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Ecological and economic impacts of increasing landscape connectivity in ecological corridors of Tanzania

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1. Introduction

Biodiversity loss remains a significant global challenge that impacts ecosystem integrity, particularly in terms of diminishing long-term ecological productivity and resilience (Ekka et al., 2023). In Sub-Saharan Africa (SSA), biodiversity loss can be predominantly attributed to agricultural activities (Jellason et al., 2021) and there is a considerable risk of subsequent negative impact on ecosystem services and livelihoods (Millennium Ecosystem Assessment, 2005; Nkonya et al., 2016). The provisioning and flow of ecosystem goods and services, depend on landscape connectivity (Elisa et al., 2024), making landscape-level restoration not only more desirable but also economically beneficial (Banerjee et al., 2021) compared to fragmented restoration efforts (Parkhurst et al., 2002; Bacar, 2025).

Conservation of ecological corridors has been proposed as a cost-effective solution to improve landscape connectivity (Liang et al., 2018; Beltrão et al., 2024). Ecological corridors are understood as structural landscape that connect protected areas enabling the movement of ecosystem goods and services, whether currently occurring or potentially possible (Caro et al., 2009; Souraditya Chakraborty, 2025). However, in degraded corridors (e.g., due to agricultural expansion), effective conservation depends on the surrounding social and political context (Lin et al., 2026), including social norms, farmers' willingness to conserve, cost–benefit considerations and collective actions (Goldman, 2009). Concerns about the direct costs and benefits of conservation appears to play the most influential role in conservation decision-making, compared to other latent variables (Wainaina et al., 2020).

Landscape connectivity, typically requires coordinated conservation decisions by different actors, including farmers, who are landholders, and the government that establish conservation programs and enforces compliance (Banerjee et al., 2017). However, such coordinated decisions often incur additional costs beyond opportunity costs for farmers (e.g., transaction costs related to coordination) (Banerjee et al., 2017) and the implementing government (e.g., expenses for mobilizing farmers and enforcing compliance). These costs and potential conservation benefits, however, are context-specific (e.g., varying across different socio-ecological systems) and likely to depend on the desired as well as existing level of conservation and landscape connectivity (Deppe et al., 2025). Understanding potential

costs and benefits of conservation measures in ecological corridors for different stakeholders and under different scenarios of connectivity is important in designing cost-effective and just conservation policies. In this study, we examine the ex-ante ecological and economic impacts of enhancing landscape connectivity in ecological corridors for farmers and the implementing government.

Higher connectivity of ecological corridors provides conservation benefits allowing a better flow of ecosystem goods and services between protected areas (Windle et al., 2009). They also provide climate change mitigation and adaptation opportunities e.g., in terms of higher carbon sequestration (Burger, 2000; Sayer et al., 2004). These ecological benefits often offer positive livelihoods outcomes (Liang et al., 2018). For example, the increased movement of wildlife populations has been shown to enhance eco-tourism opportunities, thereby boosting both local and national income (Burger, 2000; Haddad et al., 2014; Liang et al., 2018). Ecosystem goods and services from restored ecological corridors may also support environmentally friendly livelihoods, such as beekeeping (DeFries et al., 2007) and butterfly farming (Morgan-Brown et al., 2010; Anderson & Saidi, 2011). Additionally, local economies can benefit from increased carbon storage and carbon trading, while contributing to global efforts to mitigate the effect of climate change (Koh et al., 2021).

Within degraded ecological corridors, connectivity requires reduced agricultural activities and allow natural regeneration on retired agricultural land. Natural regeneration is widely considered the most cost-efficient restoration strategy compared to afforestation or reforestation, and is increasingly recognized as a an effective conservation approach for low-income regions such as sub-Sahara Africa (Holl & Aide, 2011; Chazdon & Guariguata, 2016). The role of government in shaping and enforcing restoration policies is therefore as essential as the willingness of farmers to retire privately owned land (Dayer et al., 2018). However, retiring agricultural land for conservation purposes is often associated not only with concerns over land grabbing (Goldman, 2009) but also with significant opportunity costs for farmers (Schaub et al., 2023). Consequently, only few farmers are likely to withdraw their land from cultivation (Yang et al., 2020) unless incentives, for example payments are provided to compensate for the loss (Nyanghura et al., 2024). While limited retirements may intensify farms-biodiversity interactions and escalating conservation costs, for example through

increasing human-wildlife conflicts (HWC), large-scale contiguous conservation is likely to reduce negative externalities (e.g., from HWC) relative to a lower scale and fragmented conservation (Haddad et al., 2014). Other costs include transaction costs of coordination (e.g., costs of bargaining, negotiation, or communications), which are likely to increase if many farmers are involved in the coordination process (Banerjee et al., 2012; Banerjee et al., 2017). This leads to variable conservation costs across different levels of landscape connectivity.

These costs endured by farmers could, potentially be compensated by returns from conservation-compatible livelihoods (He & Jiao, 2023). But in most cases such returns, are context-dependent, shaped by the area's specific agricultural and ecological potential (Huber et al., 2021). In SSA, for instance, wildlife-rich ecosystems are more likely to benefit from eco-tourism (Manrai et al., 2020; Meyer et al., 2021), whereas forest-based landscapes provide greater opportunities for carbon sequestration (Burger, 2000; Sayer et al., 2004). However, when the direct returns from conservation-compatible enterprises fall short of the costs incurred by farmers, conservation efforts should still be recognized, valued and compensated by the governments or the international community because it represents contributions to the public good (Wainaina et al., 2020).

Therefore, it is essential for farmers and governments to assess the potential ecological and economic impacts of their conservation decisions in order to optimize conservation and social welfare. Such assessments are, however, challenged by complex social-ecological systems characterized by multiple interactions between different factors (e.g., socioeconomic and demographic factors, local contextual factors, intrinsic motivations, management approaches, and national and international regulations (Rode et al., 2015; Gonçalves et al., 2020; Preiser et al., 2021). This high systemic complexity can increase uncertainty for farmers and governments when identifying and quantifying costs and benefits of their decisions. Potential risks can further reinforce uncertainty, climate change, for example, can negatively affect forest conditions (Corlett, 2016; Jun et al., 2025), the amount of carbon sequestered (Costanza & Terando, 2019), farmer livelihoods, and the country's economy at large (Lottering et al., 2021). A global market crisis could also lower market opportunities for ecosystem goods and services, such as eco-tourism and carbon trading.

Common deterministic empirical models (e.g., traditional cost-benefit analysis) often ignore such risks and uncertainties (see Naidoo & Ricketts, 2006 and Wainaina et al., 2020) due to data scarcity, poor data quality, or prohibitive costs of data acquisition (Landuyt et al., 2014). While, this undermines informed decisions by farmers and governments, analytical tools from the field of Decision Analysis can help to address this challenge effectively. Relevant factors for decision-making (e.g., costs, benefits, and potential risks) can be measured, estimated, or valued, even in the face of uncertainty (Howard, 1966; Hubbard, 2014). Unlike conventional economic analysis, Decision Analysis leverages data in combination with expert judgment to provide estimates when alternative information is not available. This approach is particularly advantageous for societies in low-income countries that face higher risks and uncertainties (Bateman et al., 2003) and lower data availability.

We apply the Decision Analysis approach to estimate (i) the impact of increasing landscape connectivity on biodiversity in Tanzania, using the local African savanna elephant population as an indicator[1] and the basal area of mixed natural trees as a proxy for forest stock; (ii) the costs and benefits of increasing landscape connectivity to households and the government; and (iii) the economic viability through a net present value (NPV) of increasing landscape connectivity to households and the government. The findings of this study are relevant for guiding farmers and government officials in making informed conservation decisions and for conservation organizations interested in targeted conservation investments.

2. Materials and methods

2.1 Description of study site

2.1.1 Corridor conservation initiatives in Tanzania

Most of Tanzania's biodiversity—especially forest and wildlife resources—are concentrated within largely isolated protected areas (PAs) (Mtui et al., 2017). Ecological corridors are integral for connecting isolated PAs supporting their ecological functioning and enhancing biodiversity at larger landscape scales (Kiffner et al., 2022). In recognizing the importance of ecological corridors, the government of Tanzania over time adopted several policies and

[1] We used African savanna elephant as an indicator because is a migratory species and thus of importance in landscape connectivity.

strategies to safeguard its PAs including community-based natural resource management (CBNRM) in 1990's when Wildlife Management Areas (WMAs) and Village Land Forest Reserves (VLFRs) were strategically designed and established to halt ecological deterioration in community land including ecological corridors. As in many other low income countries, CBNRM in Tanzania often failed to achieve the expected outcome (Meyer et al., 2021; Milupi, 2017; Moyo et al., 2016), due to several reasons including unmet ambitious expectations by community, particularly with regards to economic returns of conservation, but also underestimated opportunity costs and limited collective actions in management of CBNRM (Goldman, 2009).

In other areas such as the Darema corridor (2002), the Ihefu wetland (2006), and the Kilombero floodplain (2012), involuntary resettlements of farmers to other areas was a commonly applied conservation strategy. Such forced relocations, however, faced strong criticism from both national and international organizations, making it unlikely that the government will continue to follow this strategy in the future. In the course of finding an alternative feasible solution, in 2018, the government of Tanzania introduced a new regulation with the goal to identify and conserve threatened corridors with high ecological potentials. The regulation emphasizes the role of conservation sensitization in encouraging farmers to voluntarily set aside private farmland for conservation. However, it has been argued that sensitization alone is unlikely to motivate a substantial number of farmers to do so (Nyanghura et al., 2024). This is largely due to the high private costs borne by individual farmers, whereas the benefits of conservation are predominantly public goods that accrue more broadly to society (Muchapondwa & Ntuli, 2024). Hence, policy design and implementation must find ways to balance these individual costs and societal benefits for sustainable and just conservation of conservation corridors (Fu et al., 2026).

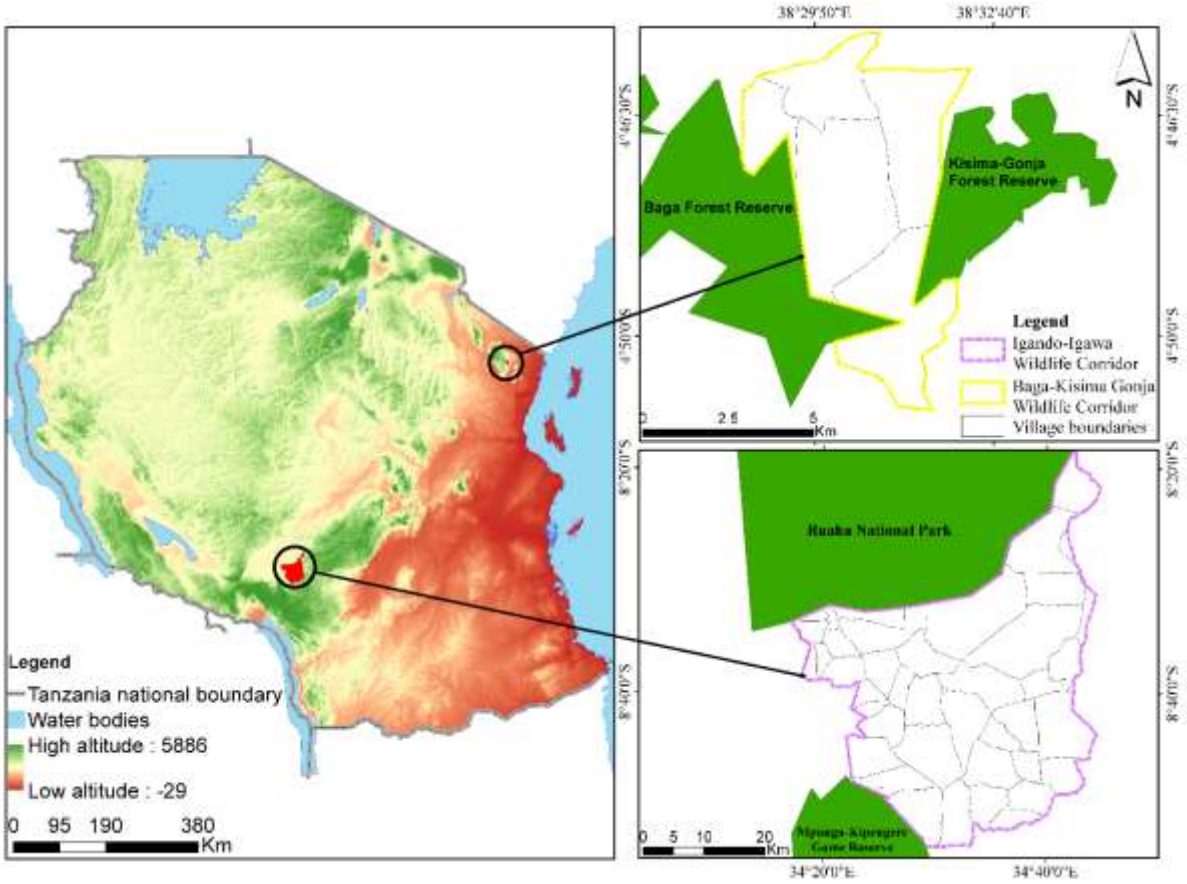


Figure. 1. Map of the study area showing the two ecological corridors (IIWC and BKG). The map is adopted from Nyanghura et al. (2024b).

2.1.2 The study area context

We conducted this study in Tanzania's Igando-Igawa Wildlife Corridor (IIWC) and Baga-Kisima Gonja (BKG) ecological corridor (Figure 1). IIWC and BKG are two ecological corridors in Tanzania that are highly threatened by agricultural expansions. The IIWC connects the Ruaha National Park and the Mpanga Kipengere Game Reserve, which are important tourism destinations in southern Tanzania. IIWC is particularly important for the movement of an increasing wildlife population, especially for the African savanna elephant (*Loxodonta africana*). The area is mainly covered by dry woodland (Massawe, 2010). On the other hand, the BKG corridor is located in the north-eastern part of Tanzania, and has an elevation between 1300 to 1910 m above sea level. The corridor connects the Baga and Kisima Gonja forest reserves in the Eastern Arc Mountains and is largely covered by Afromontane rain forest (MNRT, 2022).

Crop farming serves as the primary economic activity in both corridors with little livestock keeping. The expansion of crop farms, in the last two decades has led to a loss of approximately 75% and 56% of total forest cover in the IIWC and BKG corridors, respectively, making these corridors among the three most threatened in the country (MNRT, 2022). Maize and rice are the dominant crops in the IIWC, while the BKG corridor also supports significant horticultural production. Compared to IIWC, crop farming in BKG is generally more intensive, characterized by intercropping and crop rotation practices. Although small-scale beekeeping is common in both areas, butterfly farming represents a profitable niche enterprise especially in BKG. The widening agricultural yield gap and growing economic pressures are expected to intensify deforestation and habitat fragmentation, threatening ecological integrity and the flow of ecosystem services in both corridors. The Government of Tanzania is committed to restoring these corridors. However, the key challenge lies in determining whether the conservation decisions made by both farmers and the government can be ecological and economic feasible under uncertainties.

2.2 Decision modeling

We followed an iterative process of knowledge co-generating methods (Figure 2), to understand, model and simulate the decision context and the related outcomes. Our decision analysis approach integrated information from scientific literature and expert opinions. Decision Analysis is a holistic approach used in modeling complex interactions and allows for the integrating potential risks information (Hubbard, 2014). It is an appropriate approach in our case, where data (e.g., regarding costs of implementation) are scarce and realization of outcomes (e.g., ecosystem goods and services) is contingent upon risks (e.g., drought). Decision Analysis has been applied to analyze complex decision options in a wide range of topics, such as the restoration of irrigation reservoirs (Lanzanova et al., 2019), upscaling of agro-climate services (Luu et al., 2022), the evaluation of policies for agricultural development, (Do et al., 2020; Fernandez et al., 2021) and biodiversity conservation (Thorne et al., 2015; Dalyander et al., 2016; Nicol et al., 2016; Mattsson et al., 2019; Nascimento et al., 2020; Tamba et al., 2021; Hemming et al., 2022).

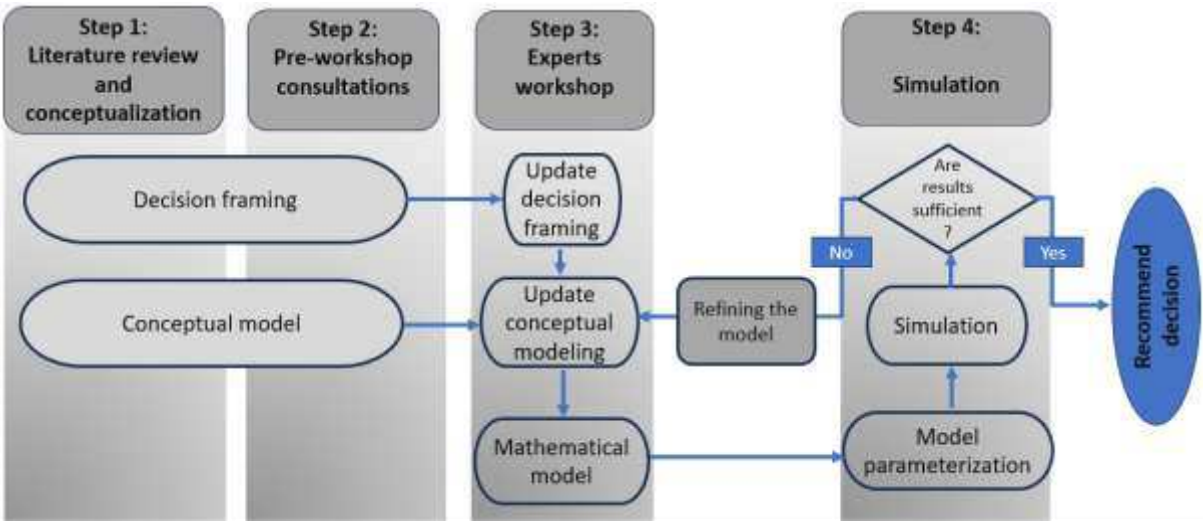


Figure. 1. Sequence of methodological activities in decision modeling (adapted from Tamba et al., 2021).

Step one: Literature review and conceptualization

We conducted a literature review on conservation challenges and decisions, focusing on work related to the two ecological corridors. We reviewed the relevant literature on conservation- in the region (e.g., Caro et al., 2009; Mashalla & Ringo, 2015; Hariohay & Røskaft, 2015; Hilty et al., 2020; Giliba et al., 2023), conservation policies and regulations in Tanzania (e.g., United Republic of Tanzania (URT), 2018, 2011, 2012) and government reports (e.g., Ministry of Natural Resources and Tourism (MNRT), 2022; URT, 2022a, 2022b).

Based on the gather knowledge, we developed a decision framework to evaluate the costs and benefits of conservation for local farmers and whether it is economically viable for the government to invest in such conservation efforts. The intended effect of the conserving ecological corridor is to enhance biodiversity through landscape connectivity, but without compromising the household income and government return for investment. We defined conservation as (i) cease crop farming activities and (ii) ensuring that such cessation is coordinated. Coordinated cessation is essential for achieving higher landscape connectivity as multiple farmers need to make pro-conservation decisions. Therefore, we framed the decision as scenarios of low, medium, and high proportion of farmlands conserved in a coordinated manner, following Mestre et al. (2017). The developed draft of decision framework (a conceptual model of the decision) were shared in subsequent stakeholder workshops, and meetings.

Step 2: Pre-workshop consultations

We presented a draft of the decision conceptual model as mentioned before in a pre-workshop consultation. This event took place as part of a side conference at the Tanzania Wildlife Research Institute (TAWIRI) in December 2022. In the discussion, we introduced researchers and scientists to Decision Analysis in conservation within the Tanzanian context, where, to our knowledge, such an approach had not been previously applied. We gathered participants' suggestions on the model's relevance to ecological restoration and implemented suggested refinements. Participants also helped us to identify potential additional experts to engage in the main stakeholder workshop, which we held subsequently (see Step 3).

Step 3: Experts workshop

In January 2024, we conducted a three-day workshop with 14 experts. The experts included representatives of local farmers from two ecological corridors (IIWC and BKG), natural and agricultural officers of the Mbarali and Bumbuli councils, a regional conservation NGO (Tanzania Forest Conservation Group), and representatives from the Tanzanian Forest Research Institute (TAFORI) and the TAWIRI. Conservation officers from Ruaha National Park, the Mpanga-Kipengele game reserve, and the Baga and Kisima Gonja forest reserves were also present.

During the workshop, we presented and finalized the decision framework. The decision framework was designed to help local farmers to decide whether they would be willing to conserve their privately owned farmland, particularly through coordinated efforts. However, as farmer’s decision to conserve may not be sufficient to ensure sufficient conservation outcomes, we also considered government interventions as equally important. Therefore, it was also necessary to consider whether it would be economically feasible for the government to invest in conservation efforts (e.g., through enforcement measures).

Depending on the pro-conservation motives of farmers, and strength of enforcement exerted by the government, different levels of coordinated conservation (i.e., connectivity) could be expected. We asked experts to decide which connectivity scenarios would be reasonable assumptions. Two types of scenarios initially emerged: two-level scenarios (low and high landscape connectivity) and three-level scenarios (low, medium, and high landscape

connectivity). Following an in-depth discussion, the experts reached a consensus to adopt the three-level scenarios: low, medium, and high landscape connectivity which aligns with our earlier assumptions based on Mestre et al. (2017). Experts described low landscape connectivity as the scenario where contiguously conserved farmland parcels do not exceed 40 percent of the total farmland in the corridor, while medium connectivity would range from 41 to 80 percent. Landscapes with more than 80 percent of farmlands conserved contiguously would represent high connectivity. This results in three possible decision scenarios: First, maintaining the status quo—where neither the farmers nor the government undertake any or limited conservation efforts. Second, a scenario where joint conservation efforts lead to partial connectivity. Third, a scenario where conservation efforts result in full or near-complete connectivity.

Stakeholders chose a 30-year timeframe for the impact of conservation to be realized. This was based on the understanding that the natural regeneration of forests and wildlife is a long-term process (Underwood et al., 2008). The choice is also supported by studies conducted in Mozambique, Tanzania, and Zambia, which have shown that basal area and carbon stocks gradually increase when abandoned farmlands are left undisturbed for forest regeneration, reaching to a somewhat recovery level within two to four decades (Williams et al., 2008; Kalaba et al., 2013; McNicol et al., 2015).

Workshop participants prepared the conceptual model following the structured processes of Martin et al. (2012) and Whitney et al. (2018). To this end, four to five members prepared conceptual models within three sub-groups and presented them during a plenary session. During the plenary discussion, the three conceptual models, from each sub-group were merged. The merged model was then used to update the original conceptual model[2] developed by a researcher based on the literature review. The final conceptual model is presented as impact pathway (Figure 3).

We transformed the impact pathway (Figure 3) into a mathematical model in the R programming language R (R Core Team, 2024) with functions from the package *decisionSupport* (Luedeling et al., 2024). The detailed description of conceptual model

[2] We did not show the initial draft of the conceptual model to the participants before they created their own to reduce the possible anchoring bias.

variables, assumptions, mathematical model and estimation are presented in section 1.1 of the supplementary materials.

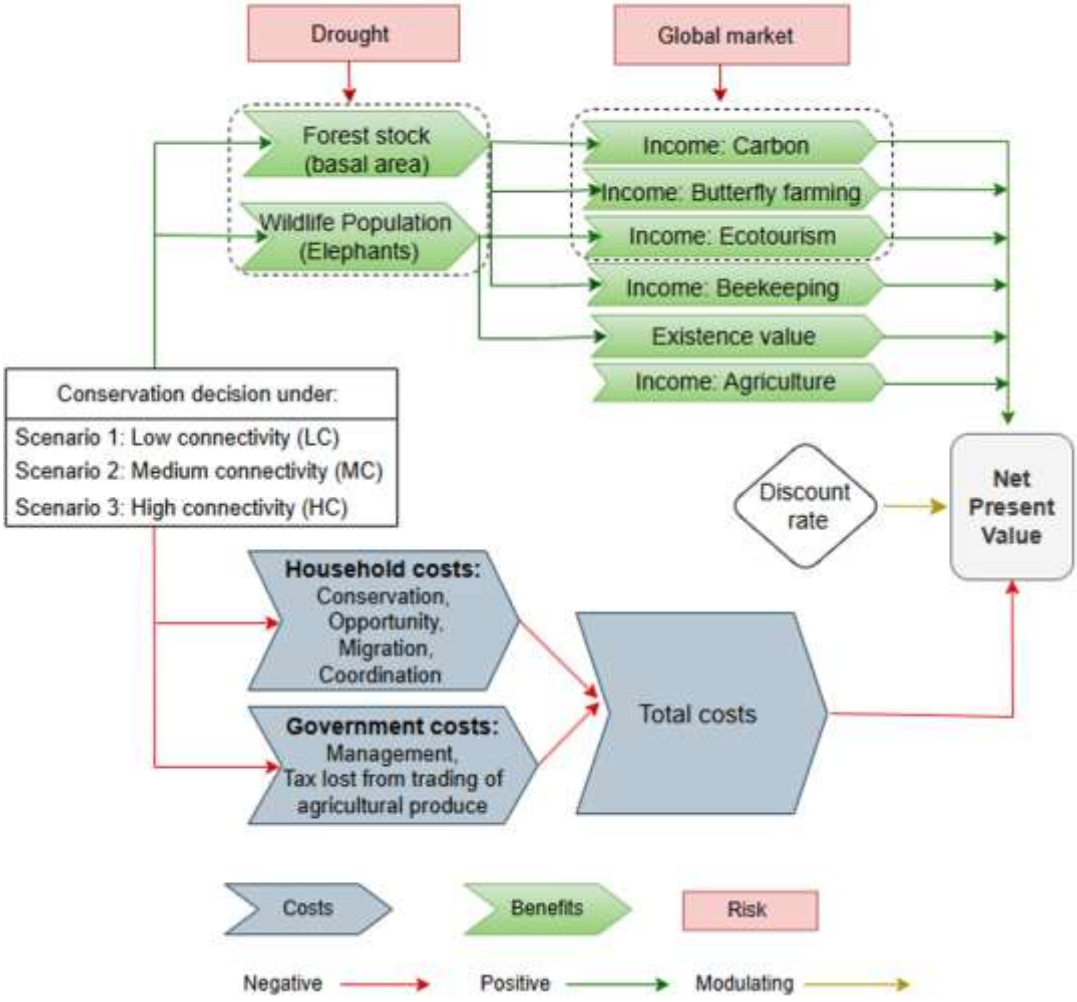


Figure. 2. Conceptual model of cost-benefit analysis of coordinated conservation decision under three scenarios of landscape connectivity in ecological corridors of Igando-Igawa and Baga-Kisima Gonja.

Step 4: Simulation

Before eliciting values for model parameterization, we used an expert calibration procedure outlined by Whitney et al. (2024). The objective of the calibration was to assess and reduce the uncertainties and bias in experts' estimations (Hubbard, 2014). During the calibration training, we made the experts aware of cognitive biases such as the anchoring effect (Kahneman, 2011). We explained three techniques to improve their ability to make accurate estimates: Equivalent bet (Hubbard, 2014), Klein's premortem (Klein, 2008), and, start with

unreasonably wide distributions (Whitney et al. 2024). The experts practiced the techniques in several rounds of trivia questions, of which most were able to improve their estimation skills. After calibration training, we asked participants to provide estimates for all variables in our model as a range, representing the lower and upper bounds, within which the expert is 90% confident the true value resides. In addition to expert-estimated inputs, all other inputs (e.g., those sourced from literature) were also presented as ranges.

We simulated both ecological outcomes (basal area and African savanna elephant population) and economic outcomes (total costs, benefits, and net present value [NPV]—at the household level, per hectare for the government, and per landscape for the government) using 10,000 iterations. We run such simulation under the status quo (i.e., the low connectivity (LC) scenario), medium connectivity (MC) and high connectivity (HC) scenarios, for two ecological corridors separately. Then we determined the change in those simulated outcomes, using the simulated estimates under LC as a counterfactual. We presented simulated distributions[3] comparing two ecological corridors (IIWC and BKG). Furthermore, we estimated the probability of economic gain (loss) as a proportion of positive (negative) values within the distribution of change in NPV. Sensitivity analysis and estimation of the value of information are presented in section 1.2 of the supplementary materials. The R code for a simulation model along with input data are presented in repository (see here https://github.com/Nyanghura/CBA_connectivity.git).

3 Results

3.1 The effect of an increase in landscape connectivity on biodiversity

Simulated outcomes under a low connectivity scenario (i.e., counterfactual) are presented in section 2.1 of the supplementary materials. Our results indicate that an increase in landscape connectivity from the low to high connectivity would increase the basal area by a median of 0.1 m^2/ha in year 1 to 10.6 m^2/ha in year 30 in IIWC and by 0.1 m^2/ha (year 1) to 15 m^2/ha (year 30) in BKG (see Figure. 4b and d). This amount is equivalent to an average of 5.1 m^2/ha/year in IIWC and 7.1m^2/ha/year in BKG respectively. Medium landscape connectivity

[3] Our distribution had extreme outliers. We therefore adjusted by consistently show the distribution of 5 to 95 percent quantile.

would enhance the basal area by a median of 2.2 m²/ha/year and 5.2 m²/ha/year in IIWC and BKG, respectively (Figure. 4a and c).

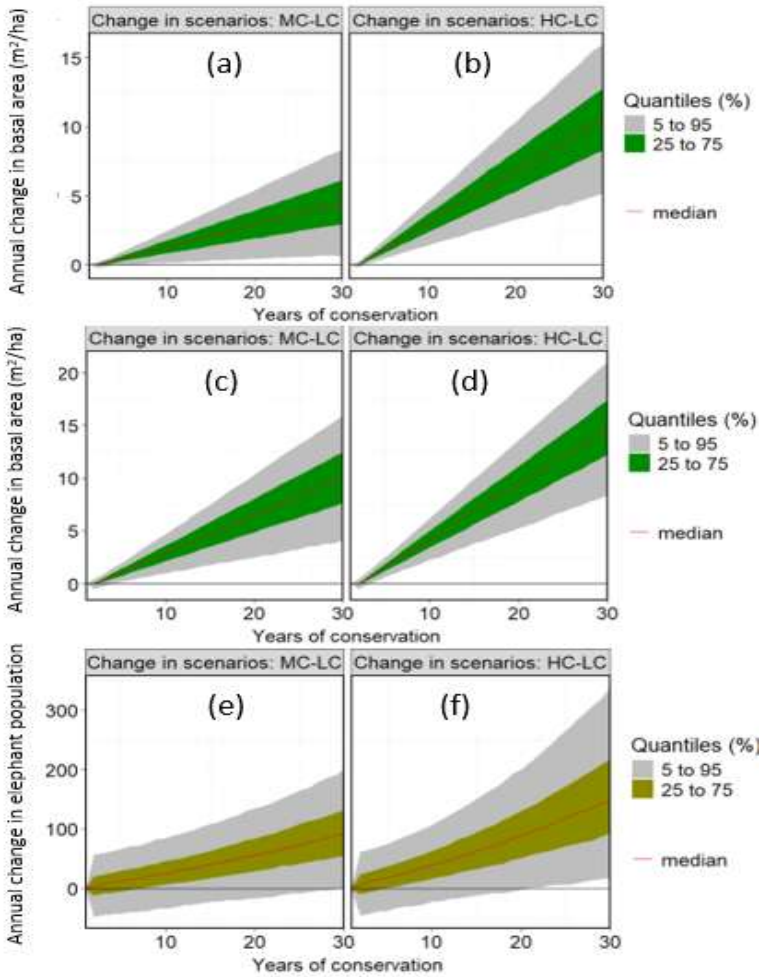


Figure. 3. Annual change in biodiversity as a result of an increase in landscape connectivity from low to medium (MC – LC) and from low to high (HC-LC). (a) and (b) show such change of basal area in IIWC. (b) and (c) show the same change in BKG. (d) and (e) represents the change of the African savanna elephant population in IIWC.

Increase in landscape connectivity to a medium level (Figure 4 e) supports relatively less migration of African savanna elephants than the increment attributed to high connectivity in IIWC (Figure 4 f). The increase in African savanna elephant population numbers range from almost zero in year 1 to a median of 146 in year 30 under high landscape connectivity. This is equivalent to the addition of around 60 African savanna elephants per year compared to the population that could have been supported under the low connectivity scenario (Figure 4 e). This increase indicates a median of 20 additional African savanna elephants per year compared to medium connectivity.

3.2 Change in annual costs of conservation for households and the government due to increase in landscape connectivity

Simulation results show that the annual costs of conservation per household in both ecological corridors consistently increases with increasing landscape connectivity. Specifically, high landscape connectivity increases median costs two to three times by USD 782 and USD 251 per household per year in IIWC and BKG respectively compared to low connectivity (Figure 5). Medium landscape connectivity, on the other hand, increases the annual household costs by approximately 2.5 times in IIWC and 1.5 times in BKG compared to low connectivity. The higher costs associated with increasing connectivity are likely due to a greater share of opportunity costs. The comparatively higher costs in IIWC may be attributed to a higher level of human-wildlife conflict than in BKG.

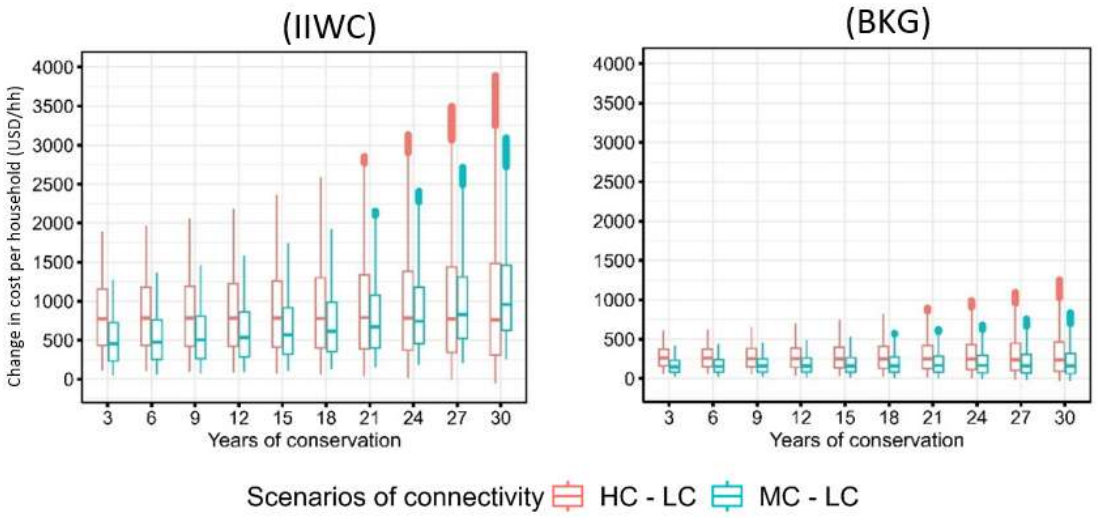


Figure. 4. Change in annual cost per household as a result of increase in landscape connectivity from LC to MC (MC-LC) and from LC to HC (HC-LC) scenarios in IIWC (left) and BKG (right).

Increasing landscape connectivity to medium and high levels in IIWC reduces the annual government costs per hectare by a median of USD 6 (60%) and USD 8 (80%), respectively (Figure 6a). However, the total governmental costs at landscape level increase to a median of USD 15,964 per year [min: USD 931 to max: USD 210,523] and USD 12,256 [min: USD 26,786 to max: USD 71,947] when landscape connectivity is raised to medium and high connectivity scenarios, respectively (Figure 6b).

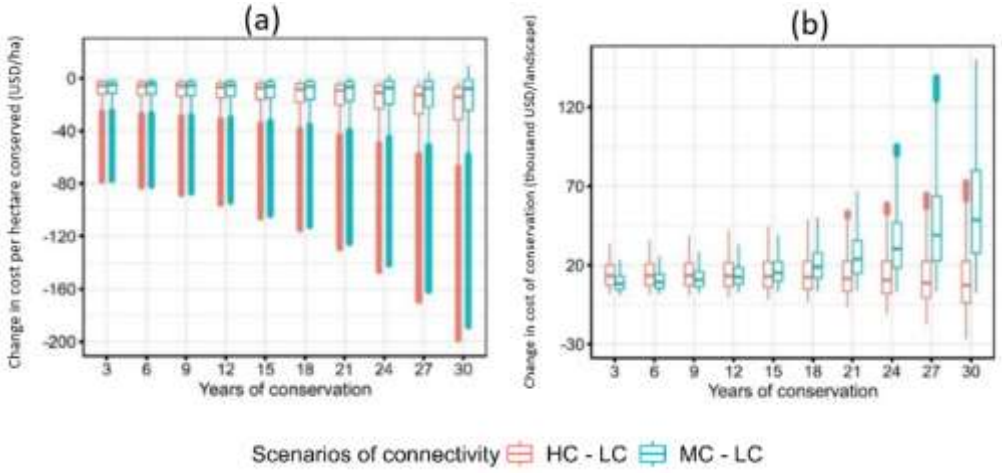


Figure. 5. Change in annual government cost due to increased landscape connectivity from LC to MC (MC-LC) and LC to HC (HC-LC) scenarios in IIWC. (a) shows the change in government costs per hectare (USD/ha) and (b) shows the change in absolute government costs for landscape conserved (thousand USD).

A similar trend was observed in BKG, where the costs per hectare of conserved farmland decreased by approximately USD 43 (70%) and USD 46 (74%) assuming medium and high connectivity, respectively. However, total government costs at the landscape level increased at a rate of about five to six times lower than the increase observed in IIWC. Specifically, these costs in BKG were around USD 2,807 (ranging from USD 864 to USD 7,011) and USD 4,933 (ranging from USD 2,483 to USD 10,643) for the medium and high connectivity respectively. This indicates that BKG achieved comparable per-hectare cost reductions with sizeable conservation investment, suggesting a more cost-efficient outcome compared to IIWC.

3.3 Change in annual benefits of conservation for households and the government under each scenario of landscape connectivity

Our findings indicate that the annual benefits per household under the medium and high connectivity scenarios were lower than those under the low connectivity scenario. This was consistently reflected by the negative differences between household benefits under high and low connectivity (HC-LC) and under medium and low connectivity (MC-LC) in IIWC (Figure 7). While there appears to be a potential for increased household benefits at BKG in future years due to improved connectivity and improved ecosystem services (see Figure 7), on average, the median benefits per year over the 30 years of intervention were generally lower by USD 78 under the medium connectivity scenario and USD 108 under the high connectivity scenario compared to the low connectivity scenario.

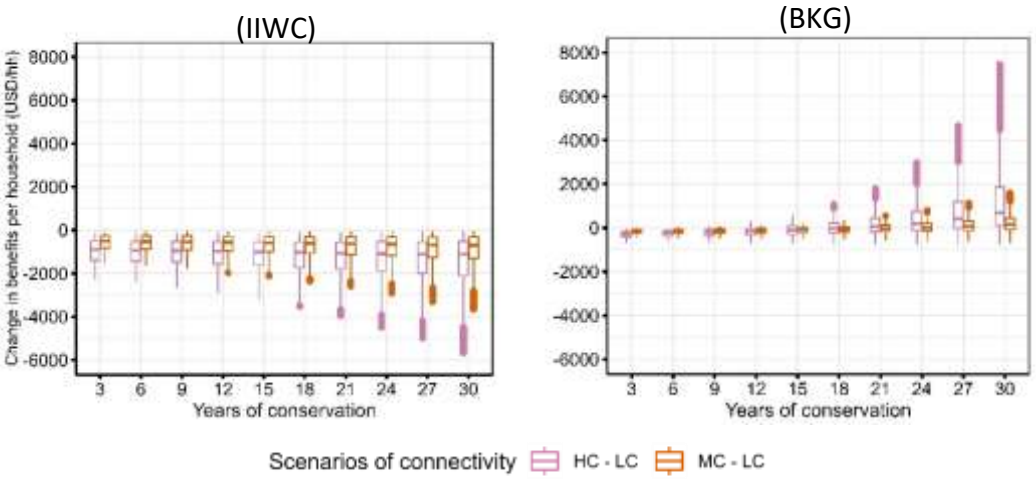


Figure. 6. Change in annual household benefits as a result of an increase in landscape connectivity from LC to MC (MC-LC) and from LC to HC (HC-LC) scenarios in IIWC (left) and BKG (right).

Consistent with the trend in household benefits, annual governmental benefits per hectare in IIWC also showed a decline (Figure 8a). Increased connectivity was linked to a reduction in governmental benefits, with median decreases of USD 1,268 per hectare for high connectivity and USD 1,179 per hectare for medium connectivity (Figure 8a). A similar annual decreasing trend was observed in BKG, though with a relatively modest magnitude—median reductions of USD 21 and USD 64 per hectare as connectivity increased to high and medium levels, respectively.

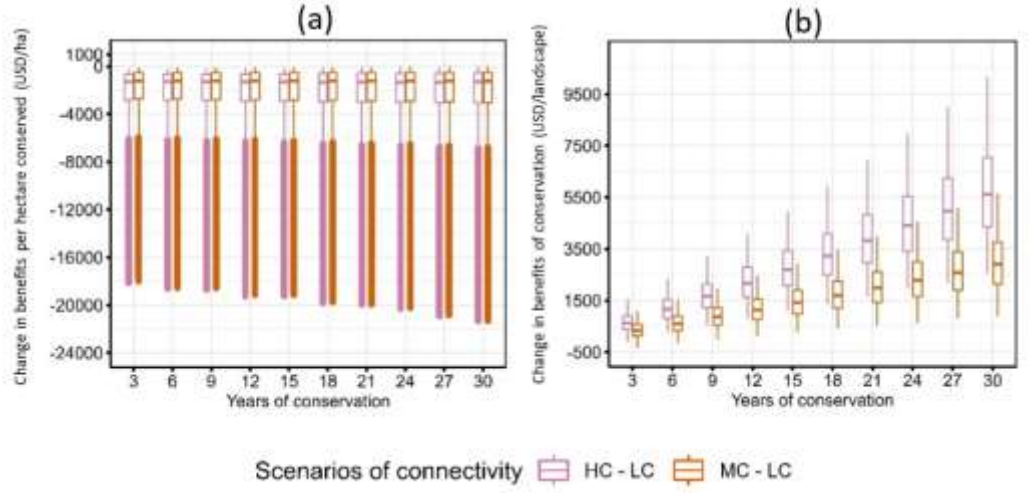


Figure. 7. Change in annual government benefits due to an increase in landscape connectivity from LC to MC (MC-LC) and from LC to HC (HC-LC) scenarios in IIWC. (a) shows the change in government benefits per hectare, and (b) shows the change in total government benefits at landscape level.

The annual conservation benefits accrued by the government in IIWC and BKG at the landscape level remained consistently positive throughout the simulation period as landscape connectivity increased to medium and high levels. The difference in annual benefits between high connectivity (HC) and low connectivity (LC) was more pronounced than between medium connectivity (MC) and LC. In IIWC, these differences were estimated at a median of USD 2.61 million (HC-LC) and USD 1.32 million (MC-LC) (Figure 8b), while in BKG, the differences were relatively small—approximately USD 0.32 million (HC-LC) and USD 0.15 million (MC-LC). These results show that increasing landscape connectivity from medium to high levels yields additional conservation benefits for the government.

3.4 Net present value

Figure 9 depicts the changes in NPV associated with increased landscape connectivity, comparing transitions from low to medium and low to high connectivity scenarios. The analysis indicates that increasing connectivity to a high level reduces the NPV for the farmer (i.e., per household) by a median of USD 21,228 [min: USD 68,199 to max: USD 1087] in IIWC and USD 3,734 [min: USD 14,799 to max: USD 5259] in BKG. Similarly, transitioning to a medium-level connectivity scenario decreases the NPV by a median of USD 13,393 [min: USD 50,071 to max: USD 1112] in IIWC and USD 2,569 [min: USD 12,345 to max: UD 950] in BKG.

In IIWC, government investments per hectare consistently resulted in a negative NPV across all changes in connectivity. In contrast BKG showed more favorable outcomes depending on the level of change. When connectivity increased from low to high, 73% of simulations yielded a positive NPV, with the highest reaching USD 6,450 per hectare (Figure 9 d). However, switching from low to medium connectivity reduced the NPV per hectare by a median of USD 60, with a 53 % probability of negative NPV (Figure 9d).

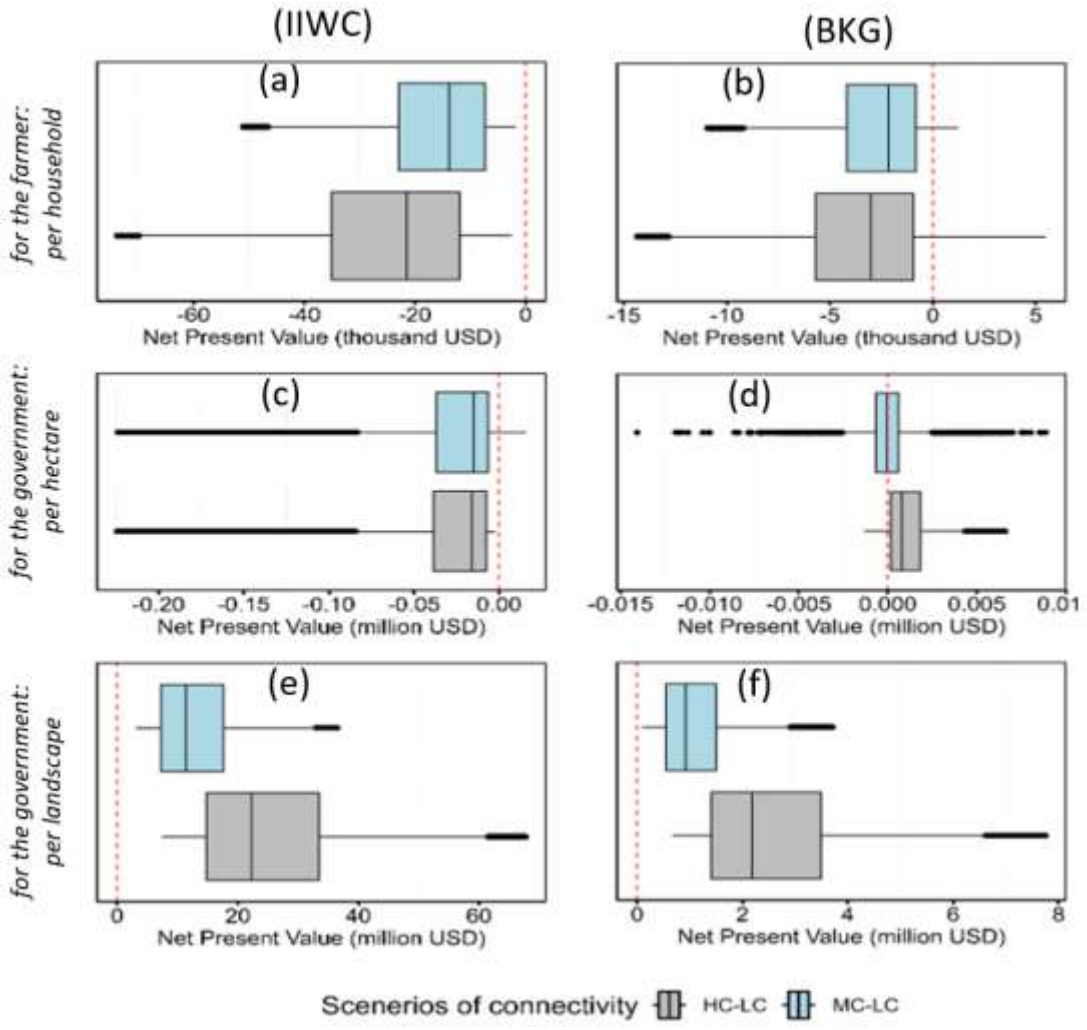


Figure. 8. Net present value differences between low and medium landscape connectivity (MC-LC) and between low and high connectivity (HC-LC) scenarios. (a) and (b) represent such difference for a farmer (per household) in IIWC and BKG respectively. (c) and (d) represent the same difference for the government (per hectare). (e) and (f) represent the same difference for the government (per landscape) in IIWC and BKG respectively.

At landscape level, we observed a consistent positive change in Net Present Value (NPV) for government investments (Figures 9 e and f). Shifting from low to high connectivity increased this value by a median of USD 22.2 million [min: USD 12,346,263 to max: USD 64,915,122] in IIWC and USD 2.4 million [min: USD 778,242 to max: USD 7,947,867] in BKG. Similarly, medium connectivity increases the NPV by approximately half the amount observed under high connectivity. The results of sensitivity analysis and values of information are presented in Table A.1 and Table A.2 respectively in the supplementary materials.

4 Discussion

4.1 Landscape connectivity and biodiversity growth

In this study we assessed the impact of landscape connectivity on forest stock and African savanna elephant population in a forest-based and a wildlife-based ecological corridor of Tanzania and analyzed the economic viability of increasing such connectivity for farmers and the government.

The simulation results indicate that increasing landscape connectivity to medium and high levels enhances forest stocks in both ecological corridors and boosts the African savanna elephant population in IIWC (Figure 4). The higher basal area observed in BKG compared to IIWC under all landscape connectivity scenarios can be attributed to the ecological attributes of the two areas. BKG is located in the Afromontane ecosystem, which is characterized by a moist and humid climate, facilitating rapid natural regeneration when farmlands are abandoned for conservation (Hishe et al., 2021). These ecological conditions also enhance resilience and stability against climate shocks, such as droughts. This is unlike IIWC, which is characterized by dry woodlands and relatively lower precipitation, likely to support only slow natural regeneration. Lower basal areas in IIWC compared to BKG under medium and high connectivity scenarios may further be attributed to the vegetation destruction caused by an increasing number of African savanna elephants, as supported by Mwambeo & Maitho, (2015) and Meyer et al. (2021). An increase in the African savanna elephant populations in IIWC under increasing connectivity is also supported by Meyer et al. (2021), who showed the association of wildlife-based conservancy and an increase in the African savanna elephant population in Namibia.

4.2 Costs of conservation to households and government

Our study indicates that conservation costs per household in both ecological corridors were about two to three times higher under medium and high landscape connectivity scenarios compared to low connectivity (Figure 5). The increase in conservation costs per household was two times higher (under medium connectivity) and three times higher (under higher connectivity) in IIWC compared to BKG. This indicates that households in the IIWC corridor are likely to be more affected by conservation than those in the BKG corridor. This could be due

to additional costs from wildlife (e.g., through Human-African savanna elephant conflicts) and lower household densities (~10 households/km² in IIWC compared to ~60 households/km² in BKG). A lower household density in IIWC is partly attributed by human migration to avoid environmental shocks, e.g., wildlife-related injuries (Salerno et al., 2024).

The rise in absolute costs incurred by the government at the landscape level as connectivity increases (see Figure 6b) can be attributed to higher management expenses. Expanding conservation to a landscape scale requires additional resources, such as more rangers for patrolling and additional time or expertise for monitoring. However, if the increase in total costs is proportionally smaller than the expansion in conserved area, the cost per unit area decreases. We observed such a decrease in government costs per hectare as landscape connectivity increases (Figure 6a). Specifically, annual costs per hectare under medium and high connectivity were approximately 0.5 to 0.8 times lower than under the lower connectivity scenario. These findings align with the results of Frazee et al. (2003), who found that expanding conservation areas can reduce operational costs of conservation per hectare by 1.2 times due to economies of scale.

4.3 Benefits of conservation to households and the government

With regard to conservation benefits for farmers, our results per household showed decreasing benefits with increasing landscape connectivity (Figure 7). This can be attributed to the loss of agricultural rent, especially in cases where such rent exceeds the revenues from alternative land uses, such as ecotourism and other income-generating activities like traditional beekeeping (Naidoo & Ricketts, 2006; Wainaina et al., 2020). In BKG, where a greater diversity of livelihood alternatives exists compared to IIWC, a larger share of opportunity costs (i.e. agricultural rent) can be compensated leading to a lower decrease of conservation benefits.

The consistent increase in absolute government benefits as landscape connectivity increases implies that the government should expect additionality with greater connectivity. Such additionality was comparable irrespective of the ecological corridor: benefits increased by approximately 33 percent from lower to medium scenario and by 76 percent from lower to higher scenario. These increments can be attributed to the enhanced opportunities for

income generation associated with increasing basal area and African savanna elephant population numbers such as carbon trading (Yang & Li, 2018) and tourism (Meyer et al., 2021).

4.4 NPV for households

We found that increasing landscape connectivity reduced the NPV per household (Figure 9) suggesting that it is relatively less beneficial for a rational farmer to engage in landscape conservation. These findings align with a findings from conservation cost-benefit analyses in SSA (Balana et al., 2012; Wainaina et al., 2020).

Differences in NPVs were most sensitive to the share of low landscape connectivity with households benefiting under low connectivity compared to when connectivity increases (Table A.1 in supplementary materials). The positive relationship between NPV and discount rates indicates that the profitability of conservation aligns with households' preferences for present benefits over future ones, as also observed by Balana et al. (2012). As connectivity increases in IIWC, net benefits of crop farming per hectare and their changes over time were found to negatively correlate with household NPV. This suggests that a decline in agricultural income imposes significant costs to households, and conservation related benefits alone cannot fully offset the costs (see also Green et al., 2018). This finding aligns with Balana et al. (2012) and Kaboré et al. (2024), who demonstrated that converting cropland to forests reduces the NPV for households.

4.5 NPV for government

Our model consistently indicated negative median NPVs per hectare for government investments in IIWC. In contrast, BKG showed greater than 50% chance of positive NPV per hectare, but only under the high connectivity scenario. This suggests that, assuming per hectare estimates, government conservation investments in IIWC connectivity are not economically viable under current conditions, whereas investments in BKG could be profitable assuming high connectivity. The observed profitability in BKG is dependent on opportunities for diverse conservation-supportive livelihoods, such as butterfly farming, which is missing in IIWC. Furthermore, lower opportunity costs in BKG compared to IIWC (e.g., foregone crop farming rents) make it easier to offset conservation costs through alternative land uses.

While governmental NPV was mostly negative per hectare, this is not the case at the landscape level, where we found positive values for medium and high connectivity in both ecological corridors. This increase was higher in high connectivity scenario indicating greater economic viability if more than 80% of the landscape is conserved contiguously. Such viability can be attributed to our assumption of conservation under community management, which often lowers the costs of operations compared to government-managed protected areas. This aligns with findings by Nyamoga (2016) and Giudice & Börner (2021), who reported reduced implementation and monitoring costs of decentralized conservation management.

Carbon-related variables, such as baseline stem carbon, annual accumulation of stem carbon stock, and the price of carbon per ton positively associated with NPVs on landscape scale (Table A.1 in supplementary materials). This suggests that enhancing carbon storage – for example, through the establishment of exclosures in conserved areas – can increase government benefits while minimizing management costs (see also Tamba et al., 2021). Our findings are supported by Balana et al. (2012), who demonstrated that the NPV of conservation interventions in the Tigray region of northern Ethiopia is volatile to changes in biomass production as well as findings by Nuru et al. (2014) and Yang & Li (2018), who observed a positive correlation between carbon market prices and profitability of conserving African forests.

4.6 Implications for conservation actors and policymakers

This study provides valuable insights for policymakers and conservationists, especially regarding the conservation of ecological corridors in Tanzania. Our findings suggest a clear increase in forest stock and African savanna elephant populations as connectivity increases. This provides an important justification for investing in the conservation of ecological corridors, with a reasonable certainty of realizing ecological outcomes in particular under high landscape connectivity. However, given the socio-ecological complexity, sustainable ecological outcomes are unlikely if social impacts are overlooked or undermined (Puri et al., 2022). It is possible for unintended political consequences to arise from the promotion of ecological corridors, which would further hamper conservation efforts. We emphasize these potential social concerns because in our case, conservation assumes halting farming activities. As a result the landscape may be placed under partial or strict exclosure, restricting local

communities` access to ecological resources such as non-timber forest products (Tamba et al., 2021). Such limitation in resource access may have negative implications for livelihoods of farmers and cause negative perceptions about conservation. For example, perception of land grabbing may gain grounds, reinforcing conflicts and political unrest.

In order to ensure fairness and equity for farmers and to support the sustainability of conservation efforts, policymakers should consider implementing a voluntary payment for ecosystem services (PES) schemes that compensate farmers for their losses. Such a policy direction would help justify confinement of conserved landscapes by restricting access to promote rapid self-regeneration of ecological assets such as carbon storage. PES has proven to be a successful policy tool for conservation in many tropical ecosystems (Wunder et al., 2020) including in the regeneration of degraded landscapes (Dong et al., 2024). However, the design and modality of PES schemes remain critical and must be carefully adopted to local contexts (Pascual et al., 2014). PES can be financed through various mechanisms, such as eco-tourism revenues from protected areas (Frazee et al., 2003), carbon trading (Koh et al., 2021) and funding from conservation organizations (Levine, 2002). The scope of payments could, however, be extended beyond covering the traditional opportunity costs to include latent outlays, such as resentments and social disruption resulting from restrictions on resource access.

Our findings for BKG suggest that household benefits (mainly from eco-friendly activities) could increase gradually as connectivity improves to medium or high levels (Figure 7). These benefits may help offset future opportunity costs of conservation. A prominent example of eco-friendly activity in BKG is butterfly farming, driven largely by international market demands (Morgan-Brown et al., 2010). This highlights a significant opportunity for the Tanzanian government to promote environmentally beneficial projects (e.g., butterfly farming) by creating favorable conditions for production and enhancing market accessibility e.g., by subsidizing eco-friendly enterprises. Previous studies on integrated conservation and development programs have shown that conservation co-benefits can compensate for opportunity costs over the long term (e.g., Blom et al., 2010).

Given the high opportunity costs of conservation, it is evident that successful conservation efforts cannot be achieved without reforms of agricultural policies that contribute to

ecological degradation. Our findings about the sensitivity of NPV to opportunity costs highlight the need to de-incentivize agricultural development in ecologically sensitive landscapes. Failing to do so may result in an increase in agricultural rent per hectare, which could further exacerbate ecosystem degradation. Such an increase in rent may further inflate the conservation budget (e.g., through higher compensation) if conservation intervention is delayed as discussed by Nkonya et al. (2016)**.**

4.7 Limitations of the study

We acknowledge the limitations of this study and highlight future key research areas. First, our study did not account for potential leakage or spill-over effects of landscape connectivity. Leakage effects might occur, for instance, through increased deforestation outside conserved landscapes, particularly if farmers face limited alternative income sources due to farmland retirement and if law enforcement outside conserved areas is inadequate. Conversely, landscape connectivity could generate spill-over effects, such as increased agricultural production in adjacent farmlands, as demonstrated by Yang et al. (2020). If this positive effect is significant, it could potentially result in a rebound effect, where increased agricultural productivity may drive the expansion of farmlands, leading to further deforestation. An empirical assessment of the likelihood and magnitude of these effects would be valuable for policymakers to better understand the broader implications of landscape connectivity.

Secondly, our modeling considered a limited range of ecosystem goods and services and their interactions in yielding benefits. For instance, we assumed that an increase in the African savanna elephant population might lower carbon stocks but it could alternatively support carbon storage indirectly. This can occur as the African savanna elephant population support seed dispersal and nutrient recycling, a vital process for the regeneration and growth of forests (Sandhage-Hofmann et al., 2021). Further research could estimate a more comprehensive NPV by including a broader range of ecosystem services (e.g., provisioning and regulating) and explicitly modeling their interaction effects.

Thirdly, we recognize that enhancing landscape connectivity may require relocations of farmers. However, not all of these relocations are likely to be entirely voluntary—some may

occur due to social or peer pressure. The social costs associated with such relocations should not be underestimated and explicitly accounted for in future modeling.

Finally, we acknowledge that our study defined landscape connectivity using only one dimension—specifically, the proportion of landscape conserved contiguously—without considering different configurations of landscape connectivity. Variations in the configuration of landscape connectivity, even with the same conserved proportions, could lead to different connectivity effects. Exploring these different configurations would be an interesting extension of our study.

5 Conclusions

Based on the discussion of our results and in consideration of the uncertainties associated with a simulation study, we carefully conclude that increased landscape connectivity supports the augmentation of ecological assets, specifically forest stock and African savanna elephant populations. However, the costs associated to increasing connectivity are disproportionately borne by local farmers. This underscores the necessity of government intervention through compensation mechanisms such as Payments for Ecosystem Services (PES) if programs for increasing ecological connectivity are implemented. Evidence from tropical regions, particularly Latin America, demonstrates that well-designed PES schemes can simultaneously achieve conservation goals and support livelihood development, provided they are carefully adapted to the prevailing social context (Pascual et al., 2014).

Our conclusions are based on a holistic analysis approach which accounted for potential risks. Thus, the recommendations and policy implications identified in this study are deemed robust for policymakers to make informed decisions. This study reinforces earlier findings (e.g., Tamba et al. 2021) that Decision Analysis can be instrumental in addressing partial information and system complexity to support decision-making processes in conservation literature. This is achieved by presenting a distribution of plausible decision outcomes through simulations of ranges and probability estimates (e.g., costs, benefits and risks) derived from experts.

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