The economics of the Food versus Biodiversity debate*

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Abstract

Ecologists discuss the "food versus biodiversity" trade-offs in the following terms: what is the land use configuration that minimizes biodiversity loss for a given food production target. This is, in economic terms, a cost-effectiveness approach related to the concept of Pareto-efficiency in the food-biodiversity outcomes map. This paper argues that economists should participate in this debate. A first set of results shows how the introduction of some basic micro-economic considerations modifies or reinforces the recommendations of the ecological literature on how to preserve biodiversity while producing food. A second set of arguments emphasizes that it is not necessarily sensible, from an economic point of view, to set the debate in terms of food versus biodiversity. A wider, welfarist approach should be used.

Keywords: Food production, Biological conservation, Trade-offs, Economics, Land use, Agricultural intensity, Soil heterogeneity.

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1 Introduction

Habitat destruction and degradation are two of the main drivers of biodiversity loss (Vitousek et al., 1997). In agricultural landscapes, agriculture expansion and intensification are major concerns for biodiversity conservation. There is a negative relationship between agricultural intensity (and thus agricultural yield) and biological density (Donald et al., 2001; Benton et al., 2002). How to produce food without harming too much biodiversity?

This question has received a lot of attention in the conservation biology literature, in particular within the "land sparing versus land-sharing" debate (Green et al., 2005; Balmford et al., 2005; Fischer et al., 2008; Ewers et al., 2009; Fischer et al., 2011). Should agricultural production be highly intensive to spare a maximal amount of natural land for nature (land-sparing solution) or should intensity be reduced as much as possible to limit the effect of farming on wild-life (land-sharing solution). The latter option relies on the definition of wild-life friendly farming practices. It requires much more land to produce a given amount of food while being partly favorable to biodiversity. Green et al. (2005) showed that if the response of biodiversity (or of the density of a particular species) to yield increase is convex, land-sparing is a better solution as a convex combination of natural habitat and highly intensive cropping produces more biodiversity and food than wild-life friendly farming. On the contrary, a concave agricultural yield - biological density relationship means that wild-life friendly farming is a good compromise to produce both food and biodiversity on the same landscape. This debate is very important as it basically supports either the funding of natural reserves to maximize the share of land spared for nature or the funding of agri-environmental schemes (or the taxation of intensity in agricultural production) to limit the impacts of food production on biodiversity.

In this debate, the focus is on the ecological response of biodiversity to agricultural intensity. There are no economic considerations. Land is assumed to be homogeneous, both for agricultural production and as a natural habitat. In this paper, I argue that economists should participate in this debate for two reasons.

A first set of results shows how the introduction of some basic micro-economic considerations modifies or reinforces the recommendations of the ecological literature on how to preserve biodiversity while producing food. I consider heterogeneous land and decreasing productivity of agriculture with respect to land use (the Ricardian hypothesis that best land is put into cultivation first), and private ownership of land which implies a decentralized optimization problem on the definition of land use and agricultural intensity. I show that in presence of decreasing returns to scale in the agricultural sector, wild-life friendly farming, *when it is a desirable option*, should not become a norm for all agricultural production. When production increases, it may be efficient, in terms of biodiversity preservation, to intensify agricultural production on the best quality land (intensive margins) instead of extending the area of less productive wild-life friendly farming on lower quality land (extensive margins). A policy mix balancing the advantages of natural reserves, intensive agriculture on high quality land and wild-life friendly farming on lower quality land is described. This policy mix combines a tax on intensity and a subsidy to natural reserves. Moreover, I show that it is not possible to define a public policy that is both market-neutral (i.e., that does not modify the food production when modifying the land use) and budget-balanced (i.e., for which the revenues from intensity taxation offset the cost of natural reserves subsidies).

A second set of arguments emphasizes that it is not necessarily sensible, from an economic point of view, to set the debate in terms of food versus biodiversity. In a welfare economics perspective, the trade-offs are between biodiversity production and agricultural profit if one considers a local scale conservation problem, or between food, biodiversity *and* a numéraire if one considers the global conservation issue. Such a perspective will be addressed in forthcoming research.

From a technical point of view, the research is based on the classical land-use share modeling framework *à la* Lichtenberg (1989). There is one dimension of land quality heterogeneity corresponding to the maximum potential yield of the field. Land-use rent maximization (Ricardian rent) is used to define land use in a given economic context. The relative areas of natural reserves (unfarmed land), wild-life friendly farming and intensive farming are defined endogenously. By considering all the possible land-use configurations, it is possible to describe the set of "production" possibilities, in terms of both food ans biodiversity, and to discuss the characteristics of its (Pareto) frontier.

The remaining of the paper is as follows. The modeling framework is described in section 2. The production possibility set and its Pareto frontier are characterized in section 3. The food and biodiversity outcomes in a non-regulated market are characterized in section 4. Section 5 presents an analysis of policy instruments to achieve efficient outcomes. A broader economic analysis of the food versus biodiversity debate is proposed in section 6. Section 7 presents our conclusions. Mathematical details and proofs are gathered in the appendix A.

2 Modeling framework

2.1 Land use share model

We develop a land use model with three possible land uses: biological reserve, wildlife friendly agricultural production, and intensive agricultural production.

2.1.1 Heterogeneous land Quality

We consider an agricultural region where land quality is heterogeneous and influences agricultural productivity. Following the literature on acreage models of agricultural land (starting from Lichtenberg, 1989), we assume that soil quality can be represented by a land quality index q, which defines the agricultural potential yield. This index is normalized into the interval $[0,1]$, with the soil of worst agricultural quality having a quality 0, and that of the best quality having a quality 1. We consider that the acreage of land that is of quality $q \in [0,1]$ is given by a density function $\phi : [0,1] \mapsto \mathbb{R}$, and that the proportion of acreage of the considered area that is of a quality lower than a threshold Q is given by $\Phi(Q) = \int_0^Q \phi(q)dq$. The function Φ is continuous and increasing, with $\Phi(1) = 1$, meaning that all fields have a quality lower or equal to the highest quality.

The yield $y(q,f)$ of agricultural production on a field is an increasing function of soil quality and intensity level (e.g., fertilizer use) f. We thus have $q_1 > q_2 \Rightarrow y(q_1,f) \geq y(q_2,f)$ and $f_1 > f_2 \Rightarrow y(q,f_1) \geq y(q,f_2)$.

For our theoretical analysis, the yield function is assumed to be linear with respect to the soil quality and fertilizer use:[1]

$$\begin{cases} y(q,f) = \left(\underline{y} + q(\bar{y} - \underline{y})\right)\left(a + (1-a)\frac{f}{f_{max}}\right) & \text{for} \quad 0 \leq f \leq f_{max} \\ y(q,f) = \left(\underline{y} + q(\bar{y} - \underline{y})\right) & \text{for} \quad f > f_{max} \end{cases} \tag{1}$$

where a is constant parameter satisfying $0 < a < 1$ which represents the fraction of potential yield achieved when no fertilizer is used and f_{max} is the upper limit of fertilizer use.[2] The soil quality parameter q is proportional to the potential yield, i.e., the maximal yield when no input is limiting. In our case, the soil quality parameter characterizes the soil with respect to all its endogenous characteristics except nitrogen, which is used as a proxy for intensity.

2.1.2 Land use rent

The basic idea underlying land use share models is to allocate land to the use generating the largest rent. In this analysis, we distinguish three potential land uses: natural reserve, wild-life friendly agricultural production, and intensive agricultural production. The rent of agricultural uses depends on land quality.

Agricultural profit We assume that there is a unique agricultural product, which price is denoted by p. This price corresponds to a market equilibrium on the food market. Depending on the scale of our analysis, this price may or may not be influenced by a change in the described supply: If one considers a large agricultural production area (or the global production system), the price will be

[1]This corresponds to a "Linear-Plateau" yield response to Nitrogen. More complex functional forms, such as the Spillman-Mitscherlich yield function (Llewelyn and Featherstone, 1997; Kastens et al., 2003; Frank et al., 1990) could be used, without modifying qualitatively the results. It would just limit the analytical resolution of the problem. Moreover, even if Mitscherlich form is preferred by economist (Bond and Farzin, 2008), partly because it is continuous and concave, from an agronomic point of view, Linear-Plateau functions perform well (Makowski et al., 2001).

[2]This upper limit corresponds to the "plateau" of a linear-plateau yield response function to nitrogen.

affected by production change. If one considers a small, price-taking production region (e.g., landscape level), the price is exogenously fixed. The price is, however, not influenced by individual production decisions, farmers being price-taker (competitive market).

We define the individual agricultural profit (per area unit) of agricultural production as a function of the soil quality q (an exogenous variable), the input quantity f (an endogenous variable); the other parameters, including the price p, the variable cost c_f of fertilizer, other costs C (assumed to be fixed), and all the agronomic parameters being constant.

$$\pi(q,f) = p\left(\underline{y} + q(\bar{y} - \underline{y})\right)\left(a + (1-a)\frac{f}{f_{max}}\right) - c_f f - C. \tag{2}$$

This profit function is linear with respect to the fertilizer level on the range $[0, f_{max}]$, implying that the optimal fertilizer use is a corner solution on this range. If the marginal profit of fertilizer use is positive, one has $f^\star(q) = f_{max}$. If the marginal profit of fertilizer use is negative, one has $f^\star(q) = 0$. Basic computation shows that the sign of this marginal profit depends on the soil quality considered. Define the threshold

$$\bar{Q} = \frac{1}{(\bar{y} - \underline{y})}\left(\frac{c_f f_{max}}{p(1-a)} - \underline{y}\right) , \tag{3}$$

for which $\frac{\partial \pi(q,f,\tau)}{\partial f}_{|q=\bar{Q}} = 0$. All fields whose quality is greater than the threshold $\bar{Q}$ will be used as intensively as possible, applying a quantity f_{max} of fertilizer. Below this threshold, no fertilizers are used (low production cropland). This defines two different agricultural land uses, corresponding respectively to intensive agricultural production and environmental friendly production. From now on, we can treat these two productions separately as two alternative land uses, with associated profit depending on the soil quality.

The optimal yield of intensive agricultural land use on any field of quality $q \geq \bar{Q}$ is given by

$$y^{int}(q) = y(q, f_{max}) = \underline{y} + q(\bar{y} - \underline{y}) . \tag{4}$$

The associated profit is

$$\pi^{int}(q) = \pi(q, f_{max}) = p\left(\underline{y} + q(\bar{y} - \underline{y})\right) - c_f f_{max} - C . \tag{5}$$

The optimal yield of wildlife friendly agricultural land use on any field of quality $q \leq \bar{Q}$ is given by

$$y^{wlf}(q) = y(q, 0) = a\left(\underline{y} + q(\bar{y} - \underline{y})\right) . \tag{6}$$

The associated profit is

$$\pi^{wlf}(q) = \pi(q, 0) = pa\left(\underline{y} + q(\bar{y} - \underline{y})\right) - C . \tag{7}$$

Note that these profit functions are increasing with the soil quality, and that, by construction of $\bar{Q}$, we have $\pi^{int}(q) \geq \pi^{wlf}(q)$ for all $q \geq \bar{Q}(\tau)$.

Natural reserve Agricultural use will take place on all land on which the agricultural land rent is larger than that of alternative uses. We thus consider a third alternative land use: the ecological reserve. Without loss of generality, we assume that it generates no revenue to the land owner, and that any opportunity cost of agricultural land is included in the fix cost C.

2.2 Competitive land use

We follow the Ricardian approach of optimal land rent and assume that decentralized decisions of land use are driven by the maximization of profit. Competitive land allocation depends on the relative profits of the different uses, i.e., on the economic context. This provides a usual theoretical foundation for the area base model, characterizing the trade-offs between the two types of agriculture (intensity) and the alternative choice to keep land as a reserve. The solution of the profit-maximization problem will divide the regional acreage into several compact sets, representing contiguous intervals of soil quality (Lichtenberg, 1989).

2.2.1 Interior solution

Assume an interior solution with three land uses. As the agricultural profit functions are increasing with the soil quality, natural reserves will occupy land of lower quality. To define reserve's land use share, one should define $\underline{Q}$ such that for all $q \leq \underline{Q}$, $0 \geq \pi^{wlf}(q)$. This threshold is given by

$$\underline{Q} = \left(\frac{C}{pa} - \underline{y} \right) \frac{1}{\bar{y} - \underline{y}} \ . \tag{8}$$

We can illustrate the reason behind the analysis with Fig. 1.

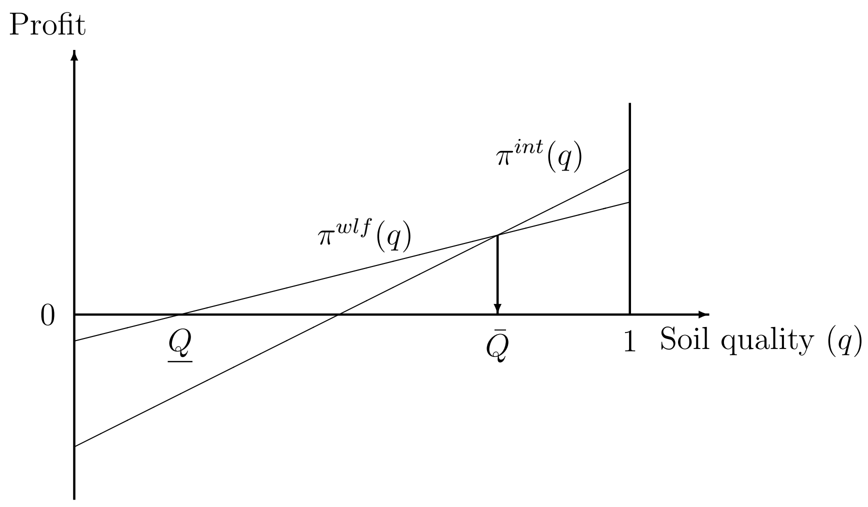


Figure 1: Profit functions and land-use: Interior solution

This interior solution is possible only if $\underline{Q} \leq \bar{Q}$. This conditions is satisfied only if wild-life friendly farming is sufficiently productive, as defined in the following proposition

Proposition 1 *There is no wild-life friendly farming if the agricultural productivity of extensive agriculture a is lower than a threshold $\hat{a}$ depending on the agricultural production costs:*

$$a \leq \hat{a} \equiv \frac{C}{C + c_f f_{max}} . \tag{9}$$

When this condition is not satisfied, the "gain" to keep land as a natural habitat is larger that the rent from wildlife friendly farming on the whole land quality range on which wildlife friendly farming would be preferred to intensive agriculture. In this case, the quality threshold separating natural habitat from agricultural use corresponds to a switch from natural habitat to intensive agriculture. There are only two land uses: natural reserves and intensive agricultural fields, and no land used wildlife friendly. This corresponds to the land sparing situation.

2.2.2 Land sparing solution

By considering the condition $\pi^{int}(q) \geq 0$, one can determine the soil quality threshold separating intensive agriculture from natural reserve. This threshold depends on both instruments, and is denoted by Q^*. One has

$$Q^* = \left(\frac{C + c_f f_{max}}{p} - \underline{y} \right) \frac{1}{\bar{y} - \underline{y}} \tag{10}$$

We can illustrate the reason behind the analysis with Fig. 2. Within the soil quality interval $[0, Q^*]$, the reserve generates the highest profit. On $[Q^*, 1]$, intensive agricultural production takes place.

Note that the thresholds depend on the agri-economic context. We shall see in Section 5 how these thresholds can be actually influenced by the means of economic incentives modifying the economic context.

2.3 Landscape production

The landscape produces agricultural, economic and biological outputs, depending on the soil quality heterogeneity of the landscape and the quality thresholds between land uses.

Even if one cannot define a priori the form of the density function representing heterogeneity (assumptions about its form amount to assumptions about the region distribution of land quality soils (Hardie and Parks, 1997)), it is possible in a theoretical approach to use flexible density functions, with sufficient parameters

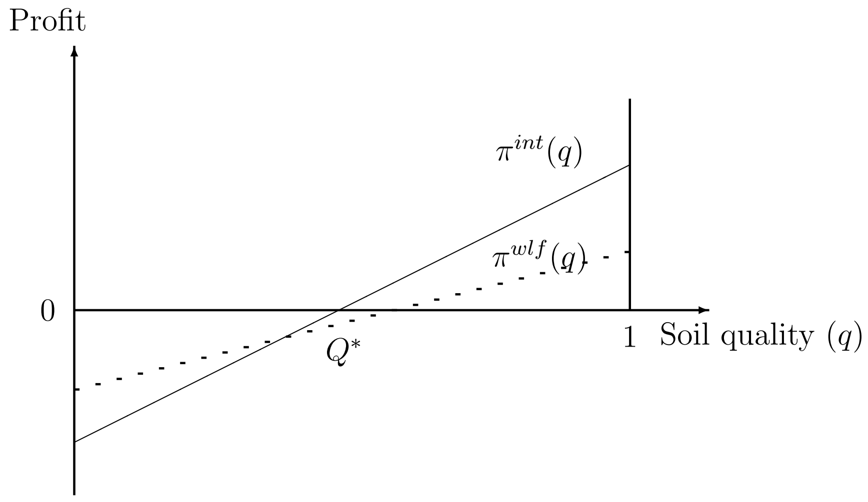


Figure 2: Profit functions and land-use: Land sparing case

to represent an important variety of distributions. For this purpose, we consider the Beta distribution: the density function of q is given by

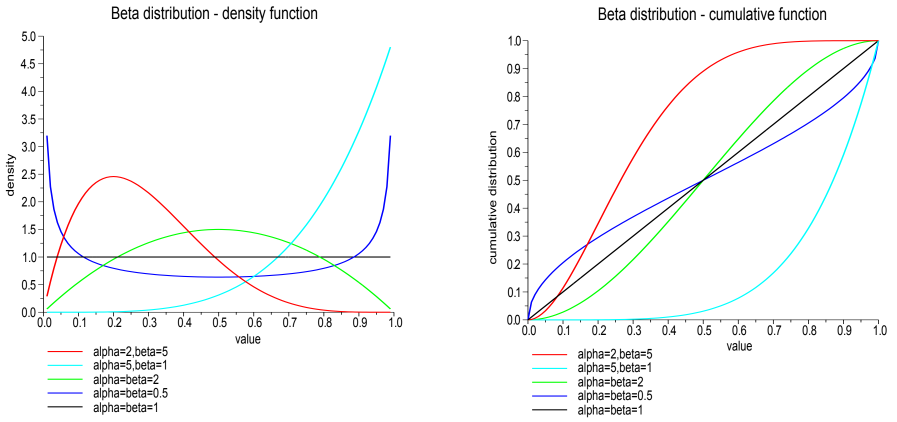
$$\phi(q, \alpha, \beta) = \frac{q^{\alpha-1}(1-q)^{\beta-1}}{B(\alpha, \beta)} , \tag{11}$$

where the Beta function $B(\alpha, \beta) = \int_0^1 q^{\alpha-1}(1-q)^{\beta-1}dq$ appears as a normalization constant to ensure that the total distribution integrates to unity. By denoting $B_Q(\alpha, \beta) = \int_0^Q q^{\alpha-1}(1-q)^{\beta-1}dq$ the incomplete Beta function, the cumulative distribution of soil quality is

$$\Phi(Q, \alpha, \beta) = \int_0^Q \phi(q, \alpha, \beta)dq = \frac{\mathrm{B}_Q(\alpha, \beta)}{\mathrm{B}(\alpha, \beta)} . \tag{12}$$

The Beta function has the great advantage of making it possible to represent a wide range of heterogeneity patterns with only two parameters.[3] Fig. 3a) represents soil quality distributions for various values for parameters α and β, including uniform, U-shaped, asymmetric (concave or convex), unimodal, and linear distributions. Fig. 3b) represents the associated cumulative distributions. The Beta function has been advocate to provide a powerful theoretical tool for application (Eugene et al., 2002; Hennessy, 2009), but we shall see that its functional form also allows explicit computation of analytical results.

[3] Beta functions are particular cases of Dirichlet distributions, for two parameters. To estimate the value of the parameters, an easy way is to compute the mean $\bar{x}$ and variance v of a distribution, which leads to $\alpha = \bar{x}\left(\frac{\bar{x}(1-\bar{x})}{v}\right)$ and $\beta = (1-\bar{x})\left(\frac{\bar{x}(1-\bar{x})}{v}\right)$.



(a) Soil quality distribution (b) Cumulative soil quality distribution

Figure 3: Beta function for various parameters (α, β)

2.3.1 Agricultural production

Given the distribution of soil quality, one gets the production areas. In particular, the share of cropland produced on soils of quality belonging to $[\underline{Q}, 1]$ will be $1 - \Phi(\underline{Q})$, that depends on the density of soil which quality is higher than the spin quality. These limits emerge from the area base model derived from the Ricardian rent hypothesis, in which land margins depend on differences in land quality. In the interior solution case, land of quality $[\underline{Q}, \bar{Q}]$ will be use extensively while land of quality $[\bar{Q}, 1]$ will be used intensively.

Agricultural production in the interior solution case Knowing threshold qualities $\underline{Q}$ and $\bar{Q}$, total agricultural production is defined by

$$Y = \int_{\underline{Q}}^{\bar{Q}} \phi(q, \alpha, \beta) y^{wlf}(q) dq + \int_{\bar{Q}}^{1} \phi(q, \alpha, \beta) y^{int}(q) dq \tag{13}$$

This expression can be transformed as follows

$$\begin{aligned} Y(\underline{Q}, \bar{Q}) &= \int_{\underline{Q}}^{\bar{Q}} \phi(q, \alpha, \beta) a \left(q(\bar{y} - \underline{y}) + \underline{y}\right) dq + \int_{\bar{Q}}^{1} \phi(q, \alpha, \beta) \left(q(\bar{y} - \underline{y}) + \underline{y}\right) dq \\ &= a \int_{\underline{Q}}^{1} \phi(q, \alpha, \beta) \left(q(\bar{y} - \underline{y}) + \underline{y}\right) dq + (1 - a) \int_{\bar{Q}}^{1} \phi(q, \alpha, \beta) \left(q(\bar{y} - \underline{y}) + \underline{y}\right) dq \end{aligned}$$

which can be integrated:[4]

$$\begin{aligned} Y(\underline{Q},\bar{Q}) &= a\left(\underline{y}(1-\Phi(\underline{Q},\alpha,\beta)) + (\bar{y}-\underline{y})\frac{\alpha}{\alpha+\beta}(1-\Phi(\underline{Q},\alpha+1,\beta))\right) \\ &+ (1-a)\left(\underline{y}(1-\Phi(\bar{Q},\alpha,\beta)) + (\bar{y}-\underline{y})\frac{\alpha}{\alpha+\beta}(1-\Phi(\bar{Q},\alpha+1,\beta))\right) \end{aligned}$$

The simplification of this expression leads to

$$\begin{aligned} Y(\underline{Q},\bar{Q}) &= \left(\underline{y}(1-\Phi(\bar{Q},\alpha,\beta)) + (\bar{y}-\underline{y})\frac{\alpha}{\alpha+\beta}(1-\Phi(\bar{Q},\alpha+1,\beta))\right) \\ &+ a\Big[\underline{y}\left(\Phi(\bar{Q},\alpha,\beta)-\Phi(\underline{Q},\alpha,\beta)\right) \\ &\quad +(\bar{y}-\underline{y})\frac{\alpha}{\alpha+\beta}\left(\Phi(\bar{Q},\alpha+1,\beta)-\Phi(\underline{Q},\alpha+1,\beta)\right)\Big] \end{aligned}$$

Agricultural production in the land-sparing case Knowing threshold quality Q^*, total agricultural production is defined by

$$Y(Q^*) = \int_{Q^*}^{1} \phi(q,\alpha,\beta) y^{int}(q) dq \tag{14}$$

This expression can be transformed as follows

$$Y(Q^*) = \int_{Q^*}^{1} \phi(q,\alpha,\beta)\left(q(\bar{y}-\underline{y})+\underline{y}\right) dq$$

which can be integrated:

$$Y(Q^*) = \underline{y}(1-\Phi(Q^*,\alpha,\beta)) + (\bar{y}-\underline{y})\frac{\alpha}{\alpha+\beta}(1-\Phi(Q^*,\alpha+1,\beta))$$

[4] We recall here that the density function $\phi(q,\alpha,\beta)$ is supposed to be a beta function satisfying $\phi(q,\alpha,\beta) = \frac{q^{\alpha-1}(1-q)^{\beta-1}}{B(\alpha,\beta)}$. We use the following computation steps:

$$\begin{aligned} \int_X^1 \phi(q,\alpha,\beta)\left(q(\bar{y}-\underline{y})+\underline{y}\right) dq &= \underline{y}\int_X^1 \phi(q,\alpha,\beta)dq + (\bar{y}-\underline{y})\int_X^1 \phi(q,\alpha,\beta)q dq \\ &= \underline{y}(1-\Phi(X,\alpha,\beta)) + (\bar{y}-\underline{y})\int_X^1 \frac{q^{\alpha-1}(1-q)^{\beta-1}}{B(\alpha,\beta)} q dq \\ &= \underline{y}(1-\Phi(X,\alpha,\beta)) + (\bar{y}-\underline{y})\frac{B(\alpha+1,\beta)}{B(\alpha,\beta)}\int_X^1 \frac{q^{(\alpha+1)-1}(1-q)^{\beta-1}}{B(\alpha+1,\beta)} dq \\ &= \underline{y}(1-\Phi(X,\alpha,\beta)) + (\bar{y}-\underline{y})\frac{B(\alpha+1,\beta)}{B(\alpha,\beta)}(1-\Phi(X,\alpha+1,\beta)) \end{aligned}$$

Knowing the general property of the complete Beta function: $B(\alpha+1,\beta) = \frac{\alpha}{\alpha+\beta}B(\alpha,\beta)$, we obtain the expression

$$\int_X^1 \phi(q,\alpha,\beta)\left(q(\bar{y}-\underline{y})+\underline{y}\right) dq = \underline{y}(1-\Phi(X,\alpha,\beta)) + (\bar{y}-\underline{y})\frac{\alpha}{\alpha+\beta}(1-\Phi(X,\alpha+1,\beta))$$

2.3.2 Economic profit

The agricultural profit (gross return) is given by the different between the agricultural revenue (price times production) and the production costs. Fixed costs are supported for all agricultural production, while variable costs (the fertilizer costs in our simple model) are relevant only for intensive production.

Economic profit in the interior solution case The mathematical expression of the profit is the following:

$$\begin{aligned}\Pi(\underline{Q},\bar{Q}) &= pY(\underline{Q},\bar{Q}) - \int_{\underline{Q}}^{1} C\phi(q,\alpha,\beta)dq - \int_{\bar{Q}}^{1} c_f f_{max}\phi(q,\alpha,\beta)dq \\ &= pY(\underline{Q},\bar{Q}) - C\left(1-\Phi(\underline{Q},\alpha,\beta)\right) - c_f f_{max}\left(1-\Phi(\bar{Q},\alpha,\beta)\right)\ . \quad (15)\end{aligned}$$

Economic profit in the land-sparing case In the land sparing case, the mathematical expression of the profit is the following:

$$\begin{aligned}\Pi(Q^*) &= pY(Q^*) - \int_{Q^*}^{1} (C + c_f f_{max})\phi(q,\alpha,\beta)dq \\ &= pY(Q^*) - (C + c_f f_{max})\left(1-\Phi(Q^*,\alpha,\beta)\right)\ . \quad (16)\end{aligned}$$

2.3.3 Ecological outcome

The proportions of the three habitats are denoted by h_R, h_W, h_I, respectively for Reserve, Wild-life friendly farming and Intensive farming. These habitats holds respectively densities of a focal species K_R, K_W, K_I. We assume that the dynamics of biological population are quite stable and that the populations arrive to their carrying capacity in each habitat. We thus consider a static land use and biological population model.

To simplify the notations, we assume that $K_I = 0$, i.e., that the species does not survive in areas used for intensive agricultural production. We also can express the carrying capacity of an area unit used for wildlife friendly farming as a fraction of the natural carrying capacity of reserves K_R, i.e., $K_W = \gamma K_R$, with $0 < \gamma < 1$. Parameter γ represent the effectiveness of environmental in supporting biodiversity.

Using this simple framework, we can define the biological output of the landscape POP as the ratio of the actual population over the maximal potential population, i.e., the population of the species if all land was kept as a natural habitat.

As the debate opposing wildlife friendly farming and land sparing is often set in terms of food production objectives, we shall consider both the agricultural production in quantity terms, and its economic value.

Biological outcome in the interior solution case This biological output can be expressed as a function of the land use shares:

$$\begin{aligned} POP(\underline{Q}, \bar{Q}) &= \frac{K_R h_R + K_W h_W}{K_R} = h_R + \gamma h_W \\ &= (1-\gamma)\Phi(\underline{Q}, \alpha, \beta) + \gamma \Phi(\bar{Q}, \alpha, \beta) \end{aligned} \tag{17}$$

Biological outcome in the land-sparing case This biological output only depends on the share of reserves in the land sparing scenario:

$$POP(Q^*) = h_R = \Phi(Q^*, \alpha, \beta) \tag{18}$$

3 Food and Biodiversity: Production possibility set

Knowing the economic, agricultural and ecological outcomes of the possible configurations of land use, we now turn toward the description of the resulting trade-offs between outcomes.

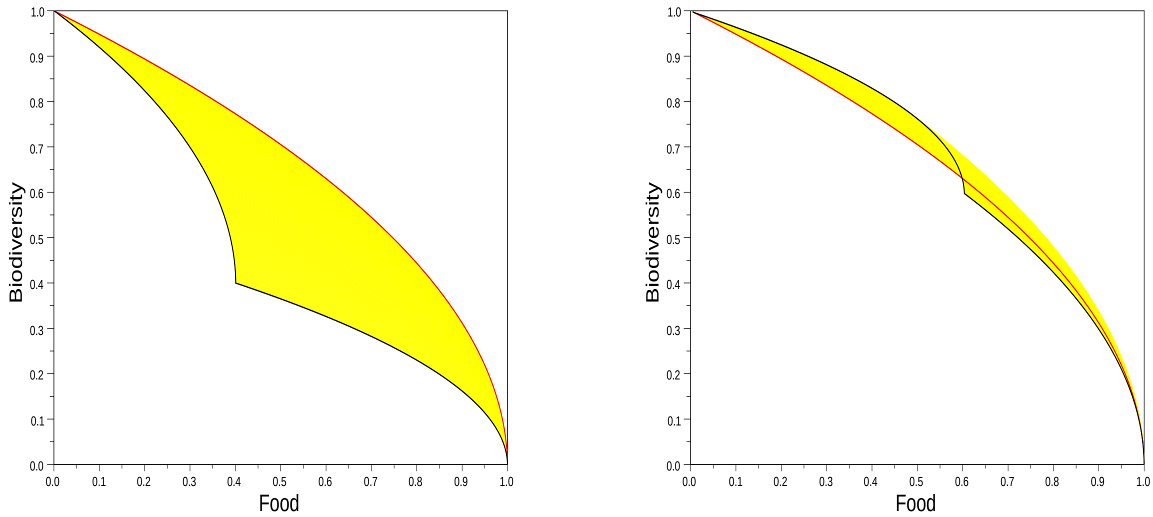
3.1 Trade-offs between food and biodiversity outcomes

By varying the level of the land-use share thresholds one can describe all the possible land uses and the associated economic, agricultural and ecological outcomes. Mapping the agricultural (food) and ecological (wildlife) outcomes, one get the social production possibility set of food and wildlife. Of interest is the upper frontier of that set, which represents the Pareto efficient outcomes of land-uses, and the necessary trade-offs between food and biodiversity production of land.

Examples of production possibility sets are represented in Fig. 4. The left-hand side panel represents the set of possible productions for parameters $a = 0.4$ and $\gamma = 0.4$. The points on the Pareto frontier are achieved with land-sparing (i.e., reserve plus intensive agriculture). The right-hand side panel represents the set of possible productions for parameters $a = 0.6$ and $\gamma = 0.6$. The points on the Pareto frontier are achieved either with wild-life friendly farming (plus natural reserves) or with a mix of the three land uses (interior solution).

The following two propositions show that if wildlife friendly farming is not efficient enough in producing food and wildlife, in a sense to be specified below, land-sparing is a better solution to achieve Pareto efficiency.

Proposition 2 (Efficient land sparing) *If $a + \gamma \leq 1$ any Pareto efficient outcome is achieved with land sparing (intensive agriculture plus natural reserves), and the set of Pareto efficient outcomes is defined by the outcomes of all possible land sparing configurations.*



(a) $a = 0.4$ and $\gamma = 0.4$

(b) $a = 0.6$ and $\gamma = 0.6$

Figure 4: Food and wildlife Production Possibility Sets.

A formal proof of the proposition is given in the appendix.

The intuition behind the proposition is that, for a given area, if a convex combination of intensive agriculture and reserve produces more than the allocation of the area to wlf farming, then land-sharing is efficient.[5] For example, consider a plot of land of given quality. This plot would produce 1 unit of wildlife if used as a natural reserve, or some y unit of food if used as an intensive field. This plot produces γ units of wildlife *and* ay units of food when used as a wlf field. Now, consider the sharing of the plot between reserve and intensive use, with proportions γ and $1-\gamma$. This mixed land-use would produce γ units of wildlife, and $(1-\gamma)y$ units of food. The ecological outcome would be the same as in the wlf case, but the agricultural outcome would differ. If $(1-\gamma)y \geq ay$, i.e., if $1-\gamma \geq a$, then the intensive production on the remaining area $1-\gamma$ is more efficient than wlf production on the whole plot. WLF production is less efficient than land-sparing production.

In this case, within the food versus biodiversity debate, it is not socially efficient to allocate land to wild-life friendly farming, and public policies should be such that individual decisions favor intensive agriculture and natural reserves. We shall describe the associated policy in the Section 5.

Wild-life friendly farming is an efficient solution only if $a+\gamma \geq 1$ (necessary

[5]The formal proof is more subtle, as land quality is heterogeneous, and land of a given quality is allocated optimally to a single use. The intuition presented here is a limiting case.

condition). We shall now detail when wlf farming is an efficient solution.

From the reverse of Proposition 2, we deduce that, when $a+\gamma > 1$, it is Pareto efficient to start agricultural production with WLF farming. This means that there are two (and only two) land uses, namely natural reserve and wlf farming, on some range of the production possibility frontier, including the corner outcome (Food,Wildlife)= $(0, 1)$. The following proposition defines to which extent wlf farming is an efficient option.

Proposition 3 (Efficient wild-life friendly farming) *If $a + \gamma > 1$, expansion of WLF agriculture increases Pareto-efficiently food production as long as*

$$\underline{Q} \geq \frac{(1-a)(1-\gamma)}{a\gamma}\bar{Q} - (a+\gamma+1)\frac{\underline{y}}{\bar{y}-\underline{y}} \ . \tag{19}$$

According to Proposition 3, as long as the quality thresholds representing land-use change from reserve to wildlife friendly farming ($\underline{Q}$) and the change from wildlife friendly farming to intensive agriculture ($\bar{Q}$) are not too different, it is Pareto-efficient to increase agricultural production by bringing into production marginal land of lower quality and use that land as wlf farming. There is an agricultural extension. Once the quality thresholds are too different, it is Pareto efficient to convert better quality land from wlf agriculture to intensive agriculture. This corresponds to an agricultural intensification.

Note that prior to the introduction of intensive agriculture, one has $\bar{Q} = 1$. This means that there will be only wlf agriculture (i.e., no intensive agriculture) as long as $\underline{Q} \geq \frac{(1-a)(1-\gamma)}{a\gamma} - (a+\gamma+1)\frac{\underline{y}}{\bar{y}-\underline{y}}$. The extreme case of full wlf agricultural use (no reserve and no intensive agriculture) is an efficient solution if $0 \geq \frac{(1-a)(1-\gamma)}{a\gamma} - (a+\gamma+1)\frac{\underline{y}}{\bar{y}-\underline{y}}$.

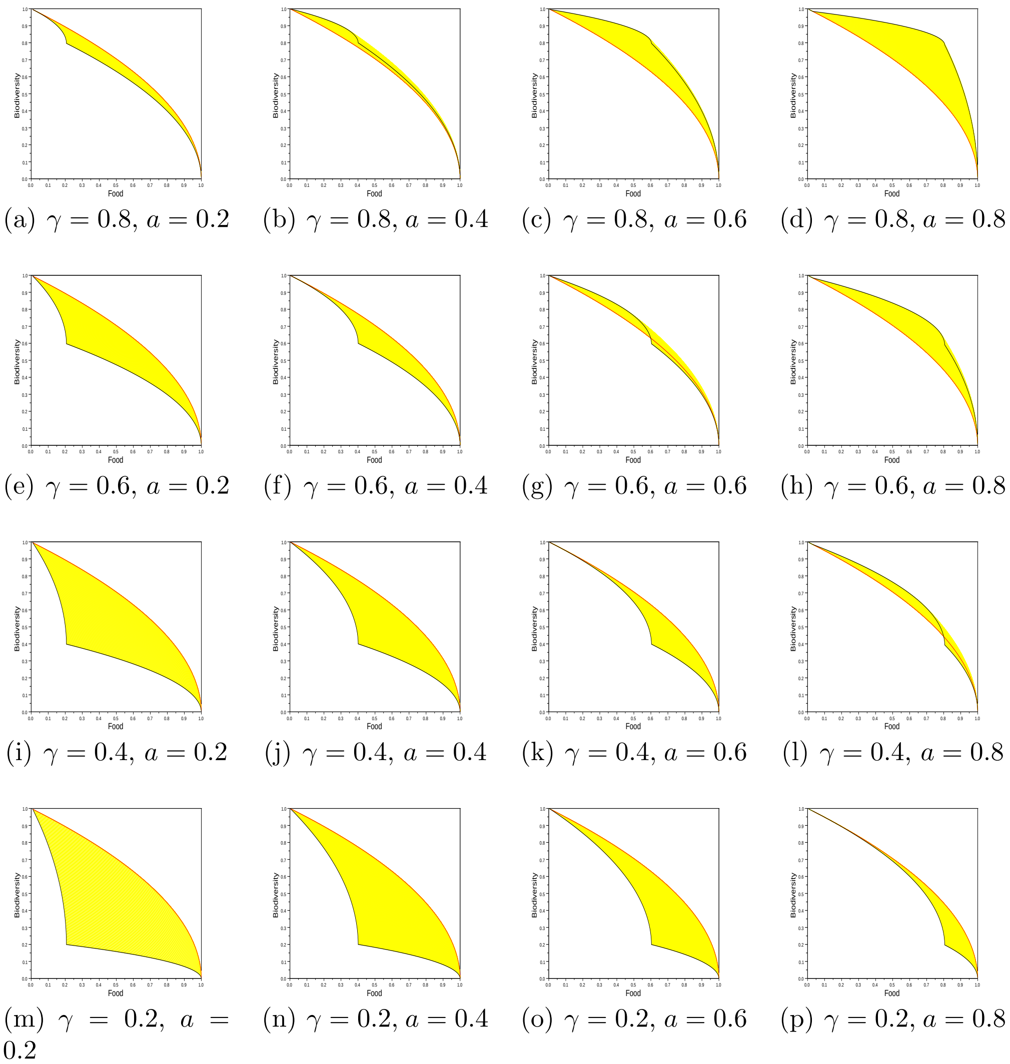
Sensitivity analysis with respect to the wildlife friendly farming parameters Fig. 5 presents a sensitivity analysis to the two main parameters of the model, the productivity of WLF farming a and the ecological benefit of WLF farming γ. This illustrates Propositions 2 and 3.

4 Food supply in a non-regulated market

In this section, we examine what is produced by the market, in terms of food and biodiversity, when the land-use is competitive and the markets non regulated.

4.1 Agricultural productivity, prices and land use

Structure of the production Within the competitive land use setting described in Section 2, land use shares are defined by the thresholds $\underline{Q}$ and $\bar{Q}$ (or the



(a) $\gamma = 0.8$, $a = 0.2$ (b) $\gamma = 0.8$, $a = 0.4$ (c) $\gamma = 0.8$, $a = 0.6$ (d) $\gamma = 0.8$, $a = 0.8$

(e) $\gamma = 0.6$, $a = 0.2$ (f) $\gamma = 0.6$, $a = 0.4$ (g) $\gamma = 0.6$, $a = 0.6$ (h) $\gamma = 0.6$, $a = 0.8$

(i) $\gamma = 0.4$, $a = 0.2$ (j) $\gamma = 0.4$, $a = 0.4$ (k) $\gamma = 0.4$, $a = 0.6$ (l) $\gamma = 0.4$, $a = 0.8$

(m) $\gamma = 0.2$, $a = 0.2$ (n) $\gamma = 0.2$, $a = 0.4$ (o) $\gamma = 0.2$, $a = 0.6$ (p) $\gamma = 0.2$, $a = 0.8$

Figure 5: Sensitivity analysis to parameters a and γ

single thresholds Q^* in the land-sparing configuration). These thresholds depend on the economic context, and in particular on the output price. A given price will be associated with a given production structure and the related production level. This shall allow us to define agricultural supply functions.

As there may be two different production configurations (corresponding to the "interior" and "land-sparing" cases described above), a first step of the analysis consists in determining the break-even prices of the two types of agriculture.

Break-even prices The break-even price of both types of agriculture is defined as the minimal price for which production starts on the best quality land ($q = 1$).

Wild-life friendly farming is more profitable than non-agricultural use on the top quality soil if its profit is positive, i.e., if

$$\begin{aligned} \underline{Q}(p) \leq 1 \quad &\Leftrightarrow \quad \left(\frac{C}{pa} - \underline{y}\right)\frac{1}{\bar{y} - \underline{y}} \leq 1 \\ &\Leftrightarrow \quad p \geq \tilde{p}^{wlf} \equiv \frac{C}{a\bar{y}} \; . \end{aligned} \tag{20}$$

In the same way, intensive agriculture becomes profitable with respect to non-agricultural use as soon as

$$\begin{aligned} Q^{*}(p) \leq 1 \quad &\Leftrightarrow \quad \left(\frac{C + c_f f_{max}}{p} - \underline{y}\right)\frac{1}{\bar{y} - \underline{y}} \leq 1 \\ &\Leftrightarrow \quad p \geq \tilde{p}^{ls} \equiv \frac{C + c_f f_{max}}{\bar{y}} \; . \end{aligned} \tag{21}$$

If the break-even price of intensive agriculture is lower than that of wild-life friendly farming, i.e., $\tilde{p}^{ls} \leq \tilde{p}^{wlf}$, agricultural production will start directly with high intensity as output price goes up. From proposition 1, we know that agricultural production will be intensive only if wild-life friendly farming is not productive enough. This is stated in the following Corollary.

Corollary 1 (of Proposition 1) *Agricultural production on a non-regulated market is exclusively intensive if* $a \leq \hat{a} \equiv \frac{C}{C + c_f f_{max}}$

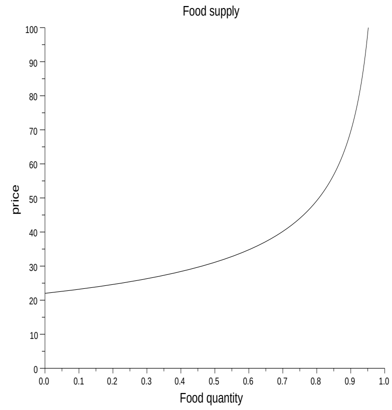
This condition states that if the relative productivity of wlf farming with respect to that of intensive farming is lower than the relative cost of the two production systems, it is never profitable to do wlf farming.

In the case in which wlf farming is profitable, i.e., $a \geq \hat{a}$, there the break-even price of the intensive agricultural production is given by the following condition:

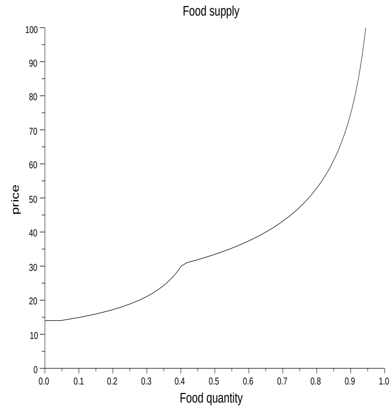
$$\begin{aligned} \bar{Q}(p) \leq 1 \quad &\Leftrightarrow \quad \left(\frac{c_f f_{max}}{p(1-a)} - \underline{y}\right)\frac{1}{\bar{y} - \underline{y}} \leq 1 \\ &\Leftrightarrow \quad p \geq \tilde{p}^{int} \equiv \frac{c_f f_{max}}{(1-a)\bar{y}} \end{aligned} \tag{22}$$

This last condition gives the break-even price of intensive agriculture once wlf is already in use on the best quality land.

Taking these two cases into account, one can draw two different agricultural supply functions, for the cases $a \leq \hat{a}$ and $a > \hat{a}$ (Fig. 6). In the latter case, there is a kink in the supply function, corresponding to the introduction of (competitive) intensive agriculture.



(a) Case $a \leq \hat{a}$



(b) Case $a > \hat{a}$

Figure 6: Food supply

4.2 Is the market producing a (Pareto)-efficient landscape outcome?

In Section 3, we have shown that Pareto efficient landscape productions correspond to land-sparing configurations when $a + \gamma \leq 1$. In such a case, wlf farming is not efficient in improving biodiversity conservation for a given production. The results in Section 4 show that wlf farming is used as a production system if $a > \hat{a}$.

From these results, we can characterize four configurations, each one being illustrated in Fig. 7.

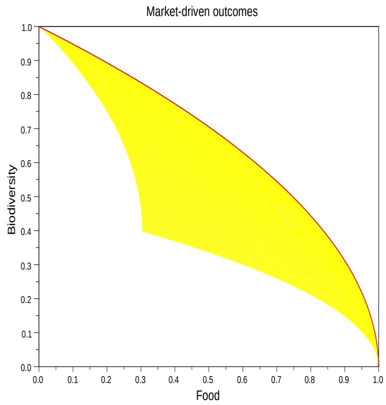
1. The market only produces intensively ($a \leq \hat{a}$) *and* Pareto-efficient production configurations correspond to land sparing ($a + \gamma \leq 1$). In this case, the food production is also efficient in (co)producing biodiversity. This case occurs when the agricultural productivity of wlf farming is relatively low and its ecological productivity is not too high (i.e., $\gamma \leq 1 - a$). This case is illustrated in Fig. 7a.

2. The market only produces intensively ($a \leq \hat{a}$) *but* wild-life friendly farming is somehow efficient from an ecological point of view, i.e., $\gamma \geq 1 - a$. In this case, the competitive agricultural market does not use wlf practices while it would improve biodiversity conservation. This case is illustrated in Fig. 7c.

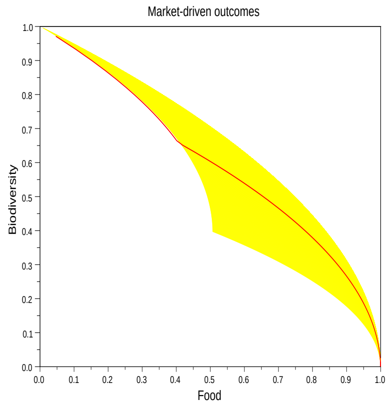
3. Wildlife friendly is competitive on some land quality ($a > \hat{a}$) *but* it is not efficient from an ecological point of view ($\gamma < 1 - a$). In this case, a land-sparing solution would perform better on the food and biodiversity production trade-off. This case is illustrated in Fig. 7b.

4. Wildlife friendly is competitive on some land quality ($a > \hat{a}$) *and* it is also

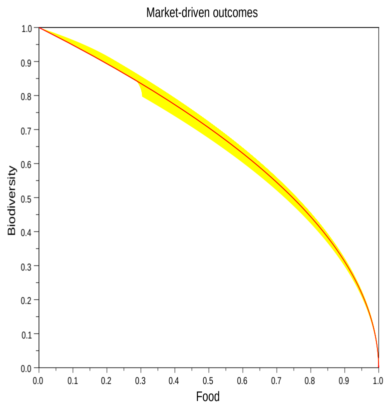
sufficiently efficient from an ecological point of view ($\gamma \geq 1 - a$) to be considered. This case is illustrated in Fig. 7d.



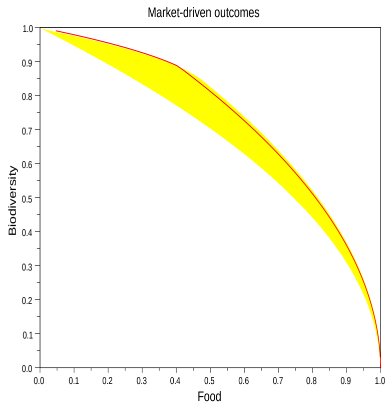
(a) $\gamma = 0.4$, $a = 0.3$



(b) $\gamma = 0.4$, $a = 0.5$



(c) $\gamma = 0.8$, $a = 0.3$



(d) $\gamma = 0.8$, $a = 0.5$

Figure 7: "Market" food and biodiversity production (red/dark line) on the production possibility set of food and biodiversity (yellow/clear shape)

In case 1., there is not possible improvement from the market outcomes. Wlf farming is not efficient from an ecological point of view, and it is not efficient either from an economic point of view. No regulation is needed.

In case 3., the market outcome is ecological inefficient as it results in the extensive use of low intensity, wlf farming while this practice is not ecologically performing. Intensification of agriculture (to spare more land for nature) would improve ecological outcome.

In cases 2., this is the opposite. Wlf farming is not competitive on the market while it would be beneficial for the biodiversity. Promoting wlf farming may be a policy option.

In case 4., wlf farming is ecologically valuable and the market makes use of this option at the extensive margins. We have seen, however, that wlf farming is ecologically interesting only on a range of soil quality (Proposition 3). This may not correspond to the economic condition on the break-even price of intensive agriculture. At some point, regulation may be need is this case also.

The next section identifies solutions to overcome these "landscape production inefficiencies" and improve the biodiversity outcome of the landscape.

5 Achieving Pareto efficient outcomes: Economic incentives and policy implications

In this section, we shall consider incentives that modify the market equilibrium with the underlying objective to achieve some "more efficient" (if not optimal) landscape food and biodiversity production.

Even if a single instrument is theoretically sufficient to optimally overcome a single market inefficiency (such as the fact that food producers do not account for biodiversity in our model), considering two instruments will be useful for two reasons. First, one may want to control both extensive and intensive margins independently in order to achieve any possible outcome of our two-dimensional food and biodiversity production possibility set. A single instrument modifies both margins at the same time, in a predetermined fashion, making it possible to "explore" only a one-dimensional subset of composite outcomes. This is an important feature of a policy tool, in particular when one considers second best solutions. Second, when the cost of the policy is a matter of concern, using two instruments makes it possible to consider budget-balancedness when one of the two instrument generates budget (e.g., a tax) and the other has a cost (e.g., a subsidy).

5.1 Controlling extensive and intensive margins with simple instruments

From now on, assume that a central planner aims at achieving a Pareto efficient solution, or any Pareto improvement from the market outcome. For this purpose, the unregulated outcome has to be modified by the means of economic incentive. The regulator has to modify the economic context such that the land-use share characterized by the thresholds $(\underline{Q}, \bar{Q})$ correspond to the targeted ones. This amounts to control the extensive $(\underline{Q})$ and intensives $(\bar{Q})$ margins of the agricultural sector. We shall assume that this is done with two instruments affecting directly these two margins: a subsidy to natural reserves which modifies the opportunity cost of agricultural use,[6] and a tax on fertilizer use to control intensity.[7] These two instruments are close to the actual policy-making (reserve subsidizing, and wild-life friendly farming policies). This will allow us to interpret our results in the light of the current debate on agricultural production regulation and make some policy recommendations to the debate between wild-life friendly farming subsiding and natural reserves creation.

Taking into account these two instruments, the land-use share thresholds are redefined as follows, in a given economic context (food price).

$$\underline{Q}(p,s) = \left(\frac{s+C}{pa} - \underline{y}\right)\frac{1}{\bar{y}-\underline{y}} \,. \tag{23}$$

$$\bar{Q}(p,\tau) = \left(\frac{(c_f+\tau)f_{max}}{p(1-a)} - \underline{y}\right)\frac{1}{(\bar{y}-\underline{y})} \,, \tag{24}$$

$$Q^*(p,\tau,s) = \left(\frac{C+s+(c_f+\tau)f_{max}}{p} - \underline{y}\right)\frac{1}{\bar{y}-\underline{y}} \tag{25}$$

Policy mix and map of potential solutions By varying the level of the two instruments within the space $[\underline{\tau},\bar{\tau}] \times [\underline{s},\bar{s}]$ one can achieve all the possible land uses and the associated economic, agricultural and ecological outcomes.

From a general point of view, given the three potential land uses, there are seven possible configurations of land use.

1. Full reserve,
2. Full wild-life friendly agriculture land use,
3. Full intensive agriculture land use,
4. Two uses: Wild-life friendly plus intensive agriculture,
5. Two uses: Reserve plus wild-life friendly agriculture,
6. Two uses: Reserve plus intensive agriculture,
7. Three land uses (interior solution).

[6] It is easier to assume that all reserve lands get the subsidy. It would, however, be possible to restrict the subsidy to land plots that would have been in agricultural use without subsidies. It is useless to subsidies unprofitable land, i.e., land of quality lower than $\left(\frac{C}{pa} - \underline{y}\right)\frac{1}{\bar{y}-\underline{y}}$, as they would be reserves without subsidies.

[7] One could alternatively consider a subsidy to wlf farming. When it is proportional to the conserved biodiversity on extensive agricultural land, one gets a "single" subsidy instrument.

Case 7 corresponds to the previously described interior solution. This interior solution is possible only if $\underline{Q} \leq \bar{Q}$. This conditions is satisfied if the opportunity cost of agricultural production, modified by the subsidy to natural resource, is sufficiently low, i.e., if

$$s \leq \hat{s} \equiv \frac{a}{1-a}(c_f + \tau) f_{max} - C \ . \tag{26}$$

Case 6 corresponds to the previously described corner case solution of land sparing. Each of these other cases can easily be deduced from the two previous cases, given the combination of extreme values for the thresholds. It is possible to describe the ranges of policy instruments for which each case to happen, as represented in Fig. 8.

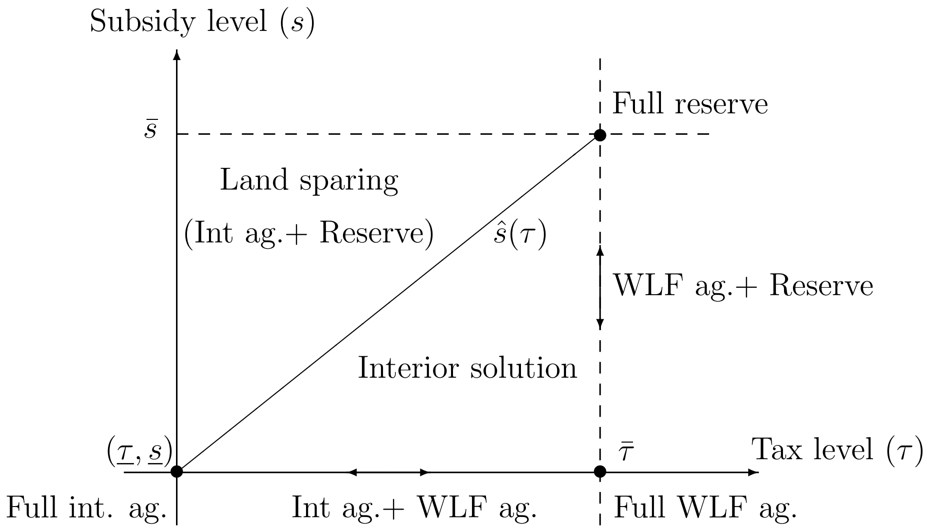


Figure 8: Policy mix map and associated land use configurations

The point $(\underline{\tau}, \underline{s})$ of the line corresponds to $\bar{Q}(p,\tau) = \underline{Q}(p,s) = 0$ while the top end point of the line matches with $\bar{Q}(p,\tau) = \underline{Q}(p,s) = 1$. Below the line, we have $\underline{Q}(p,s) < \bar{Q}(p,\tau)$, which represents the wildlife-friendly case. Above the line, we would have $\bar{Q}(p,\tau) < \underline{Q}(p,s)$, which is impossible. We are in the land sparing case with the threshold $\underline{Q}(p,s,\tau)$.[8]

The bounds of policies are:

$$\underline{Q}(p,s) \leq 0 \Rightarrow s \leq \underline{s} \equiv \underline{y}pa - C$$

[8]It can be easily checked that along the line, one has $\underline{Q}(p,s,\tau) = \bar{Q}(p,\tau) = \underline{Q}(p,s)$.

This means that the subsidy is lower than the smallest potential profit from WLF agriculture (i.e., for $q = 0$).

$$\underline{Q}(p, s) \geq 1 \Rightarrow s \geq \bar{s} \equiv \bar{y}pa - C$$

This means that the subsidy is higher than the largest potential profit from WLF agriculture (i.e., for $q = 1$).

$$\bar{Q}(p, \tau) \leq 0 \Rightarrow \tau \leq \underline{\tau} \equiv \frac{\underline{y}p(1-a)}{f_{max}} - c_f$$

This means that the net gain from the use of fertilizers on the land of worst quality (i.e., for $q = 0$) is larger than the tax, and that intensive agriculture is more profitable than wildlife farming agriculture for all land qualities.

$$\bar{Q}(p, \tau) \geq 1 \Rightarrow \tau \geq \bar{\tau} \equiv \frac{\bar{y}p(1-a)}{f_{max}} - c_f$$

This means that the net gain from the use of fertilizers on the land of best quality (i.e., for $q = 1$) is smaller than the tax, and that intensive agriculture is less profitable than wildlife farming agriculture for all land qualities.

5.1.1 Market neutral instruments

It is important to note that the thresholds, as modified by the two instruments, depend on the output price p. If one consider that the food price is determined on a market, one should consider the impact of the change in supply (due to the change in land-use and thus in production) on the market equilibrium and market price.

There are two possibilities: On the one hand, if the examined issue is that of local food production and biodiversity conservation, a change in the supply of a small price-taking region (or landscape) will not affect the food price. In this case, the results above are valid. On the other hand, if one considers a large region (or the whole economy), a change in the land-use will affect production and thus the food price. In such a case, there are two options. The first option is to defined market-neutral instrument. This is what we shall do in what follows. The second option is to take into account the market effect. This is discussed in Section 6.

Standard production theory tools (defining the marginal rate of substitution of the instruments along an isoproduction curve) and not so long (but uninteresting) computation defines a condition on the two instruments for market neutrality. For example, for an uniform distribution of soil quality, the condition reads:

$$\left(\frac{f_{max}}{1-a}\right)^2 \left(\frac{\tau^2}{2} + c_f\tau\right) = \frac{1}{2}\frac{s^2}{a} + \frac{Cs}{a} \ . \tag{27}$$

A policy defined such as to keep the production level unchanged should satisfy this condition.

5.1.2 Budget-balancedness

It is possible to define a condition on the instruments so that the revenue of the taxation of fertilizer use equals the cost of reserve subsidy. Here again, boring mathematics lead to a condition on the two instruments. For example, for an uniform distribution of soil quality, the condition reads:

$$\tau f_{max}\left(\bar{y} - \frac{(c_f + \tau) f_{max}}{p(1-a)}\right) = s\left(\frac{C+s}{pa} - \underline{y}\right) \tag{28}$$

A policy defined such as to have no "external cost" should satisfy this condition.[9]

It is interesting to note that the market-neutrality and budget-balancedness conditions (27) and (28) differ.[10] This allows use to state the following proposition:

Proposition 4 *It is not possible to define a couple of incentives (s, τ) that results in a policy that is both market-neutral and budget-balanced.*

This result means that it is not relevant to consider the food versus biodiversity debate isolated form broader economic considerations. There will be either market effects, or budget effects. The "welfare" cost of public policies to mitigate biodiversity loss is important. This result will be used in the discussion (Section 6).

5.2 Land Sparing versus Land Sharing

Given the production possibility frontier described in the previous section, it is possible to draw some conclusions for policy making.

First of all, wildlife-friendly farming is an efficient solution to preserve wildlife only if this production system is "productive enough" for both wildlife and food production in the sense that $a + \gamma > 1$. If this is not the case, land-sparing should be favored. In Fig. 9, we show this condition is extremely similar to the concave / convex density-yield relationship of Green et al. (2005). Here, however, this relation is considered at the local scale of farmer decision making (as considered in Phalan et al. (2011)), while Green et al. (2005) considered large scale density-yield relationship.

In the case in which WLF farming is sufficiently productive, it is an option to produce food and wildlife only up to some extent depending on soil heterogeneity.

[9] It would be straightforward to include an inefficiency parameter representing the implementation cost of the policy or a leakage in the monetary transfers.

[10] This is true for any soil heterogeneity distribution function.

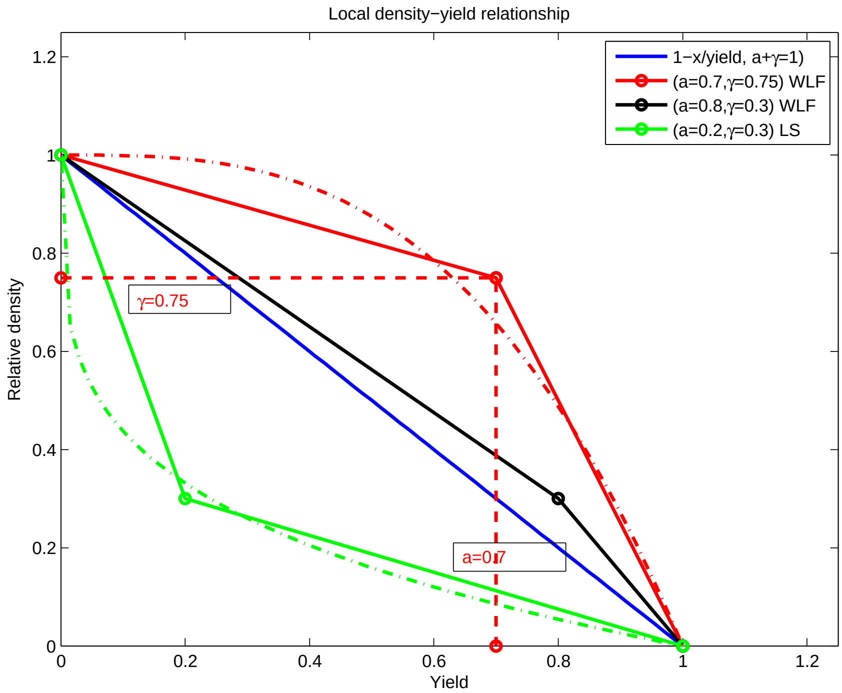


Figure 9: Local density yield relationships. Relative density of wildlife on the y-axis (w.r.t the maximum possible if all is in reserve), and local agricultural yield on a field (assuming therefore constant quality q). The three points represent the three land-uses in the model; respectively reserve, wildlife-friendly farming, and intensive agriculture. Smooth curves are reproduced to show how our model relates to that of Green et al. (2005).

If the difference in quality of the best and worst land already used for agricultural production is large, then it is required to mix WLF farming and intensive agriculture to achieve efficient outcomes. Agricultural production has to increase both at the extensive and intensive margins. The best quality land are to be used intensively first.

We can thus say that the strategy to achieve a given production target depends on the initial configuration of land-uses, and may evolve over time. In particular, when the economy starts from a low agricultural production and aims at reaching a long run equilibrium at a higher level, a sequence of policy instruments is required, and that sequence may vary with the case (soil heterogeneity, relative efficiency of wlf farming both for production and resource preservation). Fig. 10 illustrates this statement for parameters $a = 0.5$ and $\gamma = 0.6$. Let us consider the extreme initial state in which the considered area is initially unexploited (full natural reserve). Increasing production along the Pareto efficiency frontier requires first to extend agricultural area, with wlf farming. This can be done by reducing reserve revenue

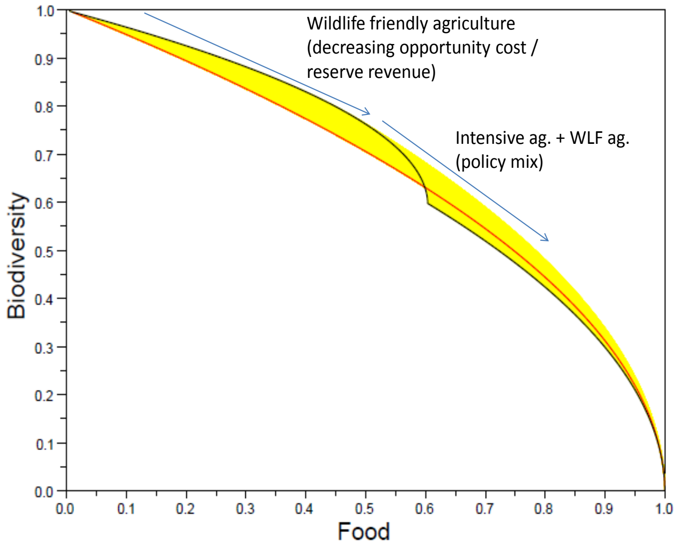


Figure 10: Dynamic policy path

(the equivalent of the subsidy in our simple model) or by reducing the opportunity cost of extensive agriculture. At some point, increasing extensive production becomes less efficient than increasing productivity on the best land already in use. It is then efficient to reduce input taxation, to give an incentive to intensive production on the best land. Extension at the margin (reduction of subsidy to reserve) and intensification on the best land take place simultaneously.[11] Fig. 11 represents the dynamic path of the policy instruments in the tax-subsidy map.

Another very important point is that improving the landscape "food-biodiversity" production toward a Pareto-efficient outcome may either require to promote wlf farming (case 2 of the market configurations p. 18) or to limit it (case 3 of the market configurations p. 18). Promoting wlf farming requires to reduce the subsidy (extension of wlf farming on lower quality land) and increase the taxation (extension of wlf farming on higher quality land). From a budget point of view, this generates revenue. On the contrary, reducing wlf farming (when it is economically profitable but not ecologically desirable) requires to increase the opportunity cost of agricultural land use (to limit the extension of wlf farming on low quality land) and to reduce the cost of intensification (subsidizing intensity) to promote an agricultural development at the intensive margins. Such a policy has a cost on the two ends. This feature is not emphasized in the literature.

[11] Usual computations from eq. (19) show that both instruments vary linearly, in order to keep the difference between thresholds $\underline{Q}(s)$ and $\bar{Q}(\tau)$ constant, satisfying condition (19).

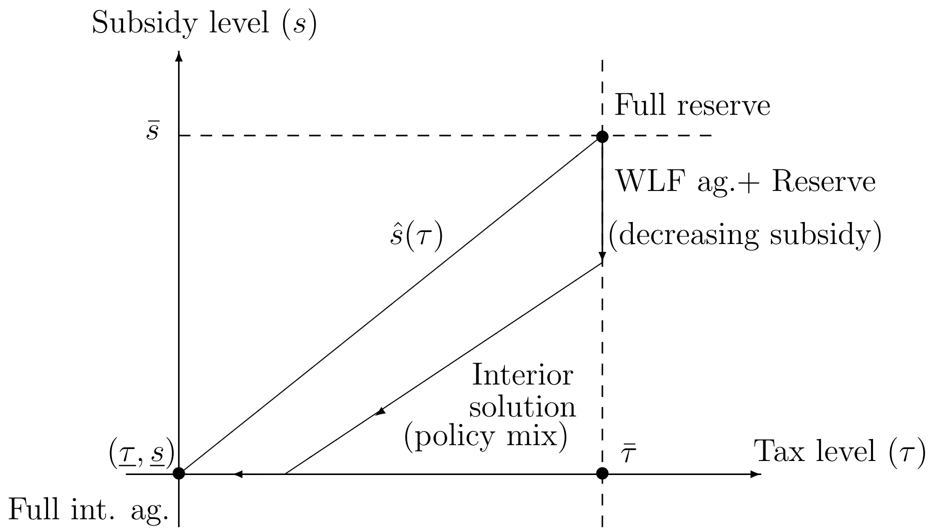


Figure 11: Sequence of policy mix for Pareto efficient configurations

Sensitivity analysis with respect to soil heterogeneity The previous illustrations correspond to a very heterogeneous soil quality (homogeneous Beta distribution, with parameters $\alpha = 1$ and $\beta = 1$, which corresponds to a equal representation of all possible land qualities). The opposite extreme case (homogeneous land quality) is the case treated in Green et al. (2005). This would correspond to a limiting case $\alpha = \beta = +\infty$ in our framework.

If land is homogeneous, the Food-Biodiversity relationship in the land-sparing scenario is linear, as in Green et al. (2005). Heterogeneous land implies a convex production possibility frontier in the land sparing case.[12]

As all our results are analytical, the qualitative results are robust to the parameters value of the soil quality heterogeneity distribution function. It is possible to assess the quantitative effects of the heterogeneity parameters by drawing the illustrations for any parameter value.

6 A broader economic perspective

The "food versus biodiversity" debate is usually addressing the following issue: what is the best land use configuration, from an ecological point of view, to produce a given amount of food? Set in these terms, it is as if the problem was one of cost-effectiveness, with the objective of minimizing the ecological cost of a given economic production.

[12] A straightforward way to exhibit this convex relationship is to think about an area with land of two distinct qualities. The relationship between food production and biodiversity would be piecewise linear, with a downward kink once all land of the best quality is already in intensive agricultural use.

The previous results emphasize that, from a standard economic point of view, the question should not be stated (only) in terms of trade-offs between food and biodiversity.

On the one hand, if one considers a small region for which agricultural output prices are given and exogenous, then there is (almost) no reason to consider food production as an outcome of interest.[13] A change in the production does not modify the consumption, and thus the consumers surplus. The producers profit,[14] however, is modified. A policy defined to improve biological conservation may also have a budget effect, which induces effects on tax-payers welfare. There is thus a trade-off between a numéraire (profit and budget balance) and biodiversity, and not between food and biodiversity. This is consistent with the huge economic literature on biodiversity conservation, focusing on conservation costs and biodiversity valuation.

On the other hand, if one considers a global economy (or a large region, or a region interested in food production), there is a trade-off between food and biodiversity. But in this case, modifying the land use has an effect on the food market and/or on the budget of the regulation agency (Proposition 4). The consumer surplus is modified. So is the producers profit and the regulation agency budget. There are trade-offs between food, biodiversity *and* a numéraire. Examining these trade-offs requires the use of a welfare economics approach. The optimal solution may not lie on the Pareto frontier of the food-biodiversity production possibility set, but on that of a 3-dimensional food-biodiversity-numéraire production possibility set. It is likely that a projection of the optimum on the 2-dimensional food-biodiversity map would corresponds to an interior solution. This would strongly modify the policy recommendations as discussed above and in the conservation literature.

On going research examines these trade-offs, and the results will complete this discussion.

7 Conclusion

In this paper, we develop a very simple model to introduce some key economic dimensions in the land-sparing versus land-sharing debate started by Green et al. (2005). The model contains essentially three agricultural and economic elements not present in Green et al. (2005)'s initial model

- Decentralized decision-making of farmers
- Variation in soil quality within the region
- Use of inputs to modify yields

[13]Food security is an exception. This case is encompassed in the alternative problem.
[14]The Ricardian rent.

We challenge the results of Green et al. (2005) in a decentralized decision context, expressing with two key parameters the wildlife density- agricultural yield function. The usual results are modified by land heterogeneity. Extending wild-life friendly agriculture is not efficient if the the potential production (land quality) of new land is too low with respect to that of best land. It is more efficient to intensify production on best lands. This departs from the classical suggestion of the ecological literature, which considers land-sparing and land-sharing as two incompatible options.

From a broader economic perspective, it has been discussed (even if not proven formally yet in this working paper) that the question of biodiversity conservation and agricultural production should not be addressed as a trade-off between food and biodiversity, but as a trade-off between food, biodiversity and the other goods represented by a numéraire. A welfare economics analysis will complete this discussion soon.

A Proofs

Proof of Proposition 2 We shall prove the proposition by recurrence over the Pareto efficiency frontier.

Step 1) Starting point: The higher ecological outcome is achieved for the land-sparing corner solution in which all land is allocated to natural reserve, i.e., $\underline{Q}(s,\tau) = 1$. The associated outcome in the (Food,Biodiversity) map is $(0, 1)$.

Step 2) Iteration: Consider a given soil quality $q \in]0, 1]$ and the associated land-sparing situation defined by quality threshold $\underline{Q}(s,\tau) = q$. Assume that the associated outcome is on the food-biodiversity production possibility frontier.

Let us consider a marginal increase of food production and the associated marginal decrease of biodiversity. For that purpose, one need to bring into cultivation the land of marginal quality. The marginal rate of transformation between food and biodiversity is given by the ration $MRT = \frac{-dPOP}{dY}$. (Note that the density of land of marginal quality $\phi(\underline{Q}(s,\tau))$ will not affect the result, as it would appear at both the numerator and denominator of the ratio.)

If the marginal land quality brought into production is use intensively, the marginal rate of transformation is $MRT_{LS} = -1/\left(q(\bar{y} - \underline{y}) + \underline{y}\right)$.

If the marginal land quality brought into production is use for wlf farming, the marginal rate of transformation is $MRT_{WLF} = -\left(1-\gamma\right)/\left[a\left(q(\bar{y} - \underline{y}) + \underline{y}\right)\right]$.

The option with the highest MRT defines the boundary of the Pareto efficiency frontier. We have

$$\begin{aligned} MRT_{LS} \geq MRT_{WLF} \quad &\Leftrightarrow \quad -1/\left(q(\bar{y} - \underline{y}) + \underline{y}\right) \geq -\left(1-\gamma\right)/\left[a\left(q(\bar{y} - \underline{y}) + \underline{y}\right)\right] \\ &\Leftrightarrow \quad 1 \geq a + \gamma \ . \end{aligned}$$

Step 3) Recurrence: Given the full reserve starting point $\underline{Q}(s,\tau) = 1$ described at step 1, and the iteration process described at step 2, one obtains the proof of Proposition 2 by recurrence.

Proof of Proposition 3 The proof follows the same steps as that of Proposition 2.

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