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Land Sparing and Land Sharing in a Heterogeneous Landscape*

Guy Meunier†

Abstract

This paper proposes a stylized model that combines a Ricardian framework of land heterogeneity with the ecological concept of a density–yield curve introduced by Green et al. (2005). Biodiversity responds to agricultural choices through two channels: an *intensity* channel, governed by the curvature of ecological damages, and a *reallocation* channel, as effort is redistributed across land qualities. I characterize how biodiversity concerns reshape the efficient allocation of land exploitation as a function of damage curvature and food-demand elasticity. In a Ricardian landscape, heterogeneity creates a baseline incentive to concentrate production on high-quality land, so that land-sparing adjustments arise for concave and for moderately curved damages. Land sharing emerges only when damages are sufficiently convex, in which case biodiversity concerns flatten the intensity profile and can expand cultivation at the extensive margin when demand is inelastic. Land heterogeneity further implies non-uniform local adjustments, especially near the cultivation threshold. I then derive policy implications for spatially uniform taxes on land use, effort, and output: the optimal mix trades off average internalization against better targeting of high-intensity land, and under quadratic costs and damages it implements the first-best allocation even with heterogeneous land. Overall, the analysis highlights the role of indirect production reallocation and market-mediated feedbacks in biodiversity-oriented agricultural policy.

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1 Introduction

Agriculture is arguably the human activity with the largest impact on biodiversity, primarily through habitat conversion and agricultural practices (Green et al., 2005; Pereira et al., 2012; Tilman et al., 2017). This reality underscores a fundamental trade-off between agricultural intensity and its direct environmental consequences, the total area farmed, and the quantity of food produced.[1] A closely related trade-off arises for climate policy, since intensification can increase greenhouse gas emissions locally while potentially sparing land for carbon storage and sequestration.[2] This trade-off lies at the heart of long-standing debates on the environmental implications of agricultural intensification, from discussions of the Green Revolution to more recent controversies surrounding the EU Green Deal.

A particularly salient illustration is the land sharing versus land sparing controversy in ecology. In their landmark study, Green et al. (2005) propose a framework to determine the agricultural yield (production per hectare) that maximizes species abundance while satisfying a fixed food production target. A key element of their approach is the density–yield curve, which relates agricultural yield to species abundance per unit of farmland. Its shape determines whether biodiversity is better preserved through extensive farming (land sharing) or through concentrating production on a small area at high intensity while sparing the rest for nature (land sparing).[3]

However, this framework assumes homogeneous land and uniform farming intensity across cultivated plots. In reality, land heterogeneity is central: differences in productivity shape both farming intensity and the frontier between farmed and unfarmed land, and generate Ricardian rents on high-quality plots. The purpose of this paper is to incorporate land heterogeneity into a stylized economic version of the density–yield trade-off, and to analyze how biodiversity concerns affect farming practices, land allocation, and policy design.

I build on and extend the framework developed in Meunier (2020). That earlier work clarified the welfare logic and policy implications of Green et al. (2005) under homogeneous land. Here, I introduce a Ricardian distribution of land qualities and an explicit agricultural market with elastic demand. Farmers decide, for each hectare, whether to cultivate it and at what intensity. Land quality determines how effort translates into output, while farming generates biodiversity damages captured by a reduced-form function $d(x)$: more intense farming causes greater local harm. The curvature of $d(\cdot)$ mirrors the curvature of the density–yield curve in Green et al. (2005), but here damages are linked to farming intensity and interact with land quality in determining yields. I analyze how an increase in the social value of biodiversity influences optimal farming practices and land uses, and derive some

[1]Approximately one-third of the Earth's ice-free land surface is used for agricultural production (Ramankutty et al., 2008). Agricultural land includes both arable land (12%) and pastures (22%). A pedagogical presentation of these figures is available at: `https://ourworldindata.org/yields-and-land-use-in-agriculture`.

[2]See Lamb et al. (2016) on the potential for land sparing to offset greenhouse gas emissions from agriculture, and Gérard et al. (2025) for an economic perspective on livestock, and the carbon opportunity costs.

[3]Green et al. (2005) were not the first to argue that intensive agriculture, while environmentally damaging locally, can benefit biodiversity by reducing the overall land required for food production (e.g., Waggoner, 1996; Borlaug, 2002). Their contribution lies in providing a simple analytical framework to determine under what conditions this trade-off favors land sparing.

policy implications from this extended analysis.

With heterogeneous land, farming intensity is increasing with respect to land quality, the least productive hectares are not farmed, while the others obtain an economic rent. Even though there is no spatial structure in the model,[4] the monotonicity of farming intensity with respect to land quality corresponds well to the geographical allocation of farming: unfarmed areas are the least productive, and neighboring land is usually extensively farmed. Biodiversity is then lower on the most productive land since it is the most intensively farmed.

The paper highlights a simple but central point: with heterogeneous land, valuing biodiversity affects not only aggregate outcomes (total output and cultivated area) but also the spatial allocation of farming effort across land qualities. Two ingredients govern this reallocation: the price elasticity of demand and the curvature of the damage function. When demand is perfectly elastic (prices fixed), effort is reduced across cultivated plots and the farmed area contracts; land is both spared and shared, but total output falls. When demand is perfectly inelastic (as in Green et al., 2005), aggregate production must be maintained and effort is reallocated across plots depending on local marginal damages, generating configurations that differ sharply from both the homogeneous-land benchmark and the fixed-price case. In particular, land heterogeneity implies that even when the aggregate pattern resembles land sparing or land sharing, local adjustments along the land-quality distribution can be nuanced, especially near the extensive margin.

I also derive policy implications. With linear instruments taxing (or subsidizing) land use, effort, and output, the optimal mix trades off average internalization against better targeting across heterogeneous plots. In particular, output taxation can indirectly target high-quality plots—where effort is highest—and is therefore especially appealing when marginal damages rise steeply with effort (strongly convex damages, land sharing). Under quadratic costs and damages, these instruments can decentralize the first-best even in a heterogeneous landscape. I further discuss how food-price objectives (e.g., fixed consumer prices) shift the optimal output instrument, and how the evaluation of set-aside policies should integrate market-mediated reallocation effects that partly offset local biodiversity gains.

Although the land sparing versus land sharing debate is prominent in ecology and policy circles, it has received relatively limited attention in economics. The economic contributions most closely related to the analytical land sparing/land sharing framework include Hart et al. (2014), Desquilbet et al. (2017), Meunier (2020), and the earlier working paper by Martinet (2013). Hart et al. (2014) reframe Green et al. (2005)'s conservation problem as a cost-minimization program and show that extreme land sharing or land sparing solutions arise under globally convex or concave shapes, while interior solutions may arise for more general forms. Desquilbet et al. (2017) stress the role of agricultural markets in shaping environmental outcomes: a shift toward higher-cost systems (e.g., organic farming) raises equilibrium prices and contracts demand, so that the associated environmental gain from lower aggregate production may dominate even in cases where a fixed-output ecological benchmark would favor land sparing. Martinet (2013) introduces heterogeneous land productivity in a two-system setting and characterizes food–wildlife trade-offs, with coexistence of intensive farming, extensive farming and natural reserves. The present paper complements

[4]The lack of a spatial structure, and the absence of an explicit scale, constitutes a frequent criticism of the framework of Green et al. (2005) (e.g. Kremen, 2015).

these contributions by allowing a continuum of practices in a Ricardian landscape and by characterizing both comparative statics and policy instruments from a normative welfare perspective.

Beyond these theoretical contributions, a large applied literature has implemented and tested land sparing/sharing ideas using numerical exercises and empirical evaluations, with complementary emphases across disciplines. On the ecological side, numerical implementations typically abstract from economic behavior and focus on biodiversity outcomes under alternative land-use configurations; for instance, Feniuk et al. (2019) provide a data-driven multi-compartment implementation of land sparing strategies that accounts for species dependent on both natural habitats and high-nature-value farmland. Interestingly, their numerical optimum often combines land sparing with a non-uniform intensity profile on cultivated land, reflecting the ecological fact that some species benefit from low-yield farming (high-nature-value farmland) in addition to natural habitat.

On the economics side, empirical evaluations of land retirement and set-aside policies quantify biodiversity gains jointly with production responses, including adjustments in yields and land use; Palmer et al. (2026) estimate biodiversity–food trade-offs when agricultural land is spared from production and discuss the importance of behavioral responses and targeting. More broadly, biodiversity-oriented interventions may also operate through changes in farming systems—for instance via crop diversification (and related approaches such as intercropping)—highlighting dimensions that are abstracted from the present reduced-form damage approach (Strobl; 2022; Bareille and Largier; 2026). Taken together, these strands motivate the present framework: even in a parsimonious model, credible policy assessment requires accounting not only for direct local effects but also for indirect adjustments through the reallocation of effort and production across land qualities and, when prices respond, through market-mediated feedbacks.

The rest of the paper is organized as follows. Section 2 introduces the model. Section 3 characterizes the first-best allocation. Section 4 analyses the influence of biodiversity concerns. Section 5 studies policy instruments and second-best implementations. Section 6 discusses limitations and extensions. Section 7 concludes.

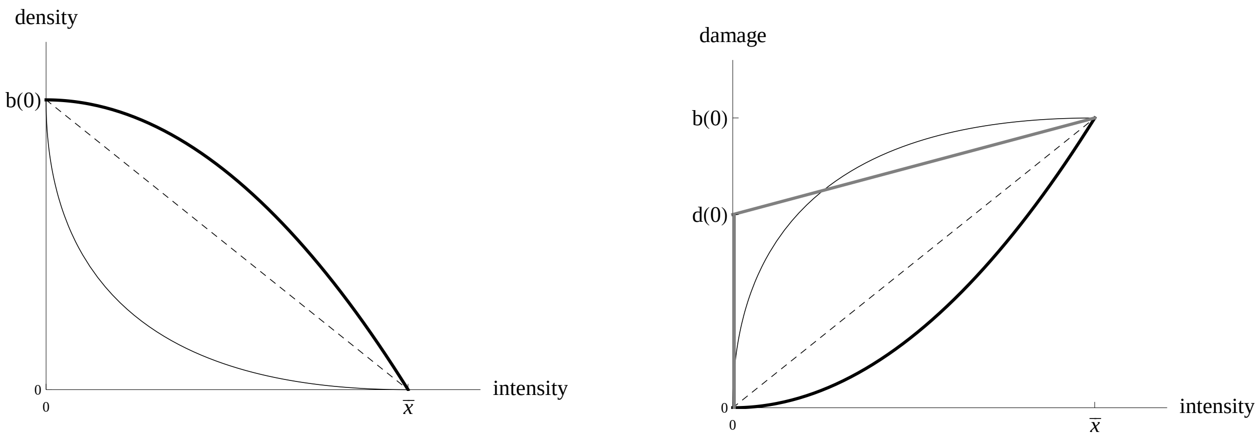
2 Model

2.1 General set-up

I consider the market for one food product. The total quantity produced is Q (in t.). This creates the gross consumer surplus $S(Q)$ (in \$), a positive increasing and concave function. For a price p (in \$/t), the corresponding demand function $Q^D(p) = S'^{-1}(p)$, is positive and decreasing.

The soil is of varying quality θ, with $\theta \in [0,1]$ distributed according to cumulative distribution G and density g ($G'(\theta) = g(\theta)$). On a plot of quality θ, an effort x costs $c(x)$ generates the yield θx and a biodiversity loss $d(x)$. The effort x will also be refered as the *intensity* of farming.

The biodiversity loss $d(.)$ is assumed positive, increasing and twice differentiable. It corresponds to the biodiversity loss compared to a counter-factual without farming. It is easier to work with the biodiversity loss than directly the biodiversity which would be $b(x)$, a decreasing function, so that $d(x) = b(0) - b(x)$ as illustrated on Figure 1. A biodiversity function would be closer to the biodiversity-yield curve of Green et al. (2005). A concave biodiversity function corresponds to a convex loss and vice versa. A convex biodiversity function captures the substantial biodiversity loss associated with the initial conversion of land for farming, and could be approximated by a linear damage with a positive initial loss $d(0)$.



(a) Concave (thick) and convex density yield curves

(b) The corresponding damage function.

Figure 1: The relationship, between the density yield curve and the damage function. A highly convex density yield curve could be approximated as a linear damage with an initial $d(0) > 0$.

The cost of farming, $c(x)$ (in \$/ha), is positive, increasing, and convex. It is assumed that land conversion entails a fixed cost, $c(0) > 0$, implying that average costs first decrease and then increase as farming intensity rises. This fixed cost can also be interpreted as the opportunity cost of farming. An assumption is needed to keep the maximization objective concave with respect to x, the environmental damage should not be too concave:

$$c''(x) + \beta d''(x) \geq 0. \tag{1}$$

For an effort function $\mathbf{x} = (x(\theta))_{\theta \in [0,1]}$, the total costs are

$$C(\mathbf{x}) = \int_0^1 (c(x(\theta))\delta_{x(\theta)>0} dG(\theta) \tag{2}$$

in which $\delta_{x(\theta)>0} = 1$ if $x(\theta) > 0$ and zero otherwise. total food production is

$$Q(\mathbf{x}) = \int_0^1 \theta x(\theta) dG(\theta) \tag{3}$$

the total biodiversity loss, or environmental damage is

$$D(\mathbf{x}) = \int_0^1 d(x(\theta))\delta_{x(\theta)>0} dG(\theta) \tag{4}$$

and the total farmed area is:

$$L(\mathbf{x}) = \int_0^1 \delta_{x(\theta)>0} dG(\theta) \tag{5}$$

Denoting β the value of one unit of biodiversity, total welfare is then

$$W(\mathbf{x}, \beta) = S(Q(\mathbf{x})) - C(\mathbf{x}) - \beta D(\mathbf{x}) \tag{6}$$

Several limitations are discussed in Section 6. In particular, biodiversity is captured by a reduced-form index that decreases with farming intensity, and the output is a single composite agricultural good. The model is best interpreted at an intermediate, policy-relevant spatial scale.

2.2 Specification

The figures obtained to illustrate the analysis are based on the following quadratic specification:

$$\begin{aligned} S(Q) &= (a - \frac{b}{2}Q)Q \\ c(x) &= c_0 + c_1 x + \frac{c_2}{2}x^2 \\ d(x) &= d_0 + d_1 x + \frac{d_2}{2}x^2 \\ &\theta \in [0,1] \text{ uniformly distributed} \end{aligned} \tag{7}$$

Calculations related to this specification are provided in Appendix A. I do not seek for realistic simulation but an illustration of analytical results and some examples for ambiguous cases. For the illustration I will set $c_0 = c_1 = c_2 = 1$, and consider a total production $Q = 2$ for the benchmark situation, and when considering a fixed total production. For the (elastic) demand cases, I will use $a = 30$ and $b = 10$ so that the elasticity is still realistically low (0.3) and the quantity and price approximately match the benchmark case.

Concerning the biodiversity loss, the parameter $d_0 = d(0)$ should be interpreted as the biodiversity of the alternative to farming, or the "biodiversity opportunity cost" (similar to the carbon opportunity cost). This alternative land use could be a natural reserve in which the biodiversity indicator is maximized, in such a case $d(0)$ is unambiguously positive. There are other less extreme situations in which it should be positive (e.g. if the extensive margin is between an arable land and a pasture). However, depending on the context considered it could be arguably negative, the case of a pasture being replaced by an intensively exploited forest is an extreme example. It will be assumed positive throughout the analysis. This fixed biodiversity cost will play a key role at the extensive margin, and, as illustrated in Figure (1), should be viewed as an extreme form of convexity of the density-yield curve, a shape that pushes for land sparing in the Green et al. (2005) framework.

3 Optimal production

3.1 First order conditions

We consider the optimal production for a given value of biodiversity β, that is, the solution of

$$\max_{\mathbf{x}\geq 0} W(\mathbf{x},\beta) \tag{8}$$

Optimal quantities are functions of β and denoted $Q^*(\beta)$, $L^*(\beta)$ and $\mathbf{x}^*(\beta) = (x^*(\theta,\beta))_\theta$ and the marginal consumer surplus at the optimum $p^* = S'(Q^*)$. There is a threshold field quality $\tilde{\theta}^*$ such that fields of lower quality are not farmed. The optimal quantities solve the first order conditions

$$p^*\theta = c'(x^*(\theta,\beta)) + \beta d'(x^*(\theta,\beta)) \qquad \text{for } \theta \geq \tilde{\theta} \tag{9}$$

$$p^*\tilde{\theta}^* = \frac{1}{x^*(\tilde{\theta}^*,\beta)}\left[c(x^*(\tilde{\theta}^*,\beta)) + \beta d(x^*(\tilde{\theta}^*,\beta))\right] \tag{10}$$

$$Q^D(p^*) = \int_{\tilde{\theta}^*}^{1} \theta x^*(\theta,\beta)dG(\theta) \tag{11}$$

At the optimum, according to equation (9), marginal social costs *per unit produced* are equalized across plots. More productive plots therefore produce more and exhibit lower environmental quality. All cultivated plots earn strictly positive profit except the marginal one, which breaks even (equation (10)).

It is useful to consider the condition satisfied by the marginal plot, which characterizes the extensive margin and the trade-off between producing and sparing land. Because of the fixed production cost, production on the marginal plot is strictly positive. Combining equations (9) and (10), the marginal effort solves:

$$\frac{c(x) + \beta d(x)}{x} = c'(x) + \beta d'(x), \tag{12}$$

an equation that is independent of the demand function and land quality. Denote its solution by $\tilde{x}(\beta)$. It equalizes average and marginal social costs, implying that total social cost per unit, $(c(x) + \beta d(x))/x$, is minimized at the threshold plot.

In a homogeneous landscape, and holding total production fixed, the purely ecological problem boils down to minimizing the average damage per unit produced, $d(x)/x$.[5] If $d(\cdot)$ is concave (resp. convex), x should be maximal (resp. minimal): biodiversity losses are minimized by land sparing (resp. land sharing) (Green et al., 2005). The solution $\tilde{x}(\beta)$ trades off production costs and environmental damages and therefore lies between the purely economic optimum and the purely ecological optimum (Meunier, 2020). To avoid confusion, I systematically indicate in parentheses the land sparing/land sharing interpretation associated with the curvature of the damage function in the homogeneous-land benchmark (as in Green et al., 2005): concave damage corresponds to the land sparing case, whereas convex damage (with $d(0) = 0$) corresponds to the land sharing case.

[5] This corner result is transparent when $d(0) = 0$, d is increasing, and x is bounded. Then concavity implies that $d(x)/x$ decreases with x, whereas convexity implies that $d(x)/x$ increases with x.

Lemma 1 *If the biodiversity damage is concave (land sparing), the threshold effort $\tilde{x}$ is increasing with respect to the value of biodiversity.*

If the biodiversity damage is convex with $d(0) = 0$ (land sharing), the threshold effort is decreasing with respect to the value of biodiversity.

Proof. The monotonicity of $\tilde{x}(\beta)$, taking the derivative of the equation (12), is given by

$$\tilde{x}_\beta = \frac{1}{\tilde{x}} \frac{d(\tilde{x}) - d'(\tilde{x})\tilde{x}}{c'' + \beta d''} \tag{13}$$

the sign of the numerator depends on the shape of $d()$, the derivative of $d(x) - d'(x)x$ being $d''(.)$. If d is concav, $d - d'x$ is increasing and since $d(0) \geq 0$ the numerator is positive and $\tilde{x}$ is increasing. If d is convex, $d - d'x$ is decreasing, and if $d(0) = 0$ the numerator is negative and $\tilde{x}$ is decreasing.

■

In a homogeneous landscape the effort $\tilde{x}$ would be applied on all farmed plots, and some land would remain unfarmed. The above lemma would then gives the monotonicity of the optimal effort with respect to the value of biodiversity. With heterogeneity, whether farming is intensified or not will depend on the quality of the plot. It is considered in the next section.

3.2 The optimal supply of food and biodiversity

The influence of the value of biodiversity on the allocation of efforts across plot transits through two channels: directly by increasing the value of damages, and indirectly through the output price. The role of the output price highlights the importance of the demand side and the quantity produced. It is very common to assume a constant output price (e.g. Lankoski et al.; 2010), but, as we will see the adjustment of the price plays a key role in the trade-off between food production and biodiversity conservation. In order to study in detail the supply of food and biodiversity I characterize the supply function as a function of the price and the value of biodiversity, before considering a variable price. There is an intensive and an extensive margin, the intensive margin corresponds to the choice of farming intensity, and the extensive margin to the choice of the area to be farmed.

The value of biodiversity is internalized by farmers, so that they maximize

$$\pi = \max\{0, p\theta x - c(x) - \beta d(x)\}, \quad \text{for all} \theta.$$

Let us denote $x^S(\theta, p, \beta)$ the quantity that equalizes price and marginal cost, ignoring the profit positivity constraint, it solves:

$$p\theta = c'(x) + \beta d'(x) \tag{14}$$

it is the effort supplied by a farmer on a field of quality θ above the threshold $\tilde{\theta}(p, \beta)$ at which the marginal and average cost coincide. The threshold is such that $x^S(p, \tilde{\theta}, \beta) = \tilde{x}(\beta)$ which is characterized by equation (12).

The total supply of food can then be written as a function of the price p:

$$Q^S(p, \beta) = \int_{\tilde{\theta}(p,\beta)}^1 \theta x^S(\theta, p, \beta) dG(\theta) \tag{15}$$

A change of the output price influences both the effort of active fields (intensive margin) and the number of active fields (extensive margin).

Concerning the extensive margin, the derivatives of the threshold quality are, by an envelop argument:

$$\tilde{\theta}_p(p,\beta) = -\frac{\tilde{\theta}}{p} \text{ and } \tilde{\theta}_\beta(p,\beta) = \frac{1}{p}\frac{d(\tilde{x})}{\tilde{x}}. \tag{16}$$

And for the intensive margin, the derivatives of individual supply are:

$$x_p^S = \frac{\theta}{c'' + \beta d''};\; x_\theta^S = \frac{p}{c'' + \beta d''};\; x_\beta^S = \frac{-d'(x^S)}{c'' + \beta d''} \tag{17}$$

The derivatives of total supply is:

$$Q_p^S = \int_{\tilde{\theta}}^1 \theta x_p^S dG(\theta) - \tilde{\theta}\tilde{x}g(\tilde{\theta})\tilde{\theta}_p = \int_{\tilde{\theta}}^1 \frac{\theta^2}{c'' + \beta d''} dG(\theta) + \tilde{x}\frac{\tilde{\theta}^2}{p}g(\tilde{\theta}) \tag{18}$$

$$Q_\beta^S = \int_{\tilde{\theta}}^1 \theta x_\beta^S dG(\theta) - \tilde{\theta}\tilde{x}g(\tilde{\theta})\tilde{\theta}_\beta = -\int_{\tilde{\theta}}^1 \frac{\theta d'(x^S)}{c'' + \beta d''} dG(\theta) - \tilde{x}\frac{\tilde{\theta}}{p}\frac{d(\tilde{x})}{\tilde{x}}g(\tilde{\theta}) \tag{19}$$

For each expression, the first term, the integral, corresponds to the intensive margin and the second term the extensive margin.[6]

The optimal output price $p^*(\beta)$ introduced in the previous section, solves: [7]

$$Q^S(p,\beta) = Q^D(p). \tag{20}$$

4 Influence of the value of biodiversity

I study how an increase in the social value of biodiversity, β, affects the optimal intensity schedule $x^*(\theta)$ and the total farmed area L^*. Since cultivated land is characterized by a threshold quality $\tilde{\theta}^*$, the farmed area is simply $L^* = 1 - G(\tilde{\theta}^*)$. An increase in β operates through two channels: a *direct* channel (higher marginal environmental costs) and, when prices are endogenous, an *indirect* channel through the equilibrium output price. To build intuition, I first consider the polar case of a fixed output price, before turning to the case of an endogenous price.

Proposition 1 *With an infinitely elastic demand, that is, a fixed price, an increase of the value of biodiversity induces to reduce all efforts (i.e. share land) and the total area farmed (i.e. spare land).*

Proof. If the price is fixed p^*, the influence of β on the individual supply for $\theta > \tilde{\theta}$ is $x_\beta^* = x_\beta^S < 0$ from equation (17) . The influence on the threshold field is $\tilde{\theta}_\beta^* = \tilde{\theta}_\beta > 0$ according to equation (16). ■

[6] Note that without any fixed cost, ($c(0) = 0$) the second term of each equation would be null: the production on the marginal plot would be null.

[7] Given that supply is increasing with respect to p and demand is decreasing, there is unique solution to this equation it corresponds to $p^*(\beta)$

With a fixed output price, an increase in β unambiguously reduces farming intensity on all cultivated plots and reduces the total farmed area. This monotonicity holds regardless of the curvature of the damage function. In that sense, biodiversity protection simultaneously induces both land sharing (lower intensity on cultivated land) and land sparing (less land cultivated), but at the cost of lower total output. This result contrasts with the homogeneous-land benchmark of Green et al. (2005) and the corresponding economic analysis in Meunier (2020), where?under fixed total production?biodiversity concerns induce higher intensity when damages are concave.

The key difference is that, under fixed prices, output is not constrained to remain constant. When β increases, the planner can reduce aggregate production, which relaxes the need to concentrate effort on a smaller area. In a heterogeneous landscape, this adjustment naturally combines a contraction of effort on cultivated plots with a retreat of the extensive margin. By contrast, under fixed output (as in Green et al. (2005)), biodiversity protection must operate through a reallocation of production across land and can induce higher intensity when damages are concave.

Endogenous prices. I now turn to the general case of a downward-sloping demand, where the output price adjusts endogenously. At the aggregate level, regardless of the curvature of $d(\cdot)$, higher biodiversity valuation reduces equilibrium quantity and raises equilibrium price.

Lemma 2 *An increase in β decreases the equilibrium quantity and increases the equilibrium price:*

$$p^*_\beta = \frac{-Q^S_\beta}{Q^S_p - Q^{D\prime}} > 0.$$

The rise in the output price counteracts the direct effect of β, and the net impact differs across land qualities. This interaction shapes both the intensive and extensive margins, as well as the overall reallocation of effort across plots.

Intensive margin. For any cultivated plot, the response of effort to β is

$$x^*_\beta = x^S_p p^*_\beta + x^S_\beta = \left[\theta p^*_\beta - d'(x)\right] \frac{1}{c'' + \beta d''} \tag{21}$$

Two forces are at play: higher β raises the marginal environmental cost (captured by $d'(x)$), while the induced increase in the output price raises the marginal revenue of effort, proportionally to land quality θ. The price channel therefore tends to strengthen the concentration of production on high-quality land. Whether this is reinforced or offset by the environmental channel depends on the curvature of $d(\cdot)$, which governs how marginal damages vary with land quality through $x^*(\theta)$.

Extensive margin. A similar trade-off governs the movement of the cultivation threshold:

$$\tilde{\theta}^*_\beta = \tilde{\theta}_p p^*_\beta + \tilde{\theta}_\beta = \left[\frac{d(x)}{x} - \tilde{\theta}^* p^*_\beta\right] \frac{1}{p}. \tag{22}$$

At the extensive margin, the sign of $\tilde{\theta}^*_\beta$?hence whether the cultivated area expands or contracts?depends on the comparison between the average environmental loss per unit produced, $d(x)/x$, and the increased economic value of production induced by higher prices.

Fixed output as a benchmark. To isolate the spatial reallocation mechanism, it is also useful to consider the polar case in which total production is fixed (as in Green et al. (2005)). In that case, the adjustment necessarily involves reallocating production across plots: some plots produce more and others less as β increases. The next two results characterize this reallocation for concave versus convex damages.

Proposition 2 *If the total production Q^* is fixed and if the damage function is concav (land sparing), an increase of the value of biodiversity induces:*

- *A reduction of the total area farmed;*
- *An increase of effort on high quality fields*
- *low-quality land to either exits cultivation or experience lower effort*
- *and an increase of the intensiveness on the marginal field.*

Proof.

Concerning the influence on the total farmed area it is:

$$\tilde{\theta}^*_\beta = \tilde{\theta}_p p^*_\beta + \tilde{\theta}_\beta = \tilde{\theta}_p \frac{-Q^S_\beta}{Q^S_p} + \tilde{\theta}_\beta$$

the sign of which is the sign of, using equations (18) and (19):

$$\tilde{\theta}_p(-Q^S_\beta) + \tilde{\theta}_\beta Q^S_p = \frac{1}{p}\frac{d(\tilde{x})}{\tilde{x}}\int_{\tilde{\theta}}^1 \frac{\theta^2}{c'' + \beta d''} dG(\theta) - \frac{1}{p}\tilde{\theta}\int_{\tilde{\theta}}^1 \frac{\theta d'(x^S)}{c'' + \beta d''} dG(\theta)$$

The terms related to the extensive margin cancel each other. The above could be rewritten:

$$\frac{1}{p}\int_{\tilde{\theta}}^1 \frac{\theta}{c'' + \beta d''}\left[\frac{d(\tilde{x})}{\tilde{x}}\theta - \tilde{\theta} d'(x^S)\right] dG(\theta).$$

If d is concave then

$$\frac{d(\tilde{x})}{\tilde{x}} > d'(\tilde{x}) > d'(x^*(\theta, \beta)),\ \forall \theta > \tilde{\theta}^*$$

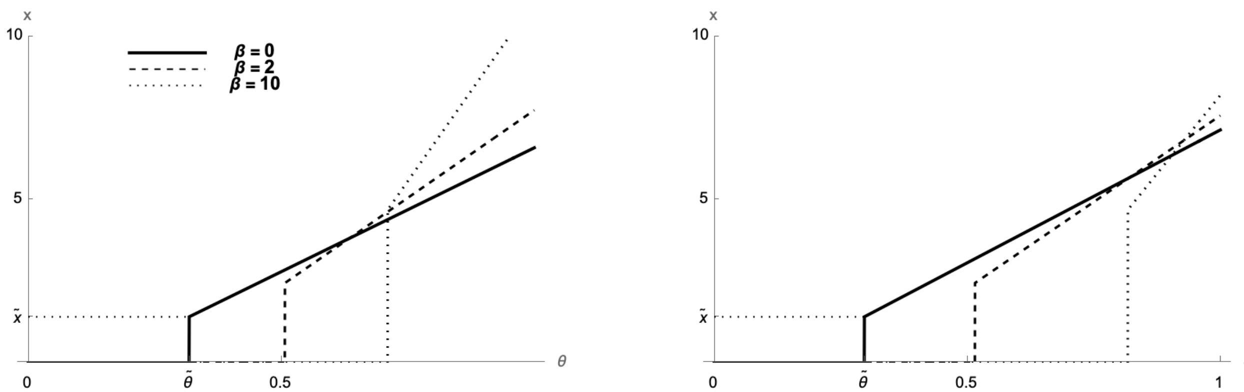
Therefore, $\tilde{\theta}^*$ is increasing with respect to β.

The influence of β on $x^*(\theta, \beta)$ is given by equation (21). If d is concave, the right-hand side is increasing with respect to θ, because $p^*_\beta > 0$ (and independent of θ) and d' is decreasing with respect to θ (x is increasing w.r.t. θ and d concav). Therefore, given that total production is fixed and the total area is decreasing, it must be the case that production increases on high quality field. Production decreases at least on fields that are no longer farmed.

The last point, on the marginal intensiveness comes from Lemma 1.

■

Proposition 2 is illustrated in Figure 2. As β increases, production becomes more concentrated on the most productive plots while land is spared. Even though production increases on the highest-quality fields, some cultivated fields may experience lower production (as in the comparison between the dashed and thick lines), although it is also possible that production increases on all remaining cultivated plots (dotted line). In all cases, intensity increases at the margin, but the marginal plot itself shifts to a higher quality level, sharpening the demarcation between cultivated and uncultivated land. Panel (a) fixes total production and illustrates pure reallocation; Panel (b) introduces an elastic demand, so total production decreases and the price response is muted relative to the fixed-output case, tempering the concentration mechanism.



(a) With a fixed total production (b) With an elastic demand

Figure 2: Allocation of efforts across fields and evolution with respect to the value of biodiversity a concave loss function (with Specification 7 and $d_0 = d_1 = 1$,$d_2 = 0$)

With a convex loss function, which is favorable to land sharing, the situation becomes more complex, and several cases may arise. The marginal environmental damage increases with farming intensity, and therefore with land quality. On a per-hectare basis, most environmental gains would be achieved by reducing effort on the most productive fields. However, on a per-unit-of-output basis, the comparison is less straightforward due to higher land productivity. With a linear damage function $d(x) = d_1 x$, the results remain clear-cut and align with the land-sparing case.

Corollary 1 *If total production Q^* is fixed and if the damage function is linear, an increase of the value of biodiversity induce to strictly reduce the total farmed area and strictly increase efforts on high quality fields.*

‘

Proof. From the proof of Proposition 2, with a linear damage function since the threshold land quality is strictly increasing and the total farmed area is strictly decreasing since $d(\tilde{x})/\tilde{x} = d'(x)$ for all x.

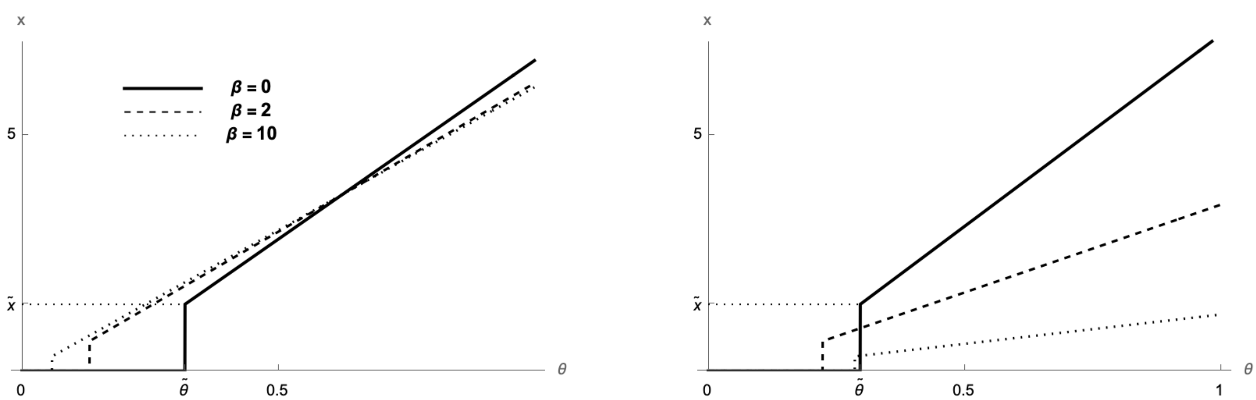
The change of effort is given by equation (21), the left-hand side is increasing with respect to θ, and given that total production is fixed and the farmed area reduced, it must be the case that production increases on high quality fields. ■

This result also holds for slightly convex damages when $d'(0) > 0$. Land heterogeneity strengthens the land-sparing force: reducing cultivated area while reallocating production toward high-quality land. Still, it is important to note that production can decrease on some cultivated plots, so that a form of land sharing may arise locally even when the aggregate pattern is land sparing.

Under the quadratic specification, further results can be obtained and a variety of configurations can be illustrated.

Corollary 2 *If the total production Q^* is fixed, with the quadratic specification (7), if the damage function is convex with $d(0) = d'(0) = 0$ (land sharing), an increase of the value of biodiversity induces to increase the total farmed area and decrease production on high quality fields.*

The proof is provided in Appendix B. The result is illustrated in Figure 3. With fixed total production (Panel a), the effort schedule rotates: farming becomes more homogeneous and spreads over a larger area, while production on high-quality plots decreases (moderately) because aggregate output must be maintained. With downward-sloping demand (Panel b), even with low price elasticity, the difference can be substantial: farming intensity is reduced on all plots and the total farmed area may become non-monotonic, as lower total output requirements allow biodiversity gains to be achieved partly through contraction of production rather than spatial reallocation alone.



(a) With a fixed total production

(b) With an elastic demand

Figure 3: Allocation of efforts across fields and evolution with respect to the value of biodiversity with a convex loss funcion ($d_0 = d_1 = 0$,$d_2 = 2$)

These results show that biodiversity concerns reshape not only aggregate output and cultivated area, but also the allocation of effort across heterogeneous plots. This raises a natural policy question: how far can spatially uniform instruments—taxes on land use, effort, and output—replicate these adjustments and target the relevant margins?

5 Policy implications

The optimal policy would indeed consist of a Pigouvian approach in which biodiversity is measured and priced, even on unfarmed plots. Farmers together with landowners would then optimally internalized the effect of biodiversity, leading to an increase of the price of food and of the price of land, even unfarmed land would generate a revenue of $\beta d(0)$ the biodiversity opportunity cost.

However, in practice, direct measure of biodiversity could be tricky (debatable point for some species), and some combination of subsidies and taxes are used.

We first described the optimal combination of tax, and the influence of heterogeneity and the shape of the density yield curve. Then discussed how the results are changed if the objective of the regulator is to protect biodiversity while keeping consumers price low and thus consumption constant and conclude with a discussion of set aside policies.

5.1 Second best subsidies and taxes

I consider three available instruments: a per-hectare tax t_0 (equivalently, a subsidy for land kept in a natural state), a per-unit-of-effort tax t_1, and a per-unit-of-output tax t_2. Farmers collectively maximize

$$\Pi = \int_{\tilde{\theta}}^{1} \left[(p - t_2)\theta x - t_1 x - c(x) - t_0\right] dG(\theta).$$

The regulator set the three taxes to maximize social welfare (equation 6), taking into account the induced responses of effort and the extensive margin.

The per-hectare instrument t_0 governs the extensive margin, i.e., the threshold land quality $\tilde{\theta}$. The two intensive instruments t_1 and t_2 affect both the level of effort and its allocation across heterogeneous plots.

Outside special cases, the first-best cannot *in general* be decentralized with linear instruments when land is heterogeneous and damages are nonlinear. In that case, the optimal intensive taxes satisfy (see Appendix C):

$$\int_{\tilde{\theta}}^{1} \left[\theta t_2 + t_1 - \beta d'(x)\right] \frac{1}{c''} \, dG(\theta) = 0, \tag{23}$$

$$\int_{\tilde{\theta}}^{1} \left[\theta t_2 + t_1 - \beta d'(x)\right] \frac{\theta}{c''} \, dG(\theta) = 0. \tag{24}$$

If only an effort tax were available, it would be set equal to the average marginal environmental damage, weighted by local responsiveness (equation 23 with $t_2 = 0$). With two instruments, the output tax t_2 can further exploit land heterogeneity by conditioning the effective marginal wedge on field quality.

When marginal environmental damages rise with field quality—as under convex damages in the present framework—the optimal policy shifts the burden from effort taxation toward output taxation, thereby dampening the incentives to intensify the most productive plots. Conversely, if marginal damages are relatively lower on high-quality plots, it becomes optimal to subsidize production and set the effort tax above average marginal damages.

Under the quadratic specification, explicit expressions can be derived.

Proposition 3 *Under the quadratic specification* $d(x) = d_0 + d_1 x + \frac{d_2}{2}x^2$ *and* $c(x) = c_0 + c_1 x + \frac{c_2}{2}x^2$, *the optimal policy satisfies*

$$t_1 = \beta d_1 \frac{c_2}{c_2 + \beta d_2} - \beta d_2 \frac{c_1}{c_2 + \beta d_2}, \tag{25}$$

$$t_2 = \beta \frac{d_2}{c_2 + \beta d_2} p, \tag{26}$$

$$t_0 = \beta\Big(d(\tilde{x}) - \tilde{x} d'(\tilde{x})\Big) = \beta \frac{c_2 d_0 - c_0 d_2}{c_2 + \beta d_2} \tag{27}$$

where $\tilde{x}$ *denotes the effort level on the threshold plot. Accordingly, if the damage function is convex (land sharing), it is optimal to tax food production and set the effort tax below average marginal damages. If the damage function is concave (land sparing), it is optimal to subsidize production and set the effort tax above average marginal damages.*

The proof is in Appendix C. An important simplification arises under the quadratic specification. Because $d'(x)$ is affine in x and the privately chosen effort $x(\theta)$ is affine in land quality θ under linear instruments, the regulator can decentralize the first-best allocation using (t_0, t_1, t_2). Choosing (t_1, t_2) such that

$$t_1 + \theta t_2 = \beta d'\Big(x^*(\theta)\Big) \quad \forall \theta$$

aligns private and social first-order conditions on every cultivated plot, while t_0 pins down the extensive margin by correcting the gap between marginal and average environmental costs at the threshold plot. This implementability result is knife-edge: outside the quadratic class, $d'(x)$ is no longer affine and cannot generally be matched by the linear schedule $t_1 + \theta t_2$, so the first-best typically becomes unattainable with these instruments.

The next corollary highlights the sign pattern of the optimal instruments in a simple and empirically relevant benchmark.

Corollary 3 (Convex quadratic damages with no baseline or linear component) *Suppose* $d(x) = \frac{d_2}{2}x^2$ *with* $d_2 > 0$ *(i.e.,* $d_0 = d_1 = 0$*). Then the optimal policy under the quadratic specification satisfies*

$$t_2 > 0, \qquad t_1 < 0, \qquad t_0 < 0.$$

That is, food production is taxed, while effort and the extensive margin are subsidized.

This policy mix may appear paradoxical: although convex damages call for extensification and a more even allocation of effort (a land sharing pattern), the optimal policy subsidizes effort. The reason is that the output tax $t_2 > 0$ curbs overall production incentives–especially on high-quality plots–so that subsidizing effort primarily relaxes the intensive-margin distortion while the production tax provides the main discipline on aggregate pressure. At the extensive margin, the subsidy $t_0 < 0$ is consistent with land sharing, as it encourages bringing marginal land into cultivation; it remains compatible with positive environmental damages because the regulator simultaneously internalizes marginal damages through the intensive instruments.

5.2 Optimal policy with a fixed consumer price

Food prices and food sovereignty are sensitive issues in agricultural policy. Many agricultural policies, notably in Europe, are partly motivated by the desire to maintain domestic production and ensure low food prices. A recurring criticism of environmental policies, such as those embodied in the EU Green Deal, concerns the risk of environmental leakage: reducing pollution domestically could shift production abroad and increase environmental damages elsewhere. One way to mitigate this risk is to maintain domestic production at levels sufficient to meet domestic demand at a politically constrained consumer price.

Suppose the regulator commits to a fixed consumer price p, below the unconstrained optimum p^*, so that domestic consumption is $D(p)$ and domestic production must meet that level. The regulator chooses policy instruments (t_0, t_1, t_2) to minimize total social costs of producing $D(p)$, accounting for both production costs and biodiversity damages:

$$\min_{t_0,t_1,t_2} \int_{\tilde{\theta}}^{1} \left[c(x(\theta)) + \beta d(x(\theta))\right] dG(\theta) \quad \text{s.t.} \quad \int_{\tilde{\theta}}^{1} \theta x(\theta)\, dG(\theta) = D(p). \tag{28}$$

Let λ denote the Lagrange multiplier associated with the production constraint (the shadow cost of supplying an additional unit of output under the price cap). Relative to the unconstrained case, the optimal intensive instruments now reflect two components: (i) marginal environmental internalization, and (ii) an additional "food security" component needed to satisfy the production constraint. Formally, the moment conditions characterizing the optimal uniform taxes become

$$\int_{\tilde{\theta}}^{1} \Big[t_1 + \theta t_2 - \beta d'(x(\theta)) + (\lambda - p)\theta\Big] \frac{1}{c''(x(\theta))}\, dG(\theta) = 0, \tag{29}$$

$$\int_{\tilde{\theta}}^{1} \Big[t_1 + \theta t_2 - \beta d'(x(\theta)) + (\lambda - p)\theta\Big] \frac{\theta}{c''(x(\theta))}\, dG(\theta) = 0. \tag{30}$$

If the production requirement is binding, then $\lambda > p$, so that $(p-\lambda) < 0$: the shadow value of output exceeds the consumer price and introduces an output-subsidy component. Relative to the unconstrained problem, the optimal output instrument t_2 is shifted downward by $\lambda - p$, while the effort component continues to govern the allocation of effort across heterogeneous plots. The per-hectare instrument t_0 continues to pin down the extensive margin.

Under the quadratic specification, the constrained-efficient allocation remains decentralizable with linear instruments. The same formulas for (t_0, t_1) apply, and the fixed-price constraint modifies t_2 to

$$t_2 = \beta \frac{d_2}{c_2 + \beta d_2} p - \frac{c_2}{c_2 + \beta d_2}(\lambda - p) = p - \frac{c_2}{c_2 + \beta d_2}\lambda.$$

This expression makes the link with the unconstrained case transparent. When the production constraint is slack, $\lambda = p$ the formula collapses to the benchmark output tax in Proposition 3. When the constraint is binding, $\lambda > p$, the shadow value of meeting demand introduces an additional output-subsidy component that reduces t_2 relative to the unconstrained benchmark. The magnitude of this adjustment is dampened by the factor $c_2/(c_2 + \beta d_2)$: when marginal damages are highly sensitive to effort (large d_2), shifting incentives through the output instrument becomes more distortionary, so a smaller share of the production-support objective is carried by t_2.

5.3 Set-aside policies

A number of policies have been implemented to protect biodiversity on agricultural land, in addition to regulations on inputs such as fertilizers and pesticides. Among them, set-aside (or land retirement) policies occupy a particular place. Historically, they were often introduced to address overproduction and stabilize markets; over time, however, they have increasingly been used (or repurposed) to deliver biodiversity benefits and to reduce diffuse pollution and run-offs.

In the Ricardian landscape considered here, the first-best allocation provides a clear benchmark for the spatial targeting of set-aside. Because land differs in productivity, retiring land is least costly in terms of foregone output when it applies to the extensive margin: for a given ecological gain per hectare, withdrawing the least productive cultivated plots minimizes the opportunity cost of land retirement. In particular, it cannot be optimal in the first best to retire productive land while cultivating lower-quality plots, as such a policy would sacrifice output without delivering larger biodiversity gains per hectare. Indeed, this argument is linked to the assumption that biodiversity benefits from retirement are captured solely by the avoided farming damage $d(x(\theta))$, and do not vary independently with land quality. Relaxing this one-dimensional structure–for instance by allowing habitat value to co-vary with productivity–could modify the optimal targeting of set-aside, an issue I return to in the discussion.

This first-best benchmark is informative about how set-aside should be targeted in an efficient allocation, but it is not sufficient to assess set-aside as a second-best reform implemented from the laissez-faire equilibrium. Because laissez-faire prices do not reflect biodiversity damages, the equilibrium price is too low from a social perspective. This wedge affects the measured opportunity cost of land retirement so that welfare-improving set-aside may extend beyond marginal land on plots such that $p\theta x - c(x) < \beta d(x)$. However, indirect effects related to the reallocation of production should be assessed carefully. By shrinking the cultivated area, set-aside reduces aggregate supply and raises the equilibrium price, which induces re-intensification on remaining plots. These indirect adjustments attenuate the output loss from land retirement, but they also partially offset its biodiversity benefits by increasing effort where farming remains active. The net welfare effect therefore depends on the strength of the induced price response and on the curvature of environmental damages.

Formally, a small increase of $\tilde{\theta}$ from the laissez-faire equilibrium (in which $t_1 = t_2 = t_0 = 0$) would be associated with the welfare change:

$$\frac{dW}{d\tilde{\theta}} = \beta d(x(\tilde{\theta}))g(\tilde{\theta}) - \beta \int_{\tilde{\theta}}^{1} d'(x)\frac{\theta}{c''}dG(\theta)\frac{dp}{d\theta}$$

If the agricultural price is fixed (e.g. under perfect trade integration or perfectly elastic demand), marginal set-aside on the extensive margin is unambiguously welfare-improving at the laissez-faire allocation: since the marginal plot earns zero profit, withdrawing it leaves private surplus unchanged while strictly reducing biodiversity damages. By contrast (see Appendix D for calculations), if the output price adjusts land retirement is compensated by higher effort elsewhere, making the net welfare effect ambiguous: it is more likely to be positive when the demand response is elastic (small price increase), supply is relatively inelastic (limited re-intensification), and environmental damages are not too convex (so that additional effort elsewhere carries limited marginal harm).

6 Discussion and limitations

This model relies on several simplifying assumptions that should be kept in mind when interpreting the results. I focus here on two related limitations: the issue of spatial scale, and the one-dimensional nature of land heterogeneity.

Spatial scale and substitutability. The relevant scale of analysis is not innocuous. In their original contribution and subsequent responses to criticism, Green et al. (2005) emphasize the *agro-ecological landscape* as the appropriate unit for interpreting the land sparing versus land sharing framework. By construction, the present model is abstract and scale-free: land quality θ indexes plots within a given domain, without specifying whether that domain corresponds to a region, a country, or a broader market.

Yet, some key assumptions implicitly embed strong forms of spatial substitutability that tend to favor land sparing. On the production side, output is perfectly fungible across plots: a unit produced on one plot is a perfect substitute for a unit produced elsewhere, so only aggregate supply matters. On the ecological side, biodiversity damages are summarized by a single index and treated as perfectly substitutable across space: a loss in one location is valued as equivalent to an equal gain in another location. Together, these assumptions mechanically strengthen the incentive to concentrate production on the most productive land while reducing pressures elsewhere.

This also clarifies why scale matters. If the relevant scale is dictated by the output market, the domain should encompass all land that can supply the considered commodity, potentially spanning heterogeneous ecosystems. In such a case, the assumption that biodiversity losses are perfectly substitutable across space becomes less compelling, as the ecological meaning of the aggregate index may vary across habitats. Conversely, if the relevant scale is dictated by a specific biodiversity indicator (e.g., the habitat of a given species), the domain may be much smaller and closer to a price-taker on a larger market. This raises additional issues of displacement of production outside the modeled domain and potential biodiversity leakage, which are not captured here and could be addressed (at least theoretically) by border adjustment mechanisms. A natural interpretation of the model, and the one emphasized in the policy discussion, is therefore at an intermediate scale (e.g., a country or jurisdiction) at which policies are implemented and where both production and biodiversity concerns are salient.

One-dimensional heterogeneity. A second limitation is that heterogeneity is unidimensional. Land quality θ affects agricultural productivity in a reduced-form way, while biodiversity impacts are driven solely by farming intensity through the damage function $d(x)$. In reality, heterogeneity is multidimensional and shapes not only yields but also ecological possibilities, such as habitat quality, species composition, and the responsiveness of biodiversity to agricultural practices. Allowing habitat value to co-vary with productivity, or allowing ecological responses to differ across plots, could alter some of the targeting implications derived in the paper—for instance for set-aside policies, where retiring productive land may be justified if those plots also provide disproportionate biodiversity benefits.

Toward a richer framework. More generally, scale and heterogeneity are intimately linked. Both economic and ecological substitutability depend on the aggregation level: reallocations that appear efficient at a large scale may entail unacceptable losses at finer spatial or ecological resolutions. A richer framework would consider multiple agro-ecological landscapes indexed by k, each with distinct productive and ecological characteristics, and would allow for imperfect substitutability both across outputs and across biodiversity components. Such extensions are left for future work.

7 Conclusion

This paper combines a Ricardian view of land heterogeneity with the density–yield logic of Green et al. (2005) to study how biodiversity concerns reshape agricultural production across space. In a heterogeneous landscape, valuing biodiversity affects not only aggregate outcomes—total output and cultivated area—but also the allocation of farming effort across plots. This generates a "Ricardian" reallocation channel that interacts with the curvature-driven land sparing/land sharing mechanism emphasized in the ecological literature.

Three main messages emerge. First, the shape of the biodiversity damage function governs whether biodiversity protection calls for further concentration of effort on high-quality land (a land sparing pattern) or, instead, for a more even distribution of effort and a broader cultivated area (a land sharing pattern). Second, land heterogeneity makes the response of effort non-uniform: even when the aggregate pattern points toward sparing or sharing, local adjustments along the land-quality distribution can be nuanced, especially near the extensive margin. Third, policy instruments must account for both margins and heterogeneity. With linear taxes on land use, effort and output, the optimal second-best policy trades off average environmental internalization against improved targeting across land qualities; under quadratic costs and damages, these instruments can decentralize the first best, and the sign pattern of the optimal mix depends sharply on curvature. When consumer prices are politically constrained, the optimal output instrument additionally reflects a production-support component linked to the shadow value of meeting demand.

The analysis also yields implications for set-aside policies. In an efficient allocation, land retirement should be targeted at the extensive margin to minimize opportunity costs. Starting from laissez-faire, however, food prices are too low because biodiversity damages are not internalized, which leads to excessive production. In that case, retiring land reduces output and can yield welfare gains even when it applies beyond marginal plots, because the foregone surplus from lower production may be smaller than the associated biodiversity benefits. At the same time, set-aside affects equilibrium incentives: by tightening supply it raises prices and induces a partial reallocation of production and effort toward the remaining cultivated land. These indirect adjustments partly offset the immediate biodiversity gains from land retirement, which calls for caution when evaluating set-aside policies, especially when marginal damages rise steeply with effort.

Several extensions would further refine the assessment, notably by allowing for multidimensional heterogeneity and imperfect ecological substitutability across space, and by making the relevant spatial scale explicit. Despite these limitations, the framework highlights a simple point: in heterogeneous landscapes, biodiversity policy is not only about how much land to farm, but also about *where* and *how* farming effort is distributed.

A final remark concerns the parsimony of the framework. The model is deliberately simple: the purpose is not to provide a fully realistic representation of agricultural landscapes, but to isolate a minimal set of ingredients—Ricardian heterogeneity and a reduced-form damage function—and to understand how they interact. This parsimony turns out to be fruitful. It delivers sharp comparative statics, clarifies the mechanisms behind land sparing versus land sharing patterns in heterogeneous settings, and highlights how biodiversity policy operates through both intensive and extensive margins as well as through the spatial reallocation of production. At the same time, drawing quantitative implications for real-world policies requires richer empirical work. In particular, the analysis stresses that policy evaluations should not focus solely on direct local effects: changes in incentives and land retirement also trigger indirect adjustments through reallocation of effort and production across land qualities. Accounting for these indirect channels is likely to be central for credible ex ante assessments of biodiversity-oriented agricultural policies.

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Appendix

A Quadratic specification calculations

With the quadratic specification (7), the optimal supply curve of an individual plot of quality θ is

$$x^S = \frac{p\theta - c_1 - \beta d_1}{c_2 + \beta d_2} \tag{31}$$

The effort on the marginal plot, which is the effort that minimizes the total social cost per unit

$$\frac{c(x) + \beta d(x)}{x}$$

is

$$\tilde{x} = \sqrt{2\frac{c_0 + \beta d_0}{c_2 + \beta d_2}} \tag{32}$$

and the corresponding cost (per unit) is

$$\tilde{C}(\beta) = \frac{c(\tilde{x}) + \beta d(\tilde{x})}{\tilde{x}} = (c_1 + \beta d_1) + \sqrt{2(c_2 + \beta d_2)(c_0 + \beta d_0)} \tag{33}$$

B Proof of Corollary 2

I proceed by first showing that some land should be less intensively farmed when β increases (Result), and then show that it must be the most productive one, and then derive the monotonicity of $\tilde{\theta}$.

Result: There is a θ for which $x^*(\beta, \theta)$ is decreasing with respect to β.

Proof.

I proceed by reductio at absurdum, and assume that x^* is increasing with respect to β for all θ. Total production being fixed derivatives satisfy:

$$\int_{\tilde{\theta}}^{1} \theta x^*_\beta dG(\theta) = \tilde{\theta}\tilde{x}\tilde{\theta}^*_\beta g(\tilde{\theta}^*).$$

consequently $\tilde{\theta}^*$ increases with respect to β if all x^* are increasing.

At the threshold, the following holds:

$$\tilde{x}(\beta) = x^*(\tilde{\theta}^*(\beta), \beta)$$

the left side is decreasing with respect to β since $d(.)$ is convex (cf Lemma 1), and the right side is increasing since x^* is increasing with respect to both arguments, and $\tilde{\theta}$ is increasing. A contradiction. ■

Then I proceed to show the Corollary: With a damage function $d(x) = d_2 x^2/2$, from equation (21), injecting the expression (31) of x, the sign of the derivative is the sign of

$$\begin{aligned}\theta p_\beta - d_2 x^* &= \theta p_\beta - d_2 \frac{\theta p - c_1}{c_2 + \beta d_2} \\ &= \theta\Big(p_\beta - \frac{d_2 p}{c_2 + \beta d_2}\Big) + \frac{d_2 c_1}{c_2 + \beta d_2}\end{aligned}$$

it is linear with respect to θ and from the Result above it is negative for some θ. Therefore, $p_\beta < p d_2/(c_2 + \beta d_2)$, and, it must be negative for large θ.

Concerning the monotonicity of $\tilde{\theta}^*$:

Either, all $x^*(\theta, \beta)$ are decreasing with β for $\theta \geq \tilde{\theta}$, and, given that total production is fixed, it must be the case that $\tilde{\theta}^*$ decreases.

Or, some $x^*(\theta, \beta)$ are increasing with β for θ close to $\tilde{\theta}$, and, making use of $\tilde{x}(\beta) = x^*(\tilde{\theta}^*(\beta), \beta)$, it must be the case that $\tilde{\theta}^*$ decreases with respect to β.

C Proof of Proposition 3

Derivation of equations (23) and (24)

With the three taxes t_0, t_1 and t_2 the efforts chosen, the threshold land quality $\tilde{\theta}$ and the market-clearing price satisfy the equations:

$$\theta(p - t_2) - t_1 = c'(x) \text{ for } \theta \geq \tilde{\theta} \tag{34}$$

$$[\tilde{\theta}(p - t_2) - t_1]x = c(x) + t_0 \text{ at } \tilde{\theta} \tag{35}$$

$$S'(Q) = p \tag{36}$$

Welfare is given by equation (6), and the tax are chosen so that:

$$\int_{\tilde{\theta}}^{1} [\theta S' - c'(x) - \beta d'(x)] \frac{\partial x}{\partial t_i} dG(\theta) - \left[\tilde{\theta} S'.x - c(x) - \beta d(x)\right] g(\tilde{\theta}) \frac{\partial \tilde{\theta}}{\partial t_i} = 0$$

injecting the market equilibrium equations gives for $i \in \{0, 1, 2\}$:

$$\int_{\tilde{\theta}}^{1} [\theta t_2 + t_1 - \beta d'(x)] \frac{\partial x}{\partial t_i} dG(\theta) - \left[\tilde{\theta} t_2 x + t_1 x + t_0 - \beta d(x)\right] g(\tilde{\theta}) \frac{\partial \tilde{\theta}}{\partial t_i} = 0$$

The tax t_0 is chosen to cancel the second term so

$$t_0 = \beta d(x(\tilde{\theta})) - t_1 x(\tilde{\theta}) - \tilde{\theta} t_2 x(\tilde{\theta}),$$

and the two taxes t_1 and t_2 are chosen to cancel the two equations (23) and (24) given in the main text because

$$\frac{\partial x}{\partial t_2} = -\frac{\theta}{c''(x)} \text{ and } \frac{\partial x}{\partial t_1} = -\frac{1}{c''(x)}$$

Proof of Proposition 3

With the quadratic cost $c(x) = c_0 + c_1 x + c_2 x^2/2$, individual production for $\theta \geq \tilde{\theta}$ is

$$x = \frac{(p - t_2)\theta - (c_1 + t_1)}{c_2} \text{ and } x(\tilde{\theta})^2 = 2\frac{c_0 + t_0}{c_2}$$

and with the quadratic damage, the equilibrium marginal environmental damage is then linear in θ:

$$d'(x) = d_1 + d_2 \frac{(p - t_2)\theta - (c_1 + t_1)}{c_2}$$

It is then feasible to find t_1 and t_2 that ensures

$$t_1 + \theta t_2 = d'(x) \ \forall \theta \geq \tilde{\theta}$$

they solve the two equations

$$t_1 - \beta(d_1 - d_2 \frac{c_1 + t_1}{c_2}) = 0 \text{ and } t_2 - \beta d_2 \frac{p - t_2}{c_2} = 0.$$

The expressions in Proposition 3 follow.

The tax t_0 is set so that

$$
\begin{aligned}
t_0 &= \beta d(x(\tilde{\theta})) - t_1 x(\tilde{\theta}) - \tilde{\theta} t_2 x(\tilde{\theta}) = \beta d(x(\tilde{\theta})) - \beta d'(x(\tilde{\theta}))x(\tilde{\theta}) \\
&= \beta(d_0 - \frac{d_2}{2}x^2) = \beta(d_0 - d_2 \frac{c_0 + t_0}{c_2})
\end{aligned}
$$

The expressions in Proposition 3 follows. Market equilibrium equations then coincide with the first order conditions of the first-best allocation (10) and (11). By unicity, they are similar.

D Set aside calculations

The market equilibrium without taxes and a given $\tilde{\theta}$ satisfies:

$$D(p) = \int_{\tilde{\theta}}^{1} \theta x dG(\theta) \text{ and } \theta p = c'(x) \; \forall \theta \geq \tilde{\theta}$$

These equations implicitly define the function $p(\tilde{\theta})$. And, at the laissez-faire equilibrium without any regulation $\tilde{\theta}$ is such that $p\tilde{\theta}x = c(x)$.

Welfare is given by equation (6), a small change of $\tilde{\theta}$, by an envelop argument, increases welfare by

$$\frac{dW}{d\tilde{\theta}} = \beta d(x(\tilde{\theta}))g(\tilde{\theta}) - \beta \int_{\tilde{\theta}}^{1} d'(x)\frac{\theta}{c''}dG(\theta)\frac{dp}{d\tilde{\theta}}$$

The change in the price is given by (derived from the market equilibrium equations above):

$$\frac{dp}{d\tilde{\theta}} = \tilde{\theta}x(\tilde{\theta})g(\tilde{\theta})\left[\int_{\tilde{\theta}}^{1} \frac{\theta^2}{c''}dG(\theta) - Q_p^D\right]^{-1}$$

at the extreme with an inelastic demand $Q_p^D = 0$ and the sign of the welfare change is the sign of

$$d(x(\tilde{\theta}))\int_{\tilde{\theta}}^{1} \frac{\theta^2}{c''}dG(\theta) - \tilde{\theta}x(\tilde{\theta})\int_{\tilde{\theta}}^{1} d'(x)\frac{\theta}{c''}dG(\theta)$$

And finally with a quadratic damage: $d(x) = d_0 + d_1 x + d_2 x^2/2$ the difference is the sum of three terms:

$$
\begin{aligned}
& d_0 \int_{\tilde{\theta}}^{1} \frac{\theta^2}{c''}dG(\theta) \\
& + d_1 x(\tilde{\theta})\int_{\tilde{\theta}}^{1} \frac{1}{c''}[\theta - \tilde{\theta}]dG(\theta) \\
& + d_2 x(\tilde{\theta})\int_{\tilde{\theta}}^{1} \frac{1}{c''}[\frac{1}{2}\theta x(\tilde{\theta}) - \tilde{\theta}x(\theta)]dG(\theta)
\end{aligned}
$$

The two first terms are striclty positive, the last one is ambiguous both because d_2 might be negative and because the sign of the integrand is ambiguous. For instance, if $c(x) = c_0 + c_2 x^2/2$ then $x = p\theta/c_2$ and the last integrand is negative so that with $d_1 = d_0 = 0$ and $d_2 > 0$ it is not worth increasing $\tilde{\theta}$ but reducing it, further sharing land.