem services

The arrangement aims to create social value beyond the financial value of the bond. We approximate this social value through a net present value. A shadow value V_e measures the social value of one unit of outcomes. Total environmental value is defined by

$$V_{\text{env}} = \sum_{t=0}^{T} I(t)\ V_e\ e^{-rt}. \tag{10}$$

Equation (10) does not claim to summarize all biodiversity in a single price; it provides an operational aggregate that facilitates comparison with fiscal costs. The parameter V_e may reflect estimates of ecosystem services, non-use values, avoided costs and resilience benefits.

In the Malagasy case, the applied literature discusses precisely the economic contribution of protected areas and the value of uses, including subsistence uses, which justifies a cautious reading and sensitivity analyses (Cooke *et al.*, 2022; Golden *et al.*, 2014).

3.7 Coupon indexation: KPI mechanism and risk sharing

The KPI-linked character of the *Lemur Bond* materializes in the indexation of the coupon to performance. Let C_t denote the coupon payment at date t. A simple formulation makes the coupon depend on a performance ratio relative to the target $I^\star$:

$$C_t = cF\left[1 + \theta\left(\frac{I(t) - I^\star}{I^\star}\right)\right], \tag{11}$$

where θ controls the intensity of indexation.

The parameter θ governs the contract's central trade-off. A high value strengthens the incentive and increases the sensitivity of debt service to performance. A value that is too high may nevertheless amplify budget volatility if outcomes fluctuate, particularly under climate shocks. In a sovereign application, contractual bounds are often required to avoid negative coupons or excessive jumps. One may thus introduce floors and caps:

$$C_t = \min\left\{\overline{C}, \max\left\{\underline{C},\ cF\left[1 + \theta\left(\left(I(t) - I^\star\right)/I^\star\right)\right]\right\}\right\}. \tag{12}$$

Indexation may also play an implicit insurance role. After an unfavourable environmental shock, a decline in $I(t)$ reduces C_t, which eases the debt burden at the moment the state must finance an emergency response. This mechanism does not cancel the shock; it redistributes part of the risk over time, provided investors accept this structure in exchange for adequate initial pricing (International Capital Market Association, 2023; Organisation for Economic Co-operation and Development, 2024).

Operationally, the KPI mechanism requires a separation between measurement, verification and adjudication. Measurement would combine remote-sensing indicators for habitat, biological surveys for lemur populations and socioeconomic surveys for pressure reduction and community resilience. The implementing agencies would transmit raw and processed data to an independent verifier selected before issuance. The verifier would certify the annual value of $I(t)$, document uncertainty and publish a summary report. If the target is missed because of implementation failure, the contract may activate a coupon step-up, a required transfer to a conservation reserve, or a corrective-action plan. If the target is missed because of a verified force majeure event, such as a severe cyclone or wildfire, the contract may activate a temporary grace period or a resilience clause. Disputes over data, attribution, or force majeure would be handled by a predefined technical committee and, if unresolved, by the legal dispute-resolution mechanism stated in the bond documentation. The formula in (11) is therefore a reduced-form representation of risk sharing; practical implementation should distinguish avoidable underperformance from certified exogenous shocks.

3.8 Implicit default threshold and sustainability indicators

To assess the financial viability of the arrangement, we define an implicit default threshold. It corresponds to the level $\overline{p}$ that keeps the expected present value of payments equal to face value F, given the required rate $r - \eta$. The calculation yields a closed-form expression:

$$\overline{p} = 1 - \frac{1 + r - \eta}{1 + c} = \frac{c - (r - \eta)}{1 + c}. \tag{13}$$

Equation (13) provides a readable metric: if c is low and if $r - \eta$ remains high, $\overline{p}$ falls, which means that the arrangement becomes more fragile in the face of default risk. Conversely, a higher greenium (larger η) lowers the required rate and increases the safety margin. This reading reinforces the idea that evidence governance influences sustainability through the green premium (Lam and Wurgler, 2024; Ntsama *et al.*, 2021).

We complement this with a benefit-cost ratio (BCR) that compares environmental value created to expected fiscal cost:

$$\mathrm{BCR} = \frac{V_{\mathrm{env}}}{C_{\mathrm{tot}}}. \tag{14}$$

A value BCR >1 indicates that expected social value exceeds discounted fiscal cost under the maintained assumptions. This metric depends heavily on V_e and on the dynamics of outcomes. It is therefore systematically accompanied by sensitivity analyses. The corresponding analytical derivations and alternative definitions of the pricing, default-threshold, composite-index and coupon specifications are provided in Appendix A.

3.9 Shocks, resilience and stochastic impulse response

The ecological trajectory is exposed to shocks such as cyclones, wildfires and episodes of anthropogenic pressure. We formalize these disturbances through a dynamic for deviation ΔI_t around the reference trajectory. We retain a first-order autoregressive process with damping:

$$\Delta I_t = \rho_t \, \Delta I_{t-1} + \varepsilon_t, \qquad |\rho_t| < 1, \tag{15}$$

where ε_t represents a stochastic innovation whose variance declines over time when damping is introduced, and where ρ_t may decline with t to reflect a gradual return to equilibrium after a shock.

In a simple version, $\rho_t = \rho$ is constant, which yields an analytical mean impulse response. For an initial shock $\Delta I_0 < 0$ and $\mathbb{E}[\varepsilon_t] = 0$:

$$\mathbb{E}[\Delta I_t] = \rho^t \, \Delta I_0. \tag{16}$$

Resilience is measured by the time required to return to a zone of normality. For a threshold $\tau \leq 0$, we define the mean return time:

$$T_R(\tau) = \min\{t \geq 0 : \mathbb{E}[\Delta I_t] \geq \tau\}. \tag{17}$$

We complement this with a probabilistic measure because the mean may hide an asymmetric distribution:

$$\pi_\tau = \mathbb{P}(\min_{0 \leq s \leq T} \Delta I_s < \tau). \tag{18}$$

These metrics bring conservation closer to a risk-management language: they distinguish the magnitude of the shock, the speed of return and the probability of a persistent critical state. This distinction is decisive for the design of a KPI-linked contract because it informs the value of θ and the choice of contingency clauses.

3.10 Monte Carlo simulation: parameter uncertainty and distributions of indicators

The empirical analysis relies on two robustness devices. The first introduces parameter uncertainty on $(\alpha, \beta, \delta, \eta, \kappa, \Gamma)$ and computes a distribution of V_{env}, BCR and $\overline{p}$ through Monte Carlo simulation. The second simulates the shock dynamic (15) in order to obtain a stochastic impulse response and confidence intervals.

For parameter uncertainty, we define sampling distributions centred on a baseline scenario. An operational specification retains truncated normal distributions in order to respect economic domains:

$$\begin{aligned}&\alpha \sim \mathcal{N}\left(\mu_\alpha, \sigma_\alpha^2\right) \text{ truncated to } (0,1) \beta \sim \mathcal{N}\left(\mu_\beta, \sigma_\beta^2\right) \text{ truncated to } (0,1)\\&\delta \sim \mathcal{N}\left(\mu_\delta, \sigma_\delta^2\right) \text{ truncated to } \mathbb{R}_+, \quad \eta \sim \mathcal{N}\left(\mu_\eta, \sigma_\eta^2\right) \text{ truncated to } \mathbb{R}_+,\\&\kappa \sim \mathcal{N}\left(\mu_\kappa, \sigma_\kappa^2\right) \text{ truncated to } \mathbb{R}_+, \quad \Gamma \sim \mathcal{N}\left(\mu_\Gamma, \sigma_\Gamma^2\right) \text{ truncated to } \mathbb{R}_+.\end{aligned} \tag{19}$$

For each draw $j = 1, \ldots, N$, we compute successively: $P_0^{(j)}$ via (4); $M^{(j)}$ via (2); $I^{(j)}(t)$ via (6); $V_{\text{env}}^{(j)}$ via (10) $\overline{p}^{(j)}$ via (13) and $\text{BCR}^{(j)}$ via (14).

From these we derive distribution statistics (mean, median, quantiles) and probabilities of critical events (for example $\mathbb{P}(\text{BCR} < 1)$). This approach aligns with a practical requirement: ecological and institutional parameters remain uncertain even when the theory of change is clear (Global Environment Facility, 2025a, b; Kremen *et al.*, 1994).

For the stochastic impulse response, we simulate N trajectories of (15) over a horizon T_{IRF} and construct confidence bands (for example, 75% and 90%) from empirical quantiles. We then report $T_R(\tau)$ and π_τ, which characterizes resilience beyond an average trajectory. The complete Monte Carlo and stochastic impulse-response procedures are detailed in Appendix B.

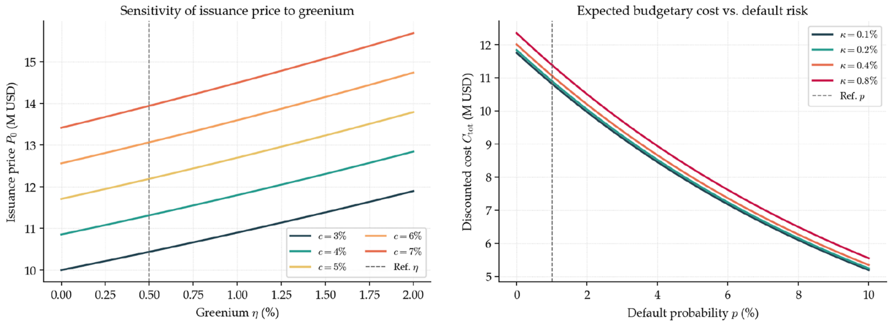
4. Results

The analytical framework laid out in our methodology depends on a handful of structural parameters whose values are not uniquely determined by the data at hand. We therefore work in two stages. First, we fix a *reference calibration* and trace out the full model solution, from bond pricing through environmental valuation and resilience metrics. Second, we systematically disturb that calibration through Monte Carlo draws and one-at-a-time perturbations, asking how much each source of uncertainty matters for the conclusions that are most relevant to investors, to the sovereign issuer and to conservation practitioners. The remainder of this section presents findings from the four computational modules in turn, with cross-references between figures kept explicit so that the narrative can be read in parallel with the graphics.

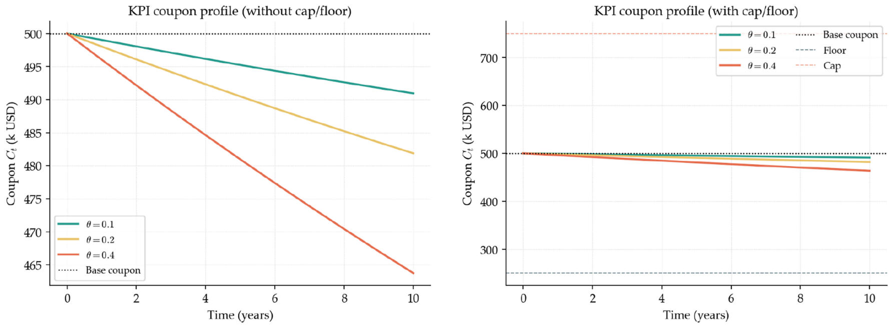
4.1 Financial structure: pricing, greenium and the cost of compliance

4.1.1 Reference bond price. Under the baseline calibration ($F = \$10$ M, $T = 10$, $c = 5\%$, $r = 3\%$, $\eta = 0.5\%$, $\kappa = 0.2\%$, $p = 1\%$), the issuance price computed from Equation (4) equals $P_0 = 12.19$ M USD, placing the bond at a 21.9% premium over par. The net implementation envelope equals $M = 10.34$ M USD after allocation and compliance costs. The expected discounted cost to the issuer, C_{tot} from Equation (5), amounts to 10.90 M USD, implying that a meaningful fiscal surplus arises from the combination of a relatively modest default probability and the dampening effect of the greenium on the effective discount rate. These two numbers bracket the deal economics: the sovereign captures just over \$1.3 M in net present-value terms on the issuance itself, before any account is taken of the environmental returns generated by deploying the proceeds.

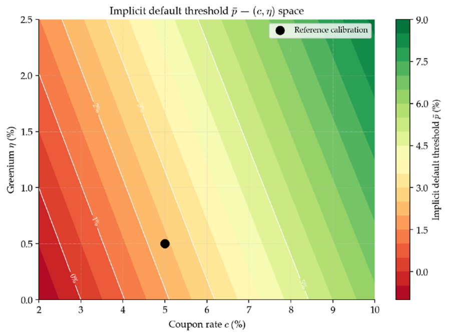
4.1.2 Greenium sensitivity and coupon mechanics. Figure 1 brings together three complementary diagnostics. Panel (a) traces P_0 as a function of the greenium η for five values of the coupon rate ranging from 3% to 7%. The relationship is strictly monotone and approximately linear over the range of η considered here, reflecting the near-proportional reduction in the effective discount rate. Crucially, the slope of each curve is the same regardless of c: the greenium operates as a parallel shift in the discount factor, so its value-creation



(a) Left: Issuance price P_0 as a function of the greenium η for five coupon rates ($c = 3\%$ to 7%). The dashed vertical line marks the reference calibration ($\eta = 0.5\%$). **Right:** Expected discounted cost C_{tot} as a function of the default probability p for four levels of compliance cost κ



(b) KPI-indexed coupon C_t over the bond's ten-year life for three indexation intensities ($\theta = 0.10, 0.20, 0.40$), without contractual bounds **(left)** and with a floor at 50% and a cap at 150% of the base coupon **(right)**



(c) Heatmap of the implicit default threshold $\bar{p}$ over the (c, η) plane (Eq. (13)). White contour lines are drawn at 0%, 1%, 2%, 3%, and 5%. The black dot marks the reference calibration

Figure 1. Financial structure of the Lemur Bond. Panel (a) documents the sensitivity of the issuance price and budgetary cost to the greenium and to the default risk, respectively. Panel (b) illustrates how the KPI-linked coupon formula re-distributes cash flows over the bond's life depending on the intensity of the indexation parameter. Panel (c) maps the region of the (c, η) space that keeps the instrument financially viable from the sovereign's perspective, under the reference maturity and risk-free rate

potential is independent of whether the sovereign chooses a high- or low-coupon structure. In practice, this is encouraging for a first-time issuer such as Madagascar, because it suggests that committing to a credible monitoring and verification architecture – the channel through which η materializes – pays off regardless of the coupon chosen to attract a diverse investor base.

Panel (a) also shows, on its right-hand side, how the expected budgetary cost C_{tot} varies with the default probability p for four levels of the compliance cost κ. At $p = 1\%$, the differences across κ levels are small enough to be almost invisible – compliance costs matter at the margin but do not dominate the fiscal arithmetic. That picture changes above $p \approx 4\%$, where the curves fan out noticeably: under elevated default risk, the compounding of $(1-p)^t$ over a ten-year horizon amplifies any additional fixed cost the issuer bears per period. The practical implication is that investing in institutional capacity to keep p low is at least as important as negotiating a lean verification contract.

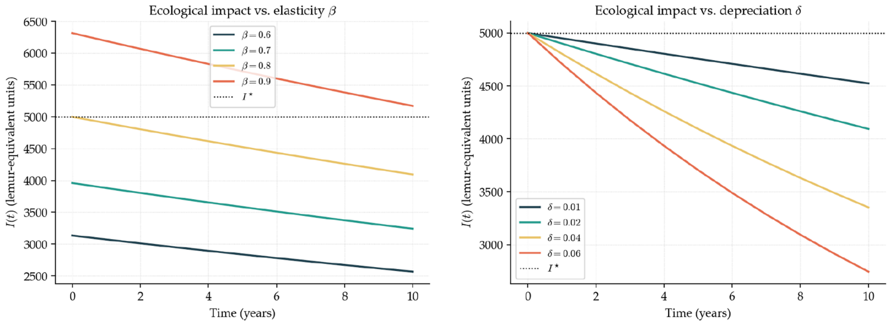
Panel (b) plots the KPI-indexed coupon C_t defined in Equation (11) over the bond's life, with and without contractual cap and floor. Without bounds, the coupon trajectory with $\theta = 0.40$ drops by roughly \$18 k per year relative to the base coupon as ecological performance declines gradually – a decline built into the reference calibration through the depreciation parameter δ. The floor at 50% of the base coupon acts as a fiscal stabiliser: even in the most adverse scenario, the sovereign's annual debt service cannot fall below half of its contractual level, limiting the extent to which a KPI shortfall translates into a windfall for the issuer at the expense of investors. The cap at 150% performs the symmetric function, protecting the sovereign from paying excessive coupons in years when ecological outcomes happen to overshoot the target – something that could matter if a particularly favourable monsoon season temporarily inflates the lemur census.

Panel (c) turns to the implicit default threshold $\overline{p}$ defined in Equation (13). The heatmap plots $\overline{p}$ over the (c, η) plane, with contour lines at 0%, 1%, 2%, 3% and 5%. The reference calibration (black dot) sits comfortably in the 2%–3% band, meaning the instrument can absorb default probabilities up to that level before the expected payment stream falls below the required return. Two features of the heatmap deserve particular attention. First, the iso-$\overline{p}$ contours run almost diagonally, confirming that greenium and coupon are near-perfect substitutes in sustaining financial viability: a sovereign that cannot raise c can achieve the same solvency buffer by strengthening its environmental credibility (and thereby enlarging η). Second, the iso-$\overline{p} = 0$ contour passes close to the $(\eta = 0, c = r = 3\%)$ corner, illustrating the boundary condition: a bond priced at the risk-free rate with no greenium has essentially zero margin for default.

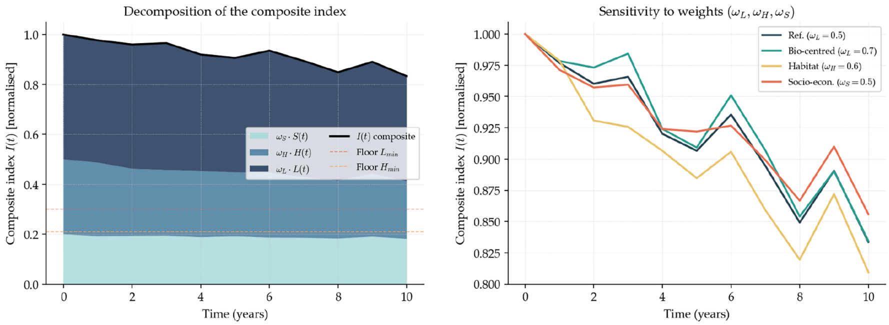
4.2 Ecological production, composite index and environmental valuation

4.2.1 Trajectory of ecological impact. The ecological production function in Equation (6) links net field implementation resources–captured by $M = \max\{\alpha P_0 - \kappa F + \Gamma, 0\}$–to a time-varying index of lemur protection. Figure 2, Panel (a) examines how the trajectory of $I(t)$ responds to changes in the two key structural parameters: the output elasticity β and the ecological depreciation rate δ.

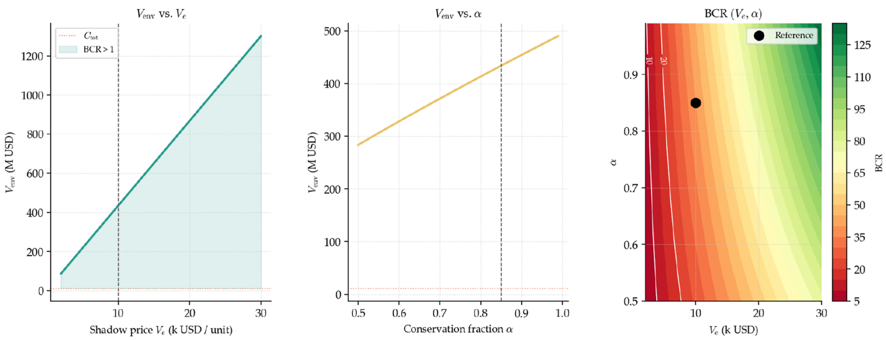
The left subplot makes the diminishing-returns structure visible. Increasing β from 0.60 to 0.90 changes how strongly net implementation resources are transformed into initial outcomes, because the productivity scale is calibrated once at the reference scenario rather than re-normalized for each elasticity value. Higher β gives more weight to the implementation scale in early periods and can generate steeper subsequent decline when effort is not maintained, a pattern that resonates with field evidence on the front-loaded nature of initial habitat restoration. The right subplot tells a starker story: as δ rises from 0.01 to 0.06, the ten-year trajectory collapses from near-stationarity to a roughly 45% loss by maturity. A δ of that magnitude is not implausible in a context where the cessation of direct ranger activity–plausible if funding gaps emerge–allows encroachment to resume at its historical rate. The implication for contract design is clear: the bond's monitoring framework should be calibrated



(a) Ecological impact trajectories $I(t)$ over a ten-year horizon. **Left:** sensitivity to output elasticity β (δ fixed at 0.02). **Right:** sensitivity to ecological depreciation δ (β fixed at 0.80). The dotted horizontal line marks the conservation target $I^\star = 5{,}000$ lemur-equivalents



(b) Composite index decomposition (Eq. (8)). **Left:** stacked area chart of the three sub-indicators under reference weights ($\omega_L = 0.50$, $\omega_H = 0.30$, $\omega_S = 0.20$); dashed lines indicate the contractual floors $\underline{L}$ and $\underline{H}$. **Right:** composite index under four alternative weighting schemes



(c) Environmental valuation and benefit-cost efficiency. **Left:** V_{env} vs. shadow price V_e; shaded region indicates BCR > 1. **Centre:** V_{env} vs. conservation fraction α. **Right:** BCR heatmap over the joint (V_e, α) space; white contour lines at BCR $= 1, 5, 10, 20$

Figure 2. Ecological production, composite index and environmental valuation. Panel (a) maps how the elasticity and depreciation parameters shape the ten-year conservation trajectory. Panel (b) unpacks the composite index into its biological, habitat and socioeconomic components and demonstrates the sensitivity of the aggregate measure to the choice of weights. Panel (c) quantifies the environmental value created relative to the budgetary cost of the instrument under a range of assumptions about the shadow price and the efficiency of fund deployment and net implementation resources

to detect rising δ early, before the deviation from target triggers a coupon adjustment that has already become fiscally disruptive.

4.2.2 Composite index and weight sensitivity. Panel (b) addresses a concern that is rarely made explicit in the KPI-linked bond literature: what happens when the aggregate index $I(t)$ moves in ways that obscure underlying ecological trade-offs? To examine this, we decompose $I(t)$ into its three constituent sub-indicators–biological ($L(t)$, lemur abundance), habitat ($H(t)$, forest cover and fragmentation) and socioeconomic ($S(t)$, local livelihoods)–using the composite structure defined in Equation (8).

The stacked area chart on the left of Panel (b) reveals that, under the reference weights ($\omega_L = 0.50$, $\omega_H = 0.30$, $\omega_S = 0.20$), the biological component accounts for roughly half of the composite value throughout the bond's life, with habitat contributing a stable secondary share and the socioeconomic component tracking a smoother, slower-declining path. The dashed horizontal lines mark the contractual floors $\underline{L}$ and $\underline{H}$ introduced in Equation (9): both are satisfied over the full horizon under the reference calibration, but the biological floor is reached well before year ten once δ is elevated.

The right subplot of Panel (b) plots four alternative weighting schemes and highlights that the ranking of scenarios is not robust across specifications. A bio-centred index ($\omega_L = 0.70$) produces a markedly steeper downward trend than the reference, while a socioeconomic-centred index ($\omega_S = 0.50$)–more reflective of community-based conservation metrics–shows considerably greater stability. This divergence is not an artefact of model assumptions: it reflects the genuine heterogeneity of conservation outcomes, and it suggests that the choice of weights should be grounded in a transparent stakeholder process rather than determined unilaterally by the issuer or the underwriter.

4.2.3 Environmental valuation and benefit-cost efficiency. Panel (c) brings together the monetary dimension of the exercise through three complementary displays. The leftmost plot shows V_{env} as a function of the shadow price V_e, with the horizontal dashed line marking C_{tot}. The shaded region above that line corresponds to configurations where the benefit-cost ratio exceeds one: at the reference V_e of \$10,000 per lemur-equivalent, V_{env} reaches \$433.7 M, yielding a BCR of approximately 39.8. This figure is large by the standards of most conservation finance instruments, but it should be treated as an upper bound under optimistic assumptions about the shadow price and the completeness of the ecosystem service valuation. At $V_e = \$2,000$ – roughly a fifth of the reference value – the BCR still exceeds seven, comfortably above the viability threshold.

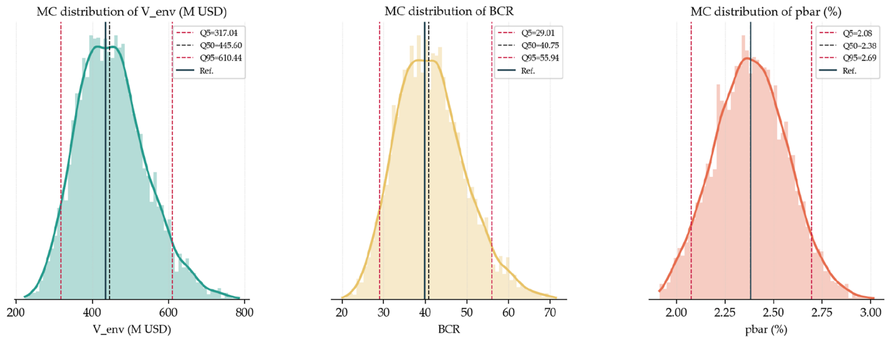
The central plot repeats the exercise for the conservation fraction α, holding κ and Γ at their reference values. Over the range [0.50, 0.99], V_{env} rises approximately logarithmically, a direct consequence of the concavity imposed by $\beta < 1$ in the production function. Moving from $\alpha = 0.50$ to $\alpha = 0.85$ captures roughly 70% of the total welfare gain from raising α all the way to unity – the familiar implication that the first increments of a conservation investment are the most valuable ones.

The rightmost panel plots BCR jointly as a function of both V_e and α, with M adjusting through Equation (2), revealing a nearly separable structure: the two determinants compound rather than interact in any complex non-linear fashion, and the BCR exceeds five across essentially the entire region shown, collapsing below one only at very low values of V_e (below \$1,000) that are difficult to justify on the basis of any credible ecosystem service estimate for Madagascar's lemur forests.

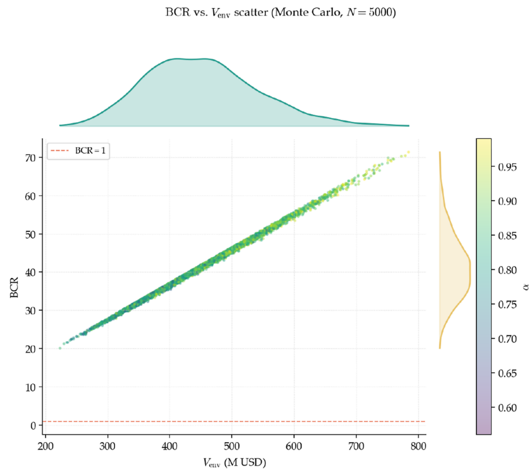
4.3 Monte Carlo analysis: parametric uncertainty and distributional outcomes

The preceding subsections established the model's behaviour at a fixed calibration point. We now turn to the question that arguably matters most for practical deployment: *how sensitive are the conclusions to the parameter values themselves?* We address this by drawing $N = 5,000$ independent samples from the truncated normal distributions specified in Equation (19), propagating each draw through the full model and recording the resulting distributions of V_{env}, BCR and $\bar{p}$, while allowing compliance costs and concessional support to enter through M.

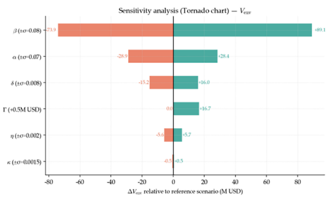
4.3.1 Distributional properties. Figure 3, Panel (a) displays the empirical density of each output, with quantile markers at the 5th, 50th and 95th percentiles and a vertical line at the deterministic reference value.



(a) Empirical densities from $N = 5{,}000$ Monte Carlo draws (histogram plus kernel density estimate) of V_{env} **(left)**, BCR **(centre)**, and implicit default threshold $\bar{p}$ **(right)**. Dashed lines mark the 5th and 95th percentiles; the solid black line is the median; the navy line is the deterministic reference value



(b) Joint scatter of BCR vs. V_{env} across all Monte Carlo draws, coloured by the realised value of the conservation fraction α. Side panels show the univariate marginal densities. The horizontal dashed line marks BCR = 1



(c) Tornado chart: marginal contribution of each sampled parameter to variation in V_{env}, evaluated at ± 1 standard deviation around the reference value. Green (rightward) bars indicate upward shocks; red (leftward) bars indicate downward shocks

Figure 3. Monte Carlo analysis of parametric uncertainty. Panel (a) shows that the distributions of the key output indicators are approximately symmetric and well-bounded, with the implicit default threshold never approaching zero. Panel (b) reveals a strongly positive joint dependence between BCR and environmental value, with α providing a secondary upward gradient. Panel (c) ranks the parameters by their contribution to environmental-value uncertainty, identifying output elasticity, allocation efficiency and ecological depreciation as central sources of risk

The distribution of V_{env} is centred around a mean of approximately \$452.2 M (standard deviation of about \$90.0 M). Its dispersion is wider than in the gross-proceeds specification because α, κ and Γ now alter the effective implementation scale M before ecological outcomes are produced. The 90% interquantile range spans roughly \$293 M, which is still far from the viability boundary under the maintained shadow-value assumptions. The BCR distribution follows the same broad pattern, with a simulated mean close to 41.4, because both environmental value and compliance-adjusted cost respond to the sampled institutional parameters.

The distribution of $\overline{p}$ is the most practically consequential of the three: it determines the structural solvency buffer. The simulated mean of 2.38% is barely distinguishable from the analytic reference value – a reassuring confirmation of internal consistency – and the 90% interval runs from roughly 2.1%–2.7%. Crucially, $\overline{p}$ never approaches zero across all 5, 000 draws, confirming that the instrument retains meaningful insolvency headroom across the full range of parameter uncertainty considered here.

4.3.2 Joint distribution and portfolio character. Panel (b) plots the joint scatter of BCR against V_{env}, with each point coloured by the realized value of α. Several features of this plot deserve comment. First, the cloud of points is essentially elliptical with a principal axis running from the lower left to the upper right, indicating a strong positive correlation between the two output metrics: parameter draws that generate high environmental value also tend to generate high benefit-cost ratios, as one would expect from the model structure. Second, the colour gradient – darker tones for low α, lighter for high α – shows a moderate upward shift as α increases, consistent with the sensitivity documented in Panel (c) of Figure 2. Third, no single point falls below BCR $=$ 1, and the marginal distributions shown in the side panels are symmetric and unimodal. Taken together, these features suggest that the Lemur Bond, as calibrated, does not carry tail risk in the conventional sense: the conditions under which it would become a net fiscal liability require parameter combinations that lie well outside the range of the sampling distributions.

4.3.3 Tornado analysis. Panel (c) distils the Monte Carlo evidence into a tornado chart that ranks the sampled parameters by their marginal contribution to variation in V_{env}. Each bar reports the change in V_{env} when the corresponding parameter moves from its reference value to one standard deviation above (green, rightward bar) or below (red, leftward bar), holding all other parameters fixed.

The output elasticity β emerges as the largest marginal driver in the local sensitivity exercise: a one-sigma downward shock reduces V_{env} by roughly \$73.9 M, whereas a one-sigma upward shock raises it by approximately \$89.1 M. This effect is amplified by the fixed reference productivity scale and by the fact that the net implementation envelope is measured in millions of dollars. The conservation fraction α ranks second, with perturbations of about \$28.9-\$28.4 M, followed by ecological depreciation δ, concessional support Γ, the greenium η and compliance cost κ. A one-sigma increase in δ reduces environmental value by about \$15.2 M, while a downward shift raises it by about \$16.0 M. A grant-like support envelope of \$0.5 M raises V_{env} by approximately \$16.7 M through M. The implication for practitioners is straightforward: monitoring effort should be prioritized where uncertainty is highest and where impact is greatest. In this specification, both the productivity of net resources and ecological persistence warrant careful empirical attention in the Malagasy context.

4.4 Stochastic impulse response and resilience

The financial and ecological modules treat environmental outcomes as a function of funding inputs. The resilience module asks a different and arguably harder question: what happens to those outcomes after the funding is committed but an exogenous shock – a cyclone, a wildfire, an episode of large-scale agricultural encroachment – disrupts the conservation trajectory mid-horizon? We formalize this through the stochastic impulse response function generated by the AR(1) process in Equation (15), calibrated with an initial shock of $\Delta I_0 = -0.15$ (a 15%

instantaneous loss relative to the ecological target), a persistence coefficient $\rho = 0.70$ and a stochastic volatility of $\sigma = 0.045$, simulated over $N = 1,000$ independent paths and a twenty-year horizon.

4.4.1 Main IRF: dynamics, uncertainty and recovery. Figure 4, Panel (a) is the centrepiece of this analysis. The fan of grey paths in the background represents 300 randomly selected individual trajectories, giving a direct visual sense of the dispersion that accumulates over time. The blue shaded bands mark the empirical 75% and 90% confidence intervals; the red and green lines trace the sample mean and median, respectively; and the dash-dotted line plots the analytical mean response $\rho^t \Delta I_0$ from Equation (16).

Several observations emerge from this panel. To begin with, the mean and median diverge slightly during the first five years, with the median recovering somewhat faster. This asymmetry is a signature of the positive skewness of the shock distribution: a small fraction of paths experience secondary adverse draws early on and pull the mean down relative to the median. It is exactly this kind of distributional nuance that scalar metrics like the mean recovery time fail to capture, and it underscores why the stochastic framing is preferable to a purely analytical approach.

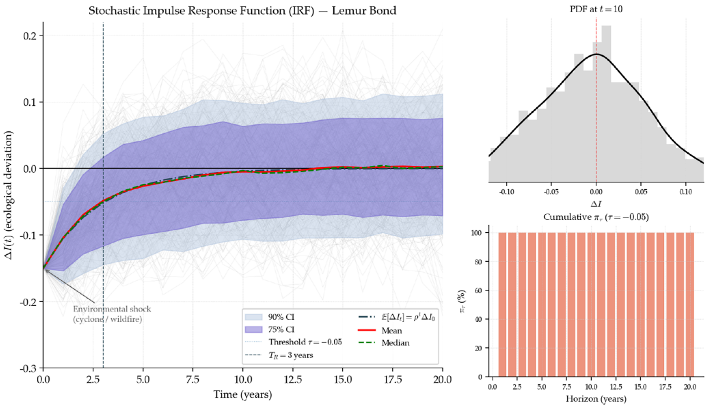
The analytical mean crosses the normalcy threshold $\tau = -0.05$ at $T_R = 3$ years, a figure that is reasonably encouraging for the bond's 10-year maturity: by the time the first KPI assessment takes place – typically around year three or four in similar instruments – the expected ecological deviation should be within acceptable bounds. The dashed vertical line at year three provides a visual anchor for that interpretation.

The two inset panels at the right of the figure add distributional depth. The upper inset shows the empirical density of ΔI at year 10, estimated by kernel density. The distribution is approximately centred on zero, confirming that the average trajectory has converged back to the pre-shock baseline by mid-horizon. The residual dispersion – a 90% range of roughly $[-0.08, +0.08]$ at $t = 10$ – reflects the cumulation of stochastic innovations over the preceding decade, not the persistence of the original shock. The lower inset plots the cumulative critical probability π_τ by horizon, defined in Equation (18). This reaches 100% at all horizons because the initial shock of -0.15 automatically breaches the threshold $\tau = -0.05$ at $t = 0$: every path, by construction, passes through the critical zone at least once. The interesting variation lies across scenarios – a point taken up in Panel (b) – rather than within the reference simulation.

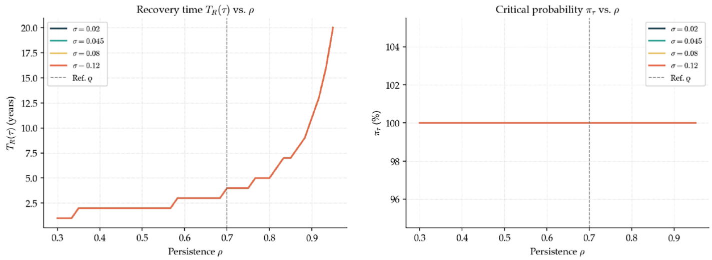
4.4.2 Resilience metrics across the parameter space. Panel (b) extends the analysis by varying ρ continuously from 0.30 to 0.95 for four values of σ. The left subplot plots the analytical recovery time $T_R(\tau)$: it rises steeply with ρ and is unaffected by σ (since the mean response $\rho^t \Delta I_0$ is deterministic). At $\rho = 0.30$ the shock is practically absorbed within two years; at $\rho = 0.90$ it takes around eleven years, which already exceeds the bond's maturity. This has a direct contractual implication: KPI assessments scheduled in the first three years of a high-persistence environment are likely to catch the system still in recovery, potentially triggering coupon adjustments that do not reflect a genuine failure of the conservation programme but rather the irreducible inertia of post-shock ecology. Scheduling a "grace period" in the bond's early years – during which KPI shortfalls are noted but not penalized – is one mechanism to address this; the analytics here provide a quantitative basis for sizing that window.

The right subplot plots the simulated critical probability π_τ for the same grid. Here, σ matters: at low persistence ($\rho = 0.30$) but high volatility ($\sigma = 0.12$), the probability of breaching τ at some point over twenty years is comparable to that under higher persistence ($\rho = 0.85$) with moderate volatility ($\sigma = 0.045$). This substitutability between persistence and noise in generating tail risk suggests that investors concerned with downside ecological outcomes should pay attention to both dimensions, not just to the speed of mean reversion.

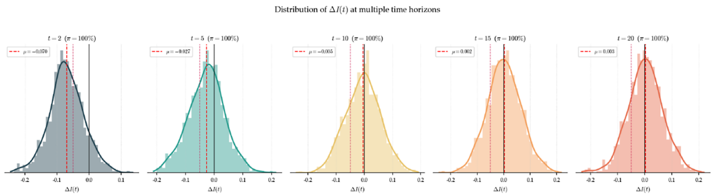
4.4.3 Distributional evolution across horizons. Panel (c) completes the picture by plotting the full empirical density of $\Delta I(t)$ at five snapshots: $t = 2, 5, 10, 15$ and 20 years. At $t = 2$ the distribution is tightly clustered around a still-negative mean, reflecting the persistence of the initial shock; by $t = 5$ the centre of mass has moved close to zero; and by $t = 10$ – the bond's



(a) Stochastic IRF for an initial shock $\Delta I_0 = -0.15$, $\rho = 0.70$, $\sigma = 0.045$, $N = 1{,}000$ simulations over a 20-year horizon. Main panel: individual trajectories (grey), 75% and 90% confidence bands (shaded), sample mean (red), sample median (green, dashed), and analytical mean response (dash-dotted). The dotted horizontal line marks the normality threshold $\tau = -0.05$; the dashed vertical line marks the analytical recovery time $T_R = 3$ years. **Upper inset:** empirical density of ΔI at $t = 10$ (histogram + kernel density estimate). **Lower inset:** cumulative critical probability π_τ by horizon



(b) Resilience metrics as a function of the persistence parameter ρ (horizontal axis) for four volatility levels $\sigma \in \{0.02, 0.045, 0.08, 0.12\}$. **Left:** analytical mean recovery time $T_R(\tau)$ (years to cross $\tau = -0.05$). **Right:** simulated critical probability π_τ over a twenty-year window (500 paths per parameter pair). The dashed vertical line marks the reference $\rho = 0.70$



(c) Empirical distribution of $\Delta I(t)$ at five horizon snapshots ($t = 2, 5, 10, 15, 20$ years). Each panel overlays a histogram and a kernel density estimate; the vertical red dashed line marks $\tau = -0.05$; the dashed red vertical line marks the snapshot mean. The cumulative critical probability π_τ up to each snapshot date is annotated in the panel title

Figure 4. Stochastic impulse response and ecological resilience. Panel (a) presents the full distributional dynamics following an acute environmental shock, together with inset diagnostics for the mid-horizon density and the cumulative probability of breaching the critical threshold. Panel (b) maps recovery time and critical probability across a two-dimensional grid of persistence and volatility values, identifying the combinations under which KPI measurement may be contaminated by natural recovery dynamics. Panel (c) tracks the evolution of the ΔI distribution from early recovery through long-run stationarity, documenting the gradual re-centring of ecological outcomes after the shock

maturity – the distribution is approximately centred, with a symmetric spread that diminishes only slowly as stochastic innovations continue to drive paths apart. The critical probability π_τ annotated in each subplot title is 100% for all horizons from $t = 2$ onwards, consistent with the initial breach at $t = 0$. What varies is the *magnitude* of the deviation and the probability of being in negative territory at the snapshot date, both of which decline monotonically with time. By $t = 20$, the unconditional probability of observing a negative value of ΔI is only marginally above 50%, reflecting the near-zero mean and the symmetric innovation structure of the AR(1) process.

Taken as a whole, these results paint a picture of an instrument that is financially robust across a wide range of conditions, ecologically productive under plausible parameter combinations and resilient to acute environmental shocks in the sense that the expected deviation returns to manageable levels well within the bond's contractual horizon. That said, the analysis also surfaces genuine sources of fragility: high ecological depreciation can erode environmental value faster than any realistic monitoring response can detect; high shock persistence can cause KPI metrics to lag the recovery of the underlying ecosystem; and the distributional spread of ecological outcomes at any given horizon is wide enough that individual projects could see significantly worse or better trajectories than the mean.

5. Discussion and recommendations

The simulations highlight a simple reality: a market instrument alone does not guarantee a robust conservation trajectory. The *Lemur Bond* creates a financing channel and a discipline of transparency. Ecological performance nevertheless remains determined by field mechanisms, implementation capacity and resilience to shocks. The discussion is organized around four axes: the credibility of additionality, the evidence architecture, the contractual design of KPIs and the integration of socio-institutional determinants specific to Madagascar.

One result emerges consistently: the green premium η is not an exogenous datum. It results from a judgement of credibility. That judgement depends on the quality of information, the traceability of flows and the consistency between promise and realization. Recent literature underscores that the label is not enough and that additionality remains a central condition (Lam and Wurgler, 2024). This critique is particularly acute in biodiversity. The boundary between "financing what already exists" and "financing change" often remains blurry, especially when budget lines or prior projects are repackaged under a sustainable label. The risk is not limited to an academic controversy. A reclassification of the instrument as greenwashing reduces η, increases the cost of capital and can weaken the fiscal balance of the structure. This mechanism is illustrated by the weak- and strong-governance scenarios reported in Table 1 and their corresponding outcomes in Table 2 in Appendix D.

Two recommendations follow. The first concerns accounting and operational separation. The expenditures financed must be isolated within a traceable chain, with an explicit mapping of activities and links with indicators. The second concerns the demonstration of additionality. It requires an explicit counterfactual scenario: the arrangement must show what would not have taken place without the issuance. This demonstration gains credibility when it combines physical indicators, implementation schedules, audits and systematic publication of deviations.

The Monte Carlo simulation indicates a substantial dispersion of environmental value, which points to structural parameter uncertainty. In a KPI logic, this uncertainty is acceptable if it is recognized, framed and reduced over time. Additional robustness checks on the discount rate, the shadow value and correlations among model parameters are reported in Appendix C. Evidence then becomes an infrastructure. It requires a monitoring system, minimal standardization of protocols and independent auditing, as recommended by contemporary guides for nature-linked instruments (International Capital Market Association, 2025).

The conservation literature reminds us that weak ecological monitoring makes learning impossible and reduces the capacity to distinguish real effects from noise (Kremen *et al.*, 1994). Participatory monitoring experiences in Madagascar show an operational path: participatory collection can strengthen coverage and ownership, provided there is investment in training, coordination and validation (Andrianandrasana *et al.*, 2005).

Three recommendations structure this architecture. First, a data protocol published before issuance, with definitions, periodicity, methods, limitations and update procedures. Second, an external audit with a clear mandate, separation of roles and publication of conclusions. Third, a triangulation strategy: remote sensing for habitat, biological inventories for populations and socioeconomic indicators for anthropogenic pressure and resilience. This triangulation limits dependence on a single indicator and reduces vulnerability to manipulation.

The choice of a composite index $I(t)$ responds to a well-identified risk: a single target may generate opportunistic substitutions in which one result improves at the expense of another. The floor rules proposed in the methodology provide a simple response. They require a minimum level of performance on biological and habitat components, which prevents an apparent socioeconomic improvement from masking a deterioration of natural capital. This logic connects with the idea of conservation planning: multiple objectives must remain coherent with spatial and budget constraints (Margules and Pressey, 2000).

Two trade-offs nevertheless need to be made explicit. The first concerns complexity. The more dimensions the index integrates, the more costly and demanding verification becomes. The second concerns interpretation. Investors and public decision-makers must understand what the index measures. An effective strategy is to retain a composite index while simultaneously publishing the disaggregated components. This transparency facilitates auditing, reduces misunderstandings and strengthens confidence.

On the financial mechanism, coupon indexation through θ must avoid turning a conservation instrument into a source of budget instability. The stochastic impulse response illustrates a phase of vulnerability after a shock. In this context, cap-and-floor clauses on coupons, together with a mechanism for handling extreme events, reduce the risk of penalizing the issuer for shocks that exceed its capacity to control. These adjustments align with recommended practices for KPI-linked bonds, where the credibility of the objective is accompanied by prudent management of financial effects (International Capital Market Association, 2023; Organisation for Economic Co-operation and Development, 2024).

In Madagascar, conservation unfolds in a system where poverty, social norms, subsistence pressures and institutional capacity interact. Work on bushmeat shows that subsistence extraction contributes to well-being and food security, which makes any restriction politically sensitive (Golden, 2009; Golden *et al.*, 2014; Jenkins *et al.*, 2011). Taboos and social norms can support conservation, but their stability depends on social cohesion and the legitimacy of institutions (Jones *et al.*, 2008; Keller, 2009). Analyses of protected-area governance highlight tensions around community consultation and decision power, which influence policy acceptability (Corson, 2012; Gardner *et al.*, 2013). Finally, work on wildlife legal frameworks reminds us that the effectiveness of rules depends on normative coherence, monitoring capacities and articulation with local practices (Rakotoarivelo *et al.*, 2011).

These elements transform the reading of simulation results. The parameters α and A do not represent technical efficiency alone. They summarize institutional compromises: coordination quality, stability of arrangements, social acceptability, effectiveness of controls and continuity of governance. One recommendation follows: the instrument must integrate, into its theory of change and its indicators, mechanisms for pressure reduction and economic alternatives rather than treating the social dimension as a marginal co-benefit. This orientation reduces the risk of displaced pressure and increases the persistence of gains.

Public GEF documentation for GEF ID 11694 emphasizes Madagascar's recurrent exposure to shocks and the need to strengthen resilient landscape and seascape management around protected areas (Global Environment Facility, 2025a, b). The literature on conservation during political crises also recalls the vulnerability of arrangements when institutional capacities deteriorate (Schwitzer *et al.*, 2014; World Bank, 2013). In this context, resilience as measured by the impulse response should not remain a descriptive result. It should influence contractual and operational design.

Two recommendations emerge. First, integrate contingency triggers based on extreme events in order to allow temporary flexibility in objectives or financial clauses while preserving credibility. Second, structure a stabilization reserve, whether budgetary or financial, to fund rapid responses after shocks. Without this type of mechanism, the instrument may be hit by a double effect: ecological shock, then deterioration in implementation capacity, which weakens the performance trajectory.

The framework is not a generic model of every green bond. It can be adapted to other nature-linked instruments, but its structure is designed for a Lemur Bond because the outcome is species-habitat specific, spatially tied to Madagascar's protected areas and dependent on local livelihoods, rule enforcement and shock resilience. A conventional green bond financing renewable energy or clean transport can often use standardized physical indicators, such as installed capacity or avoided emissions. A Lemur Bond requires a composite indicator, biological and habitat floors, community-sensitive pressure indicators and a verification system capable of handling rare ecological observations and post-shock recovery. For this reason, the title retains the Lemur Bond focus while acknowledging that some analytical blocks, especially pricing and uncertainty propagation, can inform broader biodiversity-bond design.

The credible implementation of the *Lemur Bond* requires a coherent set of choices. A realistic pathway relies on the following elements.

First, a clear definition and hierarchy of objectives. Objectives must be formulated in terms of outcomes, but anchored in an explicit theory of change linking activities, outputs and outcomes, with testable assumptions.

Second, an ex ante evidence architecture. Before issuance, publish a measurement protocol, baseline series, the reporting calendar and quality-control methods. Publication reduces uncertainty and strengthens credibility (International Capital Market Association, 2025).

Third, robust independent auditing. Separation of roles, transparency of reports and public access to audit summaries limit controversies and support the green premium (Weber and Saravade, 2019).

Fourth, a readable KPI structure. Retain a composite index, publish the components, impose biological and habitat floors and limit budget sensitivity through coupon caps and floors.

Fifth, explicit integration of communities. Benefit-sharing mechanisms and economic alternatives must be incorporated both into activities and into indicators, given the role of livelihoods in pressures on wildlife and habitat (Gardner *et al.*, 2013; Golden *et al.*, 2014).

Sixth, a resilience strategy. Establish shock-related contingency clauses and an intervention reserve in order to avoid a rupture of trajectory after major shocks (Global Environment Facility, 2025a, b).

6. Conclusion

This article has proposed an integrated framework for analyzing the *Lemur Bond*, an officially supported biodiversity-finance operation under preparation in Madagascar and not yet an issued market security. The model links financial pricing (green premium, compliance costs and default risk) to the production of ecological outcomes (decreasing returns, depreciation and composite index with floor rules), and then to an economic valuation of environmental benefits. The simulations highlight a structuring asymmetry. Financial parameters govern the cost of capital and sustainability, whereas field parameters dominate the performance trajectory and expected social value.

Three findings emerge. First, the green premium acts as a credibility channel: it depends on evidence governance and additionality, which implies that data infrastructure, auditing and transparency become decisive economic variables (International Capital Market Association, 2025; Lam and Wurgler, 2024; Ntsama *et al.*, 2021). Second, environmental value remains highly sensitive to allocation efficiency and the persistence of gains, which points back to protected-area governance, local incentives and institutional continuity (Corson, 2012; Gardner *et al.*, 2013; Schwitzer *et al.*, 2014). Third, resilience to shocks must be integrated into contractual design because Madagascar's exposure to hazards and institutional ruptures makes trajectories vulnerable even when the mean returns to equilibrium (Global Environment Facility, 2025a, b; World Bank, 2013).

The main contribution lies in the explicit articulation of finance, ecology and evidence. It clarifies the mechanisms by which a market instrument can support conservation, while also showing the conditions necessary to prevent the arrangement from being reduced to mere labelling. The limitations stem from the illustrative character of the calibration and from the availability of data needed to estimate precisely the parameters of ecological production, depreciation and valuation. A natural extension consists in empirically estimating the parameters from monitoring series, remote-sensing data, household surveys and administrative data and then testing the robustness of the model against observed shock scenarios. A second extension aims at the explicit integration of legal and governance mechanisms, notably the effectiveness of rule enforcement and the organization of use rights, which determine the persistence of results (Rakotoarivelo *et al.*, 2011).

Ultimately, a *Lemur Bond* appears to be a potentially relevant instrument for stabilizing conservation financing in Madagascar, provided that the evidence chain is designed as an infrastructure and that the contract recognizes the socio-ecological determinants governing performance. In that configuration, sustainable finance does not replace conservation policy. It can become one of its levers by disciplining transparency, lowering the cost of capital and supporting trajectories of verifiable outcomes.

Data availability
No new data set was created in this research. Replication materials supporting the findings of this study (model code, calibration targets and simulation outputs) are available on the GitHub repository.

Supplementary material
The supplementary material for this article can be found online.

References

Ahmed, R., Yusuf, F. and Ishaque, M. (2023), "Green bonds as a bridge to the UN sustainable development goals on environment: a climate change empirical investigation", *International Journal of Finance and Economics*, Vol. 29 No. 2, pp. 2428-2451, doi: 10.1002/ijfe.2787.

Andrianandrasana, H.T., Randriamahefasoa, J., Durbin, J., Lewis, R.E. and Ratsimbazafy, J.H. (2005), "Participatory ecological monitoring of the Alaotra wetlands in Madagascar", *Biodiversity and Conservation*, Vol. 14 No. 11, pp. 2757-2774, doi: 10.1007/s10531-005-8413-y.

Chan-Lau, J.A. (2025), "Biodiversity linked bonds: an option pricing based valuation approach", *Finance Research Open*, Vol. 2 No. 1, 100086, doi: 10.1016/j.finr.2025.100086.

Climate Bonds Initiative (2024), *Sustainable Debt: Global State of the Market 2023 (Report Updated February 2024; Coverage as of 31 December 2023)*, Climate Bonds Initiative, available at: https://www.climatebonds.net/files/documents/publications/Global-State-of-the-Market-Report-2023.pdf (accessed 21 February 2026).

Cooke, A., Ranaivoarison, R., Andriamahefazafy, F. and Fenn, M. (2022), "The economic contribution of Madagascar's protected areas: a review of the evidence", Final version for translation.

Corson, C. (2012), “From rhetoric to practice: how high-profile politics impeded community consultation in Madagascar’s new protected areas”, *Society and Natural Resources*, Vol. 25 No. 4, pp. 336-351, doi: 10.1080/08941920.2011.565454.

Demski, J., Dong, Y., McGuire, P. and Mojon, B. (2025), “Growth of the green bond market and greenhouse gas emissions”, *BIS Quarterly Review*, pp. 53-64.

Flammer, C. (2020), “Green bonds: effectiveness and implications for public policy”, *Environmental and Energy Policy and the Economy*, Vol. 1 No. 1, pp. 95-128, doi: 10.1086/706794.

Fontana-Raina, S. and Grund, S. (2024), “Debt-for-nature swaps: the Belize 2021 deal and the future of green sovereign finance”, *Capital Markets Law Journal*, Vol. 19 No. 2, pp. 128-151, doi: 10.1093/cmlj/kmad024.

Gardner, C.J., Nicoll, M.E., Mbohoahy, T., Oleson, K.L.L., Ratsifandrihamanana, A.N., Ratsirarson, J., René de Roland, L., Virah-Sawmy, M., Zafindrasilivonona, B. and Davies, Z.G. (2013), “Protected areas for conservation and poverty alleviation: experiences from Madagascar”, *Journal of Applied Ecology*, Vol. 50 No. 6, pp. 1289-1294, doi: 10.1111/1365-2664.12164.

Global Environment Facility (2025a), “Madagascar science-based management of biodiversity and natural resources for economic development project (GEF ID 11694)”, available at: https://www.thegef.org/projects-operations/projects/11694 (accessed 24 July 2026).

Global Environment Facility (2025b), *Work Program for GEF Trust Fund: 69th GEF Council Meeting, GEF/C.69/02*, Global Environment Facility, available at: https://www.thegef.org/sites/default/files/documents/2025-05/EN_GEF.C.69.02_Work%20Program%20for%20GEF%20Trust%20Fund-May17.pdf (accessed 24 July 2026).

Global Environment Facility (2025c), “Gef funds to boost resilient livelihoods and landscapes”, available at: https://www.thegef.org/newsroom/news/gef-funds-boost-resilient-livelihoods-and-landscapes (accessed 24 July 2026).

Golden, C.D. (2009), “Bushmeat hunting and use in the Makira forest, north-eastern Madagascar: a conservation and livelihoods issue”, *Oryx*, Vol. 43 No. 3, pp. 386-392, doi: 10.1017/S0030605309000131.

Golden, C.D., Wrangham, R.W. and Brashares, J.S. (2013), “Assessing the accuracy of interviewed recall for rare, highly seasonal events: the case of wildlife consumption in Madagascar”, *Animal Conservation*, Vol. 16 No. 6, pp. 597-603, doi: 10.1111/acv.12047.

Golden, C.D., Bonds, M.H., Brashares, J.S., Rasolofoniaina, B.J.R. and Kremen, C. (2014), “Economic valuation of subsistence harvest of wildlife in Madagascar”, *Conservation Biology*, Vol. 28 No. 1, pp. 234-243, doi: 10.1111/cobi.12174.

International Capital Market Association (2023), *Sustainability-linked Bond Principles*, ICMA, available at: https://www.icmagroup.org/assets/documents/Sustainable-finance/2023-updates/Sustainability-Linked-Bond-Principles-June-2023-220623.pdf (accessed 21 February 2026).

International Capital Market Association (2025), *Sustainable Bonds for Nature: A Practitioner’s Guide*, ICMA, available at: https://www.icmagroup.org/assets/documents/Sustainable-finance/2025-updates/Sustainable-Bonds-for-Nature-A-Practitioners-Guide-June-2025.pdf (accessed 21 February 2026).

International Development Association (2025), “Grant no. e5800 preparation grant for the landscape seascape management and lemur bond operations project: letter agreement”, available at: https://documents1.worldbank.org/curated/en/099091125101023967/pdf/P512499-e9444da2-316b-4c42-85af-f8d3385127ef.pdf (accessed 24 July 2026).

International Monetary Fund (2024), “Madagascar launches country platform for climate finance through international partnership”, available at: https://www.imf.org/en/news/articles/2024/11/14/pr-24420-madagascar-launches-country-platform-for-clim-fin-through-international-partnership (accessed 24 July 2026).

Jenkins, R.K.B., Keane, A., Rakotoarivelo, A.R., Rakotomboavonjy, V., Randrianandrianina, F.H., Razafimanahaka, H.J., Ralaiarimalala, S.R. and Jones, J.P.G. (2011), “Analysis of patterns of bushmeat consumption reveals extensive exploitation of protected species in eastern Madagascar”, *PLoS One*, Vol. 6 No. 12, e27570, doi: 10.1371/journal.pone.0027570.

Jones, J.P.G., Andriamarovololona, M.M. and Hockley, N. (2008), "The importance of taboos and social norms to conservation in Madagascar", *Conservation Biology*, Vol. 22 No. 4, pp. 976-986, doi: 10.1111/j.1523-1739.2008.00970.x.

Kaimowitz, D. and Sheil, D. (2007), "Conserving what and for whom? Why conservation should help meet basic human needs in the tropics", *Biotropica*, Vol. 39 No. 5, pp. 567-574, doi: 10.1111/j.1744-7429.2007.00332.x.

Keller, E. (2009), "The danger of misunderstanding 'culture'", *Madagascar Conservation and Development*, Vol. 4 No. 2, pp. 82-85, doi: 10.4314/mcd.v4i2.48647.

Kremen, C., Merenlender, A.M. and Murphy, D.D. (1994), "Ecological monitoring: a vital need for integrated conservation and development programs in the tropics", *Conservation Biology*, Vol. 8 No. 2, pp. 388-397, doi: 10.1046/j.1523-1739.1994.08020388.x.

Lam, P. and Wurgler, J. (2024), "Green bonds: new label, same projects", Working Paper No. 32960, National Bureau of Economic Research, doi: 10.3386/w32960.

Margules, C.R. and Pressey, R.L. (2000), "Systematic conservation planning", *Nature*, Vol. 405 No. 6783, pp. 243-253, doi: 10.1038/35012251.

Minamata Convention on Mercury (2025), "Madagascar science-based management of biodiversity and natural resources for economic development project", available at: https://minamataconvention.org/en/projects/madagascar-science-based-management-biodiversity-and-natural-resources-economic (accessed 24 July 2026).

Ntsama, U.Y.O., Yan, C., Nasiri, A. and Mbouombouo Mboungam, A.H. (2021), "Green bonds issuance: insights in low- and middle-income countries", *Financial Innovation*, Vol. 7 No. 1, pp. 1-23, doi: 10.1186/s40991-020-00056-0.

Organisation for Economic Co-operation and Development (2024), *Sustainability-linked Bonds: How to Make Them Work in Developing Countries, and How Donors Can Help*, OECD Publishing, available at: https://one.oecd.org/document/DCD(2024)4/en/pdf (accessed 21 February 2026).

Rakotoarivelo, A.R., Razafimanahaka, J.H., Rabesihanaka, S., Jones, J.P.G. and Jenkins, R.K.B. (2011), "Lois et règlements sur la faune sauvage à Madagascar: progrès accomplis et besoins du futur", *Madagascar Conservation and Development*, Vol. 6 No. 1, pp. 37-44, doi: 10.4314/mcd.v6i1.68063.

Schwitzer, C., Mittermeier, R.A., Johnson, S.E., Donati, G., Irwin, M., Peacock, H., Ratsimbazafy, J., Razafindramanana, J., Louis, E.E., Jr, Chikhi, L., Colquhoun, I.C., Tinsman, J., Dolch, R., LaFleur, M., Nash, S., Patel, E., Randrianambinina, B., Rasolofoharivelo, T. and Wright, P.C. (2014), "Averting lemur extinctions amid Madagascar's political crisis", *Science*, Vol. 343 No. 6173, pp. 842-843, doi: 10.1126/science.1245783.

The Nature Conservancy (n.d.), "Case study: Belize debt conversion for marine conservation", available at: https://www.nature.org/content/dam/tnc/nature/en/documents/TNC-Belize-Debt-Conversion-Case-Study.pdf (accessed 21 February 2026).

Weber, O. and Saravade, V. (2019), "Green bonds: current development and their future (tech. rep.)", Technical Report, doi: 10.13140/RG.2.2.10059.82722.

World Bank (2013), "Madagascar: measuring the impact of the political crisis", available at: http://www.worldbank.org/en/news/feature/2013/06/05/madagascar-measuring-the-impact-of-the-political-crisis (accessed 21 February 2026).

Corresponding author
Ambinintsoa Ramanambonona can be contacted at: ambinintsoa.uat.ead2@gmail.com