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When Does the Integration of Mitigation and Adaptation in the Land Use Sector Actually Makes Sense?

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Abstract

The phenomenon of climate change is addressed through two main strategies: mitigation and adaptation. It is broadly recognized that both strategies are interrelated, yet in the land use sector this connection is particularly strong. In fact, the mentioned sector is one of the most promising areas to combine mitigation and adaptation into a single intervention. In spite of its potential, in practice mitigation and adaptation are still treated as two different policy instruments. Concerns about efficiency have emerged as a result of such a dichotomy. However, how to manage an integrated implementation of mitigation and adaptation is still poorly understood. In this research paper, enabling conditions for an enhanced policy outcome in the land use sector were studied. Specifically, a dynamic optimization problem based on the concept of forest transition – the process of changes in forest cover over time as a country or region develops in social and economic terms – was suggested and solved. Forest transition was used to define initial value problems. After that, steady states were characterized for an unregulated economy and different policy configurations. The results show that partial policy interventions (only adaptation or only mitigation) improved the unregulated economy situation but delivered sub-optimal land allocation. It is only under an integrated implementation that optimality can be restored.

Keywords: forest transition, deforestation, reforestation, investment theory, dynamic optimization
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1. Introduction

The phenomenon of climate change is addressed through two main strategies: mitigation and adaptation. The former is defined as an intervention to reduce the sources or enhance the sinks of greenhouse gases. The latter is an adjustment in the natural or human system in response to the climate change (IPCC 2001). In other words, mitigation addresses the causes of climate change, while adaptation addresses its effects (Locatelli 2011).

Nowadays, as some degree of climate change is unavoidable, both strategies are considered equally important. Moreover, mitigation and adaptation are interrelated activities: the actions to mitigate climate change affect the costs and benefits of adaptation and vice versa (Kane and Shogren 2000). This interrelation is particularly strong in the land use sector (referred to as the LUS from now on), an area in which practically any activity or policy has a simultaneous impact on the objectives of both strategies (IPCC 2014; Locatelli *et al.* 2015). In fact, the LUS is recognized as an area with high potential to combine mitigation and adaptation into a single intervention (IPCC 2014).

Notwithstanding the potential of the LUS, in practice mitigation and adaptation are still treated as two different policy instruments. This dichotomy, however, has been identified as a source of inefficiency (Kane and Shogren 2000; Tol 2005). In order to overcome that limitation, scientific effort has increasingly explored the possibility of combining both strategies with the aim of enhancing policy outcomes (Denton *et al.* 2014). Nevertheless, it has been until recently that the synergies approach has gained prominence.

The mentioned approach relies on the assumption that mitigation and adaptation interact, thus, their combined effect is greater than the sum of their parts (Duguma, Minang, and van Noordwijk 2014; Locatelli *et al.* 2015) Previous studies that seek to provide supporting evidence for the synergies approach in the LUS have focused on identifying activities (see Ravindranath 2007 for examples in forestry and Smith and Olesen 2010 for examples in agriculture), projects (Locatelli *et al.* 2011; Locatelli *et al.* 2015) or countries' potential to deliver co-benefits (Duguma *et al.* 2014). Those are actions with mitigation goals and additional benefits to adaptation or vice versa. From an economic point of view, co-benefits can be understood as positive externalities derived from forest ecosystems.

It must be emphasized that the simple presence of co-benefits does not necessarily comply with an enhanced policy outcome. In fact, economic theory suggests that, unless those externalities are internalized, the provision of the activity in question is smaller than the social optimum (Mas-Colell, Whinston and Green 1995). Hence, it is unclear whether the activities or projects identified in the previous studies deliver substantially higher benefits or countries profit from the opportunities to do so. Moreover, from those analyses, it is ambiguous which indicators must be used to evaluate possible enhanced outcome. It is, in fact, widely recognized that further research is needed in order to understand the balance between mitigation and adaptation and how to manage them efficiently (IPCC 2014).

This research represents an effort to address that knowledge gap. Specifically, the goal is to identify the economic conditions that enable enhanced policy outcomes in the LUS for a hypothetical rural economy (production relies on land and labor). In order to achieve the mentioned goal, forest transition concept is used to operationalize and evaluate policy outcomes of adaptation and mitigation interventions implemented independently and jointly.

The rest of the paper is structured as follows: section 2 offers a review of the forest transition concept, making a special emphasis on its economic interpretation and its links to mitigation and adaptation strategies. Section 3 shows the structure of the forest transition model and its solution which characterizes the optimum land allocation. After that, the mentioned model is used to identify sources of the inefficiency. In the fourth section, policy interventions are analyzed. In this section it is also shown that, in case the mitigation activities have a direct impact on production, partial policy approaches fail to restore the optimum. In the fifth section, results are discussed in a broader theoretical and empirical context. Finally, conclusions are presented in the last section.

2. Forest transition

Forest transition refers to the process of changes in forest cover over time as a country or region develops in social and economic terms (Barbier, Burgess and Grainger 2010). The mentioned process takes place in four phases: pre-transition, early transition, late transition and post-transition (Hosonuma *et al.* 2012). Themain characteristic of the pre-transition phase is a high and stable forest cover, which implies low deforestation rates. During the early transition, deforestation rate increases and, as a consequence, forest cover declines. In the late transition, forest cover stabilizes at a relatively low level. Finally, in the post-transition phase, a reforestation process drives forest cover recovery. The end result is a "U" shape pattern of forest cover over time (Barbier, Burgess and Grainger 2010; Lambin and Meyfroidt 2010) (see Figure 1).

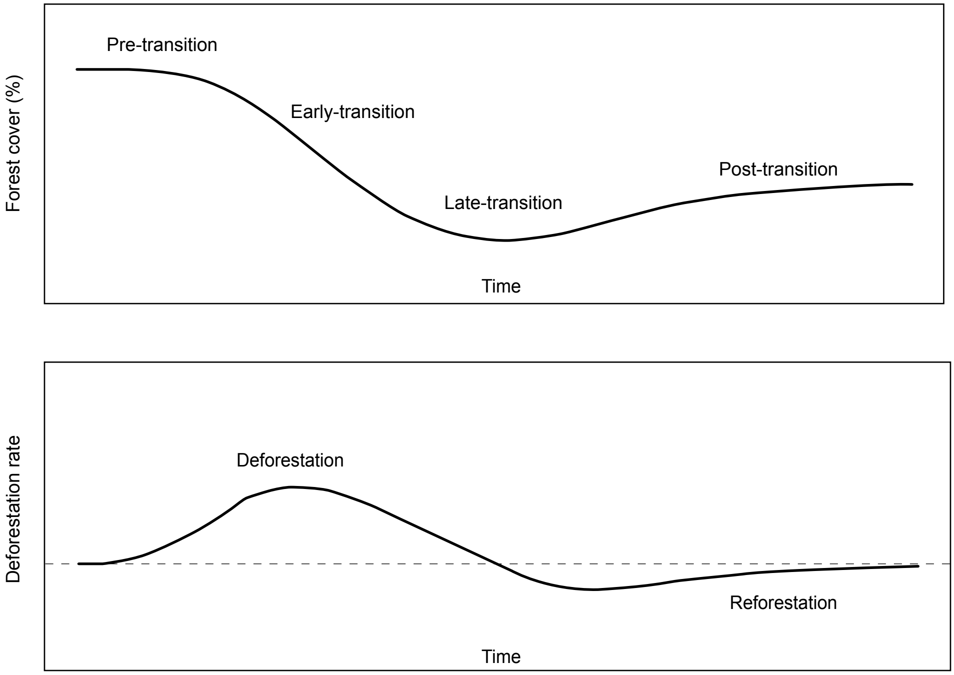

Figure 1. Forest cover and deforestation rate during different phases of forest transition process

Source: author's own elaboration.

Forest transition was originally observed in the industrialized European countries and North America. More recently some developing countries, such as Vietnam, China and Costa Rica, have also reverted the deforestation trend (Lambin and Meyfroidt 2010). However, seventy percent of tropical countries are in the early or late transition phases, which corresponds to high deforestation rates (Hosonuma *et al.* 2012).

From economic point of view, forest transition can be explained as a result of change in land value over time along with the marginal diminishing return of forest benefits (Barbier, Burgess, and Grainger 2010). This can be interpreted as follows: when a forestland is abundant, the loss in value of timber and environmental benefits are overcome by gains of alternative land use (e.g., agriculture). However, when a forestland is scarce, the relation previously described is reversed. In other words, the benefits related to the forestland are higher than the value of alternative land uses. From this perspective, changes in forest cover are seen as a process of land reallocation, in which the marginal benefits of a forest tend to equalize the marginal benefits of alternative land use.

Nonetheless, in practice the reallocation process is normally non-optimal as externalities cause significant undervaluation of the forestland (Barbier, Burgess and Grainger 2010). In addition to the economic value of timber, forests provide multiple benefits at different levels. Those additional benefits, usually referred as environmental services, are typically neglected at a private level when land use decisions are made. As a consequence, deforestation rates are higher than the social optimum and the provision of environmental services is drastically reduced (Locatelli *et al.* 2008; Barbier, Burgess and Grainger 2010). In situations in which livelihoods highly depend on the provision of the mentioned services, as it seems to be the case in rural communities in tropical countries, their reduction is translated in a significant welfare loss (Shackleton, Delang and Angelsen 2011; Reed *et al.* 2013).

It is in this scenario where adaptation and mitigation can play a significant role. According to Locatelli *et al.* (2008), mitigation and adaptation can be related to the sustainable provision of regulatory environmental services (benefits obtained from the regulation of ecosystem processes). More precisely, mitigation depends directly on the global environmental services of carbon capture and storage (denoted as the CCS from now on), while local and regional environmental services (e.g. water and micro climate regulation, soil conservation) contribute to adaptation. If it is additionally considered that activities reducing land use change, forest degradation and landscape fragmentation contribute at the same time to adaptation (because they help to conserve local and regional environmental services that are relevant to the adaptation of the society) and mitigation (they conserve or increase carbon stock). It follows that a holistic policy approach calls for interventions that consider all potential externalities derived from forest ecosystems. In other words, measures that aim at conserving and enhancing carbon stocks (for mitigation) and local or regional environmental services (for adaptation).

Therefore, this research work analyzes how land allocation between forestry and an alternative land use is influenced by mitigation and adaptation policies taking into consideration the explanation provided in the previous paragraph. That is, adaptation is considered as an intervention aimed at maintaining or increasing local/regional environmental services (through forest cover maintenance and increase), while mitigation is an intervention aimed at enhancing the global environmental services of the CCS. In addition, it must be considered that this analysis emphasizes rural economic environments where land reallocation aims at maximizing outputs and ensuring sustainable livelihoods.

3. Forest transition model

As it was previously presented, forest transition is a result of a land reallocation process driven by changes in land value over time. However, the reallocation process is distorted by the presence of multiple but possibly interrelated externalities neglected at a private level. In order to capture those elements in an economic framework, a dynamic model based on investment theory and complemented with the presence of spillovers (Barro and Sala-i-Martin 2004) and a coflow structure (Sterman 2000) has been developed.

3.1. Model setup

The model structure is represented in Figure 2.

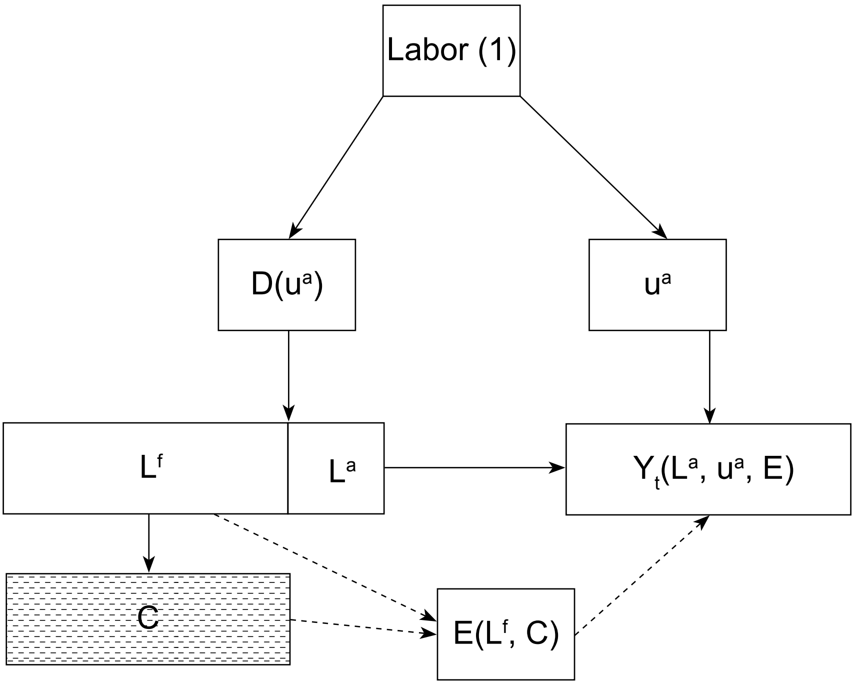

Figure 2. Structure of the dynamic model

Notes: D stands for deforestation function, u^d and u^a for the fraction of labor allocated to deforestation and alternative land use, respectively. L^f and L^a are the allocation of land to forestry and alternative land use. C represents the carbon stock, an attribute of L^f. E are the local and regional environmental services. Dotted lines are to illustrate that E is an externality. Likewise, shadow in C is to indicate that carbon stock is initially full (no net biomass growth).

Source: author's own elaboration.

To begin with, it is assumed that the economy possesses a fixed quantity of land (L), which can be distributed between two different uses: forestry (L^f) and an alternative use (L^a). In addition, one unit of labor is inelastically supplied every period of time. Production process requires L^a, a fraction of labor allocated to production process (u^a) and benefits from the presence of a forest. In particular, it is assumed that the local/regional regulatory environmental services (E) have a positive impact on output level. The provision of the mentioned services increases with the amount L^f and carbon stock (C), here interpreted as the amount of carbon contained in the biomass. This last assumption is made in order to reflect a positive correlation between the C and the provision of local/regional regulating services. Hence, the production function is defined as follows:

$$Y_t = F(L_t^a, u_t^a, E(L_t^f, C_t)) \tag{1}$$

where:
Y_t is the output at time t.

Production function satisfies neoclassical conditions in L^a and u^a. Thus, E represents a positive externality. In accordance with the previous exposition of forest transition, in which marginal decreasing benefits of forest are assumed, this externality exhibits a marginal decreasing product in both arguments (L^f, C). It is important to emphasize that carbon stock is an attribute of L^f, hence, it is formally modeled as a coflow structure of the forestland. This means that changes in L^f have an impact on C as it will be detailed in the following paragraphs.

Land can be reallocated from L^f to L^a by using a fraction of labor endowment (u^d) in deforestation activities (D). For simplicity, it is assumed that the previous relation is linear

$$D(u_t^d) = du_t^d \tag{2}$$

Where:
d is a parameter that represents labor efficiency in deforestation activities.

Finally, land reallocation has an impact on carbon stock, which is reflected in the following equation:

$$\dot{C} = -\bar{C}du_t^d \tag{3}$$

Where $\bar{C}$ is the average carbon and the negative sign is to indicate that the land reallocation decrease the carbon stock.

It is worth noting that in the previous equation $\bar{C}$ will be constant. The reason is that deforestation process is made at the expense of primary forest, in which there is no net growth of biomass (C stock is at its maximum capacity). In addition, it is considered that all carbon of cleared land is released. As a result, the proportion between C and L^f remains unaltered.

3.2. Dynamic optimization problem

Given the economic system described in the previous section and under the assumption that social welfare depends on output (the idea behind this assumption is to guarantee sustainable livelihoods), the dynamic optimization program is as follows:

$$\max_{u^a,\,L^a,C} W_0 = \int_0^\infty e^{-\rho t}\ F(L_t^a, u_t^a, E(L_t^f, C_t))dt$$

s.t.

$$\begin{aligned} &\text{i) } \dot{L}_t^a = du_t^d \\ &\text{ii) } \dot{C} = -\bar{C}du_t^d \\ &\text{iii) } \bar{L} = L_t^f + L_t^a \\ &\text{iv) } 1 = u_t^d + u_t^a \end{aligned} \tag{4}$$

As it can be seen from the previous problem specification, the system consists of one control variable (u^a) and two state ones (L^a, C). In addition, the first two constraints represent dynamic ones, while the last two represent static ones. The current value Hamiltonian (with substitution of the static constrain where required) of the previous problem then is specified as follows:

$$H_c = F\big(L_t^a, u_t^a, E(\bar{L} - L_t^a, C_t)\big) + \lambda_t(d(1 - u_t^a)) + \omega_t(-\bar{C}d(1 - u_t^a)) \tag{5}$$

Where λ and ω represent the shadow prices of L^a and C, respectively. The First-Order Conditions (FOC, omitting time subscripts for simplicity) are:

$$\begin{aligned} &\frac{\partial H}{\partial u^a} = F_{u^a} - d(\lambda - \omega\bar{C}) = 0 \\ &\dot{\lambda} = \rho\lambda - F_{L^a} + F_E E_{L^a} \\ &\dot{\omega} = \rho\omega - F_E E_C \end{aligned} \tag{6}$$

where subscripts in F and E represent the partial derivatives of the production function and environmental services (equation 1) with respect to the indicated argument.

In the equations shown in 6, the former equation represents the usual static efficiency condition; which indicates that at the optimum labor must be equally productive in both activities. The latter two equations represent the dynamic efficiency conditions, which state that at the optimum path marginal benefits and costs of land reallocation (and its impact on the carbon stock) must be balanced.

3.3. Steady state and the optimum land allocation

From the specification of the dynamic problem (equation 4) and FOC (equations 6), it is possible to derive the steady state values of the system and, more important for the purpose of this analysis, a condition for optimal land allocation between the two possible uses. To begin with, it can be determined that at the steady state all labor must be allocated to production ($u_a^* = 1$). This condition comes from the first restriction in the problem specification (equation 4).

Then, the equation of movement for u^a can be obtained by taking the derivative with respect to time of the static efficiency constraint (first equation in 6). The result is:

$$\dot{u}_t^a = \frac{d}{F_{uu}}\left(\dot{\lambda} - \dot{\omega}\bar{C}\right) \tag{7}$$

Where the subscripts in F represent the derivative with respect to the indicated argument (superscript a in u has been removed for simplicity). Making use of the fact that $u_a^* = 1$, the previous equation can be equalized to zero if and only if the second term on the right hand side is equal to zero; which implies that $\dot{\lambda} = \dot{\omega}\bar{C}$. In other words, the shadow prices of land in alternative use and of carbon (properly valued) must be balanced. Taking the second and third equations shown in 6 and working out the algebra, we get:

$$F_{L^a} - F_E E_{L^a} = \frac{\rho}{d} F_u + F_E E_C \bar{C} \tag{8}$$

Equation 8 represents the condition for the optimum land allocation at the steady state. It can be interpreted as follows: at the optimum, the marginal gain from land use change must be balanced with the marginal gains from all other productive inputs (in this case labor and carbon). This interpretation is derived from the fact that the left hand side of the equation represents the social marginal product of land allocated to the alternative land use (*S-MPLa*). Likewise, the first term on the right hand side of the equation is the value (the term ρ/d) of the marginal product of labor in production (*MPUa*). The second term is the marginal product of environmental regulatory services through carbon (*MPEc*) properly valued in terms of average carbon.

3.4. Sources of inefficiency

From equation 8, two sources of inefficiency can be identified. Namely, in the unregulated economy, externalities are unlikely to be part of decision-making process of landowners. As a consequence, marginal product of land in alternative land use is overestimated and benefits of non-land productive inputs are underestimated. More precisely, in equation 8, *S-MPLa* has two components: the direct marginal gains from land reallocation (F_{L^a} denoted from now as *MPLa*) and the marginal loss of the provision of environmental services due to the mentioned process ($F_E E_{L^a}$). The second term, however, constitutes an externality and is likely to be neglected at the private level. Similarly, on the right-hand side of equation 8, the second term, the *MPEc*, constitutes an externality and is likely to be overlooked at the private level. Thus, the unregulated economy would reallocate land in order to satisfy the following equation:

$$F_{L^a} = \frac{\rho}{d} F_u \tag{9}$$

From this perspective of the forest transition, the previous equation would correspond to the land allocation in the late transition phase. Moreover, in comparison to the condition shown in equation 8, equation 9 implies a higher and socially inefficient proportion of land allocated to the alternative land use and consequently a lower output level.

4. Policy implementation

It is worth noticing that in the assumed economy and given the interpretation of adaptation and mitigation adopted in this study, partial policy interventions (e.g., considering only land use change or only changes in carbon stock) would not restore optimal land allocation. For instance, assuming that the economy has already reached the late transition phase (from a given initial condition land allocation satisfies equation 9) and the central planner aims at restoring the optimum land allocation. A potential policy intervention is the implementation of Pigouvian taxes/subsidies. In this respect, economic theory indicates that productive activities generating the externalities must be directly taxed/subsidized (Mas-Colell, Whinston, and Green 1995). In the preset case, a possible configuration satisfying the previously mentioned principle is taxing L^a and subsidizing C. The dynamic optimization problem, hence, would be modified to:

$$\max_{u^a,\, L^a, C} W_0 = \int_0^{\infty} e^{-\rho t} \; [F\left(L_t^a, u_t^a, E\left(L_t^f, C_t\right)\right) + s_c C - t_{L^a} L_t^a] dt$$

s.t.

$$\begin{aligned} &\text{i) } \dot{L}_t^a = -r u_t^r \\ &\text{ii) } \dot{C} = g\left(1 - \frac{C}{C_{max}}\right) C \\ &\text{iii) } \bar{L} = L^f + L_t^a + L_t^r \\ &\text{iv) } 1 = u_t^r + u_t^a \end{aligned} \tag{10}$$

As it can be seen from the problem formulation, the changes with respect to previous specification (see equation 4) are the inclusion of a carbon subsidy (s_c) and a land tax (t_{L^a}) in the objective function. Likewise, as a result of assumed starting conditions, the constraints of the problem are slightly modified. In particular, land allocated to the alternative land use decreases as a function of the fraction of labor allocated to the reforestation activities (u^r). Labor productivity in reforestation is reflected by the parameter r (restriction i in 10). Reallocated land is considered as a reforested area (L^r) in which carbon sequestration takes place. Naturally, land identity holds (restriction *iii* in 10). Notice that, as a consequence of assumed starting conditions, L^f is fixed (time independent) or, in other words, along an optimal path no further deforestation takes place. Carbon sequestration follows a logistic function, where g represents the accumulation rate and C_{max} the amount of carbon at which the net growth rate is zero (restriction *ii* in 10). Finally, labor can be allocated between production and reforestation (restriction *iv* in 10).

4.1. Solution of the policy implementation problem

The current value Hamiltonian of the problem presented in equation 10 (substituting static constraints were it was required) is given by:

$$\begin{aligned} H_c &= F\left(L_t^a, u_t^a, E(\bar{L}' - L_t^a, C_t)\right) + s_c C - t_{L^a} L_t^a \\ &+\lambda_t(-r(1-u_t^a) \\ &+\omega_t\left(gC_t - \frac{gC_t^2}{\bar{L}' - L_t^a}\right) \end{aligned} \tag{11}$$

where again λ and ω represent the shadow prices of L^a and C, respectively. The term $\bar{L}' = \bar{L} - L^f$ represents available land without considering the amount of primary forest remaining (remember that L^f is time independent in this version of the model). Additionally, it must be considered that the parameter C_{max} is normalized. It allows us to make use of the fact that ${}^{C^*}/_{L^{r*}} = 1$ (at the steady state carbon stock is replenished), which simplifies calculation in later steps.

The FOC omitting time-subscripts for simplicity and considering the externality term as constant are:

$$\begin{aligned} \frac{\partial H}{\partial u^a} &= F_{u^a} - \lambda r = 0 \\ \dot{\lambda} &= \rho\lambda - \left[F_{L^a} - t_{L^a} + \omega\left(-\frac{gC^2}{(\bar{L}' - L_t^a)^2}\right)\right] \\ \dot{\omega} &= \rho\omega - \left[s_c + \omega\left(g - \frac{2gC}{\bar{L}' - L_t^a}\right)\right] \end{aligned} \tag{12}$$

Making use of the fact that at the steady state $u^a = 1$ (see constraints *i* and *iv* in 10) and considering that the equation of movement for u^a is:

$$\dot{u}_t^a = \frac{r}{F_{uu}}\dot{\lambda} \tag{13}$$

it is determined that at the steady state $\dot{\lambda} = 0$, which implies:

$$F_{L^a} - t_{L^a} = \rho\lambda + \omega g \tag{14}$$

In equation 14, we are making use of the fact that $^{C^*}/_{L^{r*}} = 1$. The value of ω at the steady state is found by equating the third condition shown in 12 to zero and again using $^{C^*}/_{L^{r*}} = 1$. The previous procedure yields:

$$\omega = \left(\frac{g}{\rho + g}\right) s_c \tag{15}$$

The next step is to substitute 14 in 15 to get:

$$F_{L^a} - t_{L^a} = \frac{\rho}{d} F_u + \left(\frac{g}{\rho + g}\right) s_c \tag{16}$$

Equation 16 corresponds to the optimal land allocation condition assuming a policy intervention.

4.2. Restoring optimality

Land allocation equation derived from the previous dynamic optimization problem – assuming the implementation of mitigation, adaptation and an integrated intervention – is shown in Table 1.

Table 1. Land allocation under different policy configurations

Policy	Tax/Subsidy		Land allocation condition
	t_{L^a}	S_c	
Mitigation	0	$\left(\frac{\rho + g}{g}\right) F_E E_C \bar{C}$	$F_{L^a} = \frac{\rho}{d} F_u + \left(\frac{g}{\rho + g}\right) s_c$
Adaptation	$F_E E_{L^a}$	0	$F_{L^a} - t_{L^a} = \frac{\rho}{d} F_u$
Integrated implementation	$F_E E_{L^a}$	$\left(\frac{\rho + g}{g}\right) F_E E_C \bar{C}$	$F_{L^a} - t_{L^a} = \frac{\rho}{d} F_u + \left(\frac{g}{\rho + g}\right) s_c$

Source: author's own elaboration.

As it can be seen from the table, by choosing tax rate $t_{L^a} = F_E E_{L^a}$ and subsidy $s_c = \left(\frac{\rho+g}{g}\right) F_E E_C \bar{C}$, all policies manage to improve the unregulated economy solution (equation 9). However, mitigation and adaptation policies are unable to restore optimality.

Mitigation policy, for example, fails to fully account for the increment in the provision of local and regional services. As a consequence, *MPLa* is overestimated in relation to its socially optimum counterpart. Thus, under this policy approach, the allocation of L^a lies between the unregulated economy solution and the optimum solution. Likewise, the adaptation policy fails to account for the positive effects of increased carbon stock on local and regional environmental services. As a result, marginal benefits from non-land productive inputs are underestimated. In this situation, it is also observed that the allocation of L^a is lower than optimum. It is only under the integrated implementation that the land allocation condition becomes identical to the optimum land allocation shown in equation 8.

The previously described results are better visualized in Figure 3. In the mentioned figure, the elements that satisfy different policy arrangements (shown in Table 1) are plotted in terms of L^a and are taking into consideration steady state values of u^a and C. As it can be seen in the figure, the thin curve represents *MPLa*, while the thick curve represents *S-MPLa.* Likewise*,* the dashed line is properly valued *MPUa* and the dotted line is *MPUa+MPEc* properly valued. The intersections of the mentioned curves correspond to the allocation of L^a in equilibrium. In accordance to equation 9, the highest land allocation to the alternative land use corresponds to the unregulated economy, labeled as point *U* in Figure 3. The figure also shows partial policy approaches (points M and A in Figure 3) that fall short of the optimum allocation (point I in Figure 3), even though they improve the unregulated economy situation.

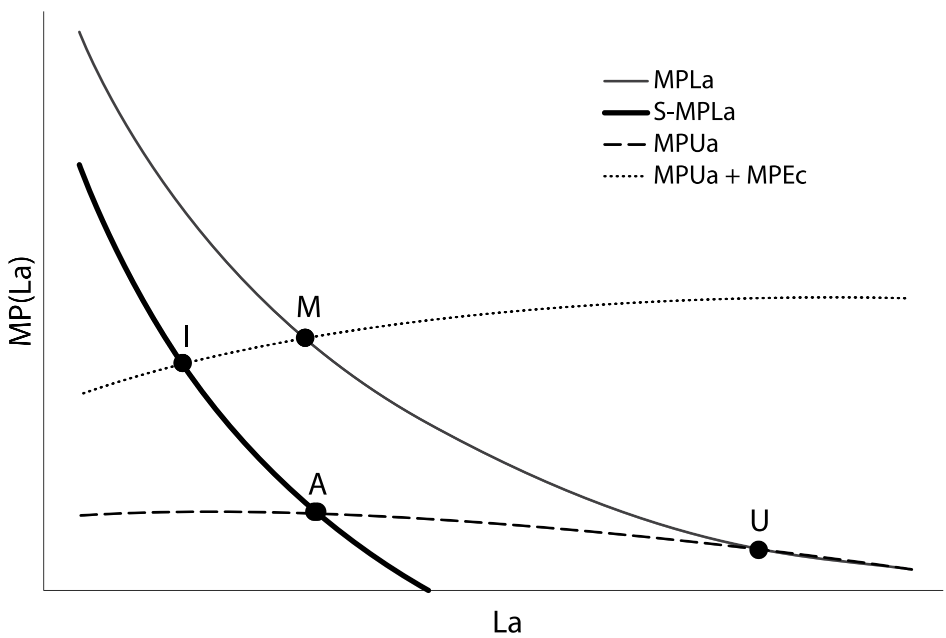

Figure 3. Land allocation at the steady state under unregulated economy and different policy configurations

Notes: *MPLa* is the marginal product of alternative land use. *S-MPLa* is the social marginal product of alternative land use. *MPUa* is the marginal product of labor in alternative land use. *MPEc* is marginal product of environmental regulatory services through carbon. Likewise, U represents the steady state in an unregulated economy and M, A and I represent the steady states under mitigation, adaptation and integrated policy, respectively.

Source: author's own elaboration.

5. Discussion

The analysis presented in this paper examines necessary conditions to enhance policy interventions through the integrated implementation of mitigation and adaptation in the LUS. The main innovation with respect to the previous studies, which mainly focused on identifying activities with co-benefits, is the use of a measurable indicator (forest cover) to assess policy outcomes. This allows us to explore management issues, which are also one of the main shortcomings of the previous literature.

The results of the analysis show that the integrated implementation of adaptation and mitigation enhance policy outcomes (land allocation is optimal) with respect to partial approaches (land allocation is sub-optimal), when mitigation has a direct impact on production or, more generally, on the objective function.

The previous result relies on two conditions: first, internalization of all relevant externalities, and second, that the restoration of forest ecosystem is able to replicate natural regeneration. About the first condition, there are at least two aspects worth further consideration. First of all, the model developed here recognized, as it had been previously documented (Kane and Shogren 2000; Duguma, Minang and van Noordwijk 2014) that complementarity between adaption and mitigation is a necessary but not sufficient condition to trigger an enhanced policy outcome. This leads to a second important consideration, namely that the interrelation between adaptation and mitigation in terms of environmental services seems to be more complex than one assumed here. For instance, Pramova *et al.* (2012) showed that ecosystem-based adaptation projects in many places increased not only local and regional environmental services (e.g. agricultural soil fertility) but also global services (CCS). Similar results are reported for the case of fodder systems in Tanzania (Duguma, Minang, and van Noordwijk 2014) However, other studies have found that CCS compared to other global environmental services (biodiversity protection) has the lowest co-benefits in relation to its provision of regional ecosystem services (Locatelli, Imbach and Wunder 2014). Which suggests that the positive link between carbon and regional benefits is not true in general. In fact, it is recognized that forest impact on regulatory services is highly dependent on site-specific conditions (Pramova *et al.* 2012). Hence, the results of this study are useful as policy prescriptive ones only when the empirical evidence supports that the main assumptions apply to the particular region.

About the second condition mentioned earlier, it is also worth emphasizing that in general it is uncertain as to what extent a replanted forest is able to restore the services delivered by its natural counterpart (Baral, Guariguata and Keenan 2016). Research efforts to link forest transition with the ecosystem service transitions have been made but without conclusive results (Vallet *et al.* 2016). However, under communal land ownership, a condition that prevails in some rural tropical economies, agroforestry systems on smallholders' land might ensure a high ecological quality restoration process (Lambin and Meyfroidt 2010).

A final consideration is related financial aspect of the proposed policy. In particular, it is important to pinpoint that the tax/subsidy scheme proposed here directly targets stock variables. Starting from a late transition phase, this implies a net decreasing of tax revenues over time (L^a is reduced over time) along with increasing subsidy expenses (C increases over time). In other words, the mechanism might not be self-sustainable in the long run. Taking into consideration that one of the biggest obstacles when it comes to land mitigation practices is precisely lack of funding (Sills *et al.* 2014), this limitation is highly relevant in practice. Thus, further research is needed to analyze financial issues regarding policy implementation.

6. Conclusions

The LUS is an area with high potential to combine mitigation and adaptation into a single policy intervention. In spite of that potential, the mentioned strategies are still treated as two different policy instruments. Concerns about efficiency have emerged as a result of such a dichotomy. However, it is still poorly understood how to manage an integrated implementation of mitigation and adaptation.

In this research paper, enabling conditions for an enhanced policy outcome in the land use sector were studied. It was assumed that the regulatory environmental services constitute a positive externality to production process and that the mentioned services positively depend on the amount of the forestland and its carbon content. Under these conditions, policies addressing only land use change (adaptation) or carbon sequestration and storage (mitigation) fail to restore optimality. It is only under the integrated implementation that optimality is restored.

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