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# Climate policy integration in the land use system with ecological thresholds

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**Abstract:** The land use sector is an area with high potential to pursue mitigation and adaptation goals alike. However, due to the complexity derived from managing landscapes with multiple objectives and the lack of tools to assess the outcome, this potential is presumably subtilized in practice. In order to contribute to filling in this knowledge gap, this paper analyses climate policy integration – the joint implementation of mitigation and adaptation measures – in the presence of ecological thresholds. Based on a hypothetical, yet realistic, economic-ecological system, the synergic properties of different isolated and integrated policy configurations were analysed using a dynamic optimization framework and simulation tools. The results indicate that, regardless of specific circumstances (e.g. observing or not noticing a regime shift), the configuration which better complied with the definition of a synergy, corresponded to a cross sectorial approach: an intervention involving coordination between agriculture and forestry. This result suggests that harmonization among the elements that compose the land use sector is the main source of an enhanced policy outcome. Thus, effective integration requires looking at the land use sector as an entity (e.g. a landscape) rather than isolated components (e.g. agriculture and forestry sectors).

***Keywords:*** mitigation, adaptation, climate policy integration, deforestation, resilience

***JEL codes:*** Q24, Q23

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## 1. Introduction

Nowadays, climate change is tackled with the implementation of mitigation and adaptation measures. Mitigation is an action that reduces the concentration of greenhouse gases in the atmosphere (IPCC, 2001). Therefore, it directly relates to the causes of climate change (Locatelli et al., 2011). Adaptation is an action that implies changes in the social or natural environment in

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response to current or expected climate stimuli (IPCC, 2001). Thus, it addresses the consequences of climate change (Locatelli et al., 2011). Both strategies are considered equally important as some degree of climate change is unavoidable (Tol, 2005). Moreover, due to its interrelation, it is conceived that the integration of both strategies might deliver substantial social and environmental benefits, for example, a higher reduction of greenhouse gases at a lower cost (Kane and Shogren, 2000).

The land use sector is an area with a high potential to pursue the mentioned integration (Duguma et al., 2014; IPCC, 2014). However, this potential is rarely utilized in practice (Duguma et al., 2014; Locatelli et al., 2011). Partly, due to the difficulty resulting from managing landscapes with multiple objectives and the lack of tools to assess the outcomes (IPCC, 2014; Locatelli et al., 2015). In order to contribute to filling in this knowledge gap, this paper analysed a fundamental aspect that might significantly influence the configuration of climate policy integration (CPI): the presence of ecological thresholds.

Ecological systems characterized by the presence of thresholds (a.k.a. tipping points, see de Zeeuw and Li (2016)) exhibit a relatively small response to external stresses over a certain range. This behaviour is a consequence of multiple stable steady states. However, when the threshold is reached, a small change in the stress triggers an abrupt change associated to a regime shift. The main consequence of the process described so far is a substantial change in the quantity and/or quality of ecosystem services provided. Moreover, in case a regime shift occurs, reducing the stress to the level where the collapse was observed does not restore the previous state. Due to the internal dynamics, it is required to reduce the stress even further (e.g. to another threshold) in order to restore the original state (Scheffer et al., 2001). The capacity of some systems to alternate between regimes is called hysteresis. However, in some cases, restoration is not possible or it proves very costly. Thus, the regime shift is considered irreversible (Scheffer et al., 2001).

Examples of ecological systems exhibiting the above behaviour have been recorded in different types of ecosystems. For instance, there is extensive evidence of shallow lakes suddenly turning from a clear water state into a murky one (Scheffer et al., 2001). Likewise, in terrestrial ecosystems, switches from a forestland to savanna (Leonel Da Silveira Lobo Sternberg, 2001) or disruption of regional climate due to deforestation (Zheng and Eltahir, 1998) have been recorded in different locations. Similarly, literature shows forest functions are not always fully recovered after land abandonment (Locatelli et al., 2017). In fact, growing evidence suggests that thresholds in ecological systems are the rule rather than the exception. Moreover, as a consequence of human influences, regime shifts are becoming increasingly common as the mentioned disturbances exacerbate resilience capacity (Folke et al., 2004).

From the economic perspective, the potential presence of ecological thresholds in terrestrial ecosystems poses a challenge to the optimal use of land resources. In the specific case of tropical deforestation, environmental goals and social needs require apparently dissimilar actions with respect to land use. For instance, avoiding further climate change and maintaining resilient ecosystems calls for forestland conservation strategy. However, welfare of rural communities in the mentioned areas is closely linked to the productive use of land (Pramova et al., 2012), which normally involves some degree of environmental degradation (e.g. deforestation or forest degradation). The problem arises from the fact that environmental degradation is usually ignored when land use decisions are made (Barbier et al., 2010). This translates into excessive deforestation that might result in a regime shift and a productivity collapse. In these circumstances, policy intervention targeted to balance environmental goals and social needs is in principle able to deliver important welfare and environmental gains.

In the present analysis, the performance of specific policy interventions was evaluated using the concept of synergy: an approach that aims at optimizing landscape functions through the implementation of mitigation and adaptation measures rather than pursuing mitigation or adaptation goals *per se* (Duguma et al., 2014). The specific interpretation of a synergy followed in this study was to achieve the highest sustainable output with least possible degree of environmental degradation. Thus, the main goal was to identify the policy configurations able to trigger synergies by comparing the performance of isolated and integrated policy approaches with respect to the unregulated scenario.

This paper is structured as follows: the next section presents the structure of the model. In the third section, the analytical solution is presented with the purpose of analysing the effect of environmental policy on land allocation. The fourth section shows simulation results of a parameterized version of the model. In the last section, the concluding remarks are summarized. Additionally, an appendix shows how resilience was measured and the computation details followed to implement model simulations.

## 2. Model

The model analysed is composed of two systems: the economic and ecological one. These systems are interlinked by land allocation. Specifically, it is assumed that forestland promotes the regeneration of the environment and agriculture land deteriorates it, though its impact can be reduced through the implementation of ecologically friendly practices. In line with recent research findings (Reed et al., 2017), it is additionally considered that output is jointly determined by the state of the environment (ecological system) and the amount of land allocated to agriculture (economic system). In what follows, each one of these systems is described in detail.

**2.1. Economic system**

The economic system considers a representative competitive firm that uses cleared land to perform production process, its goal is to maximize the discounted value of profits by choosing the investment rate and adaptation level. Investment is needed to bring forestland into production, hence, it considers both: the cost of land and the cost of clearing. Likewise, agricultural adaptation level is understood as the implementation of ecologically friendly practices (e.g. soil conservation measures, use of agroforestry and silvopastoral systems).

The economic system described so far, closely follows the adjustment cost formulation (Barro and Sala-i-Martin, 2004) and is extended to include the cost of implementing adaptation measures in the agricultural subsector. Formally, the problem of the representative firm is:

$$\max_{I,A,L_a} V_o = \int_0^\infty [Y\big(L_a(t), E(t)\big) - I(t)\left(c_l + f\left(\frac{I(t)}{L_a(t)}\right)\right) - c_a A_a(t) L_a(t)]e^{-\rho t} \tag{1}$$

$$\text{s.t.}$$
$$i)\ \dot{L}_a(t) = I(t)$$
$$ii)\ \bar{L} = L_a(t) + L_f(t)$$

where:

*Y* is the quantity of output at time *t*;

*L(t)* is the amount of land allocated to the use represented by the subscript (*a* for agriculture and *f* for forest) at time *t*;

*E(t)* is the state of the environment (as described in the next section) at time *t*;

*I(t)* is the net investment rate at time *t*;

$f(\,)$ is the adjustment cost function, assumed to be convex and satisfies f(0) = 0;
$A_a(t)$ is agricultural adaptation level (required to be nonnegative) at time $t$;
$c$ is the unitary cost of inputs indicated by the subscript ($l$ for land and $a$ for adaptation);
$\dot{L}_a(t)$ is the time derivative of agriculture land at time $t$;
$\bar{L}$ is the land endowment (fixed).

It must be considered that from the formulation of the economic system, output level is later used as an indicator of sustainability.

## 2.2. Ecological system

The ecological system determines the state of the environment based on its internal dynamics and the interaction with the economic system. The key characteristic of this system is the presence of thresholds, which allows for distinctive dynamic regimes. In order to represent the dynamic structure, the environment evolves over time, according to the following specification:

$$\dot{E}(t) = \varepsilon_f L_f(t) + \varepsilon_a\big(A_a(t)\big)L_a(t) - \phi(E(t)) \qquad (2)$$

where:
$\varepsilon_f$ is a parameter that reflects how forestland promotes environmental regeneration;
$\varepsilon_a$ is a concave function of $A$ with $\varepsilon_a(0) = 0$;
$\phi(\,)$ is a nonlinear function that represents the internal dynamics.

The first two terms on the right hand side of the previous equation represent the interaction of the economic system with the ecological one. The first term can be interpreted as an ecological factor that is promoted by the presence of forests. Similarly, the second term can be seen as an adaptation measure whose aim is to reduce the impact of agriculture in the process considered. An example of such a process is water balance: documented cases show that deforestation may significantly affect regional weather (e.g. a collapse of monsoon, see Zheng and Eltahir (1998)), the state of the environment (e.g. a collapse of cloud forest, see Scheffer et al. (2001)) or trigger a regime shift of the environment (e.g. from forestland to savanna, see Leonel Da Silveira Lobo Sternberg, 2001). These cases have the common feature that changes in forest cover disrupted water cycle. Therefore, it follows that ecologically-friendly practices in agriculture that aim at maintaining trees within the cropland, such as the use of agroforestry or silvopastoral systems, are able to reduce the ecological impact of deforestation (Harvey et al., 2014).

For the remainder of this paper, the third term of equation (2) takes the particular form:

$$\phi(E) = dE - \frac{E^2}{E^2 + 1} \tag{3}$$

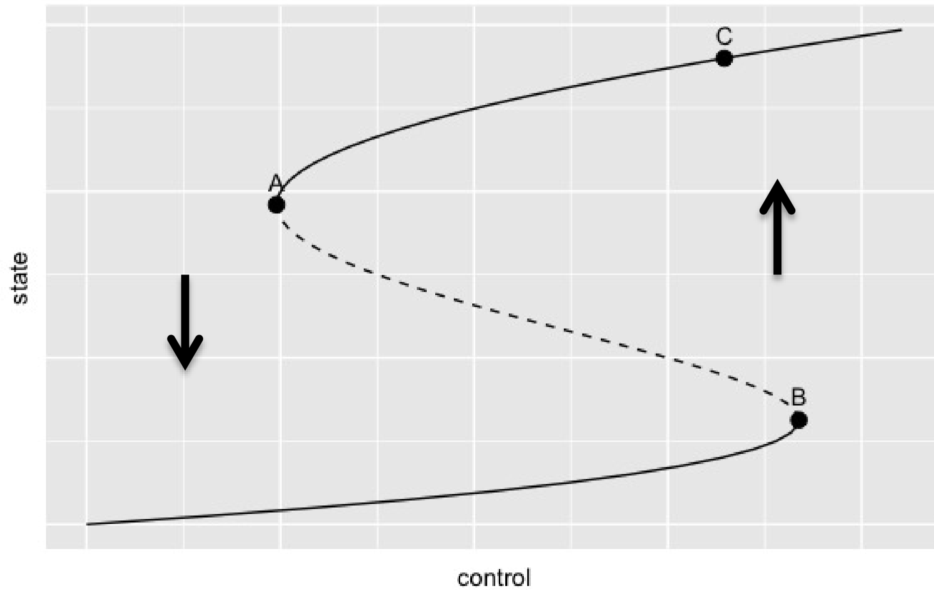
where:

*d* is a parameter that represents the decay rate of the environment.

Following the previous example, the parameter *d* can be thought to be the rate at which water leaves the ecosystem, for example as runoff or evapotranspiration. Notice that the second term in the above equation represents an internal recycling rate (Scheffer et al., 2001). In the current example, it can be treated as water condensation by trees canopy.

For a particular range of value of the parameter *d* ($0.5 < d < 3\sqrt{3}/8$ given the current formulation), the above equation gives rise to the so-called Shallow Lake Dynamics (SLD) (Heijdra and Heijnen, 2013; Mäler et al., 2003). In other words, the ecological system is characterized by two distinct dynamic regimes (represented as solid lines in Figure 1), abrupt changes occur in the vicinity of thresholds (points A and B) and hysteresis is possible. For this application, the upper branch corresponds to a high provision of ecosystem services, which translates to a high productivity of the system (desired state). Conversely, the lower branch corresponds to a low provision of ecosystem services and a low productivity (undesired state).

**Figure 1. Scheme of Shallow Lake Dynamics**




Source: author's own elaboration based on Heijdra and Heijnen (2013).

It is important to highlight that ecological system determines resilience level – measured as the distance from current location to the relevant threshold (see Appendix A.1. for details) – and the amount of forestland. These two variables are used as adaptation and mitigation indicators respectively. Likewise, resilience and output level – defined in the economic system – determine sustainability. Thus, from equations (1) and (2), it is possible to infer that land reallocation directly increases output. However, it also results in forestland reduction, which indirectly affects output level through changes in the state of the environment. As the variable mentioned can be modified through different channels given the current formulation, in the following different mitigation and adaptation instruments – further described in section 3.2 – are analysed in order to identify policy configurations (e.g. isolated or combined) able to balance economic and environmental goals. If it is considered that the state of the environment is treated as an externality under an unregulated economy, policy intervention is theoretically able to deliver welfare gains.

## 3. Land allocation at the steady state

This section uses a dynamic optimization framework to derive land allocation at the steady state under different policy configurations. In the first subsection, the unregulated situation is considered and sources of inefficiency are identified. The second subsection derives a general solution assuming different mitigation and adaptation instruments available for the policy maker. More specifically, it is demonstrated that the unregulated situation is a particular case of the general solution when no intervention takes place. Furthermore, the general effect of any policy intervention is a reduction of the share of land allocated to agriculture with respect to the unregulated situation. Therefore, environmental gains are easily anticipated. The effect of such policies on output, however, depends on specific circumstances, for instance, whether or not a regime shift is observed in the unregulated situation.

### 3.1. Unregulated economy

In the unregulated setting, it is considered that no intervention from the policy maker takes place and firms neglect the environmental effects of their land use decisions. As a consequence, the state of the environment is inaccurately considered as a constant (e.g. $E = E(0)$, where $E(0)$ is the initial value of the state variable $E$). In addition, the level of adaptation chosen by firms is assumed to be zero (e.g. there is no autonomous adaptation). Thus, the land allocation resulting from the described configuration can be found by solving the following dynamic problem (time scripts were omitted for simplicity):

$$\max_{I,L_a} V_o = \int_0^{\infty} [Y(L_a, E(0) - I\left(c_L + f\left(\frac{I}{L_a}\right)\right)]e^{-\rho t}$$

$$\text{s.t.} \quad i)\ \dot{L}_a = I \quad ii)\ \overline{L} = L_a + L_f \qquad (4)$$

The current value Hamiltonian and the first order conditions (FOC) of the previous problem are shown in Table 1. Taking into consideration that investment rate at the steady state is equal to zero, the static efficiency condition implies that $\lambda_L = c_L$. Meaning that – at the steady state – the shadow price of land is equivalent to its cost. Taking the dynamic efficiency condition equal to zero and substituting the previous relation, we get the following:

$$Y_L'(E(0)) = \rho c_L \tag{5}$$

Where the term E(0) indicates that the marginal product of land is distorted by disregarding the effects that land reallocation has on the state of the environment. Assuming an interior solution, equation (5) can be interpreted as follows: if the economy is left unregulated, the representative firm would allocate land to agriculture up to the point where the marginal gain is equal to its cost. It is important to highlight, however, that land allocation derived from the previous relation is not optimal as the marginal product of land is distorted. Consider, for example, a situation in which deforestation is at the expense of large extensions of primary forest. In that case, the ecological system would be located at the top-right of Figure 1 (e.g. point C), which corresponds to high proportion of forestland and high provision of ecosystem services. From that point, any reduction of forestland necessarily deteriorates the environment and, as a consequence, the marginal product of land tends to be overestimated (*E(0) > E(t)*).

**Table 1. Hamiltonian and FOC for the unregulated economy**

| | |
|---|---|
| Hamiltonian | $H_c = Y(L_a, E_0) - I\left(c_L + f\left(\frac{I}{L_a}\right)\right) + \lambda_L I$ |
| FOC | $\frac{\partial H_c}{\partial I} = -c_L - f\left(\frac{I}{L_a}\right) - f'\left(\frac{I}{L_a}\right)\left(\frac{I}{L_a}\right) + \lambda_L = 0$ <br> $\dot{\lambda}_L = \rho\lambda_L - Y_L' - \left(\frac{I}{L_a}\right)^2 f'\left(\frac{I}{L_a}\right)$ |

Source: Author's own elaboration.

### 3.2. Policy Intervention

In order to derive a general solution to the model presented in the previous section, a dynamic optimization framework from the point of view of the policy maker was followed. It is considered that the policy maker has at their disposal adaptation and mitigation instruments in the forestry subsector. These instruments are implementable through price or direct regulation (e.g. as taxes or quotas). In addition, the policy maker is able to induce the implementation of ecologically friendly practices in agriculture, which are interpreted as adaptation measures in this subsector. The specification of each of these policy instruments is described next.

The adaptation measure in forestry aims at internalizing the effects of land use change on the state of the environment, which translates into the fact that equation (2) explicitly enters into the decision problem as a dynamic constraint. Likewise, the mitigation instrument follows a conservation-based scheme. Specifically, it is assumed that the policy maker knows the impact that a change in forestland has on social welfare. For example, it is known that forestland is a component of the social utility function. Likewise, it is known how society weighs this component relative to social needs (the approach followed here). It is important to highlight that this form of mitigation differs from international schemes such as REDD+ (Reduction of Emissions from Deforestation and forest Degradation), which is based on avoided deforestation over a baseline.

Any specific process that leads to the implementation of ecologically friendly practices in agriculture is not explicitly considered. In turn, it is simply assumed that after the implementation of the policy, farmers select an adaptation level based on economic rationality (see equation (1)). A possible scenario under which this process seems realistic is, for instance, when farmers were unaware of such measures or did not properly measure their benefits.

Taking into consideration the previous conceptualization of policy instruments, the optimization problem faced by the policy maker is:

$$\max_{I,A_a,w_f,L_a,E} W_o = \int_0^\infty [\Pi_a + w_f U(L_f)] e^{-\rho t}$$

$$\begin{gathered} \text{s.t.} \\ i)\ \dot{L}_a = I \\ ii)\ \dot{E} = \varepsilon_f L_f + \varepsilon_a(A_a) L_a - \phi(E) \\ iii)\ \bar{L} = L_a + L_f \\ iv)\ w_f \leq w_{max} \\ v)\ w_f, A_a \geq 0 \end{gathered} \tag{6}$$

where:

$\Pi_a$ are the profits from agriculture (see equation (1));

$w_f$ is the weight attached to utility from forestland;

$U(\ )$ is a concave utility function.

The current value Hamiltonian (with the third constraint substituted) of this problem is:

$$\begin{aligned} H_c = {} & Y(L_a, E) - I\left(c_L + f\left(\frac{I}{L_a}\right)\right) - c_a A_a L_a \\ & + w_f U(\bar{L} - L_a) + \upsilon_f\left(w_{max} - w_f\right) + \lambda_L I \\ & + \lambda_E(\varepsilon_f L_f + \varepsilon_a(A) L_a - \phi(E)) \end{aligned} \tag{7}$$

where:

$\lambda_L$ is the co-state variable of agriculture land;

$\lambda_E$ is the co-state variable of the environment;

$\upsilon_f$ is Lagrange multiplier for $w_f$.

Please note that $I$, $A_a$ and $w_f$ are the control variables and $L_a$ and $E$ the state variables. Therefore, the First Order Conditions are:

$$\frac{\partial H_c}{\partial I} = -c_L - f\left(\frac{I}{L_a}\right) - f'\left(\frac{I}{L_a}\right)\left(\frac{I}{L_a}\right) + \lambda_L = 0 \tag{8}$$

$$\frac{\partial H_c}{\partial A} = -c_a L_a + \lambda_E(\varepsilon_a'(A_a)L_a) \le 0, \qquad A_a \ge 0 \tag{9}$$

$$\frac{\partial H_c}{\partial w_f} = U(\bar{L} - L_a) - \upsilon_f \le 0, \qquad w_f \ge 0 \tag{10}$$

$$\frac{\partial H_c}{\partial \upsilon_f} = w_{max} - w_f \le 0, \qquad \upsilon_f \ge 0 \tag{11}$$

$$\dot{\lambda}_E = \left(\rho + \phi'(E)\right)\lambda_E - Y_E' \tag{12}$$

$$\begin{aligned} \dot{\lambda}_L = {} & \rho\lambda_L - \left(-\varepsilon_f + \varepsilon_a(A_a)\right)\lambda_E + w_f U'\left(L_f\right) + c_a A_a - Y_L' \\ & - f'\left(\frac{I}{L_a}\right)\left(\frac{I}{L_a}\right)^2 \end{aligned} \tag{13}$$

Equations (8) to (11) represent the static efficiency conditions and determine the optimal choices of the control variables $I$, $A_a$, $w_f$ and by extension $\upsilon_f$ (respectively). Equation (8) relates to investment with the shadow price of agriculture land. Specifically, it shows that at the steady state the shadow price of land is equivalent to its cost. Otherwise, there will be incentives for the firm to invest.

Equation (9) relates the optimal choice of $A_a$ to its cost. Concretely, it implies that in case ecologically-friendly practices in agriculture are implemented (the optimal choice of $A_a$ is strictly positive), these activities will be used up to the point where their marginal benefits properly valued equal the cost. Notice that as agricultural land appears in both terms of the equation this term can be dropped out of the interpretation. Alternatively, when $A_a$ is set to zero (e.g. it is not contemplated as part of the policy design), this constraint is inactive.

Equations (10) and (11) indicate the conditions that must hold when mitigation is part of the policy design. More specifically, for strictly positive values of $w_f$, the selected weight of this component must be at its maximum possible value ($w_f = w_{max}$) and its marginal contribution to the objective function is equivalent to the utility derived from forestland. As in the previous case, if this instrument is not contemplated as part of the policy design ($w_f = 0$), then the previous considerations do not apply.

Equation (13) and (12) are the dynamic efficiency conditions, they determine the equation of motion of the shadow price of the environment and land allocation, respectively. Equation (12) indicates that along the optimal path, the gains from land use change must be balanced with its costs. As before, in case no adaptation measure in forestry subsector takes place, this last consideration does not apply.

The key result from this analysis is derived from equation (13). Rearranging this equation and using the steady state conditions previously derived ($I = 0$, $\lambda_L = c_L$), we get that at the steady state land allocation satisfies the following condition:

$$Y_L' = \rho c_L - \left(-\varepsilon_f + \varepsilon_a(A_a)\right)\lambda_E + w_f U'(L_f) + c_a A_a \qquad (14)$$

As it can be observed, the previous equation determines land allocation in terms of policy configuration. Consider, an intervention in which the mitigation component is not active. In such a case, the third term on the right hand of the equation is equal to zero. Likewise, in case no ecologically-friendly practices are implemented in agriculture ($A_a = 0$), the last term cancels out and the second term reduces to $\varepsilon_f\lambda_E$. Similarly, the effect of not implementing adaptation in forestry is double: on the one hand – the second term on the right hand side cancels out and the marginal product of land – the left hand side of equation (14) – is overestimated as it was detailed before. It is worth noticing that in the case of no policy implementation, equations (14) and (5) are equivalent.

## 4. Policy Experiments

In this section an empirically relevant initial value problem is simulated under different policy configurations in order to identify the scheme that better complies with the interpretation of synergy followed here. The implementation of the numerical solution was made in the software R (R Core Team, 2016), using the packages *deSolve* (Soetaert et al., 2010) and *rootSolve* (Soetaert and Herman, 2008). Likewise, results visualization was implemented in the same software using *ggplot2* package (Wickham, 2016).

### 4.1. Policy Configurations

The policy configurations analysed are shown in Table 2. In addition to the unregulated situation (*U*), which is used as the baseline, four policy configurations are considered: adaptation (*A*), mitigation (*M*), sectorial policy integration (*SPI*) and cross sectorial policy integration (*CSPI*). Notice that the configuration of adaptation policy involves only the implementation of the relevant instrument in forestry subsector.

**Table 2. Policy configurations**

| Policy | Configuration | | | Land allocation |
|---|---|---|---|---|
| | $A_f$ | $M_f$ | $A_a$ | |
| Unregulated | | | | $Y_L'(E(0)) = \rho c_L$ |
| Adaptation | | | | $Y_L' = \rho c_L + \varepsilon_f \lambda_E$ |
| Mitigation | | | | $Y_L'(E(0)) = \rho c_L + w_f U'(L_f)$ |
| SPI | | | | $Y_L' = \rho c_L + \varepsilon_f \lambda_E + w_f U'(L_f)$ |
| CSPI | | | | $Y_L' = \rho c_L - (\varepsilon_a(A_a) - \varepsilon_f)\lambda_E + c_a A_a$ |

Source: Author's own elaboration

The last column of Table 2 shows how the various policy configurations modified land allocation with respect to the unregulated situation. The common characteristic is that in general and regardless of the scheme followed, land allocated to agriculture decreases with respect to the unregulated economy. However, this effect is achieved through different channels. Mitigation policy, for example, achieves a reduction by increasing the opportunity cost of forestland, which in this case includes the reduction in utility due to the loss of forestland. In a similar vein, the adaptation policy increases the cost of land by including environmental degradation. Additionally, it also corrects the distortion of the marginal product of agricultural land by adjusting the state of the environment to its current value. The SPI simply combines the two previously described effects. Thus, compared to isolated efforts, the fraction of land allocated to agriculture is even smaller.

In the case of CSPI, the reduction in the share of agriculture land is achieved through an increase in the opportunity cost of land ($c_a A_a$) and the reduction in the impact of land use change on the environment ($\varepsilon_a(A_a)$). Notice that a realistic parameterization of the model suggests that $\varepsilon_f > \varepsilon_a(A_a)$, which means that the impact of deforestation can be reduced but not fully eliminated. Hence, the sign of the second term is positive.

The reduction in share of agricultural land that follows from policy implementation automatically translates to an improvement of environmental goals. However, to comply with the definition of synergy, negative effects on output level should be avoided or minimized. In this regard, the expected impact of the analysed configurations is ambiguous: on the one hand, the reduction in land leads to a reduction in output. On the other hand, an increase in the share of forestland has a positive effect on the state of the environment and thus – indirectly – on output. The net effect, nonetheless, depends on additional circumstances, for example, whether or not the unregulated situation leads to a regime shift and whether policies can avoid this outcome or not.

### 4.2. Model calibration

Simulations were initialized using observed average forest cover in countries at pre-transition phase of forest transition process[1] (Hosonuma et al., 2012) and assuming the ecological system is located at the corresponding upper branch steady state (e.g. point *C* in Figure 1). Forest cover at the mentioned stage can be up to 65 percent. Due to the fact that calculations do not refer to any specific country a value of 60 percent was used. Table 3 shows the corresponding value for the ecological equilibrium.

[1] Forest transition is the process of reduction and later recovery of forest cover in a country or region as a result of economic development. Hosonuma et al. (2012) classified 100 non-annex 1 tropical countries in one of the four categories of the process mentioned: pre-transition, early transition, late transition and post-transition.

**Table 3. Parameters used to perform simulations**

| Parameter | Value | Description | Source |
|---|---|---|---|
| **Initial conditions** | | | |
| $L_f(0)$ | 0.6 | Initial forestland fraction | Hosonuma *et al*. 2012 |
| E(0) | 1.5 | Initial state of the environment | Derived from $L_f(0)$ |
| **Economic system** | | | |
| $\alpha_L$ | 0.32 | Exponent of agricultural land in production function | Jointly determined to replicate late transition phase reported in Hosonuma *et al*. 2012 |
| $\alpha_E$ | 0.25 | Exponent of the state of the environment in production function | |
| $c_L$ | 10/9.5* | Cost of land reallocation | |
| ρ | 0.04 | Discount rate | Heijdra and Heijnen 2013 |
| **Ecological system** | | | |
| $\varepsilon_f$ | 0.15 | Environmental regeneration promoted by forestland | Zheng and Eltahir 1998 |
| $d$ | 0.52 | Environment decay rate | Heijdra and Heijnen 2013 |
| **Mitigation policy** | | | |
| $w_f$ | 0.1 | Relative weight mitigation | Jointly determined to replicate post transition phase reported in Hosonuma *et al*. 2012 |
| $\beta$ | 0.12 | Utility function exponent | |
| **Ecologically friendly practices in the agriculture subsector** | | | |
| $\Upsilon$ | 0.25 | Exponent adaptation effect function | Jointly determined to ensure positive choice of A level in agriculture |
| $c_a$ | 0.01 | Cost of adaptation | |
| $a$ | 0.25 | Adaptation effectiveness | |
| $c_a$ | 0.01 | Cost of adaptation | |
| $a$ | 0.25 | Adaptation effectiveness | |

Source: Author’s own elaboration based on specified literature.

*parameter change to trigger a regime shift

Parameters for the economic system were chosen to jointly replicate forest cover observed in countries at the late transition phase under the unregulated scenario. The idea behind it is that policy was not likely to be implemented in these locations. At the phase mentioned, forest cover was reported to take values up to 15 percent (Hosonuma et al., 2012). Therefore, using the following form for the production function:

$$Y(L_a, E) = L_a^{\alpha_L} E^{\alpha_E} \tag{15}$$

and given a typically assumed discount rate in macroeconomic literature (Heijdra & Heijnen, 2013), the rest of the relevant parameters (see equation (5)) were jointly determined to satisfy the assumptions followed (marginal decreasing product of land and forest benefits) and replicate the mentioned forest cover value.

Difficulties in determining parameters in the ecological system arise from the fact that little is known about the specific processes that give rise to the so-called Shallow Lake Dynamics. For example, threshold locations are highly uncertain and hard to predict. Yet an effort has been made to use a plausible specification. Internal dynamics (see equation (3)) were quantified following Folke et al., (2004) and Heijdra & Heijnen (2013). For the specific case of land ecosystems, it has been observed that forest cover plays a key role in determining ecosystem dynamics and regime shifts (Cochrane, 2001; Leonel, 2001). Moreover, disruptions possibly indicating a regime shift have been recorded at some locations for forest cover losses surpassing 90% of the original area. Hence, the parameter $\varepsilon_f$ was selected to define the threshold of the upper branch at around 10 percent of the specified initial forest cover (Zheng and Eltahir, 1998).

The parameters to define mitigation policy were selected to replicate forest cover values observed at the post-transition phase. The logic is that recent efforts to tackle deforestation have been made mainly driven by mitigation efforts. The reported values for this phase of the forest transition process are around 25 percent of land allocated to forest cover (Hosonuma et al., 2012).

The purpose of introducing adaptation in agriculture subsector was to analyse the effect of this measure in the overall behaviour of the model and its implications. Hence, the specific parameters in this case were selected to ensure a positive optimal choice of adaptation in agriculture subsector; otherwise, this configuration is equivalent to the adaptation scenario (see equations (9) and (14)). However, intuitively they reflect realistic features: in addition to satisfying commonly assumed economic properties (marginal decreasing benefits), they also reflect that the activities mentioned are able to reduce the impact of deforestation but not fully substitute ecological functions of forest ecosystems.

## 4.3. Model Simulations

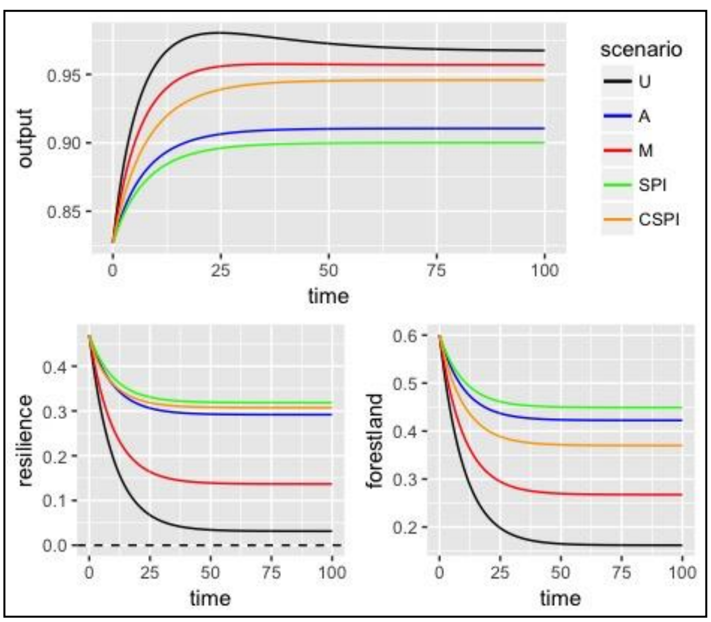
**The indicators of policy performance under the condition that a regime shift did not take place are summarized in**

Figure 2. It is worth noticing that the unregulated scenario exhibited the highest output level (top panel). However, the environmental indicators (low panel) for this scenario reveal that the higher output level was achieved at the cost of high environmental degradation. In line with the analytical procedure, the lowest share of forestland and consequently the lowest carbon stock corresponded to this scenario. In particular, forestland was reduced from 60 to only 16 percent of the total

endowment, a forest cover reduction similar to values observed in some tropical countries that have experienced important deforestation processes (e.g. countries at the late transition phase). As a consequence, the resilience of the ecosystem was seriously eroded. From an initial value of 0.47, this index was reduced to a value marginally above zero, which means that the ecological system locates very close to a threshold. Thus, all it would take to trigger a regime shift is a relatively minor shock. Taking into consideration previous observations, the output level in the unregulated scenario cannot be considered sustainable.

Figure 2 also shows that, among the policies analysed, the intervention that exhibited the highest output level was mitigation. In this case, forest cover is reduced from 60 to 27 percent, a value similar to an average forest cover observed in tropical countries that have experienced the post-transition phase. However, a closer look at environmental indicators revealed that – like in the unregulated situation – the resilience capacity of the ecosystem was seriously eroded. This behaviour can be explained when it is considered that the policy allocated the lowest land share to forestry use. As the resilience of the system is lower than in other interventions, the sustainability of *M* policy is questionable.

**Figure 2. Simulation results when no regime shift took place under the unregulated scenario**

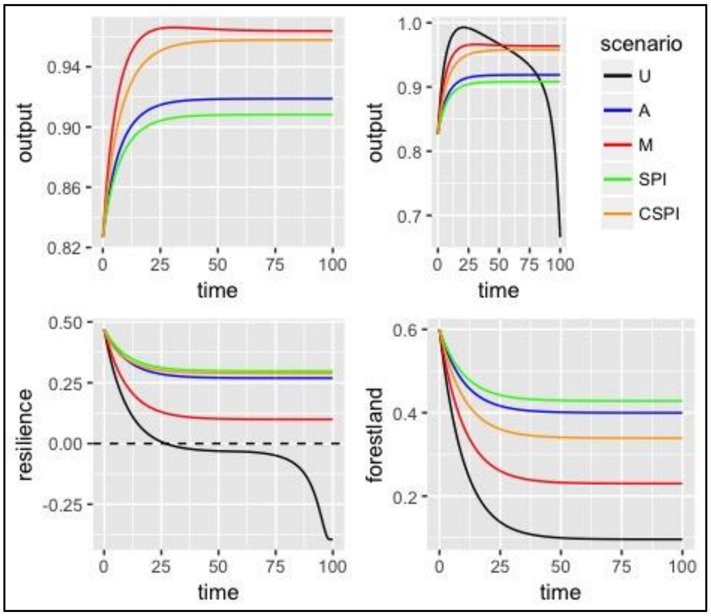



Source: Author’s own elaboration

It is worth noticing that in terms of resilience, configurations *A*, *SPI* and *CSPI* were almost indistinguishable from one another, which means that in general the output level achieved was sustainable. However, an important trade-off took place in terms of mitigation and output when policies *A* and *SPI* were considered. These policies allocated the highest shares of land to forest use, 43 and 47 percent, respectively. The output level, nevertheless, was significantly lower compared to *CSPI* (3.2 and 4.2 percentage points less at the steady state respectively). This last configuration allocated a lower fraction of land to forest use, 37 percent, but it is characterized by a relatively higher output level: 1.1 and 2.2 percent lower than in *M* and unregulated scenarios at the steady state. Taking all the previous considerations together, *CSPI* is the configuration that was consistent with the definition of synergy when no regime shift took place.

Now the situation in which the unregulated scenario triggers a regime shift is studied. The performance of the analysed policy configurations is summarized in Figure 3. One important feature to highlight is that under the assumed condition, output collapsed in the long run when no policy intervention took place (see the black line in the top right panel). The reason behind this result can be explained using the environmental indicators: excessive deforestation put the ecological system in the basin of attraction of the lower branch, which is associated with a low productivity. This process can be clearly seen in the trajectory followed by the resilience index (bottom left panel): around the year 25 of the simulation, the indicator becomes negative, meaning that the ecological threshold was surpassed. As it has been detailed before, when this happens the internal dynamics of the ecological system pushes the state of the environment to the lower branch, which resulted in the productive collapse mentioned.

**Figure 3. Simulation results when a regime shift is observed under the unregulated scenario**




Source: Author's own elaboration

A second fundamental observation is that all policy interventions studied are able to avoid the regime shift. However, a closer look at the economic performance (see the top left panel, where unregulated scenario is not included) reveals a similar pattern to the one observed in the previous case. In other words, the highest output level in the long run corresponds to mitigation policy. However – once again – resilience of the ecosystem is considerably lower compared to alternative interventions, which suggests that the sustainability of output might be compromised. As in the previous case, *CSPI* complied better with the definition of synergy. The reason is that this configuration delivered a higher output level compared to the configurations with a similar level of resilience (*A* and *SPI*), and allocated a higher fraction of land to forestry compared to *M* policy.

## 5. Conclusions

In this paper a coupled economic-ecological system characterized by the presence of ecological thresholds was studied with the aim to identify policies with synergic properties. These were interpreted as outcomes delivering the highest possible sustainable output (e.g. not declining over time) with the least possible environmental degradation. The results indicate that regardless of specific circumstances (e.g. observing or not a regime shift), the cross sectorial approach is the policy configuration that better complies with the definition of synergy. Therefore, the most relevant form of policy integration in the system analysed here requires policy coherence among the elements that conform the land use sector. Putting it differently, an effective policy relies on treating the land use sector as a whole (e.g. a landscape) rather than isolated components (e.g. agriculture and forestry subsectors).

The results obtained, therefore, suggest that implementation of forest conservation strategies, such as REDD+, should be ideally complemented with the implementation of coherent ecologically-friendly practices in agriculture in order to maintain resilient and productive landscapes. However, contextualization of regional reality and further research are needed to translate the theoretical implications turning them into specific measures able to minimize or avoid trade-off at the regional level.

It must be considered that this result relies on two key assumptions: first, ecological processes sustain the productivity of the agricultural system; and second, the agricultural sector possesses the capacity to reduce the impact of land use change on key ecological processes. Research findings provide empirical support to the assumptions on which the results derived here rely on. For example, a systematic review of the contribution of ecosystem services to crops concluded that the presence of a nearby forest and trees within the cropland have the sufficient capacity to maintain or enhance yields with respect to monoculture systems (Reed et al., 2017). Likewise, the identified mitigation and adaptation potential in agriculture (Smith and Olesen, 2010) and the possibility to foster ecologically-friendly agriculture throughout a proper management of them (Harvey et al., 2014), suggest that the second assumption holds to some extent.

It is important to highlight that this analysis focused on sustainable production of a coupled ecological-economic system. As a consequence, environmental services potentially relevant but not evidently connected to productivity were implicitly omitted from the analysis. An example of a probably important omission is biodiversity, which according to some studies has the highest correlation with the provision of other environmental services (Locatelli et al., 2014).

## Appendix

### A.1. Resilience index

The resilience index is defined as follows:

$$R = L_f(t) - T \tag{16}$$

where:

$L_f(t)$ is the amount of forestland at time $t$;

$T$ is the ecological threshold value in terms of control variable, depending on the regime governing the dynamics, $T$ takes the local minimum (the upper branch regime) or minimum (the lower branch regime) of the internal dynamics function $\phi(E)$.

The resilience index simply computes the difference between the current and the relevant threshold value of the control variable. In other words, the index indicates how much forest cover must be decreased (or increased if its sign is negative) to trigger a regime shift. Thus, positive and large values are signals of a resilient system. On the contrary, negative measures of resilience with large absolute value indicate systems that are harder to restore.

**A.2. Implementation of the numerical solution**

The economic system was simulated following a goal seeking structure (Sterman, 2000). Given by the following equation:

$$\dot{L}_a = \frac{L_a^* - L_a(t)}{AT} \tag{17}$$

where:

$L_a^*$ is the fraction of land allocation to agriculture at the steady state;

$AT$ is the adjustment time parameter (measured in years).

From the computational point of view, the previous formulation has the advantage of implicitly satisfying the trans-versality condition when the steady state and speed of convergence (reflected in the $AT$ parameter) are provided, without explicitly computing the investment level on the stable arm given the initial land allocation.

The steady state was found using the analytical representation of the desired policy configuration (see Table 2). More specifically, the relevant system of simultaneous equations was solved using the R package *rootSolve*. Then, for each policy configuration analysed, the resulting equilibrium land allocation was substituted in equation (17).

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## *Integracja polityki klimatycznej w systemie użytkowania gruntów z progami ekologicznymi.*

### *Streszczenie*

Sektor użytkowania gruntów jest obszarem o dużym potencjale do realizacji i łagodzenia celów. Jednak ze względu na złożoność wynikającą z zarządzania krajobrazem z wieloma celami i brakiem narzędzi do oceny wyników, potencjał ten jest prawdopodobnie wysubtelniony w praktyce. Aby przyczynić się do wypełnienia tej luki w wiedzy, niniejszy artykuł analizuje integrację polityki klimatycznej - wspólne wdrażanie środków łagodzących i dostosowawczych - w obecności progów ekologicznych. Opierając się na hipotetycznym, realistycznym oraz ekonomiczno-ekologicznym systemie, analizowano synergiczne właściwości różnych izolowanych i zintegrowanych konfiguracji polityk przy użyciu dynamicznej struktury optymalizacji i narzędzi symulacyjnych. Wyniki wskazują, że niezależnie od konkretnych okoliczności (np. Obserwacja lub niezauważenie zmiany reżimu), konfiguracja, która lepiej odpowiadała definicji synergii, odpowiadała podejściu międzysektorowemu: interwencji obejmującej koordynację między rolnictwem a leśnictwem. Wynik ten sugeruje, że harmonizacja elementów składających się na sektor użytkowania gruntów jest głównym źródłem ulepszonych wyników polityki. Skuteczna integracja wymaga zatem spojrzenia na sektor użytkowania gruntów jako podmiot (np. Krajobraz), a nie pojedyncze elementy (np. Sektory rolnictwa i leśnictwa).

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***Słowa kluczowe:*** łagodzenie, adaptacja, integracja polityki klimatycznej, wylesianie, odporność

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