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The Economic Value of Biodiversity Preservation

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Abstract
We study the decision to preserve diverse species when the value of biodiversity is uncertain, or even affected by ambiguity. Optimal decisions are derived both from the perspective of the producer/investor and the policy regulator (ecosystem planner). We find that while calculated risk creates a scope for biodiversity preservation, the presence of ambiguity aversion reduces it, thus accelerating the extinction of species with lower value. Our results suggest that effective conservation strategies would involve a reduction of ambiguity aversion by creating a stable and transparent policy environment. Furthermore, they may involve a two tier strategy, with one tier addressing output targets and the other conservation targets.

Keywords Endangered species · Biodiversity preservation · Biodiversity valuation · Uncertainty

1 Introduction

One major question faced by society is the decline and extinction of natural species as a consequence of human choices and activities and the resulting irreversible depletion of biodiversity. The richness and abundance of wild plant and animal species decline with the degradation of ecosystems under the pressure of intensive land use, natural resource extraction, pollution, climate change and many other threats. The various impacts of economic

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development on the environment are widely regarded as key drivers of ecological degradation and biodiversity loss.

As Weitzman (1998) points out ‘in talking about biodiversity preservation, there is always a question about what is the appropriate level of discourse’. Indeed, biodiversity is a multi-faceted concept. As Dasgupta et al. (2013) explain, the value of biodiversity derives from the value of the final goods and services it produces. The services depend on the types of species that ecosystems contain, their substitutability or complementarity in the functioning of ecological systems, and on the way that such functioning is affected by resource use. Deriving from its ‘role in the production of things that people care about’ the value attached to changes in biodiversity differs depending on geographical location, income, scientific development, spiritual and cultural perception of intact ecosystems.[1]

The ecological and economic importance of biodiversity has been extensively studied in the literature. Traditionally, economic theory has focused on the economic value of biodiversity, an approach that started with the defining work of Weitzman (1992), and then advanced by many others (e.g., Metrick and Weitzman 1998; Weitzman 1998; Heal 2000; Armsworth et al. 2004; Polasky et al. 2005; Dasgupta 2021). From an ecological perspective, higher levels of biodiversity are often associated with enhanced ecosystem stability and resilience (Hautier et al. 2015; Kinzig et al. 2001; Missirian et al. 2019). Many of these studies seem to suggest that diversity of species enhances the stability of aggregate, or community-level, properties, whereas it can enhance, erode or have little impact on resilience, interpreted as the ability of a system to return back to the initial state, rather than reducing the probability of entering more vulnerable system configurations.

Biodiversity is also associated with numerous economic benefits. Brock and Xepapadeas (2003) value biodiversity not based on diversity in the sense of genetic distances as in Weitzman (1992), but in terms of the value of characteristics or services that an ecosystem provides or enhances, when optimally managed. Their approach is an attempt to connect the ecologically/biologically oriented biodiversity metrics with an endogenous measure of economic value of biodiversity.

An emerging stream of research identifies specific anthropogenic determinants of biodiversity changes, such as forest loss, temperature changes, agricultural activities and industrial pollution. Massive wildlife losses and extinction rates of orders of magnitude larger than standard, non-anthropogenic levels, urgently demand to balance economic development and conservation and stimulate the debate about the degree to which biodiversity reacts to policy making and economic changes (Polasky et al. 2005; Ando and Amy and C. Langpap, 2018; Dasgupta 2022).

Despite the large volume of the conservation policy literature, there still is little work providing a theoretical foundation ‘for a cost-effectiveness criterion that can be used to rank priorities among biodiversity-preserving projects’ (Weitzman 1998). This may in part be due to biodiversity meaning different things to different people. Individual farmers tend to consider their decisions foremost to be investment/production decisions. The general public, on the other hand, consider biodiversity and conservation to primarily be about ‘stewardship of the earth’.

In this paper we take the perspective of a decision-maker who has to choose the species to be preserved or to let disappear, depending on their economic value, their maintenance expenditures and, last but not least, the potential opportunities offered by

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[1] In this context, the extinction of a species may be perceived as a ’loss’ in the sence of prospect theory (Kahneman and Tversky 1979; Tversky and Kahneman 1992; Wakker 2010).

the existence of diversified biological resources. A typical situation is that of a farmer who has to decide whether to invest in a monoculture, or to devote resources to plant and grow diverse species which may be of lower commercial value or may be incurring higher farming costs. Local cultivated species of fruit and vegetable are being lost as farmers replace them with higher-yielding per hectare and desease-resistant modern varieties. It is estimated that a quarter of the 1100 recognized genetic resources of fruit and vegetables worldwide are without genebank back-up and thus are at risk of being lost forever (Meldrum et al. 2018). On the other hand, an increased awareness of the benefits of diverse diets as well as research work on the healthy properties of some neglected fruit and vegetable species are contributing to reverse the trend and are attracting consumers' and farmers' interest for underutilized species. At the same time, safeguard plans are already on the agenda of international organizations (FAO International Plant Treaty, United Nations Food Systems Summits, Nagoya Protocol of the Convention on Biological Diversities (CBD), EU Common Agricultural Policy (CAP) and 2030 Sustainable Development Goals) and of national and regional governments which often fund the implementation of good agricultural practices.

Throughout this paper, the main question is to formulate the decision-maker's choice as a cost-benefit trade-off, where a special emphasis is put on the uncertainty or ambiguity surrounding operations. We analyze the effects of the different perspectives of investor/producers on the one hand and of the general public on the other, starting from the same 'objective' situation. The key variable is based on the concept of species' value, which, as explained above, is a multi-faceted concept (see Dasgupta 2000, for a deep discussion). As the emphasis is on the risky framework, species' values are modelled as stochastic processes. In Sect. 2 we develop a comprehensive model for choosing between biodiversity-maintaining alternatives. In particular, expanding on Kassar and Lasserre (2004), we introduce a more general and flexible model including several additional parameters and multidimensional processes for heterogeneous species. This allows us to investigate the determinants of the policy preserving multiple species in greater detail. In Sect. 3 we introduce the presence of ambiguity aversion into the model. As emphasized by Levin and Xepapadeas (2021), from a management perspective, deep uncertainty and aversion to ambiguity are important concepts in ecological-economic systems. Levin and Xepapadeas (2021) list major gaps in global and national monitoring systems: the lack of inventory of species; definitional ambiguities that may lead to confusing results; and lack of theories to anticipate how humans will respond to changing conditions. Therefore, 'efficient management should be based on a recognition that there are deep uncertainties and that people have preferences that are averse to deep uncertainty, or ambiguity' (page 367). Our incorporation of ambiguity aversion in Sect. 3 affects the policy towards species preservation by accelerating the extinction of more volatile growth rates, which eventually causes disruption in the preservation efforts. Section 4 analyzes some possible actions by a regulator, or an ecosystem planner, to promote biodiversity preservation. In particular, we suppose that the ecosystem planner is concerned with the total value of species, including the non-use value of social importance, and thus introduces an harvesting rule (along the lines of Brock and Xepapadeas 2002a, b) and incentives that compensate the producer for the reduced profits. Section 5 provides some insights on the introduction of more general ambiguity attitudes in the model and their effects on investors' decisions and the general public's ambitions. Section 6 concludes and discusses some policy implications, one of which is the appropriateness of following a two-tier policy approach, differentiating between policies focusing on 'investment/production' and those focusing on 'conservation'.

2 Basic Model

In this section we study the problem of a producer who has to invest in a pool of biospecies to grow and exploit and may decide whether to limit the investment to the most profitable species or to keep open the opportunity offered by biodiversity. Here we focus on the case of two species to simplify the setting.

To each species i we can associate a value v_i. This value includes a direct economic value that accrues to the producer (use, or market value). An additional component of the value may be "associated with existence values, aestetic values and non-substitutable ecosystem services as indirect (non-use) values" (Brock and Xepapadeas 2002a) which may contribute to increase the benefit stream of the species. We assume that the value v_i of species i evolves as

$$dv_i/v_i = m_i dt + \sigma_i dW_t^{(i)} \tag{1}$$

where the Wiener processes $W_t^{(i)}$, $i = 1, 2$, are correlated as $E[dW_t^{(1)} dW_t^{(2)}] = \rho dt$. The assumption that the species values are described by a Geometric Brownian motion (GBM), where m_i is the drift, or instantaneous growth rate, and σ_i^2 is the variance per unit time, is a simplification. However, it is employed in several contributions and in particular in Brock and Xepapadeas (2002a) where they suppose that species biomasses can be modeled by stochastic differential equations of the GBM type and the existing biomasses at any point in time have non-negative existence values. In Brock and Xepapadeas (2002a) species values are obtained multiplying biomasses by the price of harvested species, which is assumed to be fixed within the planning horizon. Thus, our assumption is consistent with theirs, but also allows to model non-fixed prices (e.g., GBM prices with deterministic dynamics for biomasses).

We suppose that the cost of maintaining species i is proportional to its value, that is, is $k_i v_i$, with $0 \le k_i < 1$. For example, in the case of a farm, it includes fertilizers, water supply and working hours, so the assumption of proportionality is pretty reasonable if we neglect the effect of scale economy. We also assume that there is a fixed cost, H, irrespective of the number of species used. For example, H may represent the cost for acquiring farmland to instal a plantation or an orchard. If only species i is conserved and exploited the cumulated expected return extracted from it is:

$$E_t \left[\int_t^\infty e^{-r(\tau - t)} [(1 - k_i) v_i(\tau) - H \right] d\tau = \frac{(1 - k_i) v_i(t)}{r - m_i} - \frac{H}{r} = F_i(v_i)$$

where $r > 0$ is the interest rate used to discount. In the above expression it is implicitly assumed that $r - m_i > 0$. This is a classical technical assumption which is adopted to guarantee a finite value function. Although it may be unrealistic in some circumstances, it is legitimate in times of high interest rates and a decreasing profitability of the farming sector.

Following Kassar and Lasserre (2004) we suppose that only the most valuable species is exploited for commercial use while the unexploited species may be preserved or abandoned depending on its relative cost and possible opportunities it may offer in the future. Let $F(v_1, v_2)$ denote the net present value from employing the species with the maximum value while preserving the other one. Let us denote by t^* the stopping time at which it is optimal to abandon one species as the option of keeping it around has no value.

In the subregion $v_1 \ge v_2$ one has $\max_{i=1,2} v_i = v_1$. Then F solves the following optimal stopping problem:

$$F(v_1, v_2) = \sup_{t^*} E_t\left[\int_t^{t^*} e^{-r(\tau-t)}((1-k_1)v_1(\tau) - k_2v_2(\tau) - H)d\tau + F_1(v_1(t^*))\right]$$

subject to the dynamics (1) with initial values $v_i(t) = v_i$, $i = 1, 2$. Then F satisfies the following free-boundary value problem:

$$\mathcal{L}F(v_1, v_2) + (1-k_1)v_1 - k_2v_2 - H = 0 \qquad (2)$$

on the continuation region, where $\mathcal{L} = \frac{1}{2}[\sigma_1^2 v_1^2 \partial^2_{v_1} + \sigma_2^2 v_2^2 \partial^2_{v_2} + 2\rho\sigma_1\sigma_2 v_1 v_2 \partial^2_{v_1 v_2}] + m_1 v_1 \partial_{v_1} + m_2 v_2 \partial_{v_2} - r\cdot$

On the critical threshold between the continuation region and the stopping region, F satisfies:

$F = F_1$ (continuous pasting) and $\nabla F = \nabla F_1$ (smooth pasting).

In view of homogeneity considerations the critical threshold is a line $v_2 = z^* v_1$, as specified below in Proposition 1.

Let us write a general solution for equation (2). A particular solution to equation (2) is $\frac{(1-k_1)v_1}{r-m_1} - \frac{k_2v_2}{r-m_2} - \frac{H}{r}$. The homogeneous part of equation (2) can be solved through the usual dimension reduction obtained by introducing a new variable $x = v_1/v_2$. If we search for a solution of the form $v_2 g(x)$, then g should solve the differential equation:

$$\frac{S^2}{2}x^2 g\varepsilon(x) + (m_1 - m_2)xg'(x) + (m_2 - r)g(x) = 0$$

where $S^2 = \sigma_1^2 + \sigma_2^2 - 2\rho\sigma_1\sigma_2$. If $g(x) = x^\beta$ then β should solve

$$\frac{S^2}{2}\beta^2 + (m_1 - m_2 - \frac{S^2}{2})\beta + m_2 - r = 0. \qquad (3)$$

Let $\beta_\pm$ denote the two roots of equation (3). Note that in view of the assumption $m_i < r$, $i = 1, 2$, we have: $\beta_- < 0 < 1 < \beta_+$. Therefore

$$F(v_1, v_2) = A_+(\frac{v_1}{v_2})^{\beta_+}v_2 + A_-(\frac{v_1}{v_2})^{\beta_-}v_2 + \frac{(1-k_1)v_1}{r-m_1} - \frac{k_2v_2}{r-m_2} - \frac{H}{r} \text{ for } v_1 \geq v_2$$

where $A_\pm$ are arbitrary constants.

A similar argument in the subregion $v_1 \leq v_2$ yields:

$$F(v_1, v_2) = \widetilde{A}_+(\frac{v_1}{v_2})^{\beta_+}v_2 + \widetilde{A}_-(\frac{v_1}{v_2})^{\beta_-}v_2 - \frac{k_1v_1}{r-m_1} + \frac{(1-k_2)v_2}{r-m_2} - \frac{H}{r}$$

where $\widetilde{A}_\pm$ are arbitrary constants.

As on the line $v_1 = v_2$ separating the two subregions there is indifference between exploiting species 1 rather than 2, we can apply smooth-pasting considerations to find a relationship between $\widetilde{A}_\pm$ and $A_\pm$. In particular, we obtain

$$\widetilde{A}_\pm = A_\pm \pm \frac{1}{\beta_+ - \beta_-}[\frac{\beta_\mp}{r-m_2} + \frac{1-\beta_\mp}{r-m_1}].$$

Now the continuous and smooth pasting conditions, $F = F_i$ and $\nabla F = \nabla F_i$, holding on the critical thresholds, are employed to determine the regions where it is optimal to abandon one species. Calculation below shows that the curve separating the set where both species

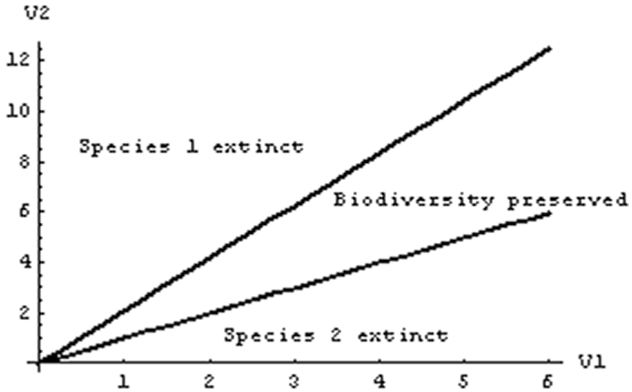

Fig. 1 Switching lines between species abandonment or preservation ($\rho = 0.5$)

are maintained from the set where only species 1 is preserved is of the form $v_2 = z^* v_1$ with $z^* \leq 1$. Similarly, abandonment of species 1 occurs whenever $v_2 \geq \hat{z} v_1$ for some $\hat{z} \geq 1$. (See Fig. 1, for an illustration). The values for z^* and $\hat{z}$ are computed in Proposition 1.

Proposition 1 *Assume that* $\frac{\beta_+-1}{\beta_+}\frac{r-m_2}{r-m_1} < \frac{1-k_2}{1-k_1} < \frac{\beta_--1}{\beta_-}\frac{r-m_2}{r-m_1}$. *Then the lines separating the set of values* (v_1, v_2) *where both species are preserved from the regions where one species is abandoned are of the form* $v_2 = z^* v_1$ (*for abandoning species* 2) *and* $v_2 = \hat{z} v_1$ (*for abandoning species* 1), *where* z^* *and* $\hat{z}$ *are computed by solving the system*

$$\begin{cases} \frac{(1-\beta_-)k_1}{r-m_1}\hat{z}^{\beta_+-1} + \frac{k_2\beta_-}{r-m_2}z^{*\beta_+} = \frac{\beta_-}{r-m_2} + \frac{1-\beta_-}{r-m_1} \\ \frac{(\beta_+-1)k_1}{r-m_1}\hat{z}^{\beta_--1} - \frac{k_2\beta_+}{r-m_2}z^{*\beta_-} = \frac{-\beta_+}{r-m_2} + \frac{\beta_+-1}{r-m_1} \end{cases} \tag{4}$$

Proof $F(v_1, v_2)$ for $v_1 \geq v_2$ is matched with $\frac{(1-k_1)v_1}{r-m_1} - \frac{H}{r}$ on the line $v_2 = z^* v_1$ along with their derivatives ∂_{v_1} and ∂_{v_2}. Three equations are obtained, but one of them is redundant. Similarly, $F(v_1, v_2)$ for $v_1 \leq v_2$ is matched with $\frac{(1-k_2)v_2}{r-m_2} - \frac{H}{r}$ on the line $v_2 = \hat{z} v_1$ along with the derivatives. In total, four equations are obtained where the unknowns are $A_\pm$, z^* and $\hat{z}$. Solving for $A_\pm$ in terms of the remaining unknowns, we are left with the two equations (4) for the unknowns z^* and $\hat{z}$. Note that the condition $\frac{\beta_+-1}{\beta_+}\frac{r-m_2}{r-m_1} < \frac{1-k_2}{1-k_1} < \frac{\beta_--1}{\beta_-}\frac{r-m_2}{r-m_1}$ is necessary for $z^* \leq 1$ and $\hat{z} \geq 1$. ☐

Fig. 1 represents an example of switching lines between the various strategies when the following parameter values are adopted: $r = 0.1, m_1 = 0.05, m_2 = 0.03, \sigma_1 = 0.3, \sigma_2 = 0.2, \rho = 0.5, k_1 = 0.5, k_2 = 0.5$.

Fig. 2 illustrates the effect of correlation on the preservation policy: if ρ becomes negative the two species complement each other in the face of negative events and the scope for conserving both of them is expanded.

Realistic values for the correlation coefficient, ρ, can be extracted from time series of the commercial values of two alternative species or varieties, used to proxy v_i if the biomasses do not exhibit significant changes in growth rate during the period. For example, we find a correlation of 0.56 between wheat and rice, of 0.41 between Annurca apple (a

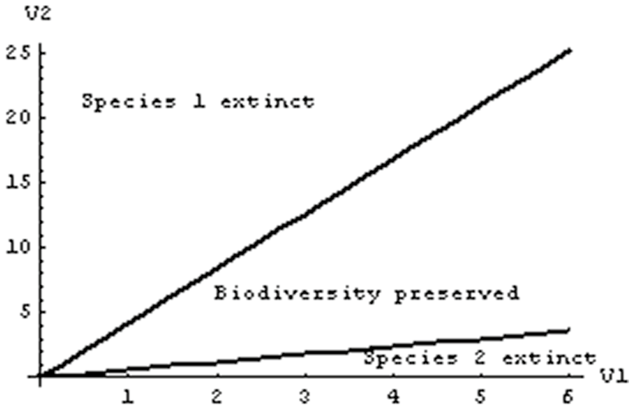

Fig. 2 Switching lines between species abandonment or preservation ($\rho = -0.5$)

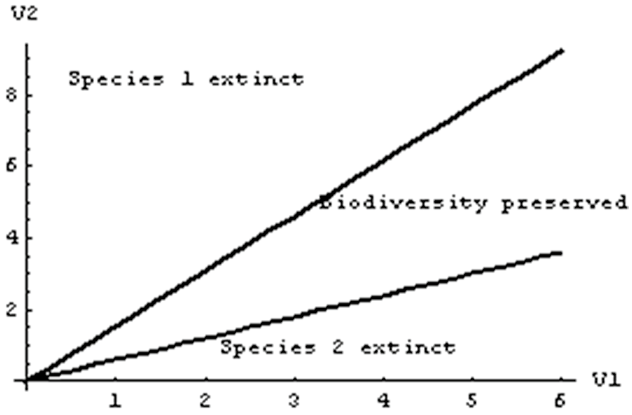

Fig. 3 Switching lines (k_2 reduced in comparison to Fig. 1)

rare variety) and Gala apple, of 0.15 between Golden Delicious apple and Decana pear, of −0.44 between cherries and Granny Smith apple (data source: www.ismeamercati.it).

An advantage of our model is that it extends Kassar and Lasserre (2004) in various directions including the relaxation of symmetry assumptions. In particular, the stochastic processes may exhibit diversified growth rates and variances and the maintenance costs for the two species may differ. Thus we can study the effect of the several model parameters on the decision-maker's choice. For example, in Fig. 3, k_2 is reduced to 0.3 while other parameters remain as in Fig. 1: the zone where species 2 is eliminated is reduced (from about 50% of all states to 34% - where the percentages refer to the relative amplitudes of the angles representing the different regions), as expected.

Another question deserving investigation is the effect of risk (measured by the σ parameter) on the scope for biodiversity preservation. In particular, our comprehensive model allows for asymmetries in σ. In Fig. 4 the solid thick lines are obtained by adopting the following parameter values: $r = 0.1$, $m_1 = 0.05$, $m_2 = 0.05$, $\sigma_1 = 0.2$, $\sigma_2 = 0.2$, $\rho = 0.5$, $k_1 = 0.2$, $k_2 = 0.2$, while the thin curves are obtained by increasing σ_1 to 0.3.

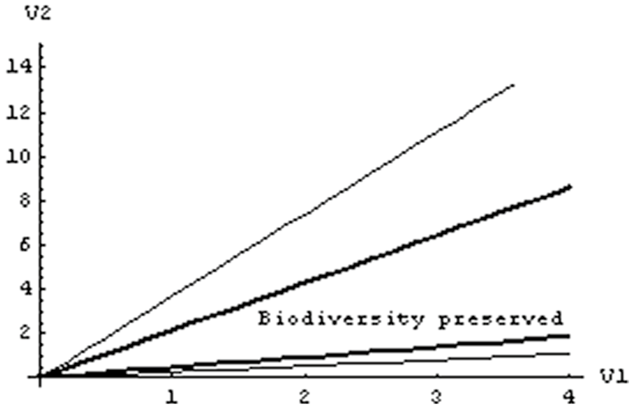

Fig. 4 Biodiversity region for two different levels of σ_1

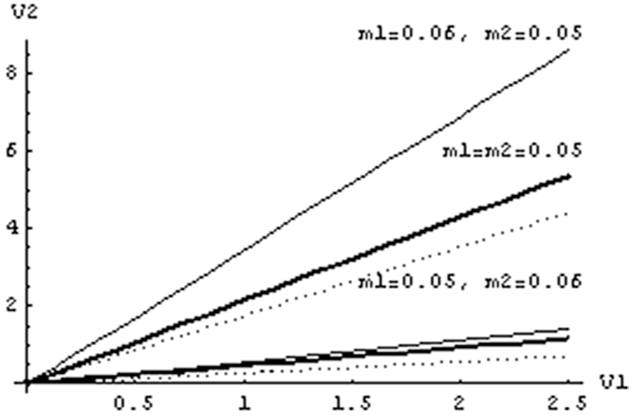

Fig. 5 Biodiversity region with varying m_i

The cone of biodiversity preservation is expanded if σ_1 is increased. Symmetrically, the same effect is obtained if σ_2 is increased to 0.3 (not shown in the pictures).

Fig. 5 illustrates the influence of the growth rate m_i on the decision to switch between preservation and abandonment policy. All parameters generating the solid thick lines are as in Fig. 4, while we increase m_1 (solid thin lines) or m_2 (dashed lines) as specified. As expected a higher growth rate of a species reduces its extinction range at the expenses of the other species.

3 Introducing Ambiguity Aversion

In this section we introduce ambiguity into the model to explore how this form of 'incalculable' risk influences the decision of preserving biodiversity. The stochastic processes are modelled as Choquet-Brownian motions following Kast et al. (2014). The theory is based on Choquet's capacities (see Chateauneuf et al. 2001). Let S denote the set of uncertain states. A capacity ν is a set function such $\nu(S) = 1$, $\nu(\emptyset) = 0$ and $\forall E, F \subseteq S$, $E \subseteq F$

implies $v(E) \leq v(F)$. In other words, capacities are non-additive unit measures used to represent beliefs. A capacity is convex (concave) if $v(E) + v(F) \leq v(E \cup F) + v(E \cap F)$, $\forall E, F$ (respectively, $\geq$ holds).

In the Choquet Expected Utility model a capacity simultaneously represents the ambiguity experienced by the decision maker and his/her attitude toward ambiguity. Let the ambiguity level of a capacity v at an event $E \subseteq S$ be denoted by $\ell_v(E) = 1 - v(S - E) - v(E)$, which reflects the combined effect of the amount of ambiguity and the decision maker's ambiguity attitude. For convex capacities, ambiguity levels attain non-negative values only. For example, if we set u_1 for states in E and u_2 for states in $S - E$, then for $u_1 > u_2$ the Choquet integral of the utility u with respect to v can be written as

$$u_1 v(E) + u_2 v(S - E) + u_2 \ell_v(E),$$

while for $u_1 < u_2$ one has:

$$u_1 v(E) + u_2 v(S - E) + u_1 \ell_v(E),$$

that is, in each case, the bad outcome is over-weighted by the ambiguity level ℓ_v. If a decision-maker's beliefs are represented by a strictly convex capacity, then $\ell_v > 0$ and he/she puts more weight on bad outcomes than an expected utility maximizer would. In this case, 'the bad outcome is 'over-weighted' by the ambiguity level of the event under such a capacity' (Kelsey and Spanjers 2004). This concept will be discussed in Sect. 5 in a more detailed way.

In Kast et al. (2014) the key variable is the capacity variable, c, which acts as a proxy for the distortive effect of ambiguity on the decision-makers' attitudes towards ambiguity; it reflects investors' ambiguity attitudes (aversion or seeking) on future prospects, with $0 < c < 0.5$ representing aversion (convex capacities), and $0.5 < c < 1$ indicating ambiguity-seeking (concave capacities). The Choquet integral overweights high outcomes if the capacity is concave and superadditive ($c > 0.5$), while emphasizing low outcomes if the capacity is convex and subadditive ($c < 0.5$). The special case $c = 0.5$ corresponds to the traditional probabilistic framework (absence of ambiguity).[2]

In order to obtain a dynamic model, Choquet-Brownian motions are considered. Choquet-Brownian motions are obtained as limit processes of binomial trees where, at each point in time $t = 0, 1, ..., T$, the uncertain states are $\left\{s_t^1, ..., s_t^{t+1}\right\} =: S_t$. There are two possible successors of every s_t at time $t + 1$: s_{t+1}^u (up movement) and s_{t+1}^d (down movement), where the conditional capacities are $v(s_{t+1}^u | s_t) = v(s_{t+1}^d | s_t) = c$ with $0 \leq c \leq 1$. The constant c is the relevant parameter and represents the effect of the decision-maker's ambiguity about the likelihood of the states to come. We focus on the case of convex capacities ($c < 0.5$) where the ambiguity level is positive.

The discrete process outlined above can be shown to converge to a continuous time generalized Wiener process with mean $2c - 1$ and variance $4c(1 - c)$ (see Kast et al. (2014), where theory and proofs are detailed). The absence of an ambiguity bias is obtained as a special case for $c = 1/2$. As specified below, the Choquet-Brownian motion can be represented as a re-parametrization of a Brownian motion with an additional parameter c relating to the ambiguity perceived by the decision maker. More precisely, now we suppose that the species value $v_i(t)$ follows a Choquet Brownian motion:

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[2] For a proof in a general context we refer to Agliardi (2017), Proposition 2.

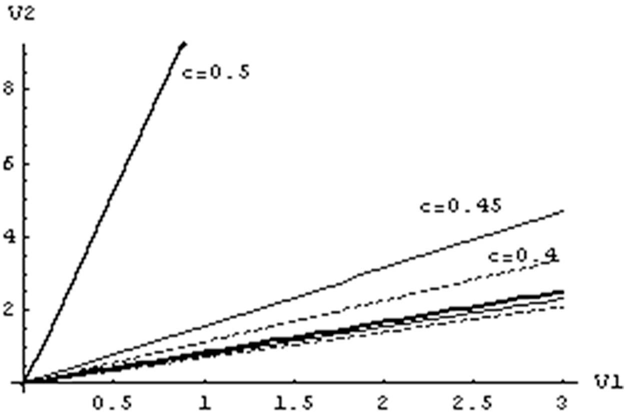

Fig. 6 Biodiversity preservation (interior of cones) for different ambiguity levels with asymmetric parameters

$$dv_i/v_i = (m_i + \sigma_i(2c - 1))dt + 2\sqrt{c(1 - c)}\sigma_i dW_t^{(i)}$$

where $W_t^{(i)}$ is a Wiener process. Thus, we assume that the actual underlying dynamic process is a standard Wiener process, and that ambiguity leads to a distortion in the perception of this process. As it is the distorted perceived process that drives the decisions, it is this distorted process that is analyzed. Observe that for the case of ambiguity aversion both drift and volatility are smaller than in the probabilistic model. That is, with ambiguity aversion mass is shifted to the “worst state” outcome, so that the drift falls and the perceived variance of the process is reduced as well.

As a first step, we simplify the setting by assuming that the two processes are driven by a single Wiener process. Since ambiguity interplays with the uncertainty parameter of the underlying stochastic factor dynamics we adopt asymmetric levels of σ_1 and σ_2 and of the other parameters.

In Fig. 6 the switching lines between species preservation and abandonment are represented for various levels of the ambiguity parameter: $c = 0.5$ (absence of ambiguity) resulting in the solid thick line, $c = 0.45$ (thin line) and $c = 0.4$ (dashed line). It is evident that the introduction of ambiguity dramatically shrinks the scope for preserving both species, from about 44% of all states to 26% (when $c = 0.45$) and finally to 16% (when $c = 0.4$), where the percentages refers to the relative amplitudes of the cones containing the states. In this numerical simulation it is assumed that σ_1 is much larger than σ_2 while equal costs are assumed: consequently, when ambiguity is introduced, the zone for keeping species 1 alive is strongly reduced in favour of the less risky species. In other words, ambiguity and ’calculated’ risk work in opposite directions.

Finally, we consider a more general framework where the two variables are driven by different Wiener processes and the impact of ambiguity on correlation is considered as well. This analysis requires the theory of multi-dimensional Choquet-Brownian motions developed in Roubaud et al. (2017). In particular, we adopt independent processes in the unambiguous benchmark case ($c = 0.5$). As shown in Roubaud et al. (2017) the correlation is given by $\rho = \frac{(1-2c)(a-c^2)}{c(1-c)}$ where the parameter a, $0 \leq a \leq c$, represents the conditional capacity of simultaneous up-movements in the two random walks. In particular, $a = c^2$ yields uncorrelated processes. In Fig. 7 symmetric parameters are adopted for the two

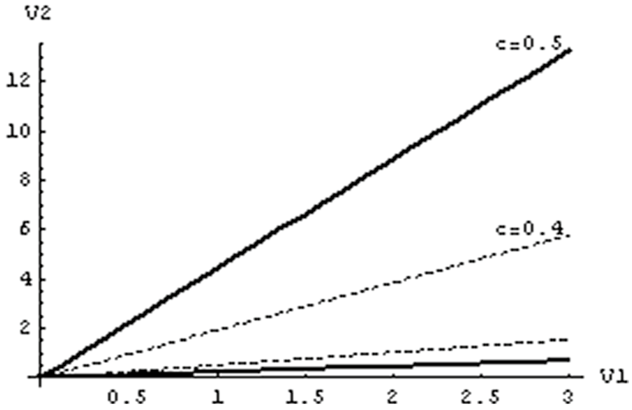

Fig. 7 Biodiversity preservation (interior of cones) for two ambiguity levels with symmetric parameters

stochastic processes. The cone of biodiversity preservation in the benchmark case is delimited by the thick solid lines, while the cone inside the dashed lines is obtained in the case $c = 0.4$ when the worst belief on a is adopted, that is, $a = c$. Even in the other extreme case ($a = 0$), not shown in the picture, the cone of biodiversity preservation lies inside the cone of the benchmark case. Thus we confirm that ambiguity tends to shrink the continuation region for biodiversity maintenance even in a truly multi-dimensional setting.

4 The Role of an Ecosystem Planner

So far the model has been developed from the perspective of an investor-producer who maximizes the use value of ecosystem, while keeping the option of biodiversity open to face risk and other forms of uncertainty. A species value includes the market value of harvested biomass, but also indirect benefits from the species existence value, such as increased ecological resilience, social reward for alignment with sustainability targets, additional profit from the recreational and aesthetic value, etc. This section adds the presence of an ecosystem or landscape planner whose main consideration is the total value of species, including the non-use values of social importance, in view of their environmental, cultural, scientific, educational content. One channel for possible action is the introduction of harvesting rules (see Brock and Xepapadeas 2002a, b) accompanied with subsidies. Let $h_i \in [0, 1]$ denote the proportion of the biomass of the i^{th} species which is harvested and assume that the producer receives a compensation for growing and maintaining the non-harvested mass. This policy can be determined by a conservation program associated with endangered species, for example, a wild species which is too much exploited and close to extinction or a cultivated plant which is going to be abandoned due to its negligible market value. An example is provided by EU rules on fishing quotas, that is, catch limits (expressed in tonnes or numbers) that are set for most commercial fish stocks, in particular, all catches of regulated species should be counted against quotas, undersized fish cannot be sold for consumption, prohibited species must be returned to the sea. EU agricultural policy has an impact on harvesting in the agri-food sector through the tariff quota allocation which is established mainly to stabilise agricultural markets. Referring to green policies, an indirect impact on harvesting decisions is related to the targets set by the common agricultural policy (CAP) of the European Commission aiming at penalizing practices associated with intensive farming systems which are harmful to public health and environment, such as overuse of chemical fertilizers and pesticides, while promoting less productive but sustainable agricultural systems, such as organic agriculture. At the same time, CAP 2023-27 incorporates 'green direct payments' to compensate farmers for adopting less productive processes with an ecological focus, for example, dedicating at least 5% of arable land to areas deprived of crops with commercial value but preserving endangered biodiversity habitats, or to support farmers and foresters for additional costs and income foregone when implementing the Birds and Habitat Directives.

In what follows we assume that the investor-producer is compensated for the growing cost of the non-harvested biomass through a unit subsidy of s_i, although other forms of incentives can be easily accommodated into the model. In the base case considered in Sect. 2, $h_i = 1$ and $s_i = 0$, that is, the *ith* species is fully harvested and no incentive policy is in force.

Let us confine the analysis to the case of two species. Then the cumulated expected return to the producer depends on $\max[h_1 v_1, h_2 v_2]$, while the unit cost k_i is reduced by a unit subsidy s_i, $i = 1, 2$. For simplicity's sake, let us consider the case where the planner's policy is applied only to species 1. Then the producer's problem of Sect. 2 is modified as follows. Let $F(v_1, v_2)$ denote the net present value from employing the species with the maximum value while preserving the other one. Let us denote by t^* the stopping time at which it is optimal to abandon one species as the option of keeping it around has no value. In the subregion $h_1 v_1 \geq v_2$, F solves the following optimal stopping problem:

$$F(v_1, v_2) = \sup_{t^*} E_t \left[\int_t^{t^*} e^{-r(\tau - t)}((h_1 - k_1 + s_1)v_1(\tau) - k_2 v_2(\tau) - H)d\tau \right.$$
$$\left. + \frac{(h_1 - k_1 + s_1)}{r - m_1} v_1(\tau)(t^*) - \frac{H}{r} \right]$$

which can be solved as in Sect. 2 just multiplying v_1 by h_1 and replacing k_1 with $\frac{k_1 - s_1}{h_1}$. Finally, we can compute the total net present value available to the ecosystem (inclusive of the value achieved by the producer). For example, when both species are kept, but the harvesting rule is applied to species 1 only, then the cumulated value of $v_2 + (1 - h_1 - s_1)v_1$ remains available to the planner. If we consider the sum of the value gained by the producer and the value left available to the eco-system, then the total value, denoted by $\widetilde{F}(v_1, v_2)$, becomes:

$$\frac{1 - k_2}{r - m_2} v_2 - \frac{H}{r} \text{ if } v_2 > \widehat{z}_{h_1, s_1} v_1;$$

$$\left\{ (1 - \beta_-)\widehat{z}_{h_1, s_1}^{\beta_+ - 1} \left(\frac{v_1}{v_2}\right)^{\beta_+ - 1} + (\beta_+ - 1)\widehat{z}_{h_1, s_1}^{\beta_- - 1} \left(\frac{v_1}{v_2}\right)^{\beta_- - 1} \right\} \frac{k_1 h_1 v_1}{(r - m_1)(\beta_+ - \beta_-)} + \frac{(1 - k_1)v_1}{(r - m_1)} + \frac{(1 - k_2)v_2}{(r - m_2)} - \frac{H}{r} \text{ if } v_1 h_1 \leq v_2 \leq \widehat{z}_{h_1, s_1} v_1;$$

$$\left\{ -\beta_- z_{h_1, s_1}^{*\beta_+} \left(\frac{v_1}{v_2}\right)^{\beta_+} + \beta_+ z_{h_1, s_1}^{*\beta_-} \left(\frac{v_1}{v_2}\right)^{\beta_-} \right\} \frac{k_2 v_2}{(r - m_2)(\beta_+ - \beta_-)} + \frac{(1 - k_1)v_1}{(r - m_1)} + \frac{(1 - k_2)v_2}{(r - m_2)} - \frac{H}{r}$$

$$\text{if } z_{h_1, s_1}^* v_1 \leq v_2 \leq v_1 h_1;$$

$$\frac{1 - k_1}{r - m_1} v_1 - \frac{H}{r} \text{ if } v_2 < z_{h_1, s_1}^* v_2.$$

Here the threshold values are determined by the producer and can be easily obtained by multiplying the corresponding thresholds obtained in Sect. 2 by h_1 and replacing k_1 with $\frac{k_1 - s_1}{h_1}$. Note that we do not solve the optimization problem from the perspective of an eco-planner because it would not be realistic in the economies around the world - with very few

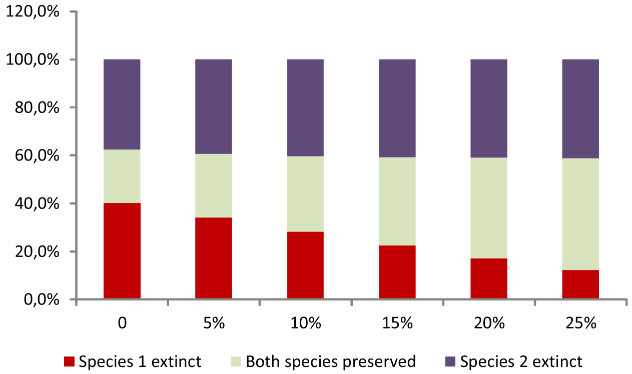

Fig. 8 Percentage of the three options when h_1=90% for several subsidy rates (s_1) displayed on the horizontal axis

exceptions related to collectivisation of agriculture and the creation of controlled farms by some totalitarian regimes. Usually the role of institutional planners is confined to set general targets, to introduce some limitations on harmful farming practices and provide incentives to sustainable ones, but the decision on the production process remains in the hands of producers.

Figure 8 represents the allocation of species when $h_1 = 1$ is replaced by $h_1 = 0.9$ and the parameter values are as in Fig. 6 with the exception of k_1 which is set equal to 0.5 to emphasize the effect. For a comparison, note that in the base case $h_1 = 1$ and $s_1 = 0$, that is, when no special policy is activated, one can compute that the region of extinction of species 1 spans about 31%[3]of all possible states. As Fig. 8 shows, if restrictions on harvesting are introduced without compensation ($s_1 = 0$), then the scope for eliminating species 1 is expanded, but it is significantly reduced when subsidies are provided (for example, to about 17% when $s_1 = 20\%$ and to 12% when $s_1 = 25\%$). Furthermore, arguing as in Sect. 3, one can compute that the presence of ambiguity may offset the subsidy policy: if, for instance the ambiguity parameter perceived by the investor is $c = 0.4$, then a subsidy rate, s_1, of 20% reduces the likelihood of eliminating species 1 only by 2.4% and the improvement with $s_1 = 25\%$ is only of 6%. In other words, in the presence of ambiguity aversion, perceived ambiguity has a disruptive effect on the policy of ecosystem planners and makes their subsidy expenditures by far less effective. As a consequence, in this context a successful safeguard plan should remove all possible sources of ambiguity, design clear targets, increase transparency in the development and monitoring process, rather than just inflating the funding mechanism.

Finally, we point out that the total value obtained under the landscape planner's policy above reaches its peak in the central region where both species are preserved (see Fig. 9, where $h_1 = 1$, $s_1 = 0$ and $\widetilde{F}(v_1, v_2)$ is plotted against v_1 and v_2). Although the critical thresholds are fixed by the producer, the peak regions for the ecosystem and the producer turn out to be both in the central area where both species are present. This reinforces the need for

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[3] Measured through the relative amplitudes of the cones representing the different regions. In the two-state case considered in this study, the amplitude of each angle can be easily computed as $\arctan(v_2/v_1)$ at the critical thresholds.

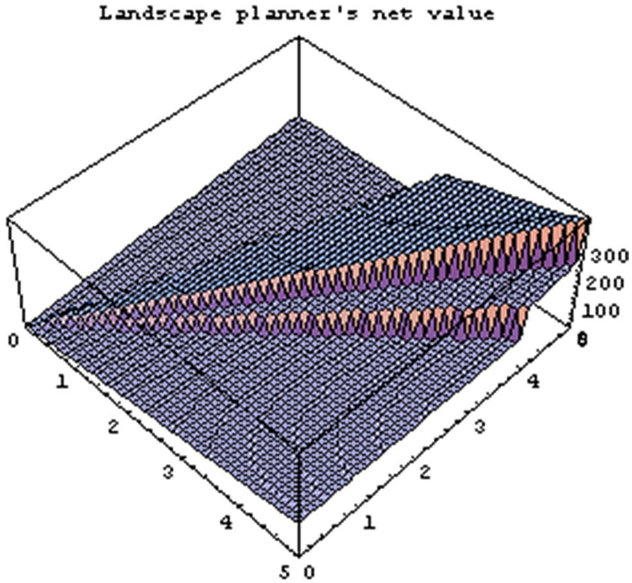

Fig. 9 The social value of growing two species in terms of v_1 and v_2

biodiversity preservation by social institutions as suggested by common wisdom and the general public, which perceives the extinction of a species as a ’loss’.

5 Discussion

In a broader context, following Chateauneuf et al. (2007), it is useful to look deeper into the parameter ‘c’, which reflects the decision maker’s ambiguity bias. In particular, one may want to separate the effects of the level of ambiguity from the effects of the decision maker’s attitude towards ambiguity. To describe the level of ambiguity, we follow the literature by denoting the level of confidence by $\gamma \in [0, 1]$ and the associated level of ambiguity $1 - \gamma$. Here $\gamma = 1$ reflects full confidence and the absence of ambiguity, whereas $\gamma = 0$ reflects no confidence and full ambiguity. Similarly, the describe the ambiguity attitude by $\delta \in [0, 1]$, where δ reflects the level of ambiguity seeking behaviour, i.e. optimism, hoping for the best, and $1 - \delta$ reflects the level of ambiguity aversion, i.e. pessimism, fearing the worst.

For given a level of confidence γ and level of optimism δ, the capacity value ‘c’ for moving up now equals $0.5 + (1 - \gamma) \times [0.5 \times \delta - 0.5 \times (1 - \delta)]$. For the absence of ambiguity, i.e. for the situation of full confidence, we obtain $c = 0.5$, as we would in the presence of ambiguity for the ambiguity attitude $\delta = 0.5$. For the combination of full ambiguity, $\gamma = 0$, and full pessimism $\delta = 0$, we find $c = 0$, whereas for full ambiguity, $\gamma = 0$, and full optimism, $\delta = 1$, we find $c = 1$.

Thus, in a world where there is ambiguity regarding the future relative usefulness of an alternative species compared to the dominant species, an investor who is pessimistically inclined will undervalue the alternative species, compromising the efforts of its conservation. Clearly, the parametrization with respect the level of ambiguity and the ambiguity attitude not only allows for comparative statics with respect to the associated parameters, but also for modelling heterogeneity of decision makers in these aspects.

The general public, for example, will not tend to perceive the conservation of a species as a decision between two investment projects in the way the investors do. Rather, the general public will be inclined to consider the extinction of a species as a loss compared to the status quo. Decisions that are driven by the evaluation of 'gains' and 'losses' could be interpreted in the context of cumulative prospect theory. In the case of non-additive weights, cumulative prospect theory combines an 'optimistic' evaluation ($\delta = 1$) for the non-additive cumulative weights for losses, with a 'pessimistic' evaluation ($\delta = 0$) for the non-additive cumulative weights for gains. In the terminology applied by Chateauneuf et al. (2007), a standard (pessimistic) capacity is applied with respect to gains, whereas a 'dual' (optimistic) capacity is applied with respect to losses.[4]

Following this reasoning, we would find that the pessimism guiding the investors' investments in the species ($\delta = 0$) would lead to sub-optimally low conservation efforts, compared to ambiguity neutral value maximizing ($\delta = 0.5$). The general public, considering the extinction of species a 'loss' in the cumulative prospect theory setting and thus applying an optimism ($\delta = 1$) would strive for conservation efforts which exceed those obtained for ambiguity neutral value maximizing. As the 'common good' is best defined as reflecting the preferences of the general public, this leads to the conclusion that, in the presence of ambiguity, not only the investors' conservation efforts are sub-optimal. But even the higher conservation effort levels reflecting ambiguity neutral maximization would still fall short of the conservation efforts requested by the general public. The insight that in the presence of ambiguity investors tend to undertake conservation efforts below those of ambiguity neutral value maximization and the general public requests conservation efforts above those of ambiguity neutral value maximization has profound policy implications which are discussed in the next section.

6 Final Remarks and Policy Implications

This paper studies the effect of risk and ambiguity on the decision of selecting between preserving biodiversity (thus incurring additional maintenance expenditures) or abandoning underutilized species. In keeping with extant literature, we show that 'calculated' risk creates a scope for biodiversity preservation as the availability of different species provides flexibility in the face of market risks (e.g. consumers' shifts in taste and habits) and increases resilience to negative externalities, such as pests, diseases, climate change, etc. On the contrary, in the presence of ambiguity averse investors/producers maintenance of agrobiodiversity becomes less convenient.

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[4] For a more detailed discussion and examples of the impact of the reference point in cumulative prospect theory on the ambiguity attitude, see Liu and Spanjers (2023).

Our findings may contribute to the evaluation of some strategies embedded in various policy frameworks at national and international levels to promote biodiversity conservation. For example, the European Commission CAP provides that EU countries can utilize a number of measures enabling farmers to enhance biodiversity on their land such as breeding traditional plant varieties, maintaining high nature value grassland, restoring and preserving wetlands as biodiversity habitats, purchasing biodiversity-friendly machinery, etc. While an adequate funding mechanism is key to a safeguard and development agenda, incentives and direct payments cannot be the sole action taken by policy-makers. As we showed, both the perceived value of species as income-generating opportunities and the attached level of uncertainty and risk play a crucial role in delineating management strategies and prioritizing actions. It is widely recognized that some additional measures can be taken by policy-makers to bend the curve of decline in biodiversity. For instance a global awareness campaign among consumers may help promoting sustainable use of species varieties, thus sustaining cultivation of local fruits and crops and diversifying farm systems. At the same time, researchers can contribute to mainstream genetic diversity investigating and valorising the benefits of diversified genetic resources in terms of ecological and nutritional role, resistance to pests, diseases and pollution, and their service in climate change mitigation. All these actions will facilitate the identification of the ’true’ value of each species (in our model, v_i) and of the wide array of services and opportunities made possible by biodiversity (in our model, the option value).

Our paper shows that ambiguity has a deterring influence on taking actions in favour of biodiversity development. As a consequence, a successful safeguard plan should avoid abrupt changes in policy measures, complicated and vexatious cross-compliance rules, lack of clear and prioritized objectives and should instead increase transparency in the development and monitoring process. A successful rescue plan should involve workers, companies and local communities acting as custodians of biodiversity. So our final question is: are the concerted global conservation policies adequate to protect biodiversity from the threats and harms that may occur from development?

Our findings suggest a two-tier policy with respect to investments and conservation. One policy tier would target the investors and their investment and production policies, under base-line expectations or obligations regarding conservation efforts. The main consideration of this tier would ensure sufficient food being available. The other policy tier would target conservation efforts financed through public subsidies, without any specific expectations or obligations regarding the economic viability of the investment and production decisions involved. The main consideration of this tier would be safeguarding biodiversity and working towards sustainability.

It would seem that in the context of EU conservation policies this type of two-tier policy is implemented in its biodiversity strategy 2030 to protect nature and to reverse the degradation of ecosystems, as part of the European ‘Green Deal’, through its new ‘Biodiversity Strategy’ and its ‘Farm to Fork strategy’, which supplement the current ‘first tier’ approach with forward looking elements of the ‘second tier’ approach. Furthermore, the type of two-tier policy approach proposed could provide a framework for countries within which to consider effective contributions to the FAO’s Strategy for Mainstreaming Biodiversity across Agricultural Sectors.

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Declarations

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