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When profitability meets conservation objectives through biodiversity offsets

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Abstract

Biodiversity offsets (BOs) are increasingly used as economic instruments to manage biodiversity and ecosystem services in the context of economic development. This study investigates the sustainability conditions of BOs. It focuses especially on both the timing and pricing of BOs in development-offset projects. To address this issue, a minimal time control model is proposed, allowing a dynamic and multicriteria approach to be combined through both ecological and economic targets. We rely here on no net loss (NNL) and positive net present value (NPV) goals. In particular, we focus on an offset marginal price, called offset sustainability price (OSP), which equalizes the NNL and payback times. We prove analytically how this OSP pricing corresponds to a win–win solution in terms of ecological-economic synergy. We also show that this OSP pricing can be very high compared to the project rate of return, particularly when the biodiversity loss is high. More globally, a static comparative analysis shows the extent to which the economic and biodiversity parameters impact the OSP. Finally, a numerical application related to mangroves and aquaculture in Madagascar illustrates the analytical findings. For this case study, we argue that the current

BO price is underestimated.

Recommendations for Resource Managers:

- The biodiversity recovery time to reach the no net loss (NNL) is not sufficiently taken into account in biodiversity offsets (BOs).
- An offset sustainability price (OSP), reconciling the profitability and NNL times, is calculated, thus strengthening the developer-pays principle of BOs.
- The OSP is the minimal offset price such that the developer is financially beneficial only after the biodiversity recovery.
- The OSP depends nonlinearly on both the developed surface area, the biodiversity initial states and dynamics as well as the economic parameters.
- With low discount rates, a multiplier effect simplifies the calculation of the OSP.

KEYWORDS

biodiversity offset, bioeconomics, mangroves, minimal time control, no net loss, sustainability

1 | INTRODUCTION

Biodiversity offsets (BOs) are used to reconcile economic development and ecosystem conservation (Bull et al., 2013). According to the OECD (2016), BOs are "measurable conservation outcomes that result from actions designed to compensate for significant residual biodiversity loss that arises through development projects." Recognized as instrumental in the transition toward sustainable economies, BO schemes have surged since the 1970–1980s (Damiens et al., 2021; IPBES, 2019; IUCN, 2016). More specifically, BO measures are the third and last step in a development project mitigation hierarchy (avoid, mitigate, and compensate) which prioritizes conservation of natural habitats. Because of their ability to provide proconservation monetary incentives, BO measures are often described as market based instruments (Panayotou, 1994). In practice, they are implemented through direct offset measures, banking compensation credits, or provisions to an offset funds system (Drechsler & Hartig, 2011). BOs often result in the implementation of restoration measures (in-kind offsets) on a degraded site or into finance to conservation measures (Buschke et al., 2019). Major features of BOs include the provision of an ecological gain in response to an ecological loss, located in a compensation site that is distinct from the impacted site, and agreed-upon criteria for ecological equivalence between the gains and losses (Vaissière et al., 2020). In addition, the offset site must be close enough to the developed site to ensure the local provision of ecosystem services (ES) (Liu et al., 2018; Moilanen et al., 2009). A major ingredient of BOs is the no net loss (NNL) objective requiring a resulting biodiversity level at least equal and preferably superior to the original level (Ermgassen et al., 2019).

Despite their increasing popularity and conceptually attractive approach (Bull et al., 2013), BO principles and methodologies are often criticized, notably regarding the concept of ecological equivalence (Maron et al., 2012) and the NNL principle (Levrel et al., 2018; Needham et al., 2019; Vaissière et al., 2020). Besides, since habitat and land-use changes are still a major driver of biodiversity loss in both developed and developing countries (Diaz et al., 2019; IPBES, 2019), BOs do not yet seem to constitute a strong enough incentive system.

In terms of quantitative methods, BOs are often appraised through equivalency analyses based on ecological equivalence assessment methods (EAMs) (Dunford et al., 2004). However, those approaches, including hybrid methods (Bas et al., 2016), compare losses and gains in biodiversity mostly by ignoring time lags, biodiversity dynamics, uncertainty, spatial considerations (Bezombes et al., 2017), and society's preferences such as the demand for ES (Shaw & Wlodarz, 2013). Notable exceptions include Laitila et al. (2014), Moilanen et al. (2020, 2009), and Thébaud et al. (2015). The role of climate change is also important as it affects habitat quality and species migration (Gerling, 2023). Specifically, a key criterion for a successful BO as emphasized by Doole et al. (2014) is to account for time. In the conservation biology literature, the time lag refers to the time necessary to recover the biodiversity lost on another site. Time lags are usually addressed thanks to the offset multiplier (or ratio) tool, with time delays being calculated according to ecological parameters or “frames of reference", such as the intrinsic growth rate, the biodiversity dynamic (Bull et al., 2013; Buschke, 2017; Peterson et al., 2018) or risk-based approaches (Bradford, 2017). Further, regarding biodiversity conservation, approaches addressing incentives and cost-effectiveness issues related to land use changes and conservation management (Ansell et al., 2016; BBOP, 2009; Birner & Wittmer, 2004; Gerling & Wätzold, 2021; Polasky et al., 2008; Wätzold & Schwerdtner, 2005), if better applied, would be useful in designing relevant BO measures. From an economic viewpoint, mastering time throughout the project implementation is a key issue for developers (Bull et al., 2013; Pope et al., 2021), although BO projects are often designed to provide the maximum benefits in a short time (Weissgerber et al., 2019) without taking the necessary additionality criteria into account. The latter entails that biodiversity gains are the result of BO measures only (Laitila et al., 2014). Moreover, the shorter the biodiversity recovery time, the quicker the deprived human population recovers access to the lost ES (Griffiths et al., 2018; Panayotou, 1994). This nature deprivation or, more exactly, the duration during which people are deprived from it, can be seen as a negative externality resulting from the development-offset project.

This paper focuses on the acceptability and sustainability of BOs in both economics and ecological terms. More specifically, our research question is: how to enhance the incentive system behind in-kind BOs using a strong sustainability approach, by taking time lags into account? Thus, using a quantitative method and modeling, we define a public policy tool based on BO time lags and prices, to reconcile economic profitability and biodiversity conservation objectives. More precisely, adopting the viewpoint of a regulating agency, we investigate the economic incentive system created by BOs via a price duration system compatible with the principles of strong sustainability. By strong sustainability, we mean here the balance between the profitability of the development project and NNL in a context of the nonsubstitutability between natural capital (biodiversity) and human made capital (Baumgärtner & Quaas, 2009; Doyen & Gajardo, 2020; Neumayer, 2012). A minimum time control model (Doyen & Saint-Pierre, 1997; Evans & James, 1989; Leigh, 1980) is therefore proposed, allowing us to combine a dynamic and multicriteria approach through both ecological and economic targets in line with strong sustainability and viability approach (Doyen et al., 2019; Oubraham & Zaccour, 2018). In particular, the NNL lag and profitability (called here "payback") time are tied to define a sustainable offset price named "offset sustainability price" (OSP) to be imposed on the developer by the public authority.

The paper presents four contributions to the literature. It first provides a spatially structured, dynamic, and bioeconomic modeling framework to study both the ecological and economic performances of BOs analytically and numerically. Second, the offset sustainability time lag and the OSP are mathematically identified and emerge as win–win ecological-economic values, with BO time and price as the decision variables. Third, a static comparative analysis shows the extent to which the economic parameters, such as the marginal revenue of the development project and the discount rate, and biodiversity parameters qualitatively affect the OSP. Finally, a numerical application related to mangroves and aquaculture in Madagascar illustrates these analytical findings.

This article is structured as follows: Section 2 presents the bioeconomic model. Section 3 provides the analytical results derived from the model. In Section 4, the results are exemplified with an aquaculture project related to mangroves in Madagascar. Section 5 discusses the findings and concludes.

2 | THE BIOECONOMIC MODEL

This section sets out the different components of the bioeconomic model used to address BOs. We first describe the biodiversity dynamics on the two sites, namely the offset and development sites, along with the mechanism accounting for habitat quality and compensation dynamics. Then the ecological and economic criteria and targets relating to the NNL and profitability goals are depicted. The offset sustainability time lag and price, denoted by OST and OSP, are then derived. We also define the ecological and economic losses from the OSP pricing.

2.1 | The biodiversity dynamics

We consider two sites denoted by $s = 1, 2$ as illustrated in Figure 1. Site $s = 1$ stands for the area of a potential development project while $s = 2$ corresponds to the potential offsetting area. For sake of simplicity, we assume here that the biodiversity state, denoted by $B_s(t)$ at time t in site s, is captured by a single proxy referring to a species abundance (say biomass). We also postulate that biodiversity dynamics on both the developed and offset sites rely on a common functional form F which justifies the offset mechanism and a potential ecological equivalence. In discrete time, biodiversity dynamics read as follows for any time t:

$$B_s(t+1) = F(B_s(t), K_s). \tag{1}$$

where K_s stands for the habitat quality of site s. Throughout the paper, we will use the Gompertz form for the biodiversity growth $F(.)$ as in Doyen et al. (2016), Levhari and Mirman (1980), and Mutshinda et al. (2009):

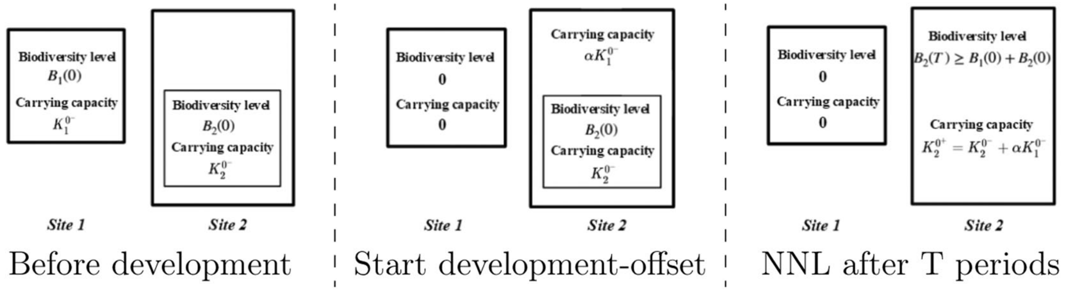

FIGURE 1 BO mechanism: three main stages of the BO mechanism involving, in both the developed site $s = 1$ and the offset site $s = 2$, the initial biodiversity levels $B_s(0)$ and carrying capacities, $K_s^{0^-}$ and $K_s^{0^+}$: before and after the development—offset process respectively and after the biodiversity recovery. BO, biodiversity offset.

$$F(B,K) = B\exp\left(r\left(1 - \frac{\ln(B)}{\ln(K)}\right)\right) = B\left(\frac{K}{B}\right)^{\frac{r}{\ln(K)}}, \tag{2}$$

where $r > 0$ is the intrinsic growth rate of the biodiversity at stake.[1]

A major interest of the Gompertz dynamics in discrete time is that its properties can be easily extended to multispecies contexts, which makes sense to address biodiversity and ecosystem issues (Doyen et al., 2016; Levhari & Mirman, 1980; Mutshinda et al., 2009). We can explicitly compute the value of the stock $B_s(t)$ at any time $t \geq 0$, as we have[2]:

$$B_s(t) = K_s\left(\frac{B_s(0)}{K_s}\right)^{\left(1 - \frac{r}{\ln(K_s)}\right)^t}. \tag{3}$$

Hereafter, we assume that the intrinsic growth r is low enough[3] namely $r < \ln(K)$ to guarantee that function F increases with biodiversity level B, namely

$$F_B(B,K) > 0. \tag{4}$$

Notation K suggests that the habitat quality is closely tied (proportional) to the carrying capacity of the resource as in Swanson (1993) and Doyen (2018). In fact, K is linked to the conservation status of the chosen site (see Section 2.2 for details). In that context, we assume that the initial biodiversity levels in both sites are smaller than their initial carrying capacity (before the development impact):

$$0 < B_s(0) \leq K_s^{0^-}, s = 1, 2; \tag{5}$$

meaning that they have a potential for growth. This does not preclude the equilibrium case where $B_s(0) = K_s^{0^-}$.

2.2 | Habitat quality and compensation dynamics

Depending on the site s considered, the habitat quality captured here by the carrying capacities K_s differs as exemplified in Figure 1. The two initial habitat qualities (carrying capacities) before operationalizing the development-offset project are hereafter denoted by $K_s^{0^-}$. Moreover, as in Barbier (2007, 2012, 2016), we consider that the sites' carrying capacities are initially proportional to their surface area, denoted by D (developed) or O (offsets), respectively. When the compensation mechanism is operated, a shift between the habitat qualities $K_s^{0^+}$ of the two sites occurs in the sense that

$$\begin{aligned} K_1^{0^+} &= K_1^{0^-} - \lambda D = 0, \\ K_2^{0^+} &= K_2^{0^-} + \lambda O, \end{aligned} \tag{6}$$

where λ corresponds to the ratio between the carrying capacity and the surface area of the habitat.[4] Moreover, we assume that there is a so-called offset ratio (Moilanen et al., 2009) also often called multiplier (Dunford et al., 2004; Laitila et al., 2014) or trading ratio (Needham et al., 2019) denoted by $\alpha \geq 1$ between the developed and offset areas as follows:

$$O = \alpha D. \tag{7}$$

We consider that α is set by the public authority (at least a minimum value) but that the developer might choose to increase it. Putting all the ingredients (1), (6), and (7) together, we see that the offset area O is a major driver of the dynamics of biodiversity and habitats. For the Gompertz dynamics, we thus obtain, in the offsetting site, the value of biodiversity at time $t > 0$:

$$B_2(t) = \left(K_2^{0^-} + \lambda O\right) \left(\frac{B_2(0)}{K_2^{0^-} + \lambda O}\right)^{\left(1 - \frac{r}{\ln\left(K_2^{0^-} + \lambda O\right)}\right)^t}. \tag{8}$$

In that situation, assuming that the initial biodiversity level $B_2(0)$ in the offset site is low, the growth of this biodiversity $B_2(t)$ can be strong. More precisely, the greater the difference between $K_2^{0^+}$ and $B_2(0)$, the faster $B_2(t)$ will increase.

2.3 | The economic value of the developed site

The revenue $R(t)$ of the developer at every period t without offset price corresponds to the expected marginal productivity g per area unit of the developed site multiplied by the number of area units developed (surface D), hence

$$R(t) = gD = g\frac{O}{\alpha}. \tag{9}$$

The offset cost $P(O)$ is also assumed to be proportional to the offset area O as in Barbier (2016) with

$$P(O) = pO. \tag{10}$$

The marginal price p can thus be considered as the unit price or value of the offsets. We consider here that the biodiversity offset price of the development-offset project only applies at initial period $t = 0$. Consequently, the net present value (NPV) of the development project is defined as the difference between the sum over a given duration T of discounted revenues $R(t)$ and the offset cost $P(O)$, namely:

$$\mathrm{NPV}(T) = \sum_{t=0}^{T} \frac{R(t)}{(1+i)^t} - pO, \tag{11}$$

with i the discount rate, set by the public authority. Using Equations (9) and (10), the NPV reads

$$\mathrm{NPV}(T) = O\left(g\frac{1 + i - (1+i)^{-T}}{\alpha i} - p\right). \tag{12}$$

The NPV thus turns out to be linear with respect to both the offset area O and offset price p but increases nonlinearly with respect to the duration T.

2.4 | Economic constraint: Payback

A development-offset project is profitable when the revenues exceed the costs, which translates into a positive NPV:

$$\mathrm{NPV}(T) \geq 0. \tag{13}$$

We define T_{DPP} the duration based on the discounted payback period (DPP), or break-even period, which refers to the necessary time period for a project cash flows to cover the initial investment (Lefley, 1996).

Using the time $T_{\mathrm{DPP}}(p)$ of a zero NPV which depends on offset price p through the relation

$$\mathrm{NPV}(T_{\mathrm{DPP}}(p)) = 0, \tag{14}$$

together with Equation (12), the economic viability constraint (13) is equivalent to:

$$T \geq T_{\mathrm{DPP}}(p) = -\frac{\ln\left(1 + i\left(1 - \frac{p}{\alpha g}\right)\right)}{\ln(1+i)}. \tag{15}$$

See Appendix Section A.1.4 for the proof.

2.5 | Biodiversity viability constraint: NNL

A compensation project (O, T, p) is considered sustainable from an ecological viewpoint when the biodiversity gains on the offset site entailed by surface area O exceed the level lost on the developed site over the period $[0, T]$. This reads as follows:

$$B_2(T) + B_1(T) \geq B_1(0) + B_2(0). \tag{16}$$

Whenever we consider that the final level of biodiversity on the development site $B_1(T)$ is negligible or equal to zero from (6), such an NNL constraint (16) can be simplified to:

$$B_2(T) \geq B_1(0) + B_2(0). \tag{17}$$

If we assume that the biodiversity dynamics F is regular enough ($r < \ln(K_2)$), the NNL requirement turns out to be equivalent to[5]:

$$T \geq T_{\mathrm{NNL}}(B(0), O), \tag{18}$$

where $T_{\mathrm{NNL}}(B(0), O)$ fulfills the equality underlying the NNL constraint such as:

$$B_2(T_{\mathrm{NNL}}) = B_1(0) + B_2(0). \tag{19}$$

Using the Gompertz dynamics (2) and Equation (3), the NNL requirement turns out to be equivalent to:

$$T_{\mathrm{NNL}}(B(0), O) = \frac{\ln\left(\ln\left(\frac{B_1(0) + B_2(0)}{K_2^{0^-} + \lambda O}\right) \ln\left(\frac{B_2(0)}{K_2^{0^-} + \lambda O}\right)^{-1} \right)}{\ln\left(1 - \frac{r}{\ln\left(K_2^{0^-} + \lambda O\right)}\right)}. \tag{20}$$

Proof of this result is given in Appendix Section A.1.3.

At this stage, we can note that the NNL time lag $T_{\mathrm{NNL}}(B(0), O)$ increases with the level of biodiversity to offset $B_1(0)$. This is clear for the Gompertz dynamics and previous formula (20). In other words, under these assumptions, we have[6]:

$$\frac{\partial T_{\mathrm{NNL}}(B(0), O)}{\partial B_1(0)} > 0. \tag{21}$$

The role of the initial biodiversity state $B_2(0)$ in the offset site is more ambiguous. It is investigated in the static comparative analysis of Appendix Section A.1.8 below.

2.6 | Offset sustainability time and price

We now consider the "Offset Sustainability Time" denoted by OST and defined as the minimal time horizon T, such that both ecological and economic constraints (17), (13) are fulfilled, given a level of offset O (the offset surface area), initial biodiversity states $B_1(0)$ and $B_2(0)$, and offset price p:

$$\mathrm{OST}(B(0), O, p) = \min(T \geq 0 | \text{ constraints (17), (13) hold true}). \tag{22}$$

We can prove (see Appendix Section A.1.5) that such an OST is related to the T_{NNL} and T_{DPP} as follows:

$$\mathrm{OST}(B(0), O, p) = \max(T_{\mathrm{NNL}}(B(0), O), T_{\mathrm{DPP}}(p)). \tag{23}$$

Said differently, to fulfill characterization (22), the OST is the maximum value among the two time lags considered.

As displayed by Figure 2 and as proved in Appendix Section A.1.6, the shape of the offset sustainability time OST with respect to the marginal offset price p strongly depends on the no net loss lag T_{NNL} (green) and payback duration T_{DPP} (red). Both intersect at the offset price OSP. We thus have:

$$\mathrm{OST}(B(0), O, p) = \begin{cases} T_{\mathrm{NNL}} & \text{if } 0 \leq p \leq \mathrm{OSP}(B(0), O) \\ T_{\mathrm{DPP}} & \text{otherwise.} \end{cases} \tag{24}$$

This offset sustainability price OSP($B(0)$, O) is characterized mathematically by equality

$$T_{\mathrm{DPP}}(\mathrm{OSP}(B(0), O)) = T_{\mathrm{NNL}}(B(0), O). \tag{25}$$

Economically, the OSP is the offset price allowing the equalization of the two time lags. In that sense, the OSP is aligned with a strong sustainability viewpoint. Consequently, using the value of T_{DPP} in Equation (15), we deduce that the OSP is defined by:

$$\mathrm{OSP}(B_1(0), O) = g\frac{1 + i - (1 + i)^{-T_{\mathrm{NNL}}(B_1(0), O))}}{\alpha i}, \tag{26}$$

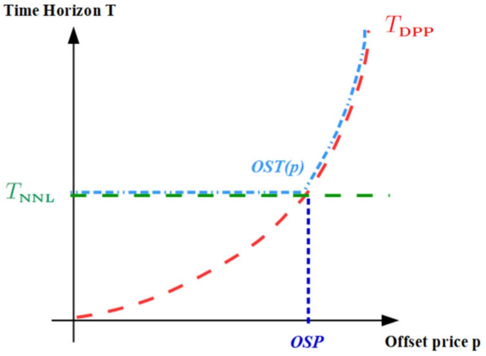

FIGURE 2 Offset sustainability time OST as a function of the marginal offset price p: the OST (in blue) emerges as the maximum value of the no net loss lag T_{NNL} (green) and payback duration T_{DPP} (red).

where $T_{\mathrm{NNL}}(B_1(0), O)$ is defined in equation (19). In the Gompertz dynamics case, we can obtain an explicit formula of $\mathrm{OSP}(B_1(0), O)$ relying on characterization (20) of the NNL sustainable lag.

2.7 | Private versus social losses within a strong sustainability approach

We use the idea of private and social losses as developed in Semaan et al. (2007) and based on Kapp (1950) and Pigou (1920) and deduce the supplementary losses induced by the adoption of the OSP regulation. In mathematical terms, we compare the ecological-economic outcomes associated with the OST duration and those focusing on either the ecological (NNL) or the economic constraint (DPP). We distinguish between the loss of time through time horizon T and the loss of monetary value through the NPV. In the present paper, the economic constraint is to achieve profitability while the ecological constraint is to achieve nature restoration. Each constraint translates in time into, respectively, T_{DPP} and T_{NNL}. Therefore, saying that the ecological constraint dominates the economic constraint means that $T_{\mathrm{NNL}} > T_{\mathrm{DPP}}$. In value terms, it means that $\mathrm{NPV}(T_{\mathrm{NNL}}) > \mathrm{NPV}(T_{\mathrm{DPP}})$. [7]

2.7.1 | Private loss due to sustainability

The private (or economic) loss is the translation of a performance gap for developers entailed by the regulation based on a strong sustainability approach. Imposed by the public authority, sustainability results in a choice of time, here the OST, and translates into the BO price OSP. The latter impacts the economic score based on the profitability time T_{DPP}: potentially, the OST will delay the profitability time and the OSP increase the amount paid by the developer.

In mathematical terms, using the constraint (24), we deduce that the economic loss denoted by ΔT_{econ} (time) and ΔV_{econ} (monetary value) respectively reads as follows:

- in time:

$$\Delta T_{econ}(p) = \mathrm{OST} - T_{\mathrm{DPP}} = \begin{cases} T_{\mathrm{NNL}} - T_{\mathrm{DPP}}, & \text{if } p \le \mathrm{OSP}, \\ 0, & \text{otherwise}. \end{cases} \tag{27}$$

- in monetary value:

$$\Delta V_{econ}(p) = \mathrm{NPV}(\mathrm{OST}) - \mathrm{NPV}(T_{\mathrm{DPP}}) = \begin{cases} \mathrm{NPV}(T_{\mathrm{NNL}}), & \text{if } p \le \mathrm{OSP}, \\ 0, & \text{otherwise}. \end{cases} \tag{28}$$

As displayed by the red curve in Figure 3, we can observe that this economic loss vanishes (in time or value) from when the marginal offset price p is greater than the OSP. In other words, setting p at or above the OSP is equivalent to focusing on the economic viewpoint. Said differently, for such high offset prices, the economic constraint becomes more stringent than the ecological one.

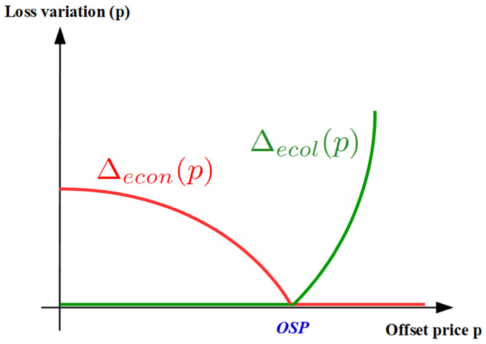

FIGURE 3 OSP as a win–win offset value: as claimed by Proposition 1, the offset sustainability price OSP emerges as a win–win offset value where both the economic loss $\Delta T_{econ}(c)$ (in red) and ecological loss $\Delta T_{ecol}(p)$ (in green) due to the adoption of the OSP as a marginal land unit price are minimized and coincide. OSP, offset sustainability price.

2.7.2 | Social loss due to sustainability

In a symmetric way, we define the social (or ecological) loss as the performance gap resulting from the adoption of the sustainability viewpoint. This social loss encompasses the society's costs. Assuming that the ecological interest tends to align with a "social" viewpoint, we use the term ecological loss (see Laitila et al., 2014) to name the "social loss due to sustainability".

In mathematical terms, again using the constraint (24), we deduce that:

- in time:

$$\Delta T_{ecol}(p) = \mathrm{OST} - T_{\mathrm{NNL}} = \begin{cases} 0, & \text{if } p \le \mathrm{OSP}, \\ T_{\mathrm{DPP}} - T_{\mathrm{NNL}}, & \text{otherwise}. \end{cases} \tag{29}$$

- in value:

$$\Delta V_{ecol}(p) = \mathrm{NPV}(\mathrm{OST}) - \mathrm{NPV}(T_{\mathrm{NNL}}) = \begin{cases} 0, & \text{if } p \le \mathrm{OSP}, \\ -\mathrm{NPV}(T_{\mathrm{NNL}}), & \text{otherwise}. \end{cases} \tag{30}$$

We can observe here, as captured by the green curve in Figure 3, that this social loss vanishes whenever the marginal offset price p is smaller than the OSP. In fact, for such low offset prices, the ecological target is more stringent than the economic one (thus $T_{\mathrm{NNL}} > T_{\mathrm{DPP}}$).

3 | RESULTS

3.1 | The offset sustainability price OSP as a win–win price

The OSP turns out to be the offset price where both economic (or private) and ecological (or social) losses due to sustainability are minimal and null. In that sense, the OSP level constitutes a "win–win" pricing (or an optimal marginal offset price in the Pareto sense), reconciling ecological and economic performances. Proposition 1 below captures this assertion in mathematical terms.

Proposition 1. *Given biodiversity levels $B_1(0), B_2(0)$ satisfying assumption* (5), *and offset area O, the OSP corresponds to both minimal and zero private and social losses* (*in time*) *due to the adoption of a strong sustainability approach in the sense that:*

- $\min_{p \geq 0} \Delta T_{econ}(p) = \Delta T_{econ}(\mathrm{OSP}) = 0$,
- $\min_{p \geq 0} \Delta T_{ecol}(p) = \Delta T_{ecol}(\mathrm{OSP}) = 0$.

Such a result is illustrated in Figure 3. The proof is given in Appendix Section A.1.7. Thus, by imposing the offset price OSP, the public authority prevents both private and social losses. In other words, the OSP emerges as the minimal offset price allowing the developer to make profit only after the biodiversity recovery time OST.

A similar result can be obtained in value NPV as follows:

- $\min_{p \geq 0} \Delta V_{econ}(p) = \Delta V_{econ}(\mathrm{OSP}) = 0$,
- $\min_{p \geq 0} \Delta V_{ecol}(p) = \Delta V_{ecol}(\mathrm{OSP}) = 0$.

Said differently, in value terms, when $p = \mathrm{OSP}$, both the financial private and social losses are null as $\mathrm{NPV}(\mathrm{OST}) - \mathrm{NPV}(T_{\mathrm{DPP}}) = 0$ and $\mathrm{NPV}(\mathrm{OST}) - \mathrm{NPV}(T_{\mathrm{NNL}}) = 0$.

3.2 | Static comparative analysis

We propose here a static comparative analysis of the sustainable offset price OSP with respect to the various parameters of the bioeconomic model. Such parameters include the expected marginal productivity g and the discount rate i on the economic side and, on the ecological side, the intrinsic growth rate r, initial biodiversity levels, carrying capacities, offset ratio α and offset surface area O. We use the explicit formula of $\mathrm{OSP}(B_1(0), O)$ in (26) together with characterization (20) of the NNL sustainable lag when a Gompertz dynamics is considered: the following Table 1 shows the qualitative results.

The proofs of this static comparative analysis are given in Section A.1.8 of Appendix A. Table 1 highlights that the OSP increases with the marginal revenue and the initial biodiversity loss on the developed site. By contrast, the OSP decreases with the discount rate, the initial biodiversity level on the offset site and the offset surface area.

This last analysis is informative in terms of decision making. Let us recall that the decision to impose a sustainable marginal offset price OSP lies in the hands of the public authority who makes its choice according to time OST. Therefore, from the developer's viewpoint, to limit the offset value OSP, strategies first include modifying the initial biodiversity conditions, for instance by changing the development site for a smaller one (decreasing the value of D), by increasing the offset surface area (increasing the value of O), or using a site with a smaller biodiversity value (thus decreasing the value of $B_1(0)$). Such an option relates to the second step of the "mitigation hierarchy" which consists in limiting the impacts on biodiversity and ecosystems. A second possibility is to choose a biodiversity reference with high growth rates r. We note that the extreme case where $B_2(0) = 0$ is problematic, since it represents a collapse of biodiversity in the offset site, with no possibility of growing and recovering.

TABLE 1 Parameter influence on the OSP: OSP static comparative analysis, when $B_1(0) \leq K_1^{O^-}$ and $O < B_2(0) \leq K_2^{O^-}$ as in assumption (5).

Parameter y	**Sign of derivative $\frac{\partial \text{OSP}}{\partial y}$**
Project return g	+
Discount rate i	−
Initial biodiversity lost $B_1(0)$	+
Initial biodiversity—offset site $B_2(0)$	−
Initial habitat quality $K_2^{O^-}$	−
Intrinsic growth rate r	−
Offset surface area O	−
Offset ratio α	−

Note: Notations + and −, respectively stand for positive and negative signs of the derivative. A positive sign means that the parameter influences positively the OSP while a negative sign means that its influence is negative.

We now discuss the influence of the discount rate i. As a general rule, the expected gains derived from a project are given a decreasing value through time. Thus, a project profitability time is greatly determined by the choice of the discount rate (Frederick et al., 2002; Green & Myerson, 2004; Laitila et al., 2014). Further, a low discount rate favors future generations and a high discount rate closer generations. An intergenerational justice approach thus leads the regulator to set the discount rate at the lowest possible value (although it remains the result of a bargain with developers). In the present case, the regulating agency, which is supposed to control the offset price here, may take advantage of a decreased value of the discount rate i. This will increase the OSP, putting more pressure on the profitability of the project, thus taking care of future generations (see Appendix Section A.2.2). The regulating agency can also modify the offset ratio α, namely the habitat quality relative gains.

As presented by Figure 4, a high initial biodiversity level $B_1(0)$ on the developed site combined with a weak initial biodiversity level $B_2(0)$ on the offset site may entail a long T_{NNL} and a high offset sustainable price OSP.In fact, given the biodiversity levels $B(0) = (B_1(0), B_2(0))$ satisfying assumption (5), and offset area O, the OSP($B(0), O$) can be high as compared to the marginal return g of the development project when the initial biodiversity level to be offset $B_1(0)$ is high. In terms of offset price, while a small OSP is more interesting for the developer and is observed in the red area, the green area corresponds to high OSP values, which are more interesting for the public authority since it matches the social objective of NNL.

3.3 | The multiplier effect on the OSP

Whenever the discount rate is close to zero ($i \approx 0$), we can quantify in a simple way the relative difference between the offset price OSP and project return g (without compensation costs). We can indeed exhibit a multiplier effect for the offset price in the sense of a linear effect with respect to g and depending on the NNL time T_{NNL}. Such a multiplier effect is captured by the following proposition.

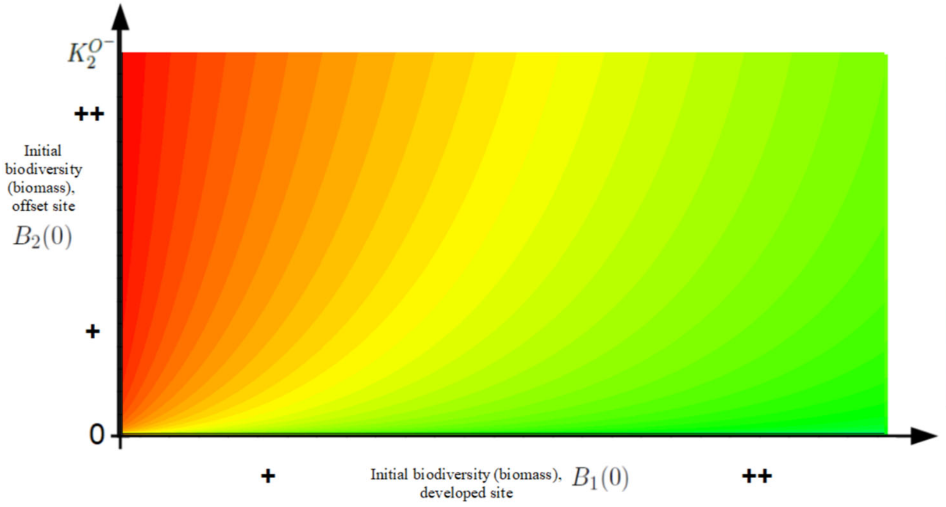

FIGURE 4 The offset sustainability price OSP as a function of the initial levels of biodiversity $B_1(0)$ and $B_2(0)$ on the developed and offset sites: the red area corresponds to situations with small initial biodiversity loss and high initial biodiversity on the offset site. As a result, biodiversity takes less time to recover than in the green area where the opposite is observed. The upper bound of $B_2(0)$ is $K_2^{O^-}$. + and ++ signs illustrate the increase of values as captured by the bar on the right-hand side.

Proposition 2. *Consider biodiversity levels* $B(0) = (B_1(0), B_2(0))$ *satisfying assumption* (5). *When the discount rate is low* ($i \approx 0$), *we have the following multiplier effect:*

$$\frac{\text{OSP}}{g}\alpha \approx 1 + T_{\text{NNL}}(B(0), O) \geq 1.$$

The formula of Proposition 2 relating to the multiplier effect provides a linear simplification of the OSP computation in the case of low discount rates. As low discount rates are common in finance (Arrow et al., 2013; Weitzman, 2001), this multiplier is a useful tool for the public authority (to favor future generations) and for the developer who can better predict the offset price he will be liable to. The multiplier effect underlying Proposition 2 on the sustainable offset price OSP with respect to the return rate g depends on the offset ratio α and the NNL duration T_{NNL}. As said previously in Section 2.5 and pointed out by inequality (21), this multiplier effect for the sustainable offset price OSP increases with the biodiversity to be offset $B_1(0)$ as captured by Figure 4. We may note that the lower the discount rate i, the higher the values of OSP (see Appendix Section A.2.2).

4 | EXAMPLE: SHRIMP FARMING AND MANGROVE REFORESTATION IN MADAGASCAR

We illustrate the previous theoretical results on BOs in the context of expanding shrimp industry in Madagascar and its associated BO measure, reforestation. Mangroves are a particular type of wetlands and a tropical forest ecosystem—growing in salt waters, located in humid and coastal areas. They provide key ES, in particular coastline protection, water purification and carbon sequestration (regulation services), maintenance of fisheries (via nurseries), and raw material provision, especially wood (provisioning services) (Barbier, 2012), besides cultural services and tourism. Mangroves in Madagascar, with 2,100 km^2 located especially on the west coast (98%) of the island, represent, respectively, about 2% and 20% of the world and African mangroves (Bosire et al., 2016; Jones et al., 2016). According to Jones et al. (2016), Madagascar lost about 21% of its mangroves (or about 57,359 ha) between 1990 and 2010 (although at a decreasing rate). Besides cyclones, the main threats to Malagasy mangrove areas are agriculture (land conversion for rice production) (35%), logging (16%), aquaculture (3%), and urban development (1%) (Razakanirina & Roger, 2013). In particular, the shrimp farming industry (Agarwal et al., 2019) is responsible for about 52% of the overall mangrove loss each year in the world.

4.1 | Model parameters

We focus here on a development-offset project implemented by AQUALMA (UNIMA group), an aquaculture firm operating in the North West of Madagascar (Figure 5). UNIMA is the biggest Malagasy shrimp exporter and is praised for its social and environmental commitments (Red and CSA labels) (Monfort & Rajaosafara, 2017; Slobodian & Badoz, 2019). In partnership with the nongovernmental organization WWF,[9] it committed to implement BOs through reforestation as a compensation for the development of a surface area of $D = 800$ ha to be used as a shrimp farm in Mahajamba bay (45,107 ha) (Darbi, 2020; Jones et al., 2015). The farm has an average productivity of 4.5 tons per year per hectare (Rajaosafara & du Payrat, 2009) and its marginal return rate without offset is here estimated[10] to $g = 70,000$ US\$ ha^{-1}.

In the present case, the biomass is assimilated to tree units. UNIMA planted about $B_2(0) = 850,000$ mangrove tree seedlings (Rajaosafara & du Payrat, 2009) in compensation for the loss of a much greater amount of biodiversity, here set to $B_1(0) = 8,000,000$ trees. We here assume that we are at equilibrium for $B_1(0)$, hence we set $K_1^{O^-} = B_1(0)$.[11] We start with equal surface areas for both the developed and offset sites, hence $\alpha = 1$ and $D = O = 800$ ha and then use an offset ratio of $\alpha = 2$. Initially, the offset site is a depleted area and its carrying capacity is

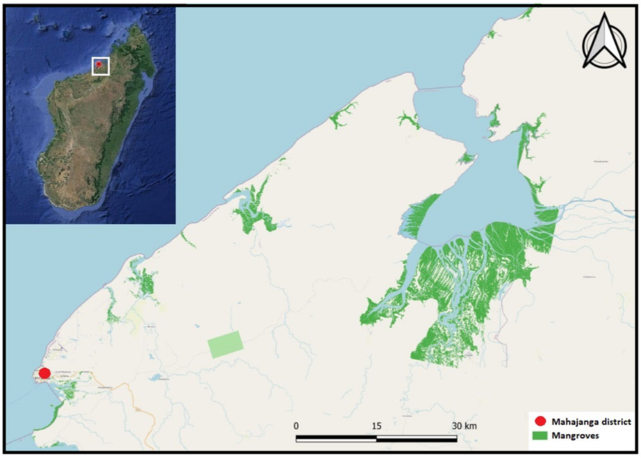

FIGURE 5 Map of the Mahajamba Bay in Madagascar.

low as compared to K_1^{O-}; we set arbitrarily[12] $K_2^{O^-} = 2 \times B_2(0) + 300,000 = 2,000,000 < B_1(0)$ (let us assume that $K_2^{O^-} > B_2(0)$ as the site, despite its poor quality, still hosts some mangrove trees). After reforestation and further rehabilitation, the carrying capacity reaches $K_2^{O^+} = K_2^{O^-} + \alpha.\ K_1^{O^-} = 2,000,000 + 1 \times 8,000,000 = 10,000,000$ (then $K_2^{O^+} = K_2^{O^-} + \alpha.\ K_1^{O^-} = 2,000,000 + 2 \times 8,000,000 = 18,000,000$) (then $K_2^{O^+} > B_2(0) + B_1(0)$).

Here, to simplify, we consider that only the species *Avicennia marina* was planted of which the annual regeneration rate[13] is $\text{reg}_{\max} = 215\%$ (Benfield et al., 2005) which gives the intrinsic growth rate $r = \ln(3.15)$ for the Gompertz dynamics.[14] The discount rate used is set to $i = 3\%$ as advocated by Weitzman (2001) and Thompson et al. (2014) for near-future projects (6–25 years). Parameter values and characteristics are summarized in the Appendix Sections A.2.1 and A.2.4.

4.2 | Results

Table 2 below displays the BOs time lag OST and price OSP induced by the mathematical analysis of the previous sections. Several configurations are compared. In the first row, we assume that the offset ratio is one ($\alpha = 1$), namely that development and offset areas coincide ($O = D$). The second row corresponds to the case of offset gains where $O > D$ namely $\alpha = 2$.

The first configuration ($\alpha = 1$) presents a large time of OST due to the NNL time T_{NNL} of about 66.5 years. The offset sustainability price (OSP = 2077×10^3 US\$ ha^{-1}) derived from the model is much greater than the marginal BO price for land repurchase ($p = 492$ US\$ 2007 ha^{-1} reported in the official documents (Rajaosafara & du Payrat, 2009). This latter price is set by the public authority and is usually aligned with land or housing prices. Similarly, with the second configuration ($\alpha = 2$), we have OST = 21.3 years and OSP = 581×10^3 US\$.

Figure 6 shows the ecological and economic trajectories associated with the sustainable offset price OSP for $\alpha = 2$.

4.3 | Results interpretation

The example reveals that, compared to the OSP model, current BO price p is set at a very low level which results in a low constraint on the developer. In fact, the underestimation of the value p arises from not accounting for the biodiversity dynamics and the time lag OST required for its recovery, nor the additionality principle. We thus argue that the biodiversity time lag is underestimated. With the present model, the OSP imposed by the public authority on the developer allows it to be taken into account through the account of the biodiversity dynamics.

TABLE 2 Example in Madagascar: computation of the offset sustainability time OST and price OSP for two levels of offset ratio: $\alpha = 1$ and $\alpha = 2$.

Offset ratio α	**Offset area** O **(ha)**	**Offset quality** $K_2^{O^+}$ **(trees)**	**BO sustainable lag** **OST (years)**	**BO sustainable price** **OSP (10^3 US\$ *ha*$^{-1}$)**
$\alpha = 1$	800	10,000,000	≈66.5	≈2,077
$\alpha = 2$	1,600	18,000,000	≈21.3	≈581

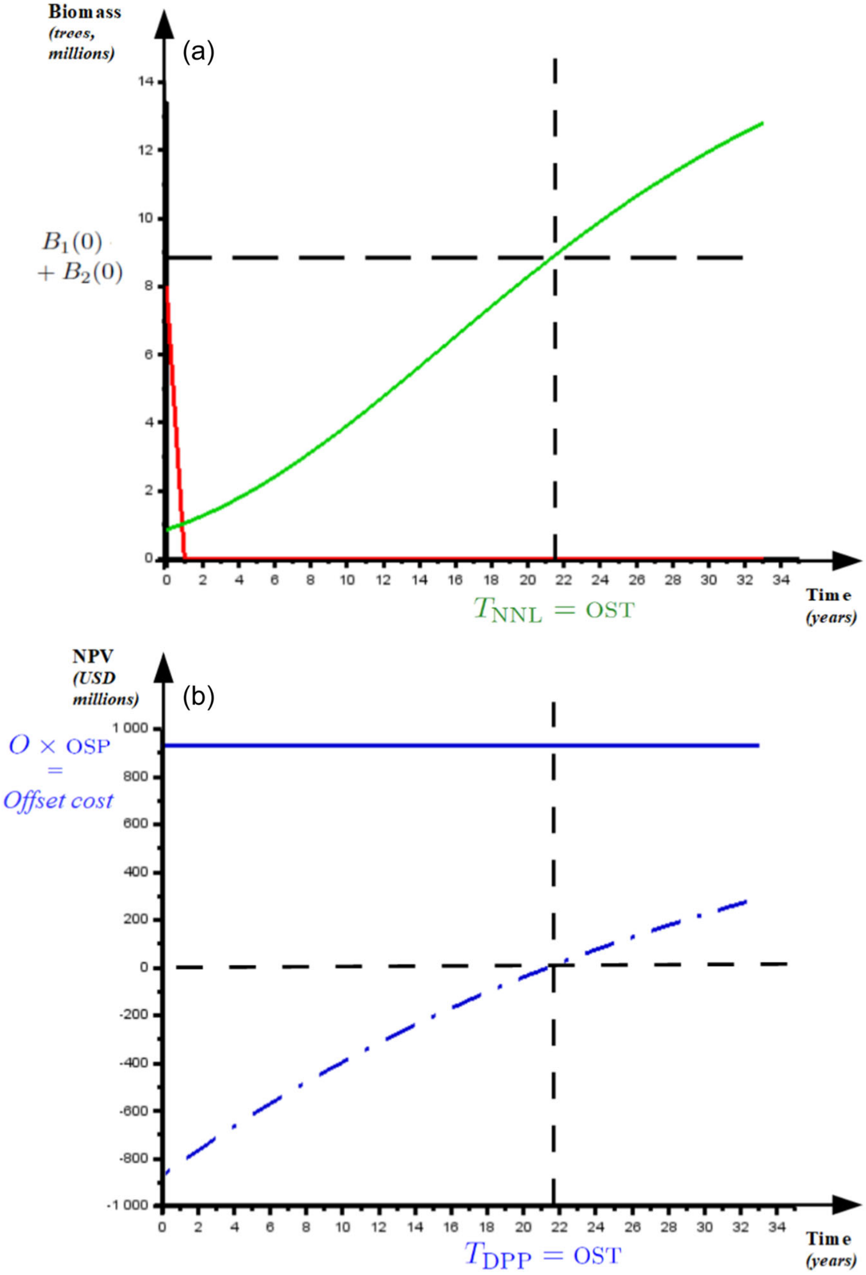

FIGURE 6 Biodiversity and economic dynamics with the offset sustainability price $p = \text{OSP}$ and offset ratio $\alpha = 2$. (a) Biodiversity trajectories are depicted on the developed (red) and offset (green) sites. Biomass $B_1(t)$ collapses rapidly after the start of the development project on the developed site while biomass $B_2(t)$ increases (with a Gompertz growth pattern) on the offset site. (b) The net present value (NPV) of the development project (lower blue line) increases over time and is positive from $t = T_{\text{NNL}} \approx 21$ years. The upper blue line represents the total offset cost $O \times \text{OST}$. We observe that the project profitability date is postponed because of the new offset price.

More precisely, it implies that the social loss resulting from the development-offset project is underestimated. Here, the OSP allows to internalize this loss - resulting from a lost access to nature—into the project costs. In fact, according to the Business and Biodiversity Offsets Programme (BBOP, 2012), there should ideally be no time gap between the impact of the development and the realization of the offsets, so as to ensure the continuing provision of ES to the local population, besides other conditions, namely that the site is (a) close enough and (b) of a similar kind (Bull et al., 2013; Moilanen et al., 2009). Thus, it could be argued that the underfunding of BOs and conservation initiatives (Buschke et al., 2019) is the result of a lack of consideration for this social loss.

The present model creates a useful public policy tool. In the hands of the public authority, it creates incentives for the developer and may therefore influences practices in the implementation of in-kind BOs. Based on the static comparative analysis in Table 1 and the sensitivity results in Table 2, it can be argued that a couple of incentives derive from the OSP model and thus may enhance the efficiency of in-kind BO systems. In fact, considering that the developer's strategy is to decrease the OSP, some actions can be identified. First, regarding the offset ratio, the second row of Table 2 reveals that increasing the offset surface area is a way for the developer to decrease the offset price OSP. In fact, the offset ratio directly affects the value of $K_2^{O^+}$and thus the OST. In the present case study, the latter decreases by about 68% and the OSP by about 72% with a 100% increase in offset surface area. Second, the developer may modify the initial biodiversity conditions, for instance by changing the development site for one with a lower initial biodiversity level $B_1(0)$. The developer can in fact decrease the richness of the developed surface area, an option which seems rather unrealistic in the example given the precise reason why shrimp cultures thrive so well in mangrove areas. Third, he may choose an offset site with a higher initial biodiversity level $B_2(0)$. However, this approach raises the additionality issue mentioned earlier. Further, this lever is limited as it appears that natural regeneration is usually more efficient than reforestation via planting operations (Fickert, 2020; Lewis, 2005), despite some positive experiences (Ferreira et al., 2015). Then, and more realistically, the initial quality of the offset site $K_2^{0^-}$ may be increased thanks to, for instance, a better irrigation system (Bosire et al., 2008). In fact, the initial carrying capacity of the offset site $K_2^{O^-}$ is a key element to take into account as it affects the final carrying capacity as $K_2^{O^+} = K_2^{O^-} + \alpha.\ K_1^{O^-}$. Intuitions are confirmed as the greater the initial site carrying capacity, the smaller the OST and thus the OSP. In other words, the greater the initial potential of the offset site, the faster the biomass growth, the smaller the OST and thus the OSP (see Appendix Section A.2.3). This potential may be increased via a better connectivity of the habitats, providing their homogeneity (i.e., proximity with biodiversity rich sites). Another option would be to select species with greater growth rates. In the present case nonetheless, the intrinsic growth rate r of the selected mangrove trees *Avicennia marina* is already very high.

Lastly, in the context of a very small discount rate (see Appendix Section A.2.2), the OSP can be anticipated as high and approximated as suggested in Proposition 2 on the multiplier effect. A major conclusion of the study of Barbier and Cox (2004) on mangroves in Thailand is that deforestation increases with greater shrimp prices through the increase of the marginal return rate g. Here, the offset price per hectare increases with g, thus providing developers a disincentive to implement such practices.

5 | DISCUSSION AND PERSPECTIVES

Our paper specifically addresses the issue of BO time lag and price. It draws on a spatially structured, dynamic and bioeconomic modeling framework to conduct an analytical and numerical analysis of both conservation and profitability performances of development projects associated with biodiversity offsets. We adopt a regulating agency's viewpoint aiming to balance these ecological-economic performances and thus promote a strong sustainability approach through BO duration and price.

The proposed model relies on the computation of a "minimal time problem" called OST to achieve two desired targets: the biodiversity NNL and payback for the developer. An offset price OSP is identified which is a minimum sustainable land unit price allowing a win–win situation. In other words, it allows a win–win outcome for both the society and the private company as it minimizes their losses due to the adoption of a strong sustainability approach (see Proposition 1). In particular, applying this offset price OSP constrains the developer who makes profit only after the biodiversity recovery is achieved. A static comparative analysis shows the impact of economic (marginal revenue of the development project, discount rate) and ecological parameters (initial biodiversity conditions, resource intrinsic growth rate) on the OSP. A particular focus on the role played by the biodiversity states of both sites exhibits a nonlinear multiplier effect on the OSP. By contrast, a linear multiplier effect is identified with respect to the initial (without offset and with low discount rate) economic return of the development project. A numerical application related to mangroves and aquaculture in Madagascar illustrates the analytical findings. It points out that the BO price magnitude has to be much higher than what is observed in reality.

The present model and results entail at least three important consequences. First, it provides incentives in the context of in-kind BOs implementation. In particular, implemented as such, the OSP encourages the developer to lower the time lag OST. This can be achieved via either the choice of a higher offset ratio, of a less rich in biodiversity developed site (as compared to the offset site), or of another equivalent but more productive species. In line with such timing issues, although not developed in this paper, the developer may anticipate the BOs, through the creation of an offset site before the development phase or the use of biodiversity banking credit (Drechsler & Hartig, 2011; Pope et al., 2021). Second, the OSP allows to take the social loss of a development-offsets project into account. In a general perspective, the OSP complies with the Developer-Pays Principle of BOs (Koh et al., 2019, 2017) which implies ecological restoration activities, contrary to a pollution tax, based on the Polluter-Pays Principle (OECD, 2008) and which only requires monetary compensation. As the OSP entails a BO cost, developers are indeed encouraged to limit their impact on biodiversity and habitat. Furthermore, using BOs, the financial benefits derived from the OSP can be directly invested in biodiversity and habitat quality enhancement. Third, the offset sustainable price OSP has important consequences regarding the land allotment process. In fact, as far as land access is concerned, our model reinforces the BO incentive system through a price mechanism linked to the ecological time lag. Land is too often attributed for free to private developers, or at a very low price. In the literature, despite rents from alternative uses (Hansen, 2009) and biodiversity credit prices (Drechsler & Hartig, 2011) or the social cost of carbon sometimes taken into account (Gallant et al., 2020), studies do not include the price of land into the restoration costs of mangroves (Barbier, 2016).

Concerning the offset area (or, equivalently, offset ratio α) choice, the present model and the static comparative analysis point out at two major concerns regarding actual BO implementation. On one hand, the offset surface area has to be large enough to ensure biodiversity recovery. Observations in developing countries where most offset surface areas (99.7%) are too small (Bull & Strange, 2018) illustrate that this remains a very concerning issue. In fact, achieving the NNL requires the use of high offset ratios (Laitila et al., 2014; Thébaud et al., 2015), a result also asserted by the presented model: the larger the offset surface area O, the smaller the OST and the OSP imposed on the developer. On the other hand, beyond its extent, a central issue at stake is the initial quality of the offset surface area receiving the biodiversity offsets. As explained by Weissgerber et al. (2019), besides additionality considerations, and contrary to what is actually implemented, biodiversity gains are greater on artificialized sites. In the present study, not only must the NNL time be low but so must the initial biodiversity state $B_2(0)$ on the offset site. This means that the offset area must initially contain a low level of biodiversity, allowing huge growth potential and thus biodiversity gains and additionality, as required by the NNL objective. One might note that a tension appears here in the choice of the offset site between a low and a zero initial biodiversity level because the latter option, as a steady state of the system, would impede the necessary growth for NNL purposes. Potential biodiversity growth can be enhanced via the site's location, through neighboring a biodiversity rich site, which is consistent with the so-called "connectivity" requirement in BO measures (Moilanen et al., 2009). In fact, adapting spatial network dynamics properties (habitat spatial distribution, area extent, soil characteristics, etc.) and temporal properties (habitat suitability over time for instance) may counterbalance the negative effects of habitat changes (Van Teeffelen et al., 2012). Regarding this issue, recent developments in the use of landscape graphs allowing to model species distribution on a given habitat (Foltête et al., 2014) or species distribution models (SDMs) (Elith & Leathwick, 2009; Miller, 2010) are informative. Notably, habitat fragmentation plays a key role in species' viability (Hanski & Gaggiotti, 2004; Hermansen et al., 2017). The example is very illustrative in this regard with the choice of mangrove trees for the offset.

In addition, the previous results can be analyzed in ecological terms, particularly with regard to the type of biodiversity chosen. Table 1 shows that a high intrinsic growth rate r accelerates the compensation by reducing both the offset sustainability time OST and price OSP. Such a result questions the choice of relevant similar species (between the two sites) when it is not possible to rely exactly on the same species, while ensuring the ecological equivalence (Maron et al., 2012).

From a governance viewpoint, this study argues for a greater involvement of the public authority, as Koh et al. (2019)—through the instruments mentioned above—, rather than a process based solely on Corporate Social Responsibility (CSR) strategies of companies implementing activities in developing countries (i.e., Rio Tinto in Madagascar) (Bidaud et al., 2015; Thompson, 2018). The choice of the discount rate by the public regulator is relevant when considering future generations and sustainability. In the context of a paradigm change regarding the objective of BOs (Damiens et al., 2021), the present model allows ecological and economic objectives to be reconciled with a strong sustainability perspective, by adopting the viewpoint of the regulating agency.

Finally, this paper calls for some extensions such as the role played by uncertainties in BOs (Bradford, 2017; Bull et al., 2013; Maron et al., 2012; Moilanen et al., 2009), the use of multispecies or multitaxa states as biodiversity proxy rather than one single state and the consideration of ES. Through the Gompertz dynamics and characterizations that can be easily extended to multispecies contexts, this current version paves the way to address the multispecies and biodiversity challenges. Besides, it also opens a way to the consideration of ES, thanks to a multicriteria viewpoint underlying the different ecological-economic targets.

AUTHOR CONTRIBUTIONS

Celine Huber: Conceptualization; Data curation; Investigation; Funding acquisition; Writing—original draft; Methodology; Resources; Formal analysis; Software; Visualization. **Luc Doyen**: Formal analysis; Methodology; Writing—review and editing; Supervision; Validation. **Sylvie Ferrari**: Project administration; Supervision; Resources; Validation; Writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Rajaosafara, S., & du Payrat, T. (2009) at https://docplayer.fr/5542093-Developpement-durable-a-madagascar-etude-de-cas.html.

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ENDNOTES

[1] Usually, the biodiversity reference is either determined by the biologists mandated by the public authority or by the developer.

[2] See Appendix Section A.1.1 for the proof.

[3] This is not too demanding since r has generally a low value as a rate.

[4] Spatiality is not explicitly considered in our paper as in, for instance, Falke et al. (2012) who studied the impacts of habitats dynamics on metapopulations. Here, the connectivity on the compensation site is implicit in the sense that the offset surface O increases the carrying capacity $K_2(O^-)$ of this site resulting in $K_2^{0^+} = K_2^{0^-} + \lambda O$.

[5] See the proof in Appendix Section A.1.2.

[6] See the proof in Appendix Section A.1.8

[7] An NPV(T_{NNL}) can be analyzed as "the discounted value of the net benefits of use of a resource"[8] and as in Overton et al. (2013) (Net Present Value of Biodiversity, NPVB), it can be defined "as a basic measure against which the no-net-loss criterion can be measured," thanks to the specification of "the relative value of biodiversity, discount functions or rates," before and after the implementation of BOs.

[8] https://www.eea.europa.eu/help/glossary/chm-biodiversity/net-present-value

[9] World Wide Fund for nature.

[10] The price of the giant tiger prawn cultivated in mangrove areas is estimated at 31.71 US$ (2020) (26 Euros 2020) per kilo (FAO, 2020). Thus, we can compute a return rate per hectare: $g = 31.71 \times 4500 = 142,695$ US\$. According to Thompson et al. (2014), the production cost can amount to half of the marginal revenue, thus we set the marginal return rate of the project to $g \approx 70,000$ US\$ ha^{-1}.

[11] Based on the rule of one tree per square meter when maturity is reached, as described in Rakotondrazafy (2022): 800 ha = 8,000,000 m^2, thus 8,000,000 trees.

[12] The sensitivity of OSP to $K_2^{O^-}$ is shown in Table A3 in Appendix Section A.2.3

[13] Natural regeneration rate refers to the speed of "the process by which juvenile plants and coppice that have established naturally replace plants which have died or have been killed" (Brown, 2004). Although we use this rate, the present case study is based on an assisted regeneration.

[14] Since $e^r \approx 1 + \text{reg}_{\text{max}}$, then $r \approx \ln(3.15)$, see Benfield et al. (2005) for the species *Laguncularia racemosa*.

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APPENDIX A

A.1 Proofs

Hereafter, for sake of simplicity, we assume (5).

A.1.1 Biodiversity dynamic with a Gompertz form in discrete time

We suppose that the biodiversity dynamics has a Gompertz form in discrete time:

$$B(t+1) = B(t)\exp\left(r\left(1 - \frac{\ln(B(t))}{\ln(K)}\right)\right). \tag{A1}$$

If we now consider the logarithm of the biodiversity $y(t) = \ln(B(t))$ as the new state of the system, we deduce the dynamics

$$y(t+1) = r + \alpha y(t),$$

where $\alpha = 1 - \frac{r}{\ln(K)}$. As $y(t)$ is a geometric-arithmetic sequence, we can also deduce

$$y(t) = \frac{r}{1-\alpha} + \alpha^t\left(y(0) - \frac{r}{1-\alpha}\right).$$

Using the value of α yields

$$y(t) = \ln(K) + \alpha^t(y(0) - \ln(K)).$$

Coming back to $B(t)$, we then obtain:

$$\begin{aligned} B(t) &= e^{y(t)} \\ &= e^{\ln(K)+\alpha^t(y(0)-\ln(K))} \\ &= Ke^{\alpha^t(\ln(B(0)-\ln(K))} \\ &= Ke^{\alpha^t \ln\left(\frac{B(0)}{K}\right)} \\ &= K\left(\frac{B(0)}{K}\right)^{\alpha^t} \end{aligned}$$

which is the desired result for every site s

$$B_s(t) = K_s \left(\frac{B_s(0)}{K_s} \right)^{\left(1 - \frac{r}{\ln(K_s)}\right)^t}.$$

A.1.2 Characterization of T_{NNL}

We consider the NNL constraint (17)

$$B_2(T) \geq B_1(0) + B_2(0). \tag{A2}$$

We aim at proving that such a NNL requirement is equivalent to

$$T \geq T_{\mathrm{NNL}}(B(0), O) \tag{A3}$$

where $T_{\mathrm{NNL}}(B(0), O)$ fulfills the equality underlying the NNL constraint in the sense that

$$B_2(T_{\mathrm{NNL}}) = B_1(0) + B_2(0) \tag{A4}$$

Assuming that $r > \log(K)$, the Gompertz dynamics satisfies the condition

$$F_B(B, K) > 0. \tag{A5}$$

Moreover we have

$$F(B, K)/B > 1 \quad \forall\, B < K. \tag{A6}$$

We prove sequentially that

$$\forall\, t \geq T_{\mathrm{NNL}}, K_2 > B_2(t) \geq B_2(T_{\mathrm{NNL}}) = B_1(0) + B_2(0)$$

- Such claim holds true for $t = T_{\mathrm{NNL}}$ because we have from offsetting relations of surfaces (6):

$$K_2 = K_2^0 + \lambda O \geq K_2^0 + \lambda D \geq K_2^0 + K_1^0 \geq B_2(0) + B_1(0) = B_2(T_{\mathrm{NNL}}) \tag{A7}$$

- We assume now that the claim holds at time t. Let us prove it at time $t + 1$. As $K_2 > B_2(t)$, we use the condition (A6) to deduce

$$B_2(t+1) = F(B_2(t), K_2) \geq B_2(t) \geq B_2(T_{\mathrm{NNL}})$$

Furthermore, as $B \to F(B, K_2)$ is an increasing function from (A5), we also have

$$B_2(t+1) = F(B_2(t), K_2)) \leq F(K_2, K_2) = K_2$$

Thus we obtain the desired result.

A.1.3 Computation of T_{NNL} for the Gompertz growth

We use the Gompertz equation (3) for offset site $s = 2$

$$B_2(t) = K_2\left(\frac{B_2(0)}{K_2}\right)^{\left(1-\frac{r}{\ln(K_2)}\right)^t}.$$

Taking twice the logarithm of this equality, we obtain

$$\ln\left(\ln\left(\frac{B_2(t)}{K_2}\right)\right) - \ln\left(\ln\left(\frac{B_2(0)}{K_2}\right)\right) = t\ln\left(1-\frac{r}{\ln(K_2)}\right).$$

Replacing $B_2(t)$ by $B_1(0) + B_2(0)$ and K_2 by $B_2(0) + \lambda O$, we obtain the desired equality for T_{NNL} namely

$$T_{\text{NNL}}(B(0), O) = \ln\left(\ln\left(\frac{B_1(0)+B_2(0)}{B_2(0)+\lambda O}\right)\ln\left(\frac{B_2(0)}{B_2(0)+\lambda O}\right)^{-1}\right)\ln\left(1-\frac{r}{\ln(B_2(0)+\lambda O)}\right)^{-1}$$

A.1.4 Payback time T_{DPP}

The very general definition (14) of payback time T_{DPP} is

$$\text{NPV}(T_{\text{DPP}}) = 0.$$

Using the characterization of the NPV in Equation (12), we have

$$g\frac{1+i-(1+i)^{-T_{\text{DPP}}}}{\alpha i} - p = 0,$$

or

$$1+i-\frac{\alpha p i}{g} = (1+i)^{-T_{\text{DPP}}}.$$

Taking the logarithm of both sides, we obtain

$$-T_{\text{DPP}}\ln(1+i) = \ln\left(1+i-\frac{\alpha p i}{g}\right)$$

and we conclude.

A.1.5 Offset sustainability time OST

The offset sustainability time denoted by OST is defined as the minimal temporal horizon T such that both ecological and economic constraints (17), (13) are fulfilled:

$$\text{OST}(B(0), O, p) = \min(T \geq 0 | \text{ constraints (17), (13) hold true}). \tag{A8}$$

Let us prove that such OST equals:

$$\text{OST}(B(0), O, p) = \max(T_{\text{NNL}}(B(0), O), T_{\text{DPP}}(p)).$$

For any time T complying with constraints (17), (13), using characterizations (A3), (15), we have

$$T \geq T_{\mathrm{NNL}},\ T \geq T_{\mathrm{DPP}}.$$

Consequently,

$$T \geq \max(T_{\mathrm{NNL}}, T_{\mathrm{DPP}}).$$

Taking the min over these T, we deduce that

$$\mathrm{OST}= \min(T, \ldots) \geq \max(T_{\mathrm{NNL}}, T_{\mathrm{DPP}}).$$

Conversely, considering $T^* = \max(T_{\mathrm{NNL}}, T_{\mathrm{DPP}})$, we can write

$$T^* \geq T_{\mathrm{NNL}},\ T^* \geq T_{\mathrm{DPP}}.$$

Using characterizations (A3), (15), we deduce that T^* satisfies constraints (17), (13). Thus

$$T^* \geq \min(T \geq 0 |\ \text{constraints (17), (13) hold true}) = \mathrm{OST}$$

and we conclude that $\mathrm{OST}= \max(T_{\mathrm{NNL}}, T_{\mathrm{DPP}})$.

A.1.6 Offset sustainability time OST and price OSP

Let us prove that

$$\mathrm{OST}(B(0), O, p) = \begin{cases} T_{\mathrm{NNL}}, & \text{if } 0 \leq p \leq \mathrm{OSP}(B(0), O), \\ T_{\mathrm{DPP}}, & \text{otherwise}, \end{cases} \tag{A9}$$

where the $\mathrm{OSP}(B(0), O)$ is characterized as in (25) by

$$T_{\mathrm{DPP}}(\mathrm{OSP}(B(0), O)) = T_{\mathrm{NNL}}(B(0), O). \tag{A10}$$

Using T_{DPP} characterization (15), the condition $T_{\mathrm{NNL}}(B(0), O) \geq T_{\mathrm{DPP}}(p)$ reads equivalently

$$p \leq g\frac{1 + i - (1 + i)^{-T_{\mathrm{NNL}}}}{\alpha i} = \mathrm{OSP}.$$

We conclude.

A.1.7 OSP as a win–win offset price

We want to prove Proposition 1

- $\min_p \Delta V_{ecol}(p) = \min_p \Delta V_{econ}(p) = \Delta V_{ecol}(\mathrm{OSP}) = \Delta V_{econ}(\mathrm{OSP}) = 0,$
- $\min_p \Delta T_{ecol}(p) = \min_p \Delta T_{econ}(p) = \Delta T_{ecol}(\mathrm{OSP}) = \Delta T_{econ}(\mathrm{OSP}) = 0.$

We focus on the proof about time T and the economic gap namely

$$\Delta T_{econ}(p) = \text{OST} - T_{\text{DPP}}.$$

Since OST$=\max(T_{\text{NNL}}, T_{\text{DPP}})$, we first deduce that,

$$\Delta T_{econ}(p) \geq 0, \forall\, p \geq 0.$$

Thus

$$\min_{p} \Delta T_{econ}(p) \geq 0.$$

As $\Delta T_{econ}(\text{OSP}) = 0$, we conclude regarding $\Delta T_{econ}(.)$.
We proceed similarly for $\Delta T_{ecol}(p)$ and economic costs ΔV_{ecol}.

A.1.8 Static comparative analysis

- Using the linearity of OSP with respect to g, we easily obtain

$$\frac{\partial \text{OSP}}{\partial g} = \frac{\text{OSP}}{g} > 0.$$

- We use the formula OSP$= \sum_{t=0}^{T_{\text{NNL}}} \frac{g(1+i)^{-t}}{\alpha}$ to deduce that

$$\frac{\partial \text{OSP}}{\partial i} = \frac{-g}{\alpha} \sum_{t=0}^{T_{\text{NNL}}} t(1+i)^{-t-1} < 0.$$

- Hereafter, for sake of simplicity, we denote the carrying capacity after offsetting $K_2 = K_2^{0^+} = K_2^{0^-} + \lambda O$. In the sequel, we also rely on the relation OSP$= \alpha g \frac{1+i-(1+i)^{-T_{\text{NNL}}}}{i}$ to determine the (qualitative) sensitivity of OST from the sensitivity of T_{NNL}. We use the formula (20) for T_{NNL} in the Gompertz case namely

$$T_{\text{NNL}} = \frac{\ln\left(\ln\left(\frac{B_1(0)+B_2(0)}{K_2}\right)\ln\left(\frac{B_2(0)}{K_2}\right)^{-1}\right)}{\ln\left(1 - \frac{r}{\ln(K_2)}\right)} = \frac{A}{\ln\left(1 - \frac{r}{\ln(K_2)}\right)},$$

where $A < 0$. We deduce that

$$\frac{\partial T_{\text{NNL}}}{\partial r} = A \frac{-\frac{1}{\ln(K_2)}}{\left(1 - \frac{r}{\ln(K_2)}\right)\ln\left(1 - \frac{r}{\ln(K_2)}\right)^2}.$$

Since $1 - \frac{r}{\ln(K_2)} > 0$ and $\ln(K_2) > 0$ (because the carrying capacity K_2 is supposed to be large enough), we obtain

$$\frac{\partial T_{\text{NNL}}}{\partial r} < 0.$$

This yields that $\frac{\partial \text{OSP}}{\partial r} < 0$.

- To prove that $\frac{\partial T_{\text{NNL}}}{\partial B_2(0)} < 0$, we proceed as follows. We use the relation

$$\ln\left(\ln\left(\frac{B_1(0) + B_2(0)}{K_2}\right)\right) - \ln\left(\ln\left(\frac{B_2(0)}{K_2}\right)\right) = T_{\text{NNL}} \ln\left(1 - \frac{r}{\ln(K_2)}\right).$$

Deriving this relation by $B_2(0)$, we obtain

$$\left((B_1(0) + B_2(0))\ln\left(\frac{B_1(0) + B_2(0)}{K_2}\right)\right)^{-1} - \left((B_2(0))\ln\left(\frac{B_2(0)}{K_2}\right)\right)^{-1} = \frac{\partial T_{\text{NNL}}}{\partial B_2(0)} \ln\left(1 - \frac{r}{\ln(K_2)}\right). \tag{A11}$$

Using again inequality (A7), we first note that $B_2(0)$ and $B_2(0) + B_1(0)$ are low as compared to $K_2 = K_2^{0^-} + \lambda O$ and consequently $\frac{B_1(0) + B_2(0)}{K_2} < 1$ and $\frac{B_2(0)}{K_2} < 1$. Since the function $B \to B\ln(B)$ is decreasing on $]0, 1]$, we deduce that the left hand-side of Equation (A11) is positive. As we also have $\ln\left(1 - \frac{r}{\ln(K_2)}\right) < 0$, we conclude that

$$\frac{\partial T_{\text{NNL}}}{\partial B_2(0)} < 0.$$

Therefore

$$\frac{\partial \text{OSP}}{\partial B_2(0)} < 0.$$

- To prove that $\frac{\partial T_{\text{NNL}}}{\partial B_1(0)} > 0$, as already stated in result (21), we proceed similarly. This time we compute the derivative with respect to $B_1(0)$ and obtain:

$$\frac{1}{(B_1(0) + B_2(0))\ln\left(\frac{B_1(0) + B_2(0)}{K_2}\right)} = \frac{\partial T_{\text{NNL}}}{\partial B_1(0)} \ln\left(1 - \left(\frac{r}{\ln(K_2)}\right)\right).$$

Since $B_1(0) + B_2(0) < K_2$, we have

$$\frac{1}{(B_1(0) + B_2(0))\ln\left(\frac{B1(0) + B_2(0)}{K_2}\right)} < 0.$$

Since r is small as compared to K_2, we have $\ln(1 - \frac{r}{\ln(K_2)}) < 0$ and we deduce

$$\frac{\partial T_{\text{NNL}}}{\partial B_1(0)} > 0,$$

Therefore

$$\frac{\partial \mathrm{OSP}}{\partial B_1(0)} > 0.$$

- To prove that $\frac{\partial T_{\mathrm{NNL}}}{\partial K_2} < 0$, we proceed similarly using that $K_2 = K_2^{0^-} + \lambda O$ and again the relation

$$\ln\left(\ln\left(\frac{B_1(0) + B_2(0)}{K_2}\right)\right) - \ln\left(\ln\left(\frac{B_2(0)}{K_2}\right)\right) = T_{\mathrm{NNL}} \ln\left(1 - \frac{r}{\ln(K_2)}\right). \tag{A12}$$

We now use the following convenient notations to simplify the formulations:

$$V(B) = \ln(K_2) - \ln(B), \tag{A13}$$

$$X(K_2) = \ln(V(B_1(0) + B_2(0))) - \ln(V(B_2(0))), \tag{A14}$$

$$Y(K_2) = \ln\left(1 - \frac{r}{\ln(K_2)}\right). \tag{A15}$$

Then the previous characterization (A12) of T_{NNL} can be written

$$X(K_2) = T_{\mathrm{NNL}} Y(K_2).$$

Deriving this relation with respect to K_2, we first obtain

$$\frac{\partial X(K_2)}{\partial K_2} = \frac{\partial T_{\mathrm{NNL}}}{\partial K_2} Y(K_2) + T_{\mathrm{NNL}} \frac{\partial Y(K_2)}{\partial K_2}.$$

We have

$$\frac{\partial X(K_2)}{\partial K_2} = \frac{1}{K_2}.\left(\frac{1}{V(B_1(0) + B_2(0))} - \frac{1}{V(B_2(0))}\right)$$

and

$$\frac{\partial Y(K_2)}{\partial K_2} = \frac{r}{K_2 \ln(K_2)(\ln(K_2) - r)} = \frac{r}{K_2 Z(K_2)},$$

where $Z(K_2) = \ln(K_2)(\ln(K_2) - r) > 0$. We then deduce that

$$\frac{\partial T_{\mathrm{NNL}}}{\partial K_2} Y(K_2) = \frac{1}{K_2}\left(\frac{1}{V(B_1(0) + B_2(0))} - \frac{1}{V(B_2(0))}\right) - T_{\mathrm{NNL}} \frac{\partial Y(K_2)}{\partial K_2} \tag{A16}$$

$$= \frac{1}{K_2}\left(\frac{1}{V(B_1(0) + B_2(0))} - \frac{1}{V(B_2(0))}\right) - \frac{r X(K_2)}{K_2 Z(K_2) Y(K_2)} \tag{A17}$$

$$= \frac{1}{K_2}\left(\frac{1}{V(B_1(0)+B_2(0))} - \frac{1}{V(B_2(0))} - \frac{r}{Z(K_2)Y(K_2)}\ln\left(\frac{V(B_1(0)+B_2(0))}{V(B_2(0))}\right)\right) \tag{A18}$$

$$= \frac{1}{K_2}(W(B_1(0)+B_2(0)) - W(B_2(0))), \tag{A19}$$

where

$$W(B) = \frac{1}{V(B)} - \frac{r}{Z(K_2)Y(K_2)}\ln(V(B)).$$

We now prove that the function W is increasing with respect to B for B large enough ($\ln(B) > r$). We indeed have

$$W'(B) = \frac{-V'(B)}{V(B)}\left(\frac{1}{V(B)} + \frac{r}{Z(K_2)Y(K_2)}\right).$$

Using the inequality $\ln(1-x) < -x$ on $[0,1[$, we obtain

$$W'(B) > \frac{-V'(B)}{V(B)}\left(\frac{1}{V(B)} + \frac{r}{\ln(K_2)(\ln(K_2)-r)\left(\frac{-r}{\ln(K_2)}\right)}\right),$$
$$W'(B) > \frac{-V'(B)}{V(B)}\left(\frac{1}{V(B)} - \frac{1}{\ln(K_2)-r}\right).$$

Since $V'(B) < 0$ and $V(B) > 0$, as soon as $\ln(B) > r$, we deduce that

$$W'(B) > 0,$$

and consequently

$$\frac{\partial T_{\mathrm{NNL}}}{\partial K_2}Y(K_2) = \frac{1}{K_2}(W(B_1(0)+B_2(0)) - W(B_2(0))) > 0.$$

Using the negativity of $Y(K_2)$, we obtain

$$\frac{\partial T_{\mathrm{NNL}}}{\partial K_2} < 0,$$

and the desired result

$$\frac{\partial \mathrm{OSP}}{\partial K_2} < 0.$$

- To prove that $\frac{\partial T_{\text{NNL}}}{\partial K_2^{0}-} < 0$, we use the linear relation $K_2^{0^+} = K_2^{0^-} + \alpha K_1^{0^-}$.
- We proceed similarly to prove that $\frac{\partial T_{\text{NNL}}}{\partial K_1^{0^-}} < 0$.
- We now prove that $\frac{\partial \text{OSP}}{\partial \alpha} < 0$. We use the characterization

$$\text{OSP} = g\frac{1 + i - (1 + i)^{-T_{\text{NNL}}}}{\alpha i}.$$

Thus

$$\begin{aligned}\frac{\partial \text{OSP}}{\partial \alpha} &= \frac{g}{i}\frac{-\alpha\frac{\partial (1+i)^{-T_{\text{NNL}}}}{\partial \alpha} - \left(1 + i - (1+i)^{-T_{\text{NNL}}}\right)}{\alpha^2} \\ &= \frac{g}{i}\frac{\alpha(1+i)^{-T_{\text{NNL}}}\ln(1+i)\frac{\partial T_{\text{NNL}}}{\partial \alpha} - \left(1 + i - (1+i)^{-T_{\text{NNL}}}\right)}{\alpha^2}.\end{aligned}$$

Using that $\frac{\partial T_{\text{NNL}}}{\partial \alpha} < 0$ (deduced in the same way as above), we conclude.

A.2 Example

A.2.1 Parameter values in the example

See Table A1.

A.2.2 Sensitivity to the discount rate in the example

Table A2 shows that, with a 1% decrease of the discount rate value ($i = 2\%$), the OSP increases by about 9,8106%. Further, with a very small discount rate (for instance $i = 0.0001\%$), the OSP is then about equal to $\frac{g\,.(1 + T_{\text{NNL}})}{\alpha} = 782,000 \text{ US\$ ha}^{-1} \approx 770,000$ US\$, a result which validates the offset multiplier effect mentioned in Proposition 2. These results show that the discount rate greatly influences the OSP. As observed, if the discount rate drops to a very low value, then its influence on the OSP vanishes. Then, the OSP value tends toward the multiplier

TABLE A1 Parameter values.

Parameter y (reference)	**Value**
Project return rate g (US\$ ha^{-1})	70,000
Discount rate i	3%
Initial biodiversity lost $B_1(0)$ (number of trees)	8,000,000
Initial biodiversity—offset site $B_2(0)$ (number of tree seedlings)	850,000
Initial habitat quality—offset site $K_2^{O^-}$ (number of trees)	2,000,000
Final habitat quality—offset site $K_2^{O^+}$ (number of trees)	18,000,000
Intrinsic growth rate r	ln(3.15)
Offset surface area O (hectares)	1,600
Developed surface area D (hectares)	800
Offset ratio α	2

TABLE A2 The discount rate and the offset sustainability price.

Discount rate *i* (%)	BO sustainable price OSP (10^3 US$ ha^{-1})
3	≈581
0.3	≈757
2	≈638
0.0001	≈782

Note: The data used are $\alpha = 2$ and parameter values in Table A1. Thus OST ≈ 21 years.

described in Section 3.3. In other words, favoring future generations via a very low discount rate leads to a high OSP value up to the threshold value obtained with the multiplier.

A.2.3 Sensitivity to the initial carrying capacity of the offset site

See Table A3.

Measurement of relative deviations (Δ) shows that the OSP is less and less sensitive to the initial carrying capacity with the increase of $K_2^{0^-}$.

The initial carrying capacity of the offset site $K_2^{O^-}$ is a key element to take into account as it affects the final carrying capacity of the offset site as $K_2^{O^+} = K_2^{O^-} + \alpha.\ K_1^{O^-}$. In the example, a 1% increase of the $K_2^{O^-}$ value decreases the OST by 4.255×10^{-4}% and the OSP by 2.86×10^{-4}%. A 1% decrease of the $K_2^{O^-}$ value increases the OST by 4.262% and the OSP by 2.87%.

A.2.4 Parameter characteristics

See Table A4.

TABLE A3 Example in Madagascar: computation of the offset sustainability time OST and price OSP: sensitivity to the initial habitat quality of the offset site $K_2^{O^-}$.

Initial habitat quality (offset site)	**Final habitat quality (offset site)**	**BO sustainable lag**	**BO sustainable price**	**Relative deviation of OST**	**Relative deviation of OSP**
$K_2^{O^-}$ **(tree number)**	$K_2^{O^+}$ **(tree number)**	**OST (years)**	**OSP (US\$ ha^{-1})**	**ΔOST (10^{-4}%)**	**ΔOSP (10^{-4}%)**
1,000,000	18,000,000	≈21.338	≈580,752		
1, 010, 000(+1%)	18, 010, 000	≈21.328	≈580, 586	≈−4.255	≈−2.86
1, 980, 000(−1%)	17, 980, 000	≈21.347	≈580, 919	≈+4.262	≈+2.87

Note: $\Delta = \frac{\mathrm{OSP}\left(K_2^{O^-*}\right) - \mathrm{OSP}\left(K_2^{O^-}\right)}{\left(K_2^{O^-*} - K_2^{O^-}\right)}$ with $K_2^{O^-*}$ corresponding to the blue line. The data used are listed in Table A1.

TABLE A4 Summary table for the model parameters: the table describes the origin, unit and type (exogenous/endogenous) of each parameter.

Parameter	Notation	Who sets the parameter?	Unit	Type
Initial biodiversity lost, developed site	$B_1(0)$	Developer (via the choice of the developed site)	Biomass (tree number)	Exogenous
Initial biodiversity, offset site	$B_2(0)$	idem	Biomass (tree number)	Exogenous
Initial habitat quality, offset site	$K_2^{O^-}$	Regulator or Developer (via the choice of the offset site)	Biomass (tree number)	Exogenous
Intrinsic growth rate	r	Regulator or Developer (depending on local regulations)	Unit ×year^{-1}	Exogenous
Offset surface area	O	Regulator or Developer	Hectares (ha)	Exogenous
Developed surface area	D	Regulator or Developer	idem	Exogenous
Offset ratio	α	Regulator (minimum offset ratio stated in local regulations) and/or Developer (can increase the minimum requirement)		Exogenous
Discount rate	i	Regulator		Exogenous
Unitary land price	p	Regulator	US$	Exogenous
Project return rate	g	Depends on the project itself	US$	Endogenous
No net loss time	T_{NNL}	Model outcome	year	Endogenous
Payback time	T_{DPP}	idem	year	Endogenous
Minimal sustainable time	OST	idem	year	Endogenous
Minimal sustainable offset price	OSP	idem	US$ × ha^{-1}	Endogenous