Interactions between Climate Change Mitigation and Adaptation in the Land Use Sector: a Dynamic Approach

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Abstract
The land use sector has been identified as an area with high potential to achieve synergies between mitigation and adaptation. However, the specific conditions leading to synergic outcomes remain poorly understood. In this research work that knowledge gap is addressed. Concretely, forest transition concept is used to analyze transitional dynamics and steady state levels of forest cover under different policy scenarios. The purpose is to observe whether joint implementation of adaptation and mitigation leads to a synergic outcome. The results show that, under the presence of positive externalities, the joint implementation gives raise to a synergy. In other words, the steady state level of forest cover indicator under the joint implementation is higher than the sum of both strategies applied independently. The same patter is observed along the transition.

Key words: Forest transition, Land use, System Dynamics, Dynamic optimization.

Introduction
The main two strategies to address climate change, mitigation and adaptation, have been traditionally used as two different policy instruments. However, there is growing evidence about the possibility of enhancing policy outcomes when these two strategies are used jointly (Denton et al., 2014). In scientific literature, the improved policy outcome is normally referred as a synergy and it means that the overall outcome is greater that the sum of its parts (Duguma, Minang, & van Noordwijk, 2014).

The land used sector, in particular, has been identified as an area where the opportunities to achieve synergies between adaptation and mitigation are significant (IPCC, 2014). Previous scientific efforts, for instance, have been able to identify activities in forestry and agriculture that contribute to both goal goals (Ravindranath, 2007). Some of those activities have been already implemented in specific projects (Bruno Locatelli, Evans, Wardell, Andrade, & Vignola, 2011; Bruno Locatelli, Pavageau, Pramova, & Di Gregorio, 2015). However, previous studies rely mainly on conceptual analysis in which synergy is defined as an activity or project delivering benefits for both objectives. This last idea of synergy does not necessarily compile with the superadditive property previously mentioned. Thus, it is unclear whether those activities or projects are in fact delivering substantially higher benefits or benefiting from the opportunities to do so. Moreover, from those analyses, it is ambiguous which indicator must be used to evaluate the synergic outcome.

In this research, our aim is to address that knowledge gap. Specifically, our goal is to identify some of the economic conditions that lead to synergic outcomes in the land use sector when adaptation and mitigation are implemented jointly. In order to achieve the mentioned goal, we use the forest transition concept and evaluate the policy outcomes of adaptation and mitigation interventions used independently and jointly. In what follows a brief review of forest transition is presented with a focus on its economic interpretation.

Forest transition refers to the process that forest cover exhibits over time as a country or region develops in social and economic terms (Barbier, Burgess, & Grainger, 2010). The mentioned process takes place in a four stages: the fist stage is characterized by the presence of a high and stable forest cover. During the second stage, economic development is assumed to cause an increasing deforestation rate and forest cover declines. In the third stage, forest cover stabilizes in a relatively low level. Finally, in the fourth stage, when development reaches a threshold, the trend is reversed and net reforestation initiates (Angelsen, 2007). The end result is a "U" shape pattern of forest cover in the long run (Barbier et al., 2010; Lambin & Meyfroidt, 2010). Forest transition was originally observed in industrialized European countries and North America. More recently some developing countries have also experienced forest transition (Lambin & Meyfroidt, 2010).

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

In practice, nonetheless, the reallocation process is normally non-optimal as externalities cause significant undervaluation of forestland (Barbier et al., 2010; Ramón & Toman, 2006). In addition to the economic value of timber, forests provide multiple benefits at local, regional and global level. Those additional benefits, commonly referred as environmental services, are normally neglected at private level when land use decisions are made. As a result, deforestation rates tend to be higher than optimal. Moreover, forest transition is postponed to a later time in the future and the provision of environmental services is drastically reduced (Barbier et al., 2010; B. Locatelli et al., 2008).

It is in this scenario where adaptation and mitigation can play a significant role. Empirical evidence shows that the time it takes to move along the forest transition curve can be significantly influenced by policy intervention. For instance, in Scotland where forest transition was left to its own accord, it took about 5 centuries to observe a forest cover recovery. Contrary, In Vietnam where active policy took place, forest transition was recorded in only 3 decades (Rudel, Schneider, & Uriarte, 2010). Furthermore, socio-economic factors are the main drivers of the reforestation phase in forest transition (Lambin & Meyfroidt, 2010). This means that, in particular, adaptation and mitigation can influence the direction, size and speed of the reforestation phase.

At the same time, adaptation is closely related to the provision of local and regional environmental services and mitigation to the provision of global ones (B. Locatelli et al., 2008). Likewise, mitigation initiatives based on financial incentives are starting to consider forest conservation as a tool to achieve global its goals (e.g. REDD+). In short, all elements to mainstream adaptation and mitigation into a single policy initiative seem to have an element in common: sustainable provision of environmental goods and services. Therefore, in this research the attention is focused on analyzing the effect of implementing adaptation and mitigation with the aim of initiating forest transition.

Materials and methods

According to what has been previously described, changes in forest cover are explained by changes in forestland value over time. In addition, it is argued that the value of forestland is significantly distorted by the presence of positive externalities neglected at private level. In order to capture those elements in a dynamic model, we have made use of investment theory and assume investment spillovers at regional level (Barro & Sala-i-Martin, 2004). The mentioned analytic techniques were used to derive the governing dynamic equations of the hypothesized economic system. In our case this correspond to a region or country facing deforestation. After that, the model was solved numerically (Ruth & Hannon, 2012). The numerical implementation was made in insight-maker[1], a web-based multi method simulation platform.

In what follows the analytical solution of the model is presented. After, it is shown how the simulation model was constructed.

Analytical development

In order to develop the analytical solution, an external adjustment cost with a positive externality framework has been developed (Barro & Sala-i-Martin, 2004). The mentioned framework assumes that two main activities take place within the analyzed economy. The first is capital investment and the second is manufactured production, which uses capital as an input. In the current context, investment is seen as the cost of adjusting trees density to its desired level. The desired level represents steady state level of capital and is determined endogenously. Likewise, the manufactured production represents the flow of environmental goods and services, which contain the local environmental ones and the global ones.

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[1] https://insightmaker.com

It is additionally assumed that investment technology exhibits decreasing returns to scale, which means that the cost function is convex. In our case we assume that the cost function is

$$C(I) = I^{\gamma} \quad (1)$$

where γ is a parameter higher than one.

The production function of for environmental goods and services is a neoclassical one and takes the form

$$Y_i = AF(K_i, T_i) \quad (2)$$

Where T_i represents the endowment of land for the representative productive unit (e.g. typical farm in the region). As the model represent a specific geographical region, it is additionally assumed that the endowment of land is fixed. Likewise, K_i represents stock of trees per unit of land. In order to account for the spillover effect, it was assumed that the productivity of the system, reflected in the parameter A, is determined by the average level of K.

Solving the dynamic optimization problem, delivers the following system of equations[2]:

$$\dot{K} = \left(\frac{p_I}{\gamma}\right)^{\frac{1}{\gamma-1}} - \delta K$$

$$\dot{p}_I = (r + \delta)p_I - p_y F_K \quad (3)$$

Where the variables with a dot represent the time derivatives of K and p_i (trees density and unitary cost of investment) respectively. The parameters r and δ represent the interest rate and depreciation rate of capital (it can be interpreted as death rate of trees). Lastly, p_y represents the unitary value of environmental goods and services and F_k the marginal product of capital.

A closer look to the system of equations also reveals that the system exhibits saddle-path dependence (Barro & Sala-i-Martin, 2004). This implies that in order to reach the steady state, the system must be initialized on its stable arm. A similar reasoning applies when policy implementations displace the demarcation lines of K or P_I (see figure 1). This fact, as it will be shown later, will have important consequences for the implementation of model simulation.

[2] Details are shown in the appendix

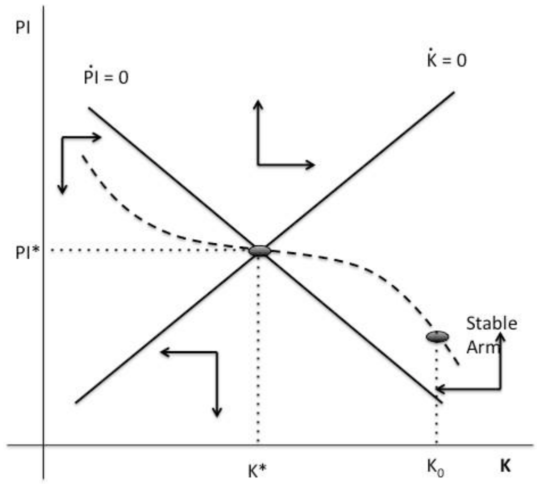

Figure 1: Phase diagram of investment model

Simulation model

The system of differential equations showed in 3 was implemented in a simulation model following the method described by (Ruth & Hannon, 2012). This method consists in deriving the structure of the analyzed system based on the equations previously mentioned. More precisely, the two equations in 3 represent the flows of the stocks K and p_I. The feedback structure of the system easily follows from those equations too (see figure 2[3]).

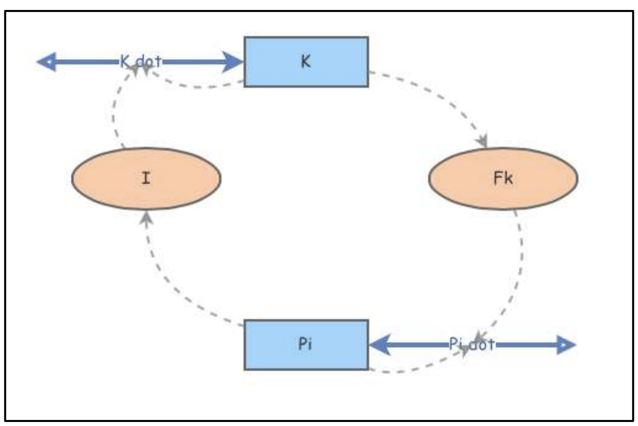

Figure 2: Stock and flow Diagram of the model

The parameters r, δ and γ, remained constant in all scenarios analyzed. However, adaptation was assumed to have an impact on F_k and mitigation was assumed to have an impact on p_y.

For adaptation, there was a differentiation between the private solution and the centralized solution. Concretely, for the private solution the externality was taken as given. Contrary, for the centralized solution, the externality term was internalized. As a result, the expression for F_k under adaptation is higher. The private solution is used when adaptation is

[3] Model parameters are not explicitly shown in the figure as they were declared as part of the macro of the model. See insighmaker manual for more details about model macros.

not implemented. However, when adaptation policy is implemented, the value for the central solution is used instead.

The previous point becomes clearer if the functional form of the production function is analyzed. The model was quantified assuming a Cobb-Douglas production function of the form:

$$Y = K^{\beta} K^{\alpha} T^{1-\alpha} \tag{4}$$

Hence, in the case of the private solution the term K^{β} was taken as a constant. Contrary, for the centralized solution, this term accounted for the derivation. The equations for private and social solution are shown next:

$$PF_k = \alpha\, K^{\beta} K^{\alpha-1}\, T^{1-\alpha}$$

$$CF_k = (\alpha + \beta)\, K^{\alpha+\beta-1}\, T^{1-\alpha} \tag{5}$$

As it can be seen from the previous equations, the term for F_k is higher under adaptation. The diminishing returns of forest benefits were captured by assuming that $\alpha + \beta < 1$.

In the case of mitigation, it was imply assumed that the value of environmental goods and services is higher under the implementation of this strategy. The logic is that before implementing mitigation project, the market value of carbon capture service is zero. However, after the implementation, the market value of this environmental service becomes positive, hence, the overall value of the environmental services increase. These last two considerations will have important implication for the development of scenarios.

Initial and transversality conditions

In order to guarantee optimality the initial condition and transversality condition must be met[4]. For this kind of problem, the initial condition is that the initial K must be positive ($K_0 > 0$). Moreover, in order to reflect forest transition and in accordance to empirical evidence, we assumed that initially forestland is plentiful. Hence, K_0 is assumed to be higher than the steady state level of K[5]. To reflect the abundance of the resource the steady stale level of K under adaptation has been used as initial value.

The transversality condition, as it was previously mentioned, is met when the system is initialized on the stable arm. In order to achieve it, the steady state levels of the system were computed (K^*, p_I^*)[6]. Given K_0, the optimizer built-in function of the software was used to determine the initial level of p_I (p_{I0}). Provided that the stable arm is defined within

[4] The initial and transversality condition correspond to the second and third constraint of the optimization problem showed in equation 16 of the appendix.

[5] See next section (results) for further details about steady states. For the moment, it is just important to highlight that the steady state level for adaptation was found to be higher that the estate state for the base case.

[6] See equation 7

a logical range of values (see figure 1), p_{I0} was identified by minimizing the final value of the following expression:

$$\min_{p_{I0}} abs(K^* - K_t) \tag{6}$$

For instance, given the initial conditions described so far, it is known that the stable arm must be between zero and p_I*. A similar method was used when interventions were implemented. The fundamental change was that instead of minimizing equation 6 choosing p_{I0}, the decision variable was *PI jump* (see full diagram of the model in the appendix), a price sock that took placed exactly in the same year that the policy started and whose purpose is to guarantee that the system places itself on the new stable arm.

Scenarios

In order to test the superadditive property (demonstrated analytically in the next section), four different scenarios were analyzed: the baseline (B), adaptation (A), mitigation (M) and the joint implementation (AM).

In the first scenario, the baseline, it is assumed that no policy intervention takes place. For the second scenario, adaptation, it was assumed that the externality is internalized. In other words, the marginal product of capital (F_K) changes from the private expression to the central expression (see equation 5). For the mitigation scenario, a payment for carbon capture is assumed. Hence, the value of environmental goods and services, reflected in the parameter p_y, increases with respect to the base case. The fourth scenario, the joint implementation (AM), assumes that both changes described so far take place at the same time.

Results

The steady state and the effect of adaptation on forest cover

The steady state values of K* and p_I* can be found by equating the system of equations shown in 3 to zero and solving for the mentioned variables. This procedure yields the following results:

$$\begin{gathered} p_I^* = \frac{p_y\, F_k^*}{r+\delta} \\ K^* = \left(\frac{p_y\, F_k^*}{(r+\delta)\gamma}\right)^{1/(\gamma-1)} \delta^{-1} \end{gathered} \tag{7}$$

Where F_K* refers to the marginal product evaluated at the optimum level of K. In this analysis, it is assumed that adapting to climate change is equivalent to internalizing the positive effects of forestland cover. As it can be seen from the previous equations, the trees density depends on F_K. As it was argued before, under the private solution the marginal product is lower that under central solution (see equation 5). Therefore, adapting to climate change creates incentives to increase K, which in turn would increase the forest cover in the region.

Effect of Mitigation

Mitigation in this model is seen as a change in p_y, hence, its effect on forest cover can be analyzed by differentiating the equation of F_K* in 7 with respect p_y. The derivate is:

$$\frac{\partial K^*}{\partial p_y} = \left(\frac{1}{\gamma - 1}\right)\left(\frac{p_y\, F_k^*}{(r+\delta)\gamma}\right)^{2-\gamma/\gamma-1} \left(\frac{F_k^*}{(r+\delta)\gamma}\right)\delta^{-1} \tag{8}$$

The derivative is positive in the economic feasible range ($p_y > 0$), which means that if the value of the environmental services increase, a likely outcome if, for instance, a REDD+ project is adopted within the region, the optimal density of trees will increase as well.

Joint effect

A synergy between adaptation and mitigation in our model will be seen if the following inequality holds:

$$K_{am}^* - K^* > (K_a^* - K^*) + (K_m^* - K^*) \tag{9}$$

Where the sub index of K^* represent the kind of intervention assumed (a for adaptation, m for mitigation and am for a joint implementation). This inequality means that the increment of forest cover is higher when both strategies are applied jointly. Rearranging terms we get:

$$K_{am}^* > K_a^* + K_m^* - K^* \tag{10}$$

From equation 7, the previous inequality can be reduced to:

$$p_y^m CF_k^* > p_y CF_k^* + p_y^m PF_k^* - p_y PF_k^* \tag{11}$$

Where the superscript on p_y represents the price under mitigation and P and C before F_k represent the private and social marginal product. If we normalize p_y to one we get:

$$p_y^m CF_k^* > CF_k^* + p_y^m PF_k^* - PF_k^* \tag{12}$$

Which results in:

$$p_y^m > 1 + \left(\frac{PF_k^*}{CF_K^*}\right)(p_y^m - 1) \tag{13}$$

This inequality holds when there is a positive externality, as the ratio PF_K^*/CF_k^* is less than one. In other words, given our assumptions, there is a synergy between adaptation and mitigation. Moreover, this synergy is amplified with the relevance of the externality.

Simulations

The analytical results presented previously have been useful to characterize the end result of the proposed policy interventions. In this section, simulation results are presented to better illustrate the transitional dynamics of the model. In order to translate the results to land use decisions, it must be additionally assumed a land allocation factor per tree. However, to keep the interpretation clear, we stick to the capital terminology.

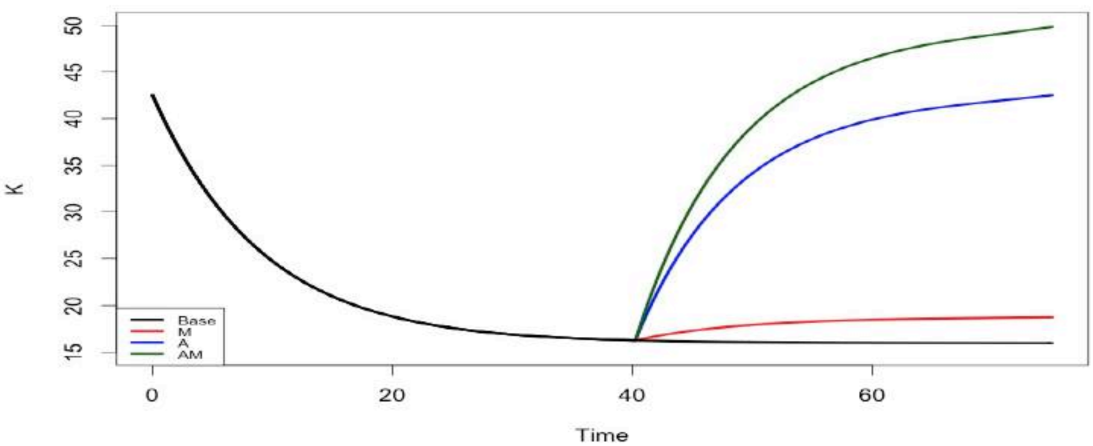

Figure 3: K level under different scenarios

The simulation results of the four scenarios contemplated are displayed in figure 3. As it can be seen, in the base scenario (black line in the graph) an important reduction of capital stock takes place at the beginning of the simulation period. In fact, during the first 20 years is when most of the capital stock is depleted. Around year 40, the stock of capital levels out and remains in this low level for the rest of the simulation. Based on the structure of the system, it is possible to infer that if no policy intervention takes place, it will not be possible for capital to recover. As a result, forest transition would not take place. It is important to highlight that this simulation reproduces the second and third stage of forest transition.

For the adaptation scenario (blue line in the graph), the policy intervention, as it was described in the previous section, takes places in year 40. As it can be seen form the graph, an important recovery of the capital stock takes place after the implementation of the intervention. The biggest gain, in fact, occurs during the first 10 years after the policy implementation. Around year 60, the capital stock has reached a value close to its steady state. Hence, from that moment on the gains are relatively small until the end of the simulation.

A similar pattern to the one described above is observed when mitigation policy is implemented (red line in the graph). After the policy is initialized, in year 40, the stock of capital slightly recover. The recovery is, however, not as drastic as in the case of adaptation. The explanation for this is that only a small change in the value of environmental goods is assumed. In the simulation p_y changes from 1 in the base scenario, to 1.1 in the mitigation one.

For the joint implementation (green line in the graph), a very similar pattern as the one described above is seen. Namely, after the policy implementation an important increase of the stock of capital is observed. With the biggest gain taking place during the first years after the policy implementation. However, as the graph reveals, during the transition the level of capital is systematically higher than in the previous scenarios. Moreover, the synergic property of the joint implementation is seen along the transition. The level of capital, as Figure 4 shows, is higher that the sum of its parts.

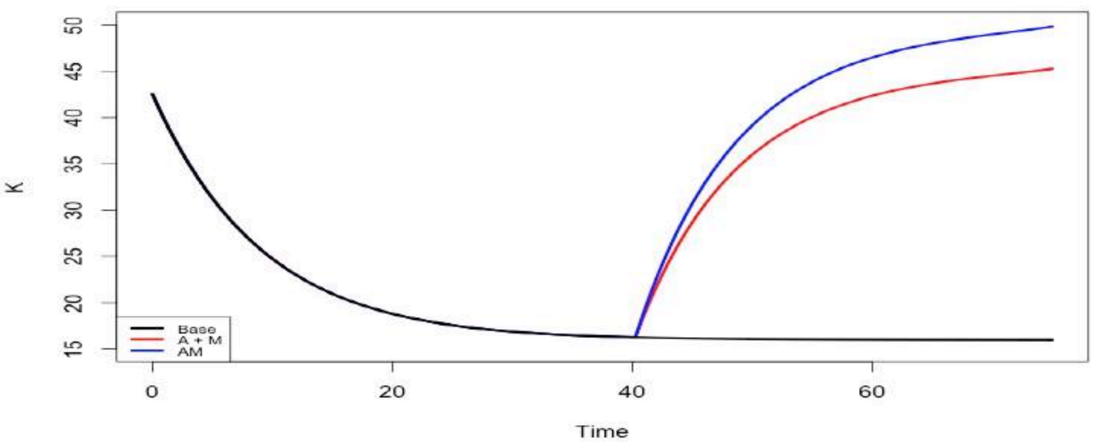

Figure 4: Illustration of a synergic property along the transition

Discussion and Conclusions

In this paper, the economic conditions that enable synergies between climate change mitigation and adaptation in the land use were analyzed. The results show that under the presence of positive externalities, an intrinsic condition to forest ecosystems, synergies between the two climate strategies depend on the internalization of the externalities and a net increase in the value of forest ecosystem services, for instance, through the payment of carbon credits. It was additionally found that in the economic environment that we assumed, forest transition is not initialized without a policy intervention. Hence, according to our study, the relevance of climate policy in the land use sector is twofold: on one hand it allows to influence land use decisions into the direction of sustainability. And, on the other hand, it allows controlling the size and speed of implementing those decisions.

The synergy to which we refer is seen is the capital stock, here interpreted as a tree density. The steady state level under the joint implementation is higher that the sum of the independently implemented policies. Likewise, along the transition the stock of capital in the joint implementation is systematically higher than the sum of the two policies implemented independently.

It is important, nonetheless, to highlight some of the practical limitations of the approach followed here. To begin with, our framework relies on well-defined land tenure, a situation that still nowadays constitute one of the biggest challenges of mitigation actions, such as REDD+ (Sunderlin, 2014). In addition, we are implicitly assuming that the net gain derived from a payment for environmental services, concretely for carbon capture and sequestration, is positive. Two important practical issues might limit this idea. First of all, in the context of REDD+, payment for mitigation initiatives is usually conditional to the development of robust indicator systems. The development of such systems has proven to be an enormous task in practice and national governments in general have failed to implement them successfully. In this regard, financial issues have been found to be an important barrier to implement those information systems (Jagger & Rana, 2014).

Secondly, and perhaps more important, mitigation activities have proven to be challenging to implement in isolation. One of the main reasons is that they tend to limit the access to forest resources. In the circumstances previously described, it is possible that the implementation of mitigation initiatives have an opposite effect, this is, a net loss in value of ecosystem services.

In spite of those limitations, the authors believe that the finding of this research effort can have important implications for policy formulation in the future, as the main conclusions of our analysis rely on desirable conditions of a joint implementation rather than *in-situ* conditions.

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Appendix

A.1. Dynamic optimization problem

The problem of the producer of the investment good is given by:

$$\max_{I} \Pi_I = p_I\, I - C(I) \tag{14}$$

The first order condition of the problem yields the usual optimization condition for competitive firms

$$p_I = C'(I) \tag{15}$$

Which implies that at the optimum production level, the price of the good equal its marginal cost.
The problem of the producer of the manufactured good is given by:

$$\begin{gathered} \max_{L,I,K} V_0 = \int_0^{\infty} e^{-rt}\left[p_y\, F(K,T) - wL - p_I I\right] \\ \text{s.t.} \\ i)\ \dot{K} = I - \delta K \\ ii)\ K_0 > 0 \\ iii)\ \lim_{t\to\infty} \lambda_t K_t = 0 \end{gathered} \tag{16}$$

The Hamiltonian of this problem is:

$$H = e^{-rt}\left[p_y\, F(K,T) - wT - p_I I\right] + \lambda(I - \delta K) \tag{17}$$

The first order conditions of the problem are:

$$\frac{\partial H}{\partial T} = e^{-rt}\left[p_y F_T - w\right] = 0 \tag{18}$$

$$\frac{\partial H}{\partial I} = e^{-rt}\left[- p_I\right] + \lambda = 0 \tag{19}$$

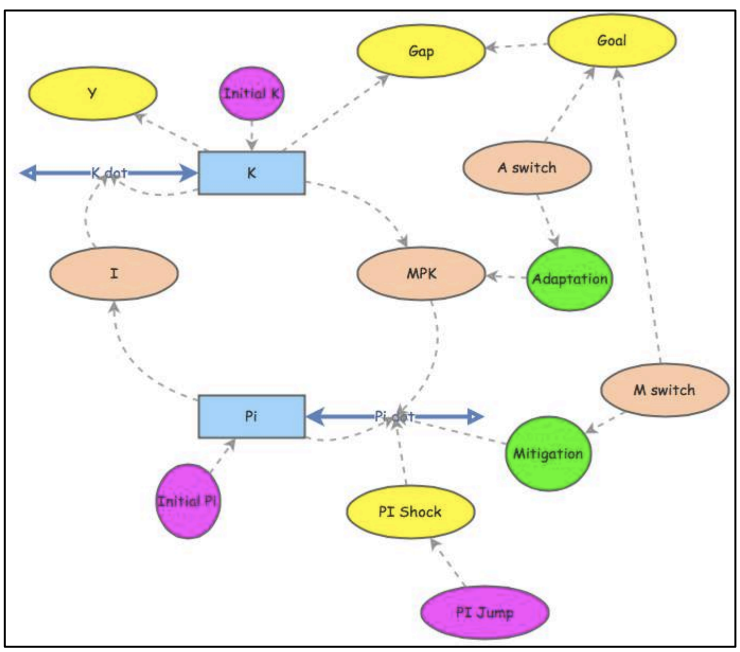
$$\frac{\partial H}{\partial K} = e^{-rt}\left[\, p_y\, F_k\right] - \lambda\delta = -\dot{\lambda} \tag{20}$$

Where the sub index of K represent the partial derivative of the production function with respect to the corresponding variable. The system of equations shown in 3 is derived from equations 15 to 20. To get the first equation shown in 3, 15 must be substituted in the first constraint of the optimization problem (16). The second equation is obtained from 19 and 20. First these two equations are transformed to current value and, after that, 20 is substituted in 21.

A.2. Supplementing Material

A web-based version of this model can be consulted at:

https://insightmaker.com/insight/48790/Forest-Transition



The preloaded configuration reproduces the base scenario (just press *simulate* to see it). The adaptation scenario is reproduced by activating *A switch*, located in the right panel of the screen. The activation means that the slider is changed from zero to one. After that, use the *optimization and goal seeking* built-in function (located in the tools menu) with the following instructions (preloaded):

Goal primitive: Gap
Goal: minimize
Goal Type: final value
Primitives to adjust: PI jump
Minimum bound: 0
Maximum bound: 10 (suggested)
Precision: 0.000001

In the advance section, change the step reduction factor to 0.01 and the press run optimization. After this, the model is set to reproduce the adaptation scenario. Press *simulate* to see the results.

For the mitigation scenario, a similar process is required. First, activate the *M switch* (and deactivate *A switch* in case it is on) and the follow the same steps as before. For the joint implementation, both switches must be activated before running the optimization. The process is the same as described before.

Finally a list of parameters is provided in the following table

Parameter	**Value**
γ	1.5
α	0.5
β	0.4
T	1 (normalized)
r	0.1
δ	0.1
p_y	1
p_y^m	1.1