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Integrated Assessment of Biodiversity and Agriculture^{*}

Johan Gars,[†]Daniel Spiro,[‡]Gustav Engström,[§]Steven J. Lade[¶]

Abstract

This paper develops a tractable integrated assessment model of the two-way interaction between biodiversity and the economy. To capture the main causes of biodiversity loss and the economic harm from it, we focus on agriculture and its expansion at the expense of forest land. We answer the question: What are the effects of pricing policies for land use on biodiversity and agricultural output? We show that there exist multiple economic-ecological equilibria and that a single "bad" policy maker can cause virtually irreversible harm – a ratchet effect of land-use change. We further find that a brown paradox may emerge in which, in anticipation of a future lenient policy maker, farmers halt current land-use change. We characterize the optimal mix and level of land-clearing fines and land-use taxes. Fines only have the effect of slowing down land-use change but cannot be used to restore biodiversity. For that land-use taxes, or other policies such as restoration subsidies, are necessary.

Keywords: Biodiversity, policy, land-use, agriculture.

JEL codes: H23, O13, Q12, Q15, Q57.

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1 Introduction

Biodiversity loss is one of the critical planetary problems facing mankind (IPBES 2019) and addressing it is one of the key policy challenges. This paper asks: What is the effect of biodiversity policies on economic output and biodiversity? In order to answer this question, we develop a simple but parsimonious model capturing the two-way interaction between the economy and biodiversity, i.e., an integrated assessment model (IAM). Our approach is inspired by the analytically tractable climate-economy IAM by Golosov et al. (2014) in two ways. First, we want to capture as much as possible of the drivers of biodiversity loss and how this affects economic conditions while keeping the model analytically tractable. Second, unlike most of the environmentaleconomics literature on biodiversity we take a more macro-oriented approach and primarily analyze pricing-type policies.¹ In order to keep the model analytically tractable while capturing as much as possible of the interaction between biodiversity and the economy, we focus on agriculture (which can be thought of as including logging) and land-use change.² The agricultural sector contributes directly to around 60% of all biodiversity loss and causes around 90% of land-use change which too is a central driver of biodiversity loss (Maxwell et al. 2016; Engström et al. 2020). Likewise, agriculture causes around a quarter of CO2 emissions which, through climate change, is a large cause of biodiversity loss (Maxwell et al. 2016). We do not model all these processes in detail but, focusing on an agent's choice of whether to expand agricultural land at the expense of forest land, indirectly capture the channels of CO2-emissions and land-use change. On the other side of the IAM – the harm from biodiversity loss – agriculture is central too as biodiversity loss directly and indirectly leads to reduced food supply. Here, we focus on earth-system effects of biodiversity, largely contributed by off-farm biodiversity. This includes carbon storage and moisture recycling, which regulate the regional and global climate. These benefits can be provided by biodiversity that is not immediately adjacent, but large areas of intact ecosystems are needed: a recent assessment proposed 50-60% of the world's ice-free land area (Rockström et al. 2023). In the model we capture

¹Brock and Xepapadeas (2003) analyze how to value biodiversity and which species to protect. Polasky, Costello, and Solow (2005) and Hannesson (2002) analyze more micro-oriented policies such as habitat and species protection, reserves and ecotourism. Albers (2022) analyzes protected-area policies in a non-formal model. Barrett (2022) studies global biodiversity agreements.

²Land-use change has been studied in partial-equilibrium settings by Pfaff (1999) who focuses on the effects of prices but not (optimal) policies; Assunção et al. (2023) who study targeting of monitoring; Araujo, Costa, and Sant'Anna (2020) who study farmers' conversion decision similar to ours, but in a partial-equilibrium framework, that is, not an IAM and without analytical results; Mendelsohn (1994) who studies the risk of eviction but does not analyze optimal policy and does not have analytical results; and Polasky, Lewis, et al. (2014) who study optimal contracts in a setting of asymmetric information in a partial-equilibrium setting. For reviews of the, mainly empirical, literature on land-conversion see Balboni, Berman, et al. (2023) and Mirzabaev and Wuepper (2023).

this in a reduced form by assuming that biodiversity loss reduces productivity of all agricultural land.³

In terms of modeling, our approach bears the most similarity to Baumgärtner (2007) and Augeraud-Véron, Fabbri, and Schubert (2019; 2021) who study biodiversity as a form of insurance against shocks. The two first papers do not study policies and the latter does not characterize a pricing policy. The modeling approach also resembles that of Ollivier (2012) who studies forest protection (REDD) without biodiversity.⁴ A very recent contribution is Giglio et al. (2024). They build a more detailed model of biodiversity to consider the fragility of ecosystem-service provision, and embed it in a model with land use.

In our model a (representative) farmer decides whether to expand agricultural land at the expense of forest land. The most productive land is used first, there is a (possibly zero) rental price of land and expansion implies a one-time clearing cost. The expansion of land reduces biodiversity (a public good) which in turn reduces agricultural productivity on all land. This implies that agricultural output is hill-shaped in the amount of land used for agriculture (Lemma 1), too much agricultural land can hurt total agricultural output. We start by studying a static model (Section 3). In an unregulated economy, equilibrium is state dependent: when initial agricultural land is low, then it will be expanded as returns to agriculture are high; when initial agricultural land is intermediate then it will remain unchanged as the clearing cost is not worth taking; and when initial agricultural land, the decentralized-equilibrium land-use change may be the same as the socially optimal but it may also be too high. The reason for why it may be too high is easy to understand: since biodiversity is a public good, farmers do not value it when deciding on whether to expand land. The reason for why decentralized land expansion may be the same as social optimum is due to the clearing cost that inhibits the land-use change (Figure 2).

We next study the optimal policy in this one-period setting (Section 3.4) and in particular

³Another type of benefit of biodiversity is the local effects from on-farm or near-farm biodiversity. This includes pollination, pest control, water quality regulation, soil protection and natural hazard mitigation (IPBES 2019). For these benefits to be provided, there needs to be sufficient intact ecosystems nearby, with a recent analysis proposing 20-25% intact ecosystems within the nearest square kilometer (Mohamed et al. 2024). See, e.g., Dasgupta (2024), Polasky, Costello, and Solow (2005), Bareille and Letort (2018), and Heal (2000), for economic analysis of such biodiversity benefits.

⁴See also Harstad (2016) and Harstad and Mideksa (2017) who study optimal contracts in forest protection with an externality (which can be interpreted as biodiversity).

two instruments: land-clearing fines and a land-use tax.⁵ We show that both their mix and levels depend non-trivially on initial agricultural land (Proposition 2). When it is initially low, then the instruments are perfect substitutes, and there exists a unique level of each one (or of both in combination) that achieves social optimum. When initial agricultural land is intermediate the land-pricing policies are still good substitutes, but there is a range of each that can achieve optimum. The reason is that, at that level of initial agricultural land, the goal of a social planner becomes to simply halt new land-use change, and this can be done with any sufficiently high clearing fines (including infinitely high ones) or with a range of land-use taxes. But the land-use tax cannot be too high as that would lead to reduction of agricultural land which is suboptimal. Finally, when initial agricultural land is high the goal of a social planner becomes to reduce it. But reduction cannot be achieved with clearing fines (since they only apply to *increased* agricultural land). Hence, here a land-use tax is necessary.⁶

We then extend the model to be dynamic, so that farmers make the land-use choices over many periods (Section 4). We here study policy positively (instead of normatively as in the oneperiod setting). We show that the bio-economic system will display ratchet effects (Propositions 3 and 5): every time a lax policy maker appears (i.e., one that imposes low land-clearing fines, e.g., Bolsonaro in Brazil, see Menezes and Barbosa Jr 2021; Perez 2021), agricultural land will expand affecting biodiversity and agricultural productivity negatively, and this land will not be converted back to forest just because a later policy maker increases the fines. This is of course intuitive, but it is also important since it explains the one-way process of land-use change in, e.g., Brazil (Butler 2017; Dourojeanni 2019) and since it implies that to reverse it, retroactive fines or land-use taxes (essentially taxation of agriculture) have to be used.

We also show that a 'brown paradox' may arise (Proposition 4). In anticipation of a future lenient policy maker, farmers may postpone forest clearing that they would have done otherwise (if the future policy maker had been stricter). The reason is that land clearing which is profitable today may be cheaper to perform later if future fines are lower. The result thus arises due to a mechanism

⁵The land-use tax applies to all agricultural land and is equivalent to a forest-land subsidy. For empirical research on land-pricing policies see, e.g., Barbier (2022) and Balboni, Berman, et al. (2023). The clearing fines in our model apply to land converted from forest to agriculture. It can be interpreted as a reduced form capturing both the size of the fine and probability of getting caught, i.e. monitoring (Mendelsohn 1994; Araujo, Costa, and Sant'Anna 2020; Assunção et al. 2023).

⁶Subsidies for restoring agricultural land would work too, but we do not analyze this formally in the paper. See Mirzabaev and Wuepper (2023), Wunder et al. (2020), Jayachandran (2013), and Balboni, Berman, et al. (2023) for, mainly empirical, results on such policy.

akin to the "green paradox" (Sinn 2008; Jensen et al. 2015) but with the reversed consequence.⁷

2 Model: Agriculture and biosphere

We will here lay out the model of agriculture and the effects on biodiversity and in the next section we present the model of the economy. Land use is central in the model and we consider a measure $\mathbb{L} = [0, \overline{L}]$ of land which is ordered so that the productivity of land piece $l \in \mathbb{L}$, if used for agriculture, is decreasing in l. We assume that the most productive land is used for agriculture. This means that we can define $L_A \in \mathbb{L}$ such that $l \in \mathbb{L}_A \equiv [0, L_A]$ is used for agriculture while the remaining land $(l > L_A)$ is not. L_A thus represents land use in agriculture.

Agricultural production on a piece of land l is denoted a(B,l), where B is the state of biodiversity. We assume that a(B,l) is differentiable in both arguments. Furthermore, we assume productivity is increasing in biodiversity and, by the assumption that lower l corresponds to more productive land, we have

$$a_B(B,l) > 0 \text{ and } a_l(B,l) < 0.$$
 (1)

We furthermore assume biodiversity is a decreasing and twice differentiable function of total land used in agriculture

$$B'(L_A) < 0. (2)$$

To derive some of the results below, we will also use the sufficient (but not necessary) condition $B''(L_A) \leq 0$. With agricultural land use L_A , total agricultural production is⁸

$$A(L_A) = \int_0^{L_A} a(B(L_A), l) dl.$$
 (3)

We assume a and $B(L_A)$ are such that

$$A(\bar{L}) > 0. \tag{4}$$

That is, even if all land would be used for agriculture, the resulting deterioration of biodiversity would not be strong enough to completely undermine agricultural production. Note that we will always have A(0) = 0.

⁷In the green paradox, tough future environmental policies (e.g., taxation on fossil fuels) will increase environmental harm (fossil-fuel extraction) today. Under the brown paradox in this paper, future *lenient* environmental policy *reduces* environmental harm today; but tough future policies do not have this effect.

⁸Clearly this specification of the agricultural production function is missing many important inputs to production e.g. capital, labor and fertilizers. This is acceptable since our model is focused on the long run production capabilities. Here changing inputs, e.g., land and biodiversity, work on longer time horizons than a year in comparison to the former which can affect production levels at the intra-year scale.

Differentiating $A(L_A)$ with respect to L_A gives

$$A'(L_A) = \underbrace{a(B(L_A), L_A)}_{\geq 0} + \underbrace{B'(L_A)}_{<0} \underbrace{\int_{0}^{L_A} a_B(B(L_A), l) \, dl}_{>0}.$$
 (5)

This expression says that when agricultural land L_A increases, there are two effects on total production. Firstly, the newly added land provides additional output. Secondly, the land expansion erodes biodiversity which decreases production on all agricultural land. Thus follows:

Lemma 1. Suppose $a_l(B,l) < 0$, $a(B,\bar{L}) = 0$, $a_B(A,l) > 0$, $B'(L_A) < 0$ and $B''(L_A) \le 0$. Then total agricultural output A is hill shaped in total agricultural land use L_A : $A'(L_A) > 0$ for $0 \le L_A < L_A^{max}$ and $A'(L_A) < 0$ for $L_A^{max} < L_A \le \bar{L}$ for some $L_A^{max} \in [0, \bar{L}]$.

Proof. In equation (5), A'(0) > 0 since the integral is zero, and $A'(\bar{L}) < 0$ when $a(B, \bar{L}) = 0$. Differentiating the derivative in (5) gives

$$A''(L_A) = \underbrace{a_l(B(L_A), L_A)}_{<0} + 2\underbrace{B'(L_A)}_{<0}\underbrace{a_B(B(L_A), L_A)}_{>0} + \underbrace{B''(L_A)}_{\le 0}\underbrace{\int_0^{L_A} a_B(B(L_A), l) \, dl}_{>0} < 0 \qquad (6)$$

which together with A'(0) > 0 and $A'(\bar{L}) < 0$ implies A is first increasing and then decreasing in L_A . Note that B being concave $(B''(L_A) \le 0)$ is a sufficient but not necessary condition. \Box

Figure 1: Agricultural output and land use



The lemma is illustrated in Figure 1. There is a food-maximizing level of land use L_A^{max} .

Beyond this point, the deterioration of biodiversity has a larger impact on agricultural output than what the additional land contributes. Burian et al. (2024) provide estimates of dependency of total output on land used for agriculture taking effects on biodiversity into account. They find that the dependency is typically concave and for some agricultural systems also hill shaped, as in our Lemma 1, with agricultural output decreasing for high levels of land use (see their Figure 3).

3 One-period model

3.1 The economy

We start by considering a one-period model of the economy and how it interacts with the biosphere. There is a cost $p_o > 0$ per unit of land use. This cost can be interpreted as an opportunity cost or a rental price. There is also a per-unit cost $c \ge 0$ associated with converting land to agriculture.⁹ Importantly, this cost is only incurred when converting forest land to agriculture and not vice versa.¹⁰ Let $L_{A,0}$ denote initial land use in agriculture. The direct costs of land use are then

$$C(L_A; L_{A,0}) = \begin{cases} p_o L_A + c(L_A - L_{A,0}) & \text{if } L_A > L_{A,0} \\ p_o L_A & \text{if } L_A \le L_{A,0} \end{cases} .$$
(7)

A representative household (of mass 1) consumes agricultural output and its demand is derived from a utility function U(A) that is assumed to be twice differentiable and such that

$$U'(A) > 0, U''(A) < 0 \text{ and } \lim_{A \to 0} U'(A) = \infty.$$
 (8)

This utility function may have other components, such as consumption of other goods and leisure. A sufficient assumption for our results is that utility is more concave in agricultural consumption than in other factors. Given the necessity of food, and based on empirical estimates, this is a reasonable assumption (Roberts and Schlenker 2009).

⁹Assuming that the cost of land conversion is positive implicitly assumes the value of the timber when clearing the forest is small. In principle our results go through also if c is negative, as long as it does not surpass the cost of land use p_o . One way to interpret our assumption here is that the clearing is illegal so that the timber cannot be sold on the market, or similarly that the farmers use fire to clear land and this fire poses a risk to their own property (Balboni, Burgess, and Olken 2021). Our modeling of a cost to land-use change is akin to Araujo, Costa, and Sant'Anna (2020). See Pfaff (1999) for a partial-equilibrium model where farmers earn a price for timber upon clearing.

¹⁰We thus assume that agricultural land, if left unfarmed, eventually turns into forest or shrubs which produce biodiversity; or similarly that if a farmer leaves a plot of land s/he has no incentives to regrow it. For a quantitative model where there are costs also of regrowing land see Araujo, Costa, and Sant'Anna (2020).

We will now consider two different equilibria. One where the effects of land use on biodiversity are internalized, and one where they are not. The first case is the social-planner solution and the second case is an unregulated decentralized equilibrium.¹¹ After that, we consider how policy can align the farmers' actions with the social optimum.

3.2 Social optimality

A social planner wants to maximize the utility of the households less the physical costs of land use in agriculture, that is,

$$\max_{L_A} U(A(L_A)) - C(L_A, L_{A,0}) \text{ s.t. } (3)$$
(9)

where $C(L_A, L_{A,0})$ is given by (7) and the properties of U are outlined in (8). The first-order conditions give that the optimal L_A^{SP} must be such that

$$U'(A(L_{A}^{SP}))A'(L_{A}^{SP}) \begin{cases} \leq p_{o} + c & \text{if } L_{A}^{SP} > L_{A,0} \\ \geq p_{o} & \text{if } L_{A}^{SP} \leq L_{A,0} \end{cases}$$
(10)

The left-hand side is monotonically decreasing since

$$\frac{d}{dL_A}U'(A(L_A))A'(L_A) = \underbrace{U''(A(L_A))}_{<0}\underbrace{\left(A'(L_A)\right)^2}_{>0} + \underbrace{U'(L_A)}_{>0}\underbrace{A''(L_A)}_{<0} < 0.$$

Substituting the derivative from (5) in the optimality condition in (10) gives

$$U'(A(L_{A}^{SP})) \left[a \left(B(L_{A}^{SP}), L_{A}^{SP} \right) + B'(L_{A}^{SP}) \int_{0}^{L_{A}^{SP}} a_{B} \left(B(L_{A}^{SP}), l \right) dl \right] \begin{cases} \leq p_{o} + c & \text{if } L_{A}^{SP} > L_{A,0} \\ \geq p_{o} & \text{if } L_{A}^{SP} \leq L_{A,0} \end{cases}$$
(11)

This condition implies that optimal land use depends on initial land use – it is history dependent. If initial land use is sufficiently small so that $U'(A(L_A))A'(L_A) > p_o + c$, agriculture should expand until the upper condition holds with equality. If initial land use is large enough so that $U'(A(L_A))A'(L_A) < p_o$, land should be abandoned until the second condition holds with equality. For intermediate initial land uses, land use should not be changed since the opportunity cost of land (p_o) is lower than the value of land use in agriculture but expanding agriculture would require

¹¹We here only consider off-farm effects of biodiversity. On-farm effects would be internalized by farmers and not give rise to a difference between the planner solution and the decentralized equilibrium. See Li, Löfgren, and Weitzman (2001) for a model of a single decision maker, i.e., the equivalent of on-farm effects.

paying the land conversion cost c and the combined cost is too high. We can define $L_A^{SP,low}$ and $L_A^{SP,high}$, given implicitly by the upper and lower part of condition (11) respectively holding with equality. Using these, we then get:

Lemma 2. There is a continuum $[L_A^{SP,low}, L_A^{SP,high}]$ of social-planner solutions depending on the initial land use such that:

- if $L_{A,0} < L_A^{SP,low}$, then $L_A^{SP} = L_A^{SP,low}$,
- if $L_{A,0} \in [L_A^{SP,low}, L_A^{SP,high}]$, then $L_A^{SP} = L_{A,0}$,
- if $L_{A,0} > L_A^{SP,high}$, then $L_A^{SP} = L_A^{SP,high}$, where $L_A^{SP,high} < L_A^{max}$.

Proof. The bullet points follow from the paragraph above. That $L_A^{SP,high} < L_A^{max}$ follows since the first-order condition (10) implies that at the optimum $A'\left(L_A^{SP,high}\right) > 0$ and this is the case when $L < L_A^{max}$.

Apart from history dependence – where optimal land use depends on initial land use – it is noteworthy from the lemma that a social planner would not choose the food-maximizing level of agricultural land L_A^{max} (see Figure 1). To see why, note first that a social planner would clearly never be on the downward sloping part of Figure 1. That would just mean paying the cost of land use p_0 while getting less food. Second, a social planner would not choose the food-maximizing L_A^{max} itself, because the clearing cost when approaching this level from below (when initial agricultural land is small) is necessarily higher than the marginal increase in food production which is zero at the peak. Similarly, when approaching this level from above (when initial agricultural land is large), the land-usage cost $p_o > 0$ makes it suboptimal to use the food-maximizing land.

3.3 Unregulated equilibrium

In an unregulated (and decentralized) equilibrium, the representative household solves

$$\max_{A} U(A) - p_A A,\tag{12}$$

that is, the household gets utility U(A) from consuming agricultural products and has to pay a price p_A for these. For simplicity, we thus let the cost of food enter the objective function. This is a reduced form for the existence of other goods of which the households consumes less when buying food, and that the utility from these goods is less concave than the utility from food. Again, this is motivated by the necessity and inelasticity of food consumption (Roberts and Schlenker 2009). The first-order condition is

$$U'(A) = p_A. (13)$$

A continuum of farmers (of mass 1) produce agricultural output by renting, and potentially converting, land.¹² When optimizing, they take A and B as given and solve

$$\max_{L_A} p_A \int_0^{L_A} a(B, l) \, dl - C(L_A; L_{A,0}) \, L_A.$$
(14)

Differentiating the maximum with respect to L_A and substituting for the price p_A from (13) gives that the marginal value of land use in agriculture is $U'(A)a(B, L_A^D)$. Note that, without further assumptions, the marginal value is potentially non-monotone. It may start increasing once L_A is large enough so that A starts to decrease. This could give rise to additional equilibria with large land use and hence we could have multiple equilibria for a given initial land use (recall that, for the social planner, there was a unique optimal level of land use for each initial condition). Note also that as $L_A \to \overline{L}$, the marginal value of land use in agriculture goes to zero since $U'(A(L_A)) < \infty$ and $a(B, \overline{L}) = 0$. To simplify the analysis, it is our maintained assumption that the left-hand side of (16) is monotonically decreasing:¹³

$$\frac{\mathrm{d}}{\mathrm{d}L_A} U'(A(L_A))a\left(B\left(L_A\right), L_A\right) < 0.$$
(15)

Given this assumption, the first-order condition to the profit-maximization problem in (14) gives that the equilibrium value L_A^D fulfills

$$U'(A)a\left(B,L_{A}^{D}\right)\left\{\begin{array}{l} \leq p_{o}+c \quad \text{if } L_{A}^{D} > L_{A,0}\\ \geq p_{o} \quad \text{if } L_{A}^{D} \leq L_{A,0}.\end{array}\right.$$
(16)

By an argument similar to that for the social-planner solution, there is a continuum of equilibria depending on initial land use. For small initial land uses, the equilibrium land use is such that the upper condition holds with equality. For large initial land uses, the equilibrium is such that the lower condition holds with equality. For intermediate initial land use, the equilibrium is to maintain

¹²Thus, by clearing land, a farmer implicitly gets property rights of it (Angelsen 1999).

¹³One example where this is fulfilled is if utility is logarithmic, $U(A) = \ln(A)$, and the land productivity is multiplicatively separable so that $a(B, l) = B\tilde{a}(l)$.

the current land use. However, there is a unique equilibrium for each initial land use $L_{A,0}$. The following lemma characterizes the unregulated equilibrium.

Lemma 3. Define $L_A^{D,low}$ and $L_A^{D,high}$ as the values of L_A where the upper and lower conditions in (16) respectively hold with equality. If the initial land use is identical for all farmers, then there exists a unique equilibrium, which is symmetric, where $L_A^D \in [L_A^{D,low}, L_A^{D,high}]$ depends on the initial land use and where:

- if $L_{A,0} < L_A^{D,low}$, then $L_A^D = L_A^{D,low}$,
- if $L_{A,0} \in [L_A^{D,low}, L_A^{D,high}]$, then $L_A^D = L_{A,0}$,
- if $L_{A,0} > L_A^{D,high}$, then $L_A^D = L_A^{D,high}$.

Proof. To see why the equilibrium is unique and symmetric if the initial land uses are the same for all farmers, consider an equilibrium that results in biodiversity B and total agricultural production A. All farmers take these as given. Now note that $U'(A(L_A)) a(B(L_A), L_A)$ and $U'(A) a(B, L_A)$ both are strictly decreasing in L_A by assumptions (15) and (1) respectively. That $U'(A) a(B, L_A)$ is strictly decreasing in L_A implies that all farmers will choose the same land use. That $U'(A(L_A)) a(B(L_A), L_A)$ is decreasing implies that there is a unique optimal choice given by (16). The bullet points then follow from $U'(A(L_A)) a(B, L_A)$ being strictly decreasing in L_A and from the land-use costs in (7). Finally, since $U'(A(L_A)) a(B(L_A), L_A)$ goes to infinity as L_A goes to zero, there will always be an equilibrium with strictly positive land use.

The lemma shows that if all farmers have the same initial land use the equilibrium is unique and all farmers have the same land use in it. We will henceforth indeed assume that initial land use is symmetric and refer to a representative farmer. Having established the socially optimal and decentralized outcomes, we are ready to compare the two. We can note that the difference between the right-hand sides of equations (16) and (11) is the marginal external cost of biodiversity degradation

$$C_E(L_A) \equiv -U'(A)B'(L_A) \int_0^{L_A} a_B(B(L_A), l) \, dl.$$
(17)

The results until now imply the following proposition:

Proposition 1. [Unregulated equilibrium and social optimum] The socially optimal land use L_A^{SP} depends on initial land use $L_{A,0}$ as described by Lemma 2. Unregulated decentralized land use L_A^D depends on initial land use $L_{A,0}$ as described by Lemma 3. Land use in the unregulated

decentralized equilibrium is larger than social optimum, $L_A^D \ge L_A^{SP}$ and biodiversity in an unregulated decentralized equilibrium is smaller than social optimum, $B_A^D \le B_A^{SP}$.

Proof. The first two sentences follow from Lemmas 2 and 3 respectively. To see why $L_A^D \ge L_A^{SP}$, note that the marginal cost of biodiversity degradation in equation (17) is positive. Hence, wherever the optimum is, the left-hand side of the equilibrium condition (16) is strictly larger than the left-hand side of the planner's optimality condition (11) for all land uses smaller than the optimum. This implies that land use will be weakly larger in the unregulated equilibrium than in the planner solution. The statement about biodiversity then follows from (2).

The proposition is illustrated in Figure 2 where the thick gray line represents social optimum and the solid black line represents the unregulated equilibrium. They are both history dependent where the outcome (vertical axis) depends on initial land use (horizontal axis), and in an intermediate range of initial conditions the land use remains unchanged. But the unregulated equilibrium has higher land use than is socially desirable. There is equality only if both solutions are in the intermediate range where land use is not changed.¹⁴

Figure 2: History dependent equilibria



¹⁴However, the intermediate range in an unregulated equilibrium may not necessarily overlap with that of the social planner. In such a case, unregulated land use would be strictly higher than under a social planner for *all* initial conditions. There is overlap if and only if $L_A^{SP,high} \leq L_A^{D,low}$.

3.4 Policy

We now consider two different policies and the extent to which they can be used to implement the optimal allocation in a decentralized equilibrium: a land-use tax τ_L (on top of the rental cost p_0) and a clearing fine τ_c (on top of the physical cost of land conversion c).¹⁵ Throughout we will only consider positive taxes, i.e., $\tau_L \geq 0$ and $\tau_c \geq 0$. The land-use tax can be interpreted as a Pigovian tax (Balboni, Berman, et al. 2023).

A farmer's total cost of land use in agriculture with the addition of these taxes is

$$C_F(L_A, L_{A,0}) = \begin{cases} (p_o + \tau_L)L_A + (c + \tau_c)(L_A - L_{A,0}) & \text{if } L_A > L_{A,0} \\ (p_o + \tau_L)L_A & \text{if } L_A \le L_{A,0} \end{cases}$$
(18)

A farmer subject to these taxes will chose land use as in Lemma 3 but with the cost C_F . Furthermore, Lemma 3 still applies and there is a unique equilibrium, which is symmetric, for any initial land use. Comparing the resulting decentralized choice with the social-planner solution in equation (11) we can see that a pair of taxes can implement the optimum if the total effect of the two taxes is to internalize the marginal external cost in equation (17). Hence a pair of taxes implements the optimum if

$$U'\left(A\left(L_{A}^{SP}\right)\right)B'\left(L_{A}^{SP}\right)\int_{0}^{L_{A}^{SP}}a_{B}\left(B(L_{A}^{SP}),l\right)dl = \begin{cases} \tau_{L}+\tau_{c} & \text{and } L_{A}^{SP} > L_{A,0} \\ \tau_{L} & \text{and } L_{A}^{SP} \leq L_{A,0} \end{cases},$$
(19)

where L_A^{SP} is the land use of the social planner outcome associated with initial land use $L_{A,0}$ given in Lemma 2. The optimal policy depends on initial land use $L_{A,0}$. For a given $L_{A,0}$, the combination of taxes that implements the optimum is not unique for two reasons. Firstly, the instruments partially work in the same way meaning that it is the combination that matters: given their total effect, they can be combined in different ways. Secondly, the asymmetry between the cost of deforestation and the reduced cost when abandoning land means that there may be slackness in the sense that there is a range where stricter policy deters further deforestation without incentivising land abandonment. Hence, social optimality can be achieved by a range of tax levels.

Proposition 2. [Optimal policy] With a land-use tax (τ_L) and a clearing fine (τ_C) , the socially optimal outcome can be implemented in a decentralized equilibrium.

¹⁵The clearing fine can also be interpreted as including the risk of being caught clearing land illegally (Assunção et al. 2023; Harstad and Mideksa 2017).

- 1. if $L_{A,0} < L_A^{SP,low}$, then social optimum is implemented by any combination of policies such that $\tau_C + \tau_L = C_E \left(L_A^{SP,low} \right)$,
- 2. if $L_{A,0} \in [L_A^{SP,low}, L_A^{SP,high}]$, then social optimum is implemented by any combination of policies such that $\tau_L + \tau_C \ge U'(A(L_{A,0})) a(B, L_{A,0}) p_0 c$ and $\tau_L \le U'(A(L_{A,0})) a(B, L_{A,0}) p_0$
- 3. if $L_{A,0} > L_A^{SP,high}$, social optimum is implemented by a unique $\tau_L = C_E \left(L_A^{SP,high} \right)$ while τ_C can be set to any value.

Proof. We need to consider different cases. For all cases the conditions are derived using that the marginal private benefit from production is $U'(A(L_A)) a(B(L_A), L_A)$ while the private costs of land use are $p_0 + c + \tau_L + \tau_C$ if land use is increased, and $p_0 + \tau_L$ if land use is decreased. Hence land use is increased if $U'(A(L_A)) a(B, L_A) > p_0 + c + \tau_L + \tau_C$ and decreased if $U'(A(L_A)) a(B, L_A) < p_0 + \tau_L$. The assumption in (15) says that the left-hand side of these inequalities is decreasing in L_A . This means that for given taxes τ_L and τ_C , and if starting from a small L_A , there will first be an interval where the first inequality is fulfilled but the second is not; followed by an interval where neither inequalities are fulfilled; and finally an interval where the second inequality is fulfilled but the first inequality is fulfilled but the second inequality is fulfilled but the first inequality is fulfilled but the second inequality is fulfilled but the first inequality is fulfilled but the second inequality is fulfilled but the first inequality is fulfilled but the second inequality is fulfilled but the first inequality is fulfilled but the second inequality is fulfilled but the first is not.

If $L_{A,0} < L_A^{SP,low}$ then, by Lemma 2, the policy should induce deforestation to exactly $L_A^{SP,low}$. This is done by having the combined effect of the policy exactly make the farmers internalize the marginal external cost at that point by setting $\tau_C + \tau_L = C_E \left(L_A^{SP,low} \right)$. Land use will then be increased until $U'(A(L_A)) a(B, L_A) = p_0 + c + \tau_L + \tau_C$ which happens for $L_A = L_A^{SP,low}$. This proves point 1.

If, instead, initial land use is in the intermediate range $L_{A,0} \in [L_A^{SP,low}, L_A^{SP,high}]$, by Lemma 2, the optimally implies $L_A = L_{A,0}$. This means that the policy should be strict enough to deter land expansion but not so strict that it induces land abandonment. The condition for deterring land expansion is that $\tau_L + \tau_C \geq U'(A(L_{A,0})) a(B, L_{A,0}) - p_0 - c$. The condition for not inducing land abandonment is $\tau_L \leq U'(A(L_{A,0})) a(B, L_{A,0}) - p_0$. If we set $\tau_C = 0$ we can see that the span that τ_L should lie in has size c precisely reflecting the asymmetry in costs when increasing and decreasing land use. This proves point 2.

Finally, if initial land use is such that $L_{A,0} > L_A^{SP,high}$ then, by Lemma 2, the polices should precisely induce land abandonment to get land use $L_A^{SP,high}$. When decreasing land use, only the land-use tax matters. It should be set so that at the desired land use level, farmers precisely internalize the external cost: $\tau_L = C_E \left(L_A^{SP,high} \right)$. Land is then abandoned until $U'(A(L_A)) a(B, L_A) = p_0 + \tau_L$ which happens for $L_A = L_A^{SP,low}$. This proves point 3.

A corollary follows the proposition:

Corollary 1. If $\tau_C = 0$, the optimum can always be implemented using a land-use tax τ_L . If $\tau_L = 0$, the optimum can be implemented using clearing fines τ_C if and only if $L_{A,0} \leq L_A^{SP,high}$.

The proposition and corollary are illustrated in Figure 3. The upper panel shows the equilibrium outcome under no policy (black) and the social-planner solution (gray). The middle panel then shows which land-use tax τ_L^* would make a decentralized economy achieve social optimum, under the assumption that the clearing fines $\tau_C = 0$. The lower panel shows the reverse, that is, optimal clearing fine τ_C under the assumption that the land-use tax $\tau_L = 0$. The proposition and figure express that optimal policy is history dependent: both in its mix and in its extent.

Starting with the policy mix, the corollary says when each of the policies should be used. When current land-use is low or intermediate $(L_{A,0} < L_A^{SP,high})$, clearing fines or land-use taxes can be used interchangeably – either one or a combination of them would work in achieving optimum. But if land-use is extensive, then this no longer holds. This is because land-clearing fines (τ_C) cannot be used to reverse land-use changes that have already taken place – for that land-use taxes need to be used. This is of course intuitive, yet it is an important policy implication. It is also suggestive of ratchet effects in land use and biodiversity loss: if land has been cleared (for instance, because of a lax policy maker was in office), then it will be hard to reverse it. We will see similar properties in the dynamic model that we turn to in the next section.

As for the extent of policy, also this varies depending on initial land use. When initial land use is low $(L_{A,0} < L_A^{SP,low})$, a social planner would want there to be some clearing, but less than what the market wants. Hence, a the effect of the policy should be to incentivise land expansion to $L_A^{SP,low}$ but not further. This gives a unique level of $\tau_L + \tau_C$; and any combination of taxes with that sum can be used. For intermediate initial land uses $(L_{A,0} \in [L_A^{SP,low}, L_A^{SP,high}])$, the social planner would want the land use to remain unchanged. This can be achieved by a sufficiently high land-use tax τ_L^* making land use unprofitable. But such a tax cannot be too high, since then profitability of land would fall enough to incentivize farmers to abandon land. This is indicated by the gray surface in the middle panel. Alternatively, optimum can be achieved by a sufficiently high clearing fine τ_C . For such a policy, there is no upper bound since it doesn't make land use per se unprofitable, but only its conversion. This is indicated by the gray area in the lower panel. It can be noted that the



lower bound on the taxes (the lower bound of the gray surface, $U'(A(L_{A,0})) a(B, L_{A,0}) - p_0 - c)$ is falling with the initial land use.¹⁶ This is because profitability of land is decreasing by itself as food prices and productivity of land fall when more land is used for agriculture. Hence, more lax policy can be used. Finally, when initial land use is extensive $(L_{A,0} > L_A^{SP,high})$, the tax that implements the optimum is unique and chosen to induce land abandonment to exactly $L_A^D = L_A^{SP,high}$.

In conclusion, the sum of pricing policies is unique for low and high initial land uses but not for intermediate values. For low and high values of initial land use, the policy should induce an exact change in land use. This implies a specific strength of policy needed. When land use should increase, a combination of the taxes can be used, but when land use should decrease, only the land-use tax works. For intermediate initial land uses, policy should deter from changing land use. Given the asymmetry between increases and decreases in terms of costs and policies, there is some slack and the strength of policy required is not uniquely determined.

4 Dynamic model

We will here make the model dynamic to analyze the effects of time-varying policies. The demand function for agricultural output, implied by the households' utility maximization, is the same in all periods. Furthermore, we focus on a case where the opportunity cost of land, p_o , the land-use tax τ_L , and the land-conversion cost, c, are all constant, while τ_C may vary over time. In each period $t \in \mathbb{N}^{++}$ the representative farmer chooses land use $L_{A,t}$ to maximize the sum of discounted profits given the land use from the previous period $L_{A,t-1}$. As before, the representative farmer takes total agricultural output $\{A_t\}$ and biodiversity $\{B_t\}$ as given but can predict these values in equilibrium. It thus solves the following dynamic profit-maximization problem:

$$\max_{\{L_{\{A,t\}}\}_{t=1}^{\infty}} \sum_{t=1}^{\infty} \beta^{t-1} \left[p_A(A_t) \int_0^{L_{A,t}} a(B_t, l) \, dl - C_{F,t}(L_{A,t}; L_{A,t-1}) \right].$$

The land-use decision in period t now affects profits in that period but also in future periods since it affects the land-clearing cost in those periods. We start by stating a useful result about symmetry of equilibria.

Lemma 4. All decentralized equilibria will be symmetric in the sense that if all land owners start from the same initial land use, they will have the same land use as each other in all future periods.

¹⁶In the figure, this fall is illustrated linearly, but it can be non linear.

Proof. To see this, note that for any given sequence of A_t and B_t , each land owner's marginal profit from land use in each period is strictly decreasing in their own land use $L_{A,t}$ since p_A is independent of the individual land owner's decision while $a(B_t, L_{A,t})$ is decreasing and $C_F(L_{A,t}; L_{A,t-1})$ is increasing in $L_{A,t}$. While the optimality conditions in (16) can hold with inequality in periods where land use is not changed, they will hold with equality when land use is changed. Hence, for given sequences of A_t and B_t , there is a unique equilibrium choice of land use for each individual land owner. When starting from all owners having the same land use, if a land-use change maximizes profits for one farmer, it would also be optimal for the other farmers to expand their lands. Furthermore, the value of land use of each farmers is decreasing in the land use of other farmers and therefore if some change would be optimal for one user, when the other owners also make the same change, the value of making that change decreases for everyone. Combined this implies that there will be a unique equilibrium for any sequence of taxes and it will be symmetric as long as initial land use is the same for all owners.

The lemma thus establishes that, with a representative farmer at the onset, there is also a representative farmer in equilibrium. With rational expectations, in symmetric equilibria, the equilibrium $L_{A,t}$ must be such that

$$B(L_{A,t}) = B_t \text{ and } A_t = A(B_t, L_{A,t}).$$
 (20)

Another convenient result – if policy is constant – follows.

Lemma 5. Suppose all policies are constant, that is $\tau_{c,t} = \tau_c$ for all $t \ge t'$. Then land-use will be unchanged after period t'. Let $L_A^{\tau_c}$ denote the choice of land use when the policies are constant with clearing fines τ_c . If initial land use is small, then $L_A^{\tau_c}$ is decreasing in τ_c .

Proof. Note that, apart form the initial land use, the problem facing the land owner is the same in all periods from t' and onward. Hence if land expansion is profitable in some time period t > t', it would have been so also at time t'. This proves the first sentence. If initial land use is small, so that land use will be expanded, the problem facing the representative farmer is then to choose $L_A^{\tau_c}$ that solves

$$\max_{L_{A}^{\tau_{c}}} \sum_{t=1}^{\infty} \beta^{t-1} p(A) \int_{0}^{L_{A}^{\tau_{c}}} a(B,l) dl - \beta \left[\left(p_{o} + \tau_{L} \right) L_{A}^{\tau_{c}} + \left(c + \tau_{c} \right) \left(L_{A}^{\tau_{c}} - L_{A,0} \right) \right] - \sum_{t=2}^{\infty} \beta^{t-1} \left(p_{o} + \tau_{L} \right) L_{A}^{\tau_{c}}.$$

Taking the first-order condition, using (20) and rewriting gives

$$p\left(A\left(L_{A}^{\tau_{c}}\right)\right)a\left(B\left(L_{A}^{\tau_{c}}\right),L_{A}^{\tau_{c}}\right) = p_{o} + \tau_{L} + (1-\beta)\left(c+\tau_{c}\right).$$
(21)

The LHS is continuous, goes to infinity if $L_A^{\tau_c} \to 0$ and becomes zero if $L_A^{\tau_c} = \overline{L}$. There is thus at least one $L_A^{\tau_c}$ that fulfills (21). By assumption (15), the LHS is decreasing in $L_A^{\tau_c}$, implying that there is exactly one $L_A^{\tau_c}$ that fulfills (21) and it corresponds to a maximum. The RHS is increasing in τ_c which, together with assumption (15) proves the final sentence of the lemma.

The first point of the proposition simply establishes that the dynamic model with constant policy behaves similarly to the static model – there is a direct jump to the long-run steady state. The only difference is that the value of agricultural production now contains the discounted infinite stream of profits. This means that our results (e.g., about optimal policy) from the static model carry over to a dynamic setting with constant policy. As in the static case, the choice of land under a constant policy, denoted by $L_A^{\tau_c}$, naturally is decreasing in the clearing fines τ_c . This will be useful now when we analyze time-varying fines.

In practice the clearing fines $\tau_{c,t}$ may of course vary over time due to, for instance, changes in political leadership. For example, in Brazil, Bolsonaro essentially abolished fines while the government before and after had much stricter policies (Menezes and Barbosa Jr 2021; Perez 2021). We now show the consequences of this in a set of results (recall that p_o , τ_L and c are assumed constant).

Proposition 3. [A single bad policy maker] Suppose $\tau_{c,t'} \ge \tau_{c,t}$ for all $t' \ge t$, then $L_{A,t} \ge L_A^{\tau_{c,t'}}$ and it will be constant from t and onward.

Proof. Since the clearing fines only apply to land expansion, the clearing fines being higher in the future does not deter expansion in period t. Hence, if $L_{A,t-1} < L_A^{\tau_{c,t}}$ then land use will be expanded to $L_A = L_A^{\tau_{c,t}}$ at time t. If land use is already larger than that, $L_{A,t-1} \ge L_A^{\tau_{c,t}}$, land use will be unchanged with $L_{A,t} = L_{A,t-1}$.

The proposition considers the effects of a single 'bad' policy maker and it can be illustrated with the following thought experiment. Suppose there is one economy with a low and constant clearing fines $\tau_{c,t} = \tau_c \forall t$. Compare this to a second economy where the clearing fines are *high* in all periods except the current period, where it is equal to the same low τ_c as in the first economy. The proposition says that land use will be the same in both these economies, i.e., the single bad policy maker in the second economy does the same harm as the constant presence of equally bad policy makers in the first economy. This result is important but intuitive: since the clearing fines are only incurred upon conversion, it is enough that one lenient policy maker appears. This is the dynamic counterpart of the result in Proposition 2 that clearing fines cannot be used to restore land. A further implication of the clearing fines is the following:

Proposition 4. [Brown paradox] If there is some t' > t such that $\tau_{c,t'} < \tau_{c,t}$ and $L_A^{\tau_{c,t}} > L_{A,t-1}$, then $L_{A,t} < L_A^{\tau_{c,t}}$.

Proof. We consider the case where $L_A^{\tau_{c,t}} > L_{A,t-1}$ which means that, in period t, land use in the previous period is smaller than that motivated by the current clearing fines $L_A^{\tau_{c,t}}$. Hence, land expansion is potentially profitable. In some future period the clearing fines will be lower than the current level. Land expansion cannot be profitable beyond $L_A^{\tau_{c,t}}$. Since the clearing fines will be lower that the lower in the future, we know that at some point land use will be expanded. Formally, assume that land use will be expanded at times t' > t and t'' > t' and ... and $t^{(N)} > t^{(N-1)}$, and denote the chosen land use at those times, that will be unchanged between these times, by $L_{A,t^{(n)}}$. This induces some sequences of agricultural production $\{A_t\}$ and biodiversity $\{B_t\}$ that are exogenous to the individual farmer. The contribution of revenues and costs between times $t^{(n)}$ and $t^{(n+1)}$, where land use is $L_{A,t^{(n)}}$, to total discounted profits is

$$\sum_{t=t^{(n+1)}}^{t^{(n+1)}} \beta^{t-1} \left[p\left(A_{t^{(n)}}\right) \int_{0}^{L_{A,t^{(n)}}} a\left(B_{t^{(n)}},l\right) dl - \left(p_{o} + \tau_{L}\right) L_{A,t^{(n)}} \right] - \beta^{t^{(n)}-1} \left(c + \tau_{c,t^{(n)}}\right) \left(L_{A,t^{(n)}} - L_{A,t^{(n-1)}}\right) \\ = \frac{\beta^{t^{(n)}-1} - \beta^{t^{(n+1)}-1}}{1-\beta} \left[p\left(A_{t^{(n)}}\right) \int_{0}^{L_{A,t^{(n)}}} a\left(B_{t^{(n)}},l\right) dl - \left(p_{o} + \tau_{L}\right) L_{A,t^{(n)}} \right] \\ - \beta^{t^{(n)}-1} \left(c + \tau_{c,t^{(n)}}\right) \left(L_{A,t^{(n)}} - L_{A,t^{(n-1)}}\right).$$

$$(22)$$

The maximization problem facing the farmer is

$$\max_{\left\{L_{A,t^{(n)}}\right\}_{n=0}^{N}} \sum_{n=0}^{N} \left[\begin{array}{c} \frac{\beta^{t^{(n)}-1}-\beta^{t^{(n+1)}-1}}{1-\beta} \left(p\left(A_{t^{(n)}}\right) \int_{0}^{L_{A,t^{(n)}}} a\left(B_{t^{(n)}},l\right) dl - \left(p_{o}+\tau_{L}\right) L_{A,t^{(n)}} \right) \\ -\beta^{t^{(n)}-1} \left(c+\tau_{c,t^{(n)}}\right) \left(L_{A,t^{(n)}}-L_{A,t^{(n-1)}}\right) \end{array} \right].$$

The first-order condition with respect to $L_{A,t}$ gives

$$p(A_t) a(B_t, L_{A,t}) = p_o + \tau_L + (1 - \beta) (c + \tau_{c,t}) + (1 - \beta) \frac{\beta^{t'-t}}{1 - \beta^{t'-t}} \underbrace{(\tau_{c,t} - \tau_{c,t'})}_{>0}.$$

Comparing this to the condition with constant policies in (21), we can see that the righthand side is larger here. The assumption in equation (15) then implies that the resulting land use here is smaller compared to what it would have been with constant policies. Furthermore, the same arguments as in the proof of Lemma 5 gives existence and uniqueness. This proves the proposition. Note that if either the time to the next land-use change, t' - t, goes to infinity or the difference $\tau_{c,t} - \tau_{c,t'}$ goes to zero, then the difference goes to zero.

The proposition says that if farmers expect a lenient policy (low τ_c) in the future, then they may refrain from clearing the forest today. The reason is that clearing entails a cost and this cost is smaller if done under a lenient policy. The farmer compares this to the costs of waiting with the clearing – profits are individually smaller while waiting. But if the wait is short or the future policy is much more lenient, then it is profitable for the farmer to wait. This is essentially an inverse "green paradox" (Sinn 2008; Jensen et al. 2015) – expected environmentally harmful future policies may imply better environmental outcomes today. It may be noted, however, that if the lenient policy is *not* expected (e.g., if the farmer thinks the current policy will prevail forever) then the land expansion will be made immediately as that, in expectation, implies a longer stream of profits.

Having illustrated expectations and the effects of a single policy maker, we now turn to characterizing the full dynamics of land use. We can start by noting that – since τ_L, p_0 and c are constant – it is never optimal to decrease land use except, possibly, in the first period. To see this, note that the cost of maintaining land use is always (weakly) lower than the cost of increasing land use. Hence, if it is not worth maintaining current land use, it can not have been profitable to increase land use to this level in any previous period. This implies the following lemma:

Lemma 6. Suppose p_0 , c and τ_L are constant but τ_c varies with time. Then, in a decentralized equilibrium, land use does not decrease in any period t > 1.

The lemma says that land use is not decreasing, the next proposition shows that, on top of this, land use is increasing.

Proposition 5. [Ratchet effects] Suppose $L_{A,0} < L_A^{D,low}$, where $L_A^{D,low}$ is defined in Lemma 3, then:

1. $L_{A,t}$ does not decrease for any t.

2. If $\tau_{c,t} < \tau_{c,t'}$ for all t' < t, then $L_{A,t''} > L_{A,t-1}$ for some $t'' \ge t$.

Proof. The first point follows from Lemma 6. If $\tau_{c,t}$ is the lowest it will ever be, land use from then on is given by (21) which is higher than $L_{A,t-1}$ since $L_{A,0}$ was lower than $L_A^{D,min}$ and τ_c has been higher in all previous periods. If $\tau_{c,t''} < \tau_{c,t}$ for some t'' > t one of the following must happen at some point: we reach the lowest τ_c that will ever happen, or the difference between τ_c in some period and the lowest ever τ_c is arbitrarily small. In both cases the land use will be arbitrarily close to the land use $L_A^{\tau_c,t''}$, because of the logic in the last paragraph of the proof of proposition 4, and that land use is larger than $L_{A,t-1}$.



Figure 4: History dependent equilibria and ratchet effects

Figure 2 illustrates the central implication of the proposition: that there are ratchet effects so that, if the current clearing fines are lower than they have been before, agricultural land will expand (either in that same period, or in a later period due to the brown paradox in Proposition 4); but if clearing fines are higher, land use remains and is not decreased. This will continue until a policy maker sets the fine $\tau_{c,t}$ to zero. This has the implication that bad land-clearing policies have irreversible effects on biodiversity and agricultural productivity loss, at least when land-use taxes are constant.

5 Conclusions

This paper studies pricing-type policies of land-use change aimed at holding back biodiversity loss due to the expansion of agricultural land at the expense of forests. We show that agricultural output is hill-shaped in the amount of agricultural land and that an unregulated equilibrium may, but will not always, convert too much forest land compared social optimum. In this setting, we study optimal policy using two instruments: fines for converting forest land to agriculture and landuse taxes. We show that their mix and levels depends on the amount of land used for agriculture. For instance, when agricultural land is already expansive, clearing fines do not work, and land taxes are necessary;¹⁷ when agricultural land is intermediate, a range of fines and land taxes (and their combination) can implement optimum and their minimum level is decreasing in the amount of current agricultural land; and when current agricultural land is small, then a unique level of either fines or land taxes (or a mix) achieves social optimum.

We also show that if policy is not optimal, land-expansion and biodiversity loss will experience ratchet effects: every time a lenient policy maker appears, land will expand and biodiversity will reach a new low level along with lower agricultural productivity. We also show that a 'brown paradox' may arise: in anticipation of a future lenient policy maker, farmers may postpone forest clearing that they would (if the future policy maker would have been stricter) have done otherwise. From a policy perspective, this result implies that policy makers that *are* concerned about biodiversity loss and land-use change may want to pretend that they will have future lax policies. The extent to which they can actually fool farmers into believing this (a signaling game) is however not dealt with in this paper.

In this paper, we focus on attempts to increase agricultural production through increased land use. Another option is through intensification which is the focus of Burian et al. (2024). They find that output can be hill-shaped in intensification as well and analyze when this can lead to intensification traps.

Another aspect that has not been pursued in this paper is the possibility of multiple equilibria and tipping points. In the model we made functional-form assumptions (see equation (15)) implying that the return to agricultural expansion was monotonically decreasing. It is quite possible that the preferences for food could be such that $U'(A(L_A))U'(A(L_A))a(B(L_A), L_A)$ would be non-

¹⁷Alternatively, restoration subsidies would be needed (Mirzabaev and Wuepper 2023; Wunder et al. 2020; Jayachandran 2013; Balboni, Berman, et al. 2023), a policy not analyzed formally in this paper.

monotonic. Then there could exist multiple equilibria in a decentralized setting and tipping points in a dynamic setting. That is, ones a threshold is crossed, very strict policy would be needed to return to the better equilibrium. This is akin to classic non-convexities when the biosphere and economic agents interact (Dasgupta 1996; Franklin Jr and Pindyck 2018; Gars and Spiro 2018; Li, Crépin, and Lindahl 2024).

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