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# MANAGING POTENTIAL CONFLICTS BETWEEN CARBON SEQUESTRATION PROGRAMS AND BIODIVERSITY

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# Managing potential conflicts between carbon sequestration programs and biovidersity*

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**Abstract**

This paper presents an optimal control model to analyze reforestations with two different species, including commercial values, carbon sequestration and biodiversity or scenic values. We first solve the model qualitatively with general functions and then develop it assuming quadratic functions. We discuss the implications of partial or total internalization of environmental values and show that internalizing only carbon sequestration may have negative impacts on biodiversity/scenic values. To evaluate the practical relevance reforestations in the South-west of Spain with cork-oaks and with eucalyptus are compared. We do the analysis with two different carbon crediting methods, the Carbon Flow Method and the Ton Year Accounting Method, showing that the first implies to increase more the forest surface than the second. However, the first implies as well to decrease the proportion of cork-oaks compared to eucalyptus, while the second method increases the proportion of cork-oaks. A contingent valuation study shows that cork-oak reforestations have a positive impact on visitors' welfare while reforestations with eucalyptus impact negatively. If biodiversity-scenic values would be internalized, no eucalyptus reforestations would take place at all.

Key words: optimal control, forests, carbon sequestration, biodiversity, carbon accounting.

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# 1 Introduction

Countries which have ratified the Kyoto Protocol, a development of the United Nations Framework Convention on Climate Change, will need to reduce their greenhouse gas emissions, on average, to 5% below 1990 levels by 2012. One of the alternatives included in the Kyoto Protocol to achieve this goal is to plant trees[1], since trees sequester carbon from the atmosphere by growing and reduce therefore carbon dioxide concentrations. This is know as 'afforestation and reforestation' in the terminology used in the Kyoto Protocol and the Marrakech Accords, an agreement that completes the Protocol. Although it is not yet sure if the Kyoto Protocol will continue after 2012 in its current form it is almost sure that some kind of international policy on climate change will continue, and the rules to be set up for reforestation programs will probably rely heavily on those developed for the Kyoto Protocol, giving the enormous amount of negotiation effort already invested into them.

According to the Marrakech Accords, Parties can issue credits through afforestation and reforestation by means of art. 3.3 of the Kyoto Protocol if the land is located in an Annex I country[2] that ratifies the Protocol (or eventually via art. 6 and Joint Implementation), and by means of art. 12 (Clean Development Mechanism) if the land is located in any Non-Annex I Party. Thus, incentives will probably be created to get forest managers to take carbon sequestration into account.

For credits earned by CDM projects two methods have finally been accepted: the t-CERs and the l-CERs. The main difference between the two crediting procedures is the lifetime of the credit, 5 years in the case of the t-CER and up to 30 years with the l-CERs. Nevertheless, both methods are subject to a maximum time limit of 60 years (Caparrós and Jacquemont, 2005).

However, since our application will use data from Spain we will focus on the incentive schemes that could be applied in Annex-I countries, although the model could easily be applied to the CDM framework since we annualize values (ensuring that the incentive are not changed, see below) to ease the analytical resolution. For afforestation and reforestations undertaken inside an Annex-I country the two methods just describe are not applicable, since what matters is the national annual budget. Therefore, a reasonable incentive mechanism to be set up by the government is what is known as the Carbon Flow Method (CFM). This method was proposed in the early literature on the impact of carbon sequestration on optimal rotations (Englin an Callaway (1993) or Van Kooten et al. (1995)) and essentially implies that the forest owner gets paid when carbon sequestration takes place and has to pay when carbon is released. An alternative method that could be considered is what is known as the Ton Year Accounting Method (Moura-Costa and Wilson (2000)). This method implies to

[1] Increasing carbon sequestration by means of forest management alternatives is also considered in the Kyoto Protocol and in the Marrakech Accords. A discussion of the implications for forest management of taking into account commercial values, carbon sequestration and recreational values can be found in Caparrós *et al.* (2003).

[2] Essentially the OECD countries and the economies in transition

pay a given amount to the forest owner each year as long as the carbon stays in the forest. Both methods are described in more detail in the Appendix.

It is usually accepted that biodiversity increases when degraded and agricultural lands are converted into forests (IPCC, 2000). However, this is only true in regard to indigenous forests and not when the 'reforestation' is actually the setting up of rapidly growing alien species plantations. It is also not true where pre-existing land uses have high biodiversity values (IPCC, 2000). Matthews *et al.* (2002) have quantified bird biodiversity associated to reforestations in the United States and have found further evidence of the potential negative impacts of reforestation regimes. Therefore, and as indicated in Jacquemont and Caparrós (2002), the 'afforestation and reforestation' alternative may potentially conflict with the goal of the Convention on Biodiversity, since incentives to increase carbon sequestration may favor the use of fast growing alien species, which can potentially be negative for biodiversity (as shown in Caparrós and Jacquemon (2003 and 2005) neither the convention on climate change (UNFCCC) nor the convention on biodiversity (CBD) have adequate mechanisms to avoid this possibility). A similar argument can be elaborated linking carbon sequestration and scenic values, since fast growing plantations tend to have lower scenic beauty.

Van Kooten (2000) proposed an optimal control model to evaluate carbon sequestration via 'afforestation and reforestation' with one single species, without taking into account biodiversity or scenic values. This model was extended in Caparrós and Jacquemont (2003) to include two species and biodiversity values. Nevertheless, since this paper focused on the legal and economic implications of the Protocol the model was not solved (only first order conditions were used) and not applied. Moons *et al.* (2004) also deal, using a GIS-based model, with the establishment of new forests for carbon sequestration purposes, including recreation and other values in the analysis. Their model is solved numerically and highlights the empirical importance of taking into account recreational values.

In this paper we solve the model proposed in Caparrós and Jacquemont (2003) qualitatively using general functions, develop it for quadratic functions and apply it to compare reforestations in the South-west of Spain with two different species: cork-oak, a native slow growing species, and eucalyptus, an alien fast growing species that has been used in this area in the past. The first species is assumed to have positive biodiversity values while the second is assumed to have a negative impact in terms of biodiversity, at least in the area under consideration. Nevertheless, since biodiversity is not easy to monetarize we have conducted a contingent valuation survey to value the contribution of a reforestation with either one of the species referred above to the welfare of the visitors. The results of this contingent valuation study show that the visitors perceive reforestations with cork-oaks as having a positive impact on their welfare while they perceive reforestations with eucalyptus as having a negative impact on their welfare.

Our results show that both incentive mechanism described above to foster carbon sequestration imply an increase in the surface devoted to forest, although this increase is higher with the CFM method (yielding a steady-state were pasture almost disappears for high carbon prices). However, the most relevant result is that the CFM method implies to decrease the proportion of cork-oak over eucalyptus, while the TYAM method yields the opposite result, increasing the proportion of cork-oak over eucalyptus (compared to the equilibrium with no carbon sequestration incentives). Therefore, in terms of biodiversity-scenic values the second method is superior to the first one. In fact, we show that if biodiversity-scenic would be internalized, even to a limited extent, no reforestations with eucalyptus would occur at al.

The rest of the article is organized as follows. Section 2 presents the model and discusses it with general functional forms. We show that the equilibrium point will generally be a saddle point, and analyze qualitatively the optimal path under the assumption that pasture land has constant returns to scale. Section 3 analyzes the model with quadratic functions, dropping the assumption that the marginal value of pasture is constant. Section 4 shows the results of the application in the South-west of Spain. Section 5 concludes.

# 2 The model

We assume that the agent can choose between two types of forest, and that type 1 has greater biodiversity-scenic values while type 2 has greater carbon sequestration potential. A typical example of this situation is when reforestation with a natural indigenous species alternative (forest type 1) is compared with a fast growing alien species (forest type 2). In the case study presented below we compare reforestations with cork-oaks (type 1) and with eucalyptus (type 2) in the South-west of Spain.

Define: $L=$ total land available for reforestation; $f_0(t)$ = pasture land at time $t$ ; $f_1(t)=$ reforested land of forest type 1; $f_2(t)$ = reforested land of forest type 2. To simplify we can eliminate $f_0(t)$ from the model by setting $f_0(t) = L - f_1(t) - f_2(t)$ and leave $f_1$ and $f_2$ as state variables. Obviously, $f_i$ cannot have negative values. Nevertheless, for simplicity, we analyze the problem without explicitly incorporating this restriction and check afterwards our results for non-negativity.

Define further: $r$ = discount rate, $u_i(t)=$ total area reforested at time t of forest type $i$ $(i = 1, 2)$ (control variables), and $K_i(u_i)$ = reforestation cost for forest type $i$ $(i = 1, 2)$, a function of the amount of land reforested in a given year. The control variable $u_i(t)$ refers only to the amount of new land devoted to forest (or deforested) and not to the reforestation or natural regeneration needed to maintain the current forest surface. We assume $K_i'(u_i) > 0$ and $K_i''(u_i) > 0$ (e.g. as specialized labor becomes scarce, salaries increase).

Finally, define $F_i$ $(f_i)(i = 0, 1, 2)$ as space-related functions showing the annual net capital income values for pasture land $(i = 0)$ or forest land of type $i$ $(i = 1, 2)$. We assume $F_i' > 0$ and $F_i'' < 0$. These functions are supposed to have three terms: $F_i(f_i) = W_i(f_i) + C_i(f_i) + B_i(f_i)$. Where: $W_i$, $C_i$ and $B_i$ represent annual net capital income associated with commercial uses (timber, cork, fire-wood, livestock breeding etc.), carbon sequestration and biodiversity-scenic values respectively. Forest-related data are strongly time-related but, for modeling reasons, it is interesting to annualize them, ensuring that investment incentives are not changed[3] (Van Kooten, 2000).

The objective function is:

$$\begin{aligned} MaxV &= \int_0^\infty \Pi_t e^{-rt} dt \\ \Pi_t &= F_1(f_{1t}) - K_1(u_{1t}) + F_2(f_{2t}) - K_2(u_{2t}) + F_0(L - f_{1t} - f_{2t}) \end{aligned}$$

st.

$$\dot{f}_1 = u_1 \tag{1}$$
$$\dot{f}_2 = u_2 \tag{2}$$

And initial conditions: $f_1(0) = f_1^0;\ \ f_2(0) = f_2^0$.

Using the current-value Hamiltonian and dropping time notation the Pontryagin maximum principle conditions are:

$$MaxH_c = \Pi + \lambda_1 u_1 + \lambda_2 u_2, \tag{3}$$

$$\dot{\lambda}_1 = r\lambda_1 - \frac{\partial H_c}{\partial f_1} = r\lambda_1 - \left[F_1'(f_1) + \frac{\partial F_0(L - f_1 - f_2)}{\partial f_1}\right] \tag{4}$$
$$\dot{\lambda}_2 = r\lambda_2 - \frac{\partial H_c}{\partial f_2} = r\lambda_2 - \left[F_2'(f_2) + \frac{\partial F_0(L - f_1 - f_2)}{\partial f_2}\right] \tag{5}$$

equations (1) and (2) and the transversality condition $\lim_{t\to\infty} \lambda_i(t) = 0,\ i = 1, 2$.

$\Pi$ is a concave function, since it is the sum of concave functions and convex functions (with a negative sign). In addition, the equations of motion for the state variables are linear in the control variables. Thus, the Mangasarian sufficient conditions will hold.

Equation (3) implies:

$$\begin{aligned} \frac{\partial H_c}{\partial u_1} &= -K_1'(u_1) + \lambda_1 = 0 \\ \frac{\partial H_c}{\partial u_2} &= -K_2'(u_2) + \lambda_2 = 0 \end{aligned}$$

Solving for $\lambda_1$ and $\lambda_2$:

$$\lambda_1 = K_1'(u_1) \tag{6}$$
$$\lambda_2 = K_2'(u_2) \tag{7}$$

[3] Calling $z(t)$ to the real flow of net benefits associated to any of the values described above ($z(t)$ could also be decomposed in quantity times price), the present value of the investment is: $PV_z = \int_0^\infty z(t)e^{-rt}dt$. And the annualised value $Z$ which assures equal investment incentives checks $Z = rPV_z = r\int_0^\infty z(t)e^{-rt}dt$.

And in the steady-state we will have $\dot{\lambda}_1 = \dot{\lambda}_2 = \dot{f}_1 = \dot{f}_1 = u_1 = u_2 = 0$. Hence, substituting (6) (respectively (7)) in (4) (respectively (5)) we obtain the following FOC for the steady-state:

$$\frac{F_1'(f_1)}{r} - K_1'(0) = \frac{F_0'(L-f_1-f_2)}{r} \tag{8}$$

$$\frac{F_2'(f_2)}{r} - K_2'(0) = \frac{F_0'(L-f_1-f_2)}{r} \tag{9}$$

where:

$$F_0'(L-f_1-f_2) = -\frac{\partial F_0(L-f_1-f_2)}{\partial f_1} = -\frac{\partial F_0(L-f_1-f_2)}{\partial f_2}$$

Taking (8) and (9) together we have:

$$\frac{F_1'(f_1)}{r} - K_1'(0) = \frac{F_2'(f_2)}{r} - K_2'(0) = \frac{F_0'(L-f_1-f_2)}{r} \tag{10}$$

The interpretation of equation (10) follows conventional lines. In the steady-state equilibrium the stream of net revenues associated with the reforestation of one additional hectare of forest type 1 has to be equal to the revenues associated to one additional hectare reforested with forest type 2, and to the revenues associated to the use of that hectare as pasture.

To find the dynamic path we derive (6) and (7) with respect to time:

$$\dot{\lambda}_1 = K_1''(u_1)\dot{u}_1 \tag{11}$$

$$\dot{\lambda}_2 = K_2''(u_2)\dot{u}_2 \tag{12}$$

Substituting in (4) (respectively (5)):

$$\dot{u}_1 = \frac{rK_1'(u_1) - [F_1'(f_1) - F_0'(L-f_1-f_2)]}{K_1''(u_1)} \tag{13}$$

$$\dot{u}_2 = \frac{rK_2'(u_2) - [F_2'(f_2) - F_0'(L-f_1-f_2)]}{K_2''(u_2)} \tag{14}$$

## 2.1 Saddle point

Dockner (1985) gives necessary and sufficient conditions for a system with two state variables to have a saddle point (assuming $r > 0$). These conditions imply (i) $D < 0$ and (ii) $0 < |J_E| \leq (D/2)^2$, where $D$ is as defined below and $|J_E|$ is the determinant of the Jacobian matrix of the system evaluated at the equilibrium point.

The determinant of the Jacobian matrix for the system formed by (1)(2)(13) and (14) evaluated at the equilibrium point is:

$$|J_E| = \begin{vmatrix} \frac{\partial \dot{f}_1}{\partial f_1} & \frac{\partial \dot{f}_1}{\partial f_2} & \frac{\partial \dot{f}_1}{\partial u_1} & \frac{\partial \dot{f}_1}{\partial u_2} \\ \frac{\partial \dot{f}_2}{\partial f_1} & \frac{\partial \dot{f}_2}{\partial f_2} & \frac{\partial \dot{f}_2}{\partial u_1} & \frac{\partial \dot{f}_2}{\partial u_2} \\ \frac{\partial \dot{u}_1}{\partial f_1} & \frac{\partial \dot{u}_1}{\partial f_2} & \frac{\partial \dot{u}_1}{\partial u_1} & \frac{\partial \dot{u}_1}{\partial u_2} \\ \frac{\partial \dot{u}_2}{\partial f_1} & \frac{\partial \dot{u}_2}{\partial f_2} & \frac{\partial \dot{u}_2}{\partial u_1} & \frac{\partial \dot{u}_2}{\partial u_2} \end{vmatrix}$$

Since $\frac{\partial \dot{f}_i}{\partial f_j} = \frac{\partial \dot{f}_i}{\partial f_i} = \frac{\partial \dot{u}_i}{\partial u_j} = 0$, and $\frac{\partial \dot{f}_i}{\partial u_i} = 1$ we have:

$$|J_E| = \frac{\partial \dot{u}_1}{\partial f_1}\frac{\partial \dot{u}_2}{\partial f_2} - \frac{\partial \dot{u}_1}{\partial f_2}\frac{\partial \dot{u}_2}{\partial f_1} > 0 \tag{15}$$

D is defined as follows (Dockner, 1985);

$$D = \begin{vmatrix} \frac{\partial \dot{f}_1}{\partial f_1} & \frac{\partial \dot{f}_1}{\partial u_1} \\ \frac{\partial \dot{u}_1}{\partial f_1} & \frac{\partial \dot{u}_1}{\partial u_1} \end{vmatrix} + \begin{vmatrix} \frac{\partial \dot{f}_2}{\partial f_2} & \frac{\partial \dot{f}_2}{\partial u_2} \\ \frac{\partial \dot{u}_2}{\partial f_2} & \frac{\partial \dot{u}_2}{\partial u_2} \end{vmatrix} + 2\begin{vmatrix} \frac{\partial \dot{f}_1}{\partial f_2} & \frac{\partial \dot{f}_1}{\partial u_2} \\ \frac{\partial \dot{u}_1}{\partial f_2} & \frac{\partial \dot{u}_1}{\partial u_2} \end{vmatrix}$$

And in our system this simplifies to:

$$D = -\frac{\partial \dot{u}_1}{\partial f_1} - \frac{\partial \dot{u}_2}{\partial f_2} < 0 \tag{16}$$

Comparing (15) and (16) we can see that $|J_E| \leq (D/2)^2$ also holds, since we can re-write it as

$$\frac{\partial \dot{u}_1}{\partial f_1}\frac{\partial \dot{u}_2}{\partial f_2} - \frac{\partial \dot{u}_1}{\partial f_2}\frac{\partial \dot{u}_2}{\partial f_1} \leq \left(\frac{\frac{\partial \dot{u}_1}{\partial f_1}}{2}\right)^2 + \left(\frac{\frac{\partial \dot{u}_2}{\partial f_2}}{2}\right)^2 + \frac{1}{2}\frac{\partial \dot{u}_1}{\partial f_1}\frac{\partial \dot{u}_2}{\partial f_2}$$

or

$$0 \leq \left(\frac{\partial \dot{u}_1}{\partial f_1} - \frac{\partial \dot{u}_2}{\partial f_2}\right)^2 + 4\frac{\partial \dot{u}_1}{\partial f_2}\frac{\partial \dot{u}_2}{\partial f_1}$$

and this inequality is always checked.

Thus, the system will generally have a saddle-point, the best kind of stability that we can expect in this type of two state-variable dynamic systems (Dockner, 1985).

## 2.2 Phase-diagram

Setting $F_0'(f_0) = \alpha \geq 0, \forall f_0$ (that is, the marginal value of pasture land is constant) we can analyze graphically the paths of both reforestations independently since both systems described by equations (13) and (14) are "decoupled"[4]. We will analyze the phase-diagram for species 1 (for species 2 the analysis would be analogous).

Since $F_1'(f_1) = X > 0$ and $K_1'(u_1) = Y > 0$ are monotonic functions we can write $F_1'^{-1}(X) = f_1 > 0$ and $K_1'^{-1}(Y) = u_1 > 0$. And since $F_1''(f_1) < 0$ and $K_1''(u_1) > 0$, we know that $(F_1'^{-1})'(X) < 0$ and $(K_1'^{-1})'(Y) > 0$.

[4]However, this implies indirectly that the land restriction is not taken into account.

From (1) we can show that the $\dot{f}_1 = 0$ isocline follows the $f_1$ axis:

$$\dot{f}_1 = 0 \Leftrightarrow u_1 = 0$$

And from (13) we have:

$$\dot{u}_1 = 0 \Leftrightarrow F_1'(f_1) = rK_1'(u_1) + \alpha \tag{17}$$

Thus:

$$f_1 = F_1'^{-1}\left(rK_1'(u_1) + \alpha\right) > 0$$

Deriving with respect to $u_1$:

$$\frac{\partial f_1}{\partial u_1} = \frac{\partial F_1'^{-1}}{\partial X}\frac{\partial X}{\partial u_1} = \frac{\partial F_1'^{-1}}{\partial\left(rK_1'(u_1) + \alpha\right)} rK_1''(u_1) < 0$$

To plot the $\dot{u}_1 = 0$ isocline we look for the values for $f_1 = 0$ and for $u_1 = 0$ : With $f_1 = 0$ (from (17)):

$$u_1 = K_1'^{-1}\left(\frac{F_1'(0) - \alpha}{r}\right)$$

Thus $u_1 > 0$ if $F_1'(0) > \alpha$. I.e. the reforestation in a given year with species 1 will be positive if the marginal value of the first unit of land reforested with this species 1 is higher than the marginal value of a unit of pasture land (which is supposed to be constant). We assume that this holds, otherwise no reforestation would occur at all.

For $u_1 = 0$:

$$f_1 = F_1'^{-1}(rK_1(0) + \alpha) > 0$$

In addition, we have

$$\begin{aligned} \frac{\partial \dot{f}_1}{\partial u_1} &= 1 > 0 \\ \frac{\partial \dot{u}_1}{\partial f_1} &= \frac{-F_1''(f_1)}{K_1''(u_1)} > 0 \end{aligned}$$

Plotting this information we get figure 1.

**[Figure 1 here]**

The long-term equilibrium is the intersection of the $\dot{u}_1 = 0$ isocline and the $\dot{f}_1 = 0$ isocline. That is, in the long-term equilibrium the amount of forest type 1 is: $f_1^* = F_1'^{-1}(rK_1(0) + \alpha) > 0$ (since at the equilibrium $u_1 = 0$). Given the streamlines this will be a saddle point. If the initial amount of forest type 1 ($z_1$) is lower than the optimal amount $f_1^*$ the optimal approach is to reforest forest type 1 (a positive $\mathrm{u}_1$) following the stable branch northwest of the long-term equilibrium. If the initial amount of forest type 1 is higher than $f_1^*$ the optimal approach is to follow[5] the stable branch southeast of the long-term equilibrium (i.e. to reduce the amount of forest type 1, a negative $u_1$).

To check the saddle-point we can write the Jacobian determinant for this sub-system with one state-variable:

$$|J|_E = \begin{vmatrix} \frac{\partial \dot{f}_1}{\partial f_1} & \frac{\partial \dot{f}_1}{\partial u_1} \\ \frac{\partial \dot{u}_1}{\partial f_1} & \frac{\partial \dot{u}_1}{\partial u_1} \end{vmatrix} = \begin{vmatrix} 0 & 1 \\ \frac{\partial \dot{u}_1}{\partial f_1} & \frac{\partial \dot{u}_1}{\partial u_1} \end{vmatrix} < 0$$

A sufficient condition for a saddle-point with one state variable is $|J_E| < 0$. Since $\partial \dot{u}_1 / \partial f_1 > 0$, we have $|J_E| < 0$.

## 2.3 Timber, carbon and biodiversity-scenic values

Until now we have discussed the system focusing on the overall valuation function ($F$). In this section we will discuss the impact of different values for conventional commercial uses (timber, cork, firewood), carbon sequestration (a value that might become a market value in the future) and biodiversity values. To make things interesting, we will assume $B'_1 > B'_2$, and $C'_1 < C'_2 \; \forall f$ (i.e. species 1 has higher marginal values for biodiversity and species 2 has higher marginal values for carbon sequestration).

Building on the results of the last section, and recalling the additive form of the valuation function assumed, we can compare the optimal amount of space devoted to each species in the equilibrium:

$$\frac{f_1^*}{f_2^*} = \frac{F_1'^{-1}(rK_1(0) + \alpha)}{F_2'^{-1}(rK_2(0) + \alpha)} = \frac{(W'_1 + C'_1 + B'_1)^{-1}\,(rK_1(0) + \alpha)}{(W'_2 + C'_2 + B'_2)^{-1}\,(rK_2(0) + \alpha)}$$

In the current market situation only the timber values (W) will be considered. In the future, carbon may become a market value and W and C will be considered by private decision makers. From a social point of view, however, W, C and B should be taken into account. Let us assume, to focus on the differences in carbon and biodiversity values between species 1 and 2, that current market values (W) are equal in both species and that reforestation costs are also equal for both species. In this setting, we have $\left(\frac{f_1^*}{f_2^*}\right)_W = 1$, where the sub-index of the bracket indicates the value(s) considered (only W). Since we have assumed $C'_1 < C'_2$, we will have $\left(\frac{f_1^*}{f_1^*}\right)_{WC} < 1$, if current (timber) and future (carbon) market values are taken into account. Given $B'_1 > B'_2$, if current market values (timber) and biodiversity-scenic values are taken into account we have $\left(\frac{f_1^*}{f_1^*}\right)_{WB} > 1$. This is the situation that a public decision maker probably takes into account today (if we assume that carbon sequestration plays no role for the

[5] In any case, the optimal approach never implies to reforest first and deforest afterwards, so that the annualization of the revenues as described above does not change the investment incentives.

time being). Finally, the value of $\left(\frac{f_1^*}{f_1^*}\right)_{WCB}$ depends on the relative importance of carbon and biodiversity-scenic values. Figure 2 depicts this situation (in this figure biodiversity values for species 2 are supposed to be negative).

[**Figure 2 here**]

That is, we might have a situation where future market forces (timber plus carbon) favor species 2 while present market forces equalize the amounts of both species, and social benefits (timber, carbon sequestration and biodiversity-scenic values) would favor species 1. If only timber and biodiversity-scenic values are taken into account (probably the social values currently considered) the relative amount of species 1 in the equilibrium should even be bigger. In addition, these values (especially scenic values) are local by their nature while carbon sequestration benefits are global. Thus, implementing an incentive for carbon sequestration might, in this particular case, imply a stress for local social benefits.

However, the general forms used in the discussion so far do not allow us to say if this situation is relevant in the real world. Thus, we will continue the discussion with particular functional forms to prepare the application to a multiple-use forests in Spain.

# 3 Quadratic functions

We will now continue the analysis assuming particular functional forms. This will allow us to relax again the assumption that marginal values for pasture land are constant (which we only used to draw the phase diagram). We will assume quadratic functions for all functions, since these functions are well suited to depict the decreasing returns typical of forestry outputs (areas most suited for a given species are reforested first). In addition, the additive property of the coefficients in this type of functions is very convenient for the discussion on the three different types of benefits generated by the forests under consideration.

For the valuation functions we have:

$$\begin{aligned} F_i &= a_{i0} + a_{i1} f_i + (1/2) a_{i2} f_i^2, \quad (i = 0, 1, 2) \\ F_i' &= a_{i1} + a_{i2} f_i > 0 \Rightarrow a_{i1} > 0 \\ F_i'' &= a_{i2} \leq 0 \Rightarrow a_{i2} \leq 0 \\ a_{i0} &\geq 0 \end{aligned}$$

For reforestation costs we set $k_{ij} \geq 0$ $(i = 1, 2;\ j = 0, 1, 2)$, since $K_i'(u_i) > 0$ and $K_i''(u_i) > 0$ . In addition, for the valuations functions $(F_i)$ a negative value may well have a economic sense for large numbers of $f_i$, but negative reforestation costs have no sense.

$$K_i = k_{i0} + k_{i1} u_i + (1/2) k_{i2} u_i^2 \quad (i = 1, 2)$$

In addition, we have:

$$\begin{aligned} F_i &= W_i + C_i + B_i \\ W_i &= w_{i0} + w_{i1} f_i + (1/2) w_{i2} f_i^2 \\ C_i &= c_{i0} + c_{i1} f_i + (1/2) c_{i2} f_i^2 \\ B_i &= b_{i0} + b_{i1} f_i + (1/2) b_{i2} f_i^2 \end{aligned}$$

Thus:

$$a_{ij} = w_{ij} + c_{ij} + s_{ij}$$

The FOC are now:

$$a_{11} + a_{12} f_1 - r k_{11} = a_{01} + a_{02}(L - f_1 - f_2) \tag{18}$$
$$a_{21} + a_{22} f_2 - r k_{21} = a_{01} + a_{02}(L - f_1 - f_2) \tag{19}$$

Solving for $f_1$ and $f_2$ using Cramer's rule and rearranging:

$$\begin{aligned} f_1^* &= \frac{a_{02}[(a_{11} - rk_{11}) - (a_{21} - rk_{21})] + a_{22}[(a_{11} - rk_{11}) - (a_{01} + a_{02}L)]}{-a_{12}a_{22} - a_{12}a_{02} - a_{02}a_{22}} \\ f_2^* &= \frac{a_{02}[(a_{21} - rk_{21}) - (a_{11} - rk_{11})] + a_{12}[(a_{21} - rk_{21}) - (a_{01} + a_{02}L)]}{-a_{12}a_{22} - a_{12}a_{02} - a_{02}a_{22}} \end{aligned}$$

Since $a_{i2} \leq 0$ the denominator is negative. In the numerator all the terms in brackets are positive. The second square bracket in each expression should be positive, since it is the difference between the net marginal benefit for the first unit of land (the best) with one of the forest species and the marginal benefit for pasture for the last unit of land ($L$). If this difference is not positive, no reforestation will occur at all for this particular species. The first square bracket will be positive for one species and negative for the other. Let us suppose that $(a_{11} - rk_{11}) > (a_{21} - rk_{21})$, i.e. that the net marginal benefit for the first unit of land is higher with species 1 than with species 2. In this case the first square bracket will be positive for $f_1$ and negative for $f_2$. This will ensure a positive value for $f_1$. For a positive value of $f_2$ we would need:

$$|a_{02}[(a_{21} - rk_{21}) - (a_{11} - rk_{11})| < |a_{12}[(a_{21} - rk_{21}) - (a_{01} + a_{02}L)|$$

That is, the difference between the marginal benefit of the first unit of land with species 2 and the marginal benefit with pasture for the last unit (multiplied by the term indicating the variation in the marginal value of species 1) must be larger than the difference between the first unit of land with each one of the two forest species (multiplied by the term indicating the variation in the marginal value for pasture). Of course, in the particular case where $a_{02} = 0$ and marginal pasture value is constant (as assumed in the last part of the general function section) it is easy to show that $f_1^* > 0$ and $f_2^* > 0$, since the first square bracket in the numerator vanishes in both expressions.

To study the relation between $f_1$and $f_2$ in the equilibrium we set (multiplying numerator and denominator by $(-1)$):

$$\frac{f_1^*}{f_2^*} = \frac{(a_{02}+a_{22})(rk_{11}-a_{11}) - a_{02}rk_{21} + a_{02}a_{21} + a_{22}(a_{01}+a_{02}L)}{(a_{02}+a_{12})(rk_{21}-a_{21}) - a_{02}rk_{11} + a_{02}a_{11} + a_{12}(a_{01}+a_{02}L)}$$

An increase in the constant part of the function describing marginal reforestations costs for species 1 ($k_{11}$) reduces the ratio $f_1^*/f_2^*$ (it decreases the numerator and increases the denominator). That is, an increase in the plantation costs of species 1, reduces the relative amount of species 1 in the equilibrium.

An increase in the constant part of the function describing marginal reforestations costs for species 1 ($k_{21}$) increases the ratio $f_1^*/f_2^*$. That is, an increase in the plantation costs of species 2, reduces the relative amount of species 2 in the equilibrium.

An increase in $a_{11}$ increases the ratio $f_1^*/f_2^*$ .That is, the higher the fix part of the marginal value function of species 1 the higher the relative amount of species 1 in equilibrium.

An increase in $a_{21}$ decreases the ratio $f_1^*/f_2^*$. The higher the fix part of the marginal value function of species 2 the higher the relative amount of species 2 in equilibrium.

Finally, an increase in the marginal value of the last unit possibly devoted to pasture land $(a_{01} + a_{02}L)$, increases the ratio $f_1^*/f_2^*$ as long as $a_{12} < a_{22}$. That is, as long as the absolute value of the term describing the decrease of species 1 marginal value is higher than this value for species 2.

For the discussion in terms of $a_{ij} = w_{ij} + c_{ij} + b_{ij}$, and in order to focus on carbon sequestration and biodiversity-scenic values, we will normalize pasture values to zero (i.e. $a_{0j} = 0$), set conventional commercial values equal for species 1 and 2 ($w_{ij} = w_j$, $i = 1, 2$) and assume equal reforestation cost functions for both species. Thus:

$$\frac{f_1^*}{f_2^*} = \frac{-a_{22}(a_{11}-rk_1)}{-a_{12}(a_{21}-rk_1)}$$

or, writing $a_{ij}$ out:

$$\frac{f_1^*}{f_2^*} = \frac{-(w_2+c_{22}+b_{22})(w_1+c_{11}+b_{11}-rk_1)}{-(w_2+c_{12}+b_{12})(w_1+c_{21}+b_{21}-rk_1)} \tag{20}$$

In the particular case where $B_i' = C_i' = 0\ \forall i, x$, these assumptions imply:

$$\left(\frac{f_1^*}{f_2^*}\right)_W = \frac{(-w_2)(w_1-rk_1)}{(-w_2)(w_1-rk_1)} = 1$$

Setting $C_i' = 0\ \forall i, x$ (no value for carbon sequestration) and assuming strictly positive values for timber and biodiversity-scenic values we have (with $B_1' > B_2'$ $\forall x$):

$$\left(\frac{f_1^*}{f_2^*}\right)_{WB} = \frac{(-w_2 - b_{22})(w_1 + b_{11} - rk_1)}{(-w_2 - b_{12})(w_1 + b_{21} - rk_1)} > 1$$

That is, in this particular case the proportion of species 1 will be higher than the proportion of species 2. Remark that this is probably the situation that a public planner should favor in the current situation, if we assume that carbon sequestration has not yet entered the public decision making process.

Setting $B_i = 0\ \forall i, x$ and considering only future market values (i.e. timber and carbon sequestration) we have (with $C_1' < C_2'\ \forall x$):

$$\left(\frac{f_1^*}{f_2^*}\right)_{WC} = \frac{(-w_2 - c_{22})(w_1 + c_{11} - rk_1)}{(-w_2 - c_{12})(w_1 + c_{21} - rk_1)} < 1$$

Hence, in this situation the proportion of species 2 will be higher than the proportion of species 1, although we have supposed that current market forces do not favor any of these species.

From a social point of view, all values shown in (20) should be included. In this case, $\left(\frac{f_1^*}{f_2^*}\right)_{WCB}$ will be $> 1$ or $< 1$ depending on the relative importance of carbon sequestration and biodiversity-scenic values.

For $> 1$ we need:

$$\frac{[(w_1 - rk_1) + (c_{11} + b_{11})]}{-(w_2 + c_{12} + b_{12})} > \frac{[(w_1 - rk_1) + (c_{21} + b_{21})]}{-(w_2 + c_{22} + b_{22})}$$

That is, the constant part of the marginal valuation function for species 1 $(c_{11} + b_{11})$ has to be larger than this part for species 2 $(c_{21} + b_{21})$, and/or the part describing the decreasing part of the marginal valuation function has to be lower, in absolute terms, for species 1 $(c_{12} + b_{12})$ than for species 2 $(c_{22} + b_{22})$.

As expected, the results obtained in the general function section concerning the nature of the equilibrium can be recovered with the quadratic functions. The path of $u_i$ is:

$$\dot{u}_1 = \frac{rk_{11} + rk_{12}u_1 - [a_{11} + a_{12}f_1 - a_{01} - a_{02}(L - f_1 - f_2)]}{k_{12}} \quad (21)$$

$$\dot{u}_2 = \frac{rk_{21} + rk_{22}u_2 - [a_{21} + a_{22}f_2 - a_{01} - a_{02}(L - f_1 - f_2)]}{k_{22}} \quad (22)$$

The Jacobian determinant simplifies to:

$$|J_E| = \frac{\partial \dot{u}_1}{\partial f_1}\frac{\partial \dot{u}_2}{\partial f_2} - \frac{\partial \dot{u}_1}{\partial f_2}\frac{\partial \dot{u}_2}{\partial f_1} = \frac{a_{12}a_{22} + a_{12}a_{02} + a_{02}a_{22}}{k_{12}k_{22}} > 0$$

In addition,

$$D = -\frac{\partial \dot{u}_1}{\partial f_1} - \frac{\partial \dot{u}_2}{\partial f_2} = \frac{a_{12} + a_{02}}{k_{12}} + \frac{a_{22} + a_{02}}{k_{22}} < 0$$

And finally we can see that $|J_E| \leq (D/2)^2$ holds since we can re-write this condition as:

$$0 \leq \left( \frac{a_{12} + a_{02}}{k_{12}} - \frac{a_{22} + a_{02}}{k_{22}} \right)^2 + 4 \frac{a_{02}}{k_{12}} \frac{a_{02}}{k_{22}}$$

Hence, $(f_1, f_2, u_1, u_2) = (f_1^*, f_2^*, 0, 0)$ will be a saddle point for any set of values of parameters in our model.

# 4 Applied results

Neither the discussion with the general forms nor the discussion with the particular functional forms allow us to say if this situation is relevant in the real world. Thus, we will now apply the model just described to a multiple-use forest in Spain: the Alcornocales Natural Park (located in the South-west of Spain). This Natural Park has an extension of about 170,000 hectares and is partially covered by cork-oaks, which have suffered a slow deforestation process in the last decades. Eucalyptus have also been used in the past in this area for reforestation. Forests (mainly cork-oaks) cover currently about 53% of the total surface of the area.

Before analyzing possible measures for the biodiversity-scenic values, which are always highly controversial, we will focus on the current economic incentives for reforestation and on those to be probably implemented in the near future to take into account carbon sequestration. Currently the forest owner focuses on commercial values and on net subsidies (subsidies minus taxes) from the state. The latter are actually very important in the area under consideration since the Spanish government, within the EU framework, has established a strong incentive for reforestations with cork-oaks. We have estimated different functions for commercial values (including timber or cork) and for net subsidies. The reason for doing so is that net subsidies can be seen as a proxy for biodiversity-scenic values, since these are the reasons invoked to set up these policies. The quadratic functions estimated, together with a brief description of the data used to estimate these functions can be found in the Appendix.

Turning to our results, our data show that with the current incentives, market values plus net subsidies, the equilibrium quantities would imply a considerable increase in the surface devoted to eucalyptus. However, surface devoted to cork-oak would actually be larger (about 7% larger) than the surface devoted to eucalyptus.

Once an incentive for carbon sequestration is introduced using the CFM method the amount of forests increases, especially due to the increase in eucalyptus, although the surface devoted to cork-oak also increases. Figure 3 shows the equilibrium quantities devoted to cork-oak and eucalyptus a for different carbon prices. As it can be seen, with a price of 90 €/t C (about 25 €/t $CO_2$) allmost all of the total surface available would be devoted to forest.

**[Figure 3]**

If the incentive for carbon sequestration is set up using the TYAM method the forest surface also increases, although less; with the maximum price of 90 €/t C considered forests would cover 69% of the surface (see Figure 4). Nevertheless, the important difference is that now the increase of forest surface takes place using mainly cork-oaks. Figure 5 shows the proportion of cork-oaks over eucalyptus at equilibrium for different values of carbon sequestration and for the two carbon crediting methods considered. As shown, the TYAM tends to increase the proportion of cork-oaks substantially, while the CFM tends to reduce this proportion.

[**Figure 4**]

[**Figure 5**]

Tables 1 and 2 summarize the results available from a contingent valuation study with 900 interviews undertaken to visitors of the Alcornocales Natural Park (focus groups and 115 pre-test interviews have also been done). Half of the interviewees were asked about a reforestation with cork-oak trees (showing them the evolution of this kind of reforestation in a booklet) and the other 450 subjects were asked about reforestation with eucalyptus (giving them a similar booklet describing a reforestation with eucalyptus). Since the results shown in table 1 (which correspond to the main survey) were already obtained in the pre-test that was done during the design phase, the interviewees were asked about their willingness to pay (WTP) to ensure a reforestation with cork-oaks and about their WTP to avoid a reforestation with eucalyptus. Table 2 shows the results obtained for these valuation questions (open ended).

[**Table 1 here**]

[**Table 2**]

What can we say using these data about the optimal path or the optimal equilibrium level? This is always a difficult task since it implies to give a value for biodiversity-scenic values, which is already a difficult task, but also implies to add market values for commercial output (valued as price times quantity) with values in terms of hicksian surplus (in the case of the biodiversity-scenic values). The results obtained have therefore to be taken with care. Nevertheless, the exercise may be interesting for illustration.

In table A.3 we show the data obtained estimating a quadratic function for biodiversity-scenic values using the data of the CV studies described above. In the case of cork-oaks we cannot add subsidies and the data of the CV study since we would be double-counting (as stated anove, these are the main values considered by setting up the subsidies). If we eliminate the current subsidies and ad the values obtained from the CV study it turns out that the value of $F_1$ is negative from the first unit, since the value to visitors is not enough to compensate the commercial losses (and this implies that the model has no sense since cork-oak is not a relevant species in this setting). One of the reasons is the low number of visitors in the area, the other reason is that most of the biodiversity-scenic values are actually not active use values so that the visitors are not the only relevant population. We shall therefore keep the subsidies as a proxy of the biodiversity-scenic values in the case of cork-oaks. For eucalyptus there are no subsidies (just conventional taxes) so that no double-accounting exists if we add the values obtained from the CV study. As figure 6 shows, if biodiversity-values are internalized as just described, the equilibrium values would imply virtually no reforestation with eucalyptus (e.g. with a carbon price of 20 €/t C and the CFM method 0.025% of the surface should be devoted to eucalyptus) and an increase in the surface devoted to cork-oaks (as compared to the situation with no carbon internalization). The increase of the cork-oak surface would be more relevant with the CFM method, so that this method would probably be better in terms of carbon sequestration (without harming biodiversity-scenic values since eucalyptus would anyway not be planted). However, this is only the case if the negative impact of eucalyptus on the welfare of the visitors is taken into account, and this is not what markets currently do. Thus, as long as biodiversity-scenic values are not internalized it is probably more appropriate to enforce a more conservative method like the TYAM. This method will increase the amount of forest surface less, but it will not favor fast growing species with fast rotations.

# 5 Conclusion

This paper has presented an optimal control model to analyze reforestations with two different species, including in the analysis commercial values, carbon sequestration values and biodiversity or scenic values. Using general functions we have shown that the model will generally yield a saddle point, the best kind of stability that can be expect in this type of two state-variable dynamic systems. Assuming quadratic functions we have found analytically the equilibrium point, and discussed the implications of partial or total internalization of the environmental values (i.e. carbon sequestration and biodiversity/scenic values). Our discussion has shown that internalizing only carbon sequestration may have negative impacts on biodiversity/scenic values. Nevertheless, the practical relevance of this result can only be determined through applications and we have therefore applied the model to reforestations in the South-west of Spain, comparing reforestations with cork-oaks and reforestations with eucalyptus. Our results have shown that visitors value reforestations with cork-oak positively while they consider that reforestations with eucalyptus have a negative impact on their welfare. We have compared the equilibrium outcomes with two different carbon crediting methods: the Carbon Flow Method and the Ton Year Accounting Method. We have shown that with both methods the forest surface increases, although this increase is more relevant with the CFM method.

However, we have also shown that with the CFM method the increase in forest surface takes place essentially using eucalyptus while with the TYAM the increase takes place using mainly cork-oaks. Finally, we have shown that if the negative impact of eucalyptus on the welfare of the visitors is taken into account, the equilibrium would imply virtually no surface devoted to eucalyptus, regardless of the crediting method used for carbon.

In practical terms our results imply that if biodiversity-scenic values are properly internalized it may be convenient to use the CFM since it tends to increase forest surface more and species like eucalyptus would not be used due to the impact on biodiversity-scenic values. However, if biodiversity-scenic values are not internalized by markets, as is in fact the case, it may be more appropriate to used a method like the TYAM that will increase less forest surface but that will not favor fast growing alien species such as the eucalyptus in the South-west of Spain.

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# A Appendix

## A.1 Growth and yield models

The empirical illustration focuses on cork oak (*Quercus suber*) and eucalyptus (*Eucalyptus globulus*) plantations over Aljibe Mountains' sand-stone soils (in the South-west of Spain). We use growth functions for three site qualities (high, medium and low). Cork oak growth functions, as well as the initial height and diameter at breast high (DBH) conditions for different site qualities, are taken from Sánchez et al., (2005). Eucalyptus growth functions are our own estimations based on data provided by ENCE[6] for permanent plots in Huelva Mountains (also in the Sout-west of Spain). For analytical convenience we assume that cork-oak and/or eucalyptus afforestation projects lead to permanent forest. Thus, we analyze an infinite sequence rotations at fixed $T_i$ intervals.

The optimal rotation for eucalyptus is obtained as defined below, taking into account commercial as well as carbon sequestration values (and the particular carbon crediting method under consideration). The functional form of the eucalyptus growth function is:

$$v_i(t) = k\ t^a\ \ e^{-bt} \tag{23}$$

where $v_i$ is the timber volume per hectare measured in $m^3$, subscript $i$ indexes the quality of the site ($i$ =high, medium, low). The specific site qualities parameters are shown in Table A.1.

**[Table A.1]**

Carbon sequestration at any moment in time is given by $\alpha v\prime(t)$, where $\alpha$ is a carbon expansion factor ($\alpha = e_f \phi$) being $e_f$ an expansion factor from timber biomass to total biomass (including roots) and $\phi$ the tons of carbon per $m^3$ of timber biomass. We use a carbon content factor ($\phi$) of 0.20 for eucalyptus and an expansion factor of 1.5.

For cork-oak the rotation is exogenously given. The reason is that cork (bark) is its main woody output (which extraction does not imply tree felling) and the striping turn corresponds to the time required for reaching natural cork stoppers thickness (Montero et al., 2005). In the Aljibe area cork is stripped every 9 years, after the first time the cork layer is removed (28 years). The overall rotation, from planting to regeneration fellings, is also taken from Montero et al. (2005) since its main purpose is to favor cork production (cork-oak timber has a small value and is not considered while determining rotation). The revenues and costs of the entire rotation cycle of cork oak stands are estimated considering the normative silvicultural treatments, as well as, the cork and firewood yields estimated by Montero et al. (2005). Costs and prices are taken from Campos *et al.* (2005).

For cork oak, the specific site carbon sequestration function are estimated for a hectare of cork oak stands, considering Montero et al. (in press) functions

[6] ENCE is a large Iberian and American integral wood-transforming forest company, and we are most grateful for the data provided.

that relate cork oak diameter at breast high with different biomass fraction dry weight (trunk, branches, leaves and roots), the carbon content in cork oak biomass ($\phi$=0.472) and the number of standing cork trees along the cork oak rotation cycle. The particular carbon sequestration functions have the same form as eq. (23), but instead of timber volume ($v_i(t)$), the dependent variable is carbon sequestration, measured in carbon tons ($c_i(t)$) per hectare (Table A.2):

$$c_i(t) = k \ t^a \ \ e^{-bt} \tag{24}$$

**[Table A.2]**

Prices for timber, cork and firewood), as well as costs, are assumed to remain constant (at 2002 average prices), see Table A.3. Carbon sequestration benefits are analyzed considering a set of carbon prices ranging from 0 to 90 euros per ton of carbon (approximately between 0 and 25 €/ton of $CO_2$).

**[Table A.3]**

## A.2 Carbon sequestration accounting methods

Carbon sequestration revenues are estimated considering two alternative carbon accounting methods: carbon flow and ton year accounting.

### A.2.1 Carbon flow method

As stated in the introduction this method was first used, to analyse optimal rotations by Englin and Callaway (1993) but the variation proposed by Van Kooten et al. (1995) is simpler and has been frequently used, and so will we. The carbon flow method assumes that landowners get paid as carbon is sequestered by biomass growth and pay when carbon is releases through harvesting. The amount of released carbon on harvesting depends on the final use of timber. Van Kooten, et al. (1995) suggest to introduce a parameter ($\beta$) that represents the fraction of timber that is harvested but goes into long-term carbon storage structures and landfills (this is the main difference with Englin and Callaway (1993) who assume a decay function) .

The present discounted value (PV) of the net benefits from carbon sequestration and timber over all future rotations of eucalyptus at fixed $T$ intervals is (Van Kooten, et al., 1995):

$$PV_{CFM} = \frac{P_F v(T)e^{-rT} - P_c\alpha \left(1-\beta\right) v(T)e^{-rT} + P_c\alpha \int_0^T v\prime(t)e^{-rt}dt}{(1-e^{-rT})} \tag{25}$$

the first term refers to the value of timber, the second to the price paid for carbon released and the third to the carbon benefits that forest owners get from carbon that is removed from the atmosphere. $P_F$ is the net price of timber cubic meter, $P_C$ represents the value of the carbon credit/tax per carbon ton that is removed from or released into the atmosphere. The FOC is:

$$
\begin{aligned}
& (P_F + P_c\alpha\beta)v\prime(T) \\
= \quad & \frac{r}{(1-e^{-rT})}\left[(P_F + P_c\alpha\beta)v(T) + rP_c\alpha\int_0^T v(t)e^{-rt}dt\right] - rP_c\alpha v(T).
\end{aligned} \tag{26}
$$

Cork oak rotation age is given by the normative silvicultural models, but regeneration felling is not the only moment at which carbon is released since cork oaks are subject to different silvicultural treatments which imply biomass extraction (Montero et al., 2005). The complexity on cork oak management and the multi-periodical carbon release recomended to estimate year to year carbon uptake and release. We have estimated the annual carbon flows assuming that a $\beta$ fraction of extracted biomass goes into long-term carbon storage structures, and fitted a carbon stock function (Table A.3).

### A.2.2 Ton year accounting method

For the TYAM we assume that the government derives to growers carbon credits adjusted on the basis of the *equivalence factor* ($\varepsilon$) from sequestering 1 $CO_2$ ton in the forest biomass for one year. This equivalence factor is estimated based on the cumulative radiative forcing of an emission of $CO_2$ over a 100-years time horizon. Moura-Costa and Wilson (2000) estimate $\varepsilon$ to be 0.0182 t $CO_2$.

For the TYAM we get the following expression for the present value:

$$
PV_{TYAM} = \frac{P_F v(T)e^{-rT} + P_c\alpha\varepsilon\int_0^T v(t)e^{-rt}dt}{(1-e^{-rT})} \tag{27}
$$

where the second term of eq (27) represents the carbon benefits that forest owners for having carbon sequestered in their forest (the TYAM does not imply any reimbursement of carbon credits upon harvest). In fact, this method yields a similar result to Hartman´s (1973) formula since the standing forest has a value. The FOC used to determine the optimal rotation for the eucalyptus is now:

$$
\begin{aligned}
& P_F v\prime(T) + P_c\alpha\varepsilon v(T) \\
= \quad & \frac{r}{(1-e^{-rT})}\left[P_F v(T) + P_c\alpha\varepsilon\int_0^T v(t)e^{-rt}dt\right]
\end{aligned} \tag{28}
$$

For estimating carbon benefits in case of cork oak we use the fitted cork oak carbon sequestration function (Table 3), and the equivalence factor $\varepsilon$.

## A.3 Estimated quadratic functions

Table A.4 shows the quadratic functions estimated. Current net subsidies are considered as a proxy for biodiversity-scenic values.

**[Table A.4]**

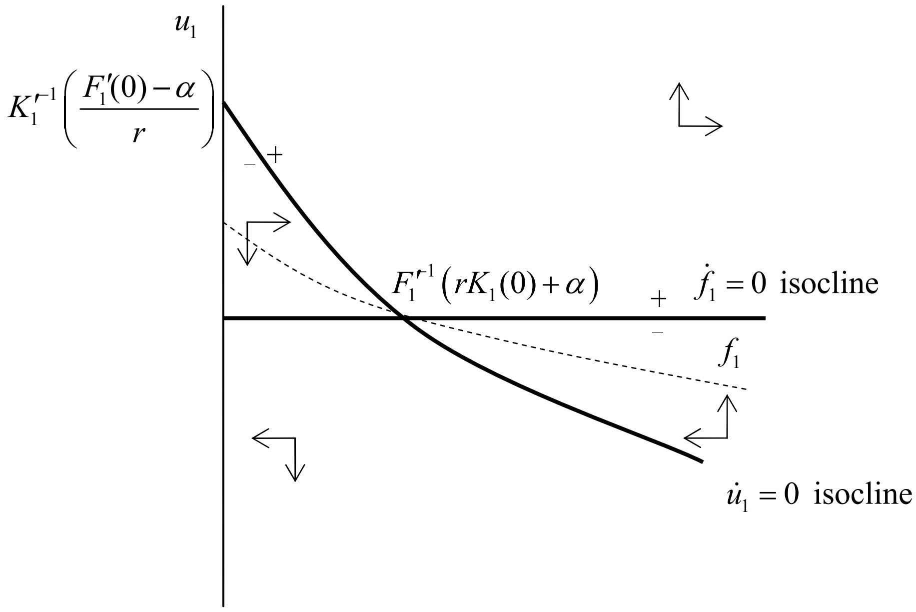


Figure 1. Phase-diagram with general functions.

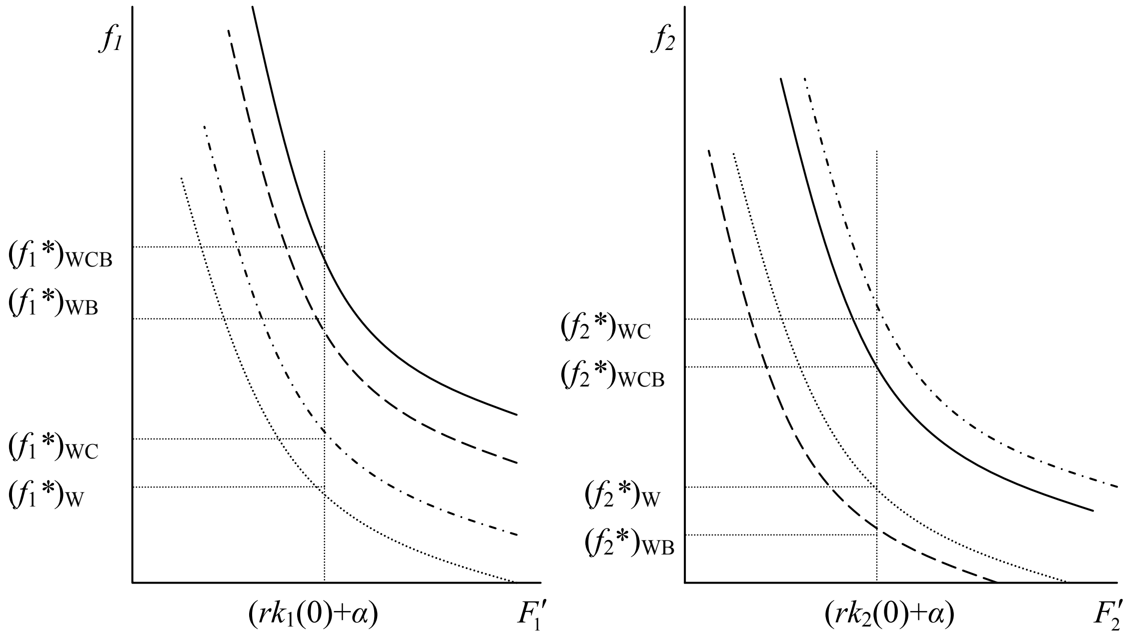


Figure 2. Equilibrium reforestation amounts for species 1 and 2. The functions shown are the marginal value functions for timber (dotted line), timber and carbon sequestration (dashed-dotted line), timber and biodiversity-scenic (dashed line) and timber, carbon and biodiversity-scenic (full line).

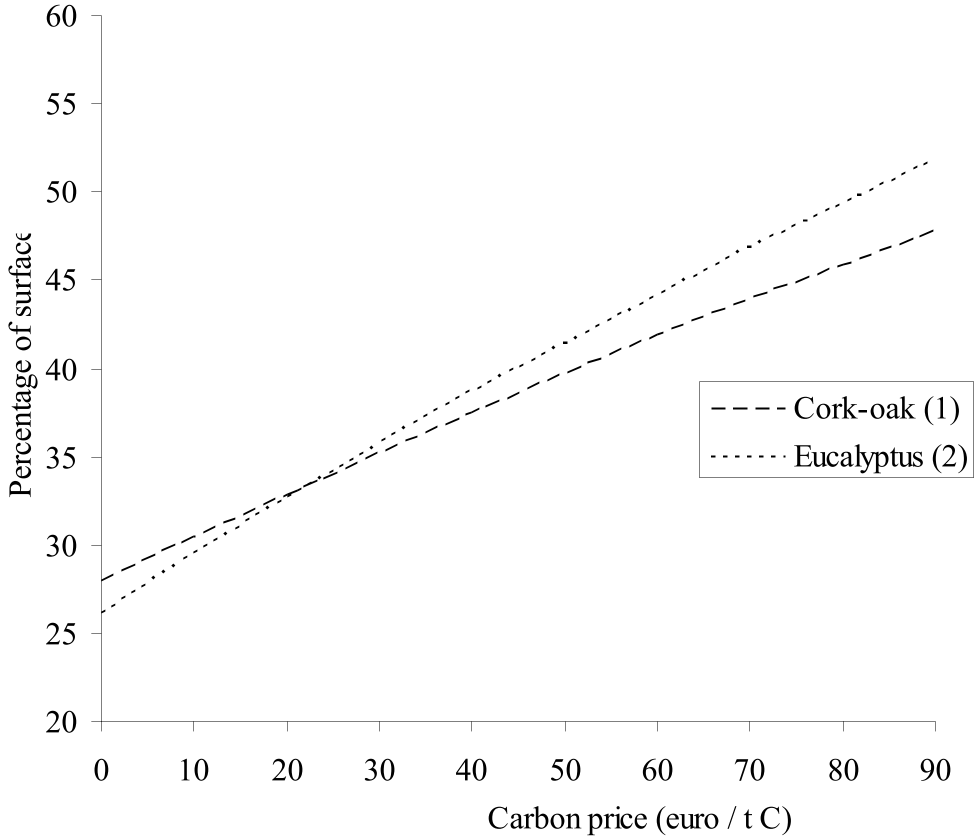


Figure 3. Equilibrium surface for cork-oak (species 1) and eucalyptus (species 2) in the ANP using the Carbon Flow Method (CFM).

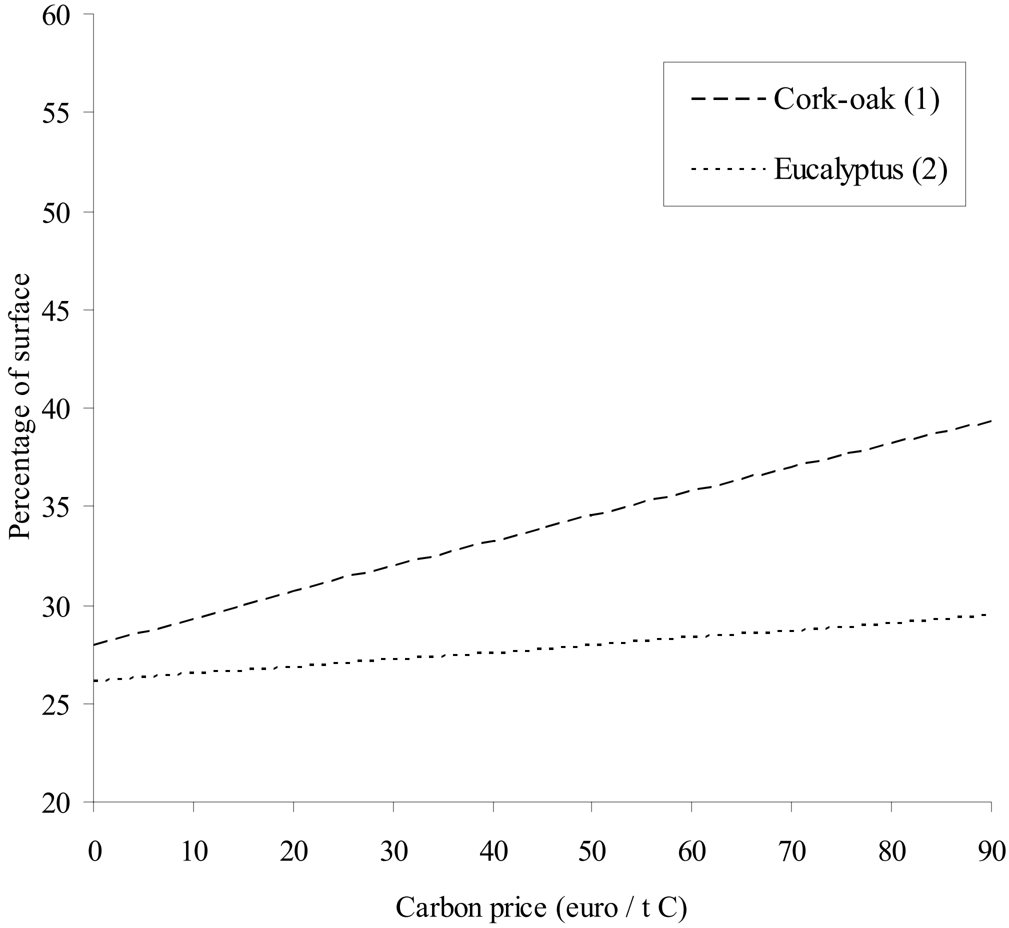


Figure 4. Equilibrium surface for cork-oak (species 1) and eucalyptus (species 2) in the ANP using Ton Year Accounting Method (TYAM).

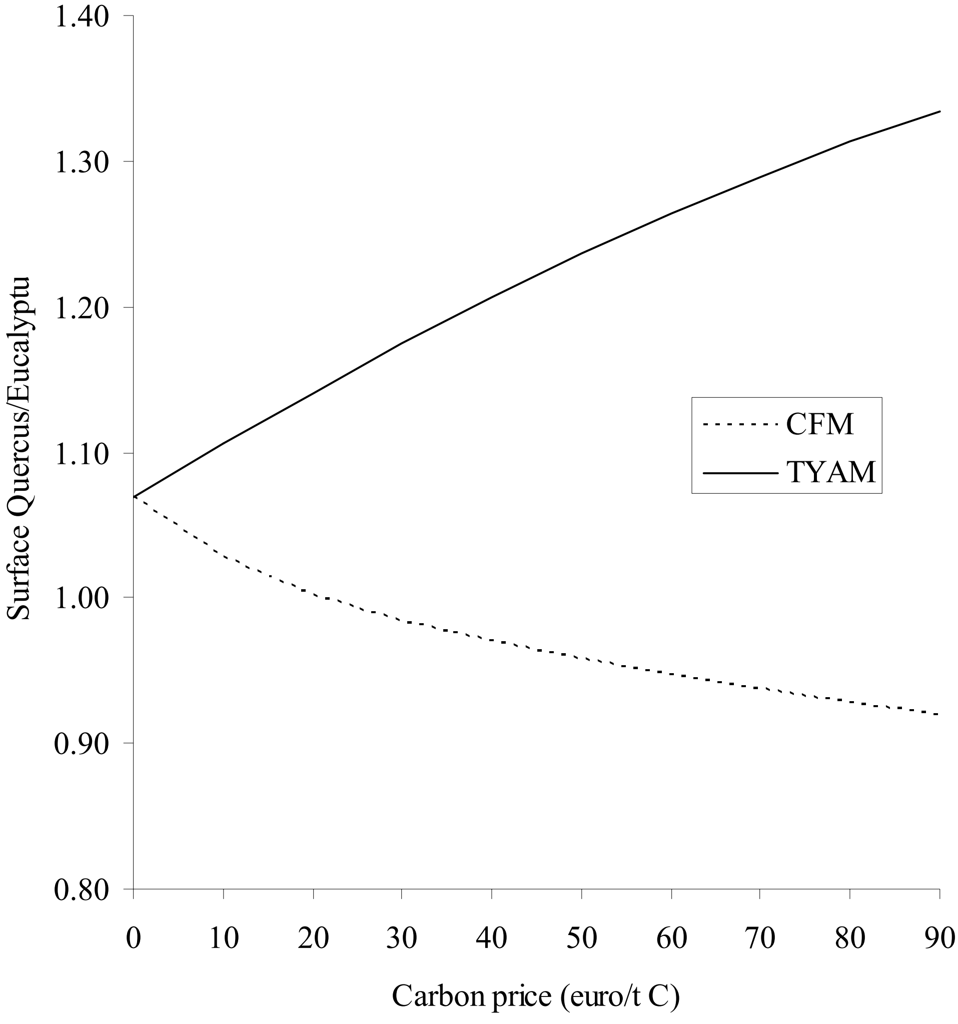


Figure 5. Equilibrium ratio of cork-oaks over eucalyptus for different carbon prices and for the CFM and the TYAM.

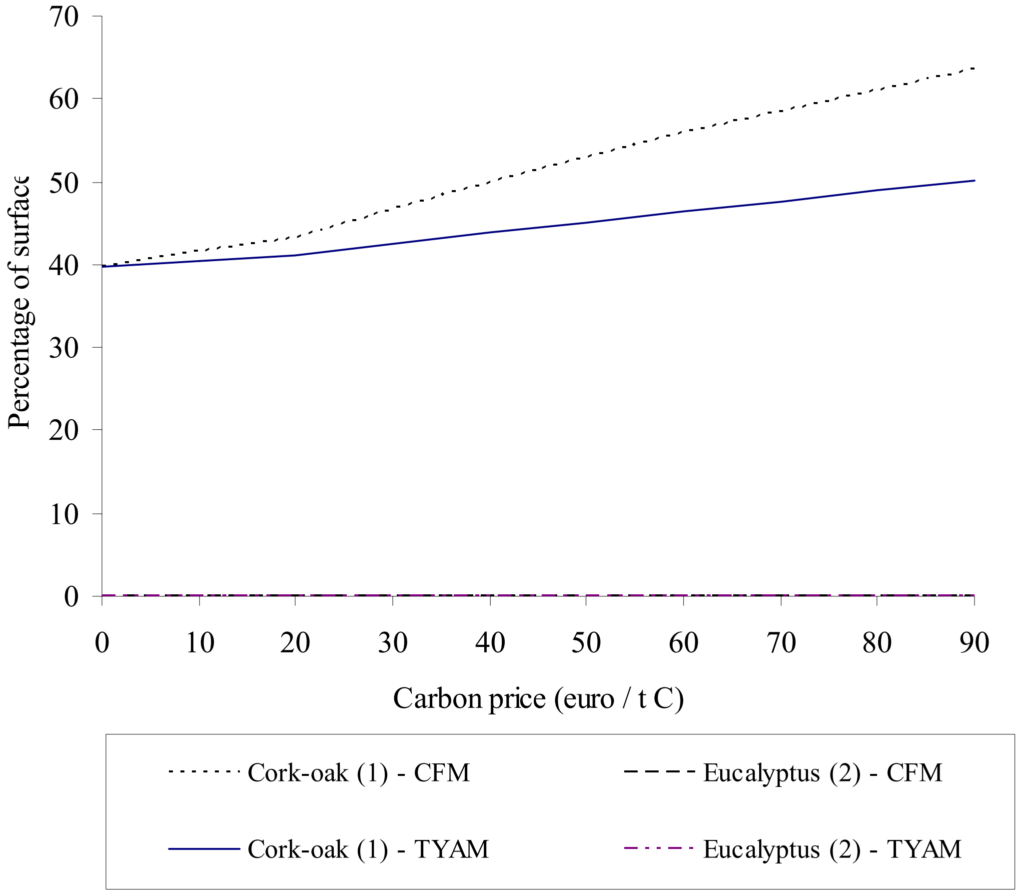


Figure 6. Equilibrium ratio of cork-oaks over eucalyptus for different carbon prices and for the CFM and the TYAM if eucalyptus is internalized.

Table 1. Subjective valuation of a reforestation with different species in the Alcornocales Natural Park (ANP)

| | Could you tell us what is your opinion about a reforestation with …. in the ANP? (percentage) | |
|---|---|---|
| | Cork-oaks | Eucalyptus |
| Very negative | 0.7 | 58.9 |
| Negative | 2.5 | 31.0 |
| Indifferent | 2.2 | 2.5 |
| Positive | 42.9 | 6.1 |
| Very positive | 51.8 | 1.6 |

Table 2. Willingness to pay to ensure a reforestation with cork-oaks and to avoid a reforestation with eucalyptus in the Alcornocales Natural Park

| | Reforestation to maintain current forest surface (compensate deforestation) | | Reforestation to increase a 20% current forest surface | |
|---|---|---|---|---|
| | WTP to *ensure* this reforestation with *cork-oaks* | WTP to *avoid* this reforestation with *eucalyptus* | WTP to *ensure* this reforestation with *cork-oaks* | WTP to *avoid* this reforestation with *eucalyptus* |
| Total answers | 450 | 450 | 450 | 450 |
| Valid answers | 425 | 408 | 425 | 408 |
| Mean (€) | 26.96 | 24.21 | 30.49 | 29.68 |
| Median (€) | 12.00 | 10.00 | 12.00 | 10.00 |
| Standard deviation | 58.43 | 61.73 | 60.60 | 88.65 |

Table A.1. Parameters of the growth functions for different site qualites

| Sites of quality | Eucalyptus (timber) | | | | Cork-oak (carbon sequestration)* | | | |
|---|---|---|---|---|---|---|---|---|
| | Parameters | | | $R^2$ | Parameters | | | $R^2$ |
| | k | a | b | | k | a | b | |
| High | 0.6935 | 2.6943 | 0.1136 | 0.984 | 0.9623 | 1.0467 | 0.0060 | 0.651 |
| | (0.2686) | (0.2041) | (0.0111) | | (0.3600) | (0.0967) | (0.0007) | |
| Medium | 0.5088 | 2.6943 | 0.1136 | 0.984 | 0.8157 | 1.0241 | 0.0060 | 0.667 |
| | (0.1971) | (0.2041) | (0.0111) | | (0.2800) | (0.0891) | (0.0007) | |
| Low | 0.3568 | 2.6943 | 0.1136 | 0.984 | 1.0223 | 0.8106 | 0.0032 | 0.679 |
| | (0.1382) | (0.2041) | (0.0111) | | (0.3558) | (0.0897) | (0.0006) | |

Note: Standard errors are in parenthesis.
* A $\beta$ of 0.2 is assumed.

Table A.2. Outputs, costs and prices (euro, year 2002)

| Class | Unit (U) | Price (€ $U^{-1}$) | Quantity reliant on site quality ($U\ ha^{-1}$ along the rotation cycle)* | | |
|---|---|---|---|---|---|
| | | | High | Medium | Low |
| Cork oak | | | | | |
| Summer stripped cork | t | 1,100 | 72.9 | 54.3 | 38.8 |
| Winter cork | t | 100 | 23.6 | 16.9 | 10.8 |
| Firewood | t | 30 | 139.6 | 106.0 | 72.6 |
| Harvesting costs (cork) | t | 263.0 | | | |
| Eucalyptus** | | | | | |
| Timber (farm gate) | $m^3$ | 34.8 | 143.6 | 105.3 | 73.9 |
| Harvesting costs | $m^3$ | 10.8 | | | |

Note: Standard errors are in parenthesis.
* Cork oak cycle last 144 years, in case no carbon is accounted for eucalyptus rotation length is 12 years.
** Timber volume in a €0 price per sequester carbon ton context.

Table A.3. Parameters estimated for the quadratic functions (euros/ha)

| | | Pasture | | | Quercus | | | Eucaliptus | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Description | Function | $a_{01}$ | $a_{02}$ | $R^2$ | $a_{11}$ | $a_{12}$ | $R^2$ | *T (years)* | $a_{21}$ | $a_{22}$ | $R^2$ |
| Commercial (Timber, firewood and/or cork) | W | 140.00000 | -0.00053 | 1.00000 | -230.09180 | -0.00065 | 0.95676 | 9.7 | 266.57248 | -0.00101 | 0.99745 |
| Biodiversity-scenic values | | | | | | | | | | | |
| Subsidies | B | | | | 480.23689 | | | | -8.28756 | | |
| Contingent valuation | B | | | | 104.99000 | -1.76480 | 1.00000 | | -91.15800 | 1.41160 | 1.00000 |
| Carbon sequestration (CFM) | C | | | | | | | | | | |
| Price 10 €/tC | C | | | | 10.04547 | -0.00004 | 0.99658 | 10.2 | 13.98739 | -0.00005 | 0.99745 |
| Price 20 €/tC | C | | | | 20.09093 | -0.00008 | 0.99658 | 10.6 | 27.79865 | -0.00011 | 0.99745 |
| Price 30 €/tC | C | | | | 30.13640 | -0.00011 | 0.99658 | 11.4 | 41.60950 | -0.00016 | 0.99745 |
| Price 40 €/tC | C | | | | 40.18187 | -0.00015 | 0.99658 | 12.2 | 55.53044 | -0.00021 | 0.99745 |
| Price 50 €/tC | C | | | | 50.22734 | -0.00019 | 0.99658 | 13.0 | 69.63380 | -0.00026 | 0.99745 |
| Price 60 €/tC | C | | | | 60.27280 | -0.00023 | 0.99658 | 13.8 | 83.96800 | -0.00032 | 0.99745 |
| Price 70 €/tC | C | | | | 70.31827 | -0.00026 | 0.99658 | 14.6 | 98.56575 | -0.00037 | 0.99745 |
| Price 80 €/tC | C | | | | 80.36374 | -0.00030 | 0.99658 | 15.4 | 113.44897 | -0.00043 | 0.99745 |
| Price 90 €/tC | C | | | | 90.40921 | -0.00034 | 0.99658 | 16.2 | 128.63197 | -0.00049 | 0.99745 |
| Carbon sequestration (TYAM) | C | | | | 3.79111 | -0.00001 | 0.99852 | 9.9 | 1.35701 | -0.00001 | 0.99745 |
| Price 10 €/tC | C | | | | 7.58223 | -0.00003 | 0.99852 | 10.0 | 2.70093 | -0.00001 | 0.99745 |
| Price 20 €/tC | C | | | | 11.37334 | -0.00004 | 0.99852 | 10.4 | 5.35678 | -0.00002 | 0.99745 |
| Price 30 €/tC | C | | | | 15.16446 | -0.00005 | 0.99852 | 10.7 | 7.98075 | -0.00003 | 0.99745 |
| Price 40 €/tC | C | | | | 18.95557 | -0.00007 | 0.99852 | 11.0 | 10.58431 | -0.00004 | 0.99745 |
| Price 50 €/tC | C | | | | 22.74669 | -0.00008 | 0.99852 | 11.3 | 13.17759 | -0.00005 | 0.99745 |
| Price 60 €/tC | C | | | | 26.53780 | -0.00010 | 0.99852 | 11.7 | 15.76957 | -0.00006 | 0.99745 |
| Price 70 €/tC | C | | | | 30.32892 | -0.00011 | 0.99852 | 12.0 | 18.36832 | -0.00007 | 0.99745 |
| Price 80 €/tC | C | | | | 34.12003 | -0.00012 | 0.99852 | 12.3 | 20.98113 | -0.00008 | 0.99745 |
| Price 90 €/tC | C | | | | 37.91115 | -0.00014 | 0.99852 | 12.7 | 23.61468 | -0.00009 | 0.99745 |
| | | | | | $k_{11}$ | $k_{12}$ | | | $k_{21}$ | $k_{22}$ | |
| Reforestation costs | K | | | | 2419.2848 | | | | 2295.6915 | | |