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Summary

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 solve the model qualitatively with general functions and discuss the implications of partial or total internalization of environmental values, showing that internalizing only carbon sequestration may have negative impacts on biodiversity-scenic values. To evaluate the practical relevance, we compare reforestations in the South-west of Spain with cork-oaks (a slow growing native species) and with eucalyptus (a fast growing alien species). We do the analysis with two different carbon crediting methods: the Carbon Flow Method and the Ton Year Accounting Method. With the .first method forest surface increases more, but using mainly eucalyptus. With the second, additional reforestations are done mainly using cork-oaks. We value the impact on visitors of these reforestations using stated preferences methods, showing that when these values are internalized cork-oaks are favored.

Keywords: Optimal Control, Forests, Carbon, Sequestration, Biodiversity, Scenic, Stated Preferences, Carbon Accounting

JEL Classification: Q23, Q26, Q51, Q57

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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, 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[1].

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, 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 indicated in Caparrós and Jacquemont (2003 and 2005). The authors also show that neither the convention on climate change (UNFCCC) nor the convention on biodiversity (CBD) have adequate mechanisms to avoid this possibility, especially in the case of the 'afforestations and reforestation' alternative since most of the limits established for carbon sequestration alternatives do not affect this option[2]. Although it has received less attention, a similar argument can be elaborated linking carbon sequestration and scenic values, since fast growing plantations tend to have lower scenic beauty. In this article we will treat these values indistinctly, as values that are currently not internalized by markets and that will probably remain outside of markets in the near future (while carbon

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[1] The United States have decided not to ratify the Kyoto Protocol, but during the negotiations of the Protocol and the Marrakech Accords they were one of the Parties more clearly advocating for the extensive use of carbon sequestration, or 'sinks' altenatives, so that forest alternatives will continue to be a fundamental part of their carbon policy (Richards et al., 2006).

[2] 'Forest management' has a strong quantitative limit that probably will imply that no incentives are established by Annex I countries since the limit will be reached anyway. In addition, the definition given explicitly includes a reference to biodiversity. Finally, most forest management options to increase carbon sequestration tend to increase forest rotations and this is generally positive for biodiversity. The remaining LULUCF alternatives are expected to be less important. See Caparrós and Jacquemont (2003 and 2005) for more details.

sequestration values are about to be internalized).

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[3] 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. In the first case, each country can decide how to incentivate carbon sequestration in its own land. What is going to matter at the international level is the total carbon budget of the country, since the Kyoto targets are based on net emissions. Therefore, a reasonable incentive mechanism to be set up by Annex-I governments 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 by the government[4] (a subsidy) when carbon sequestration takes place and has to pay (a tax) when carbon is released (Feng *et al.* (2002) describe a similar system calling it the 'pay-as-you-go' method). The value of this carbon subsidy-tax is set equal to the carbon price associated to CO_2 emissions. Richards *et al.* (2006) also present this method as one of the best alternatives to be used in the US. An alternative method, or set of methods, is well represented by what is known as the 'Ton Year Accounting Method' (TYAM), see Moura-Costa and Wilson (2000). This method implies to pay a given amount to the forest owner each year as long as the carbon stays in the forest. The price to be paid is based on the carbon emission price and an *equivalence factor* (ε) that captures the benefit associated to sequestering one ton of CO_2 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). An essentially similar method is the carbon 'rental fee' used in Sohngen and Mendelsohn (2003), where the forest owner gets paid a fee for each ton of carbon stored for one year. Although the method used to calculate this fee in Sonhngen and Mendelsohn's paper is totally different, based on the expected increase in carbon emission prices, what matters for our purposes is that the owner gets paid for the total number of tons of carbon sequestered (not for the increase in carbon) and that the amount paid is substantially lower than the carbon price. The 'variable-lenght-contract' method described in Feng et al. (2002) is also similar to the TYAM, as the authors recognize. Thus, by analyzing the outcome with the CFM and the TYAM we cover most of the methods proposed so far in the literature, at least those targeting directly carbon[5].

For credits earned by CDM projects two methods have finally been accepted within the Kyoto-Marrakech framework: the t-CERs and the l-CERs (Olshewski and Benítez, 2005). The main difference between the two crediting procedures is

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

[4] For both methods (CFM and TYAM) the money could actually come from a well defined emission trading scheme.

[5] Lubowski et al. (2006) analyze the impact of a constant per hectare payment for land use changes into forests, without explicetly targeting the carbon sequestered.

the lifetime of the credit, 5 years in the case of the t-CER and up to 30 years with the l-CERs (both methods are subject to a maximum time limit of 60 years). The t-CER method can be seen as a variation of the TYAM 'type' of methods (paying for the standing forest, not for growth), with the particularity that the price is paid every 5 years and that the contract has a maximum time limit. Nevertheless, although our model could be applied to the CDM framework, we focus on Annex-I countries (Spain in the application) and discuss the two methods described in the previous paragraph.

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. Applying this model to Canada, the author makes a strong argument in favor of large scale plantations using fast growing species. The model that we are going to present here develops this model in three ways: (i) we include a second tree species, what implies to have a second state variable and a second control variable, (ii) we include biodiversity-scenic values in the analysis, and (iii) we allow for more general functions. We characterize the steady-state of the model and show phase diagrams under some additional assumptions (constant marginal value for pastureland). We then apply it to data for the South-west of Spain and discuss the outcomes with the two carbon accounting methods described above.

Moons et al. (2005) and Muys et al. (2003) also deal, using a GIS-based model in the first case and an integrated assessment model in the second case, with the establishment of new forests for carbon sequestration purposes, including recreation and other values in the analysis. These models are solved numerically and highlight the empirical importance of taking into account recreational values. In Caparrós *et al.* (2003) recreational values and carbon sequestration values are optimized jointly while determining the optimal rotation, but this model does not deal with reforestations. The remaining and extensive literature on reforestations set up for carbon sequestration purposes does not incorporate neither biodiversity nor recreational or scenic values in the analysis (for a review, see Richards and Stokes (2004)).

In the applied section of this paper, we 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, or the ecosystem associated with it, is assumed to have positive biodiversity values. Oaks (cork-oaks and holm-oaks) are the main tree species in Mediterranean forests, one of the hot-spots for biodiversity in the world (Huntsinger and Bartolome, 1992). The second species 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 estimated the impact on visitors' welfare of a reforestation with these species using stated preferences methods. We do not claim to be able to separate biodiversity values from scenic values, since visitors are probably considering both when valuing reforestations. Thus, we will refer to biodiversity-scenic values in the application. The results show that 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. To put a dollar value on these welfare changes we have conducted a choice experiment to value the contribution of cork-oak reforestations to the welfare of the visitors. We have also measured the impact of reforestations with eucalyptus (and with cork-oaks) using the contingent valuation method. To integrate these values into our model, we have assumed that a share of these welfare changes could be internalized through additional subsidies for cork-oaks or through compensations to refrain from using eucalyptus (see below).

Turning to the results of our applied model, we first show that with current market values reforestations with cork-oaks would not take place even if carbon sequestration values were internalized. Nevertheless, with the current system of subsidies for cork-oak reforestations the new incentives for carbon sequestration would significantly increase the optimal amount of cork-oaks in a scenario without competition with eucalyptus. If we allow for competition with eucalyptus, we show that both incentive mechanism described above to foster carbon sequestration (CFM and TYAM) 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, we also show 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). In fact, with the TYAM method most of the increase in surface takes place using cork-oaks. Furthermore, if biodiversity-scenic values were internalized, the amount of surface devoted to eucalyptus would be significantly smaller than the amount devoted to cork-oaks, even after internalizing carbon using either one of the accounting methods discussed in this paper (except for the CFM under high carbon prices).

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 is a saddle point and analyze qualitatively the optimal path under the assumption that pastureland has constant returns to scale. Section 3 contains the application in the South-west of Spain. We first analyze the model with the quadratic functions used in the application, dropping the assumption that the marginal value of pasture is constant. The section continues by showing the results obtained internalizing only carbon sequestration and then moves on to show the results obtained internalizing biodiversity-scenic values as well. Section 4 concludes.

2 The model

We assume that the agent (forest owner) 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 to the amount of new land devoted to forest (although u could imply a deforestation for some initial conditions we will focus on situations where it implies reforestations, see below). 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 return values for pasture land $(i = 0)$ or for each type of forest i $(i = 1, 2)$. We assume[6] $F_i' > 0$ 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 returns associated with commercial uses (timber, cork, firewood, grazing resources rent etc.), carbon sequestration and biodiversity-scenic values respectively (we will discuss below the internalization of the latter values). Forest-related data are strongly time-dependant but for modeling reasons it is interesting to annualize them, ensuring that investment incentives are not changed (Van Kooten, 2000). That is, following Van Kooten we will assume that once a piece of land is converted it stays in the new status, so that we can find an annualized value that is equivalent to the future stream of benefits associated to this type of land use[7]. This is the same assumption made in Van't Veld and Plantinga (2005) and essentially the same than the assumption made in Feng et al. (2002). Since we start in a situation where $f_1(0) = f_2(0) = 0$ (in land that is suitable for the 'afforestation and reforestation alternative) this assumption is reasonable in empirical terms, since the high costs associated with a reforestation ensure that the conversion to a particular forest type is only worthwhile if the forests stays for a sufficiently long period of time.

Once a portion of land is devoted to forest the owner chooses the rotation optimally, taking into account the existing incentives. That is, he or she will follow Faustmann's formula if only commercial values are considered and the appro-

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[6] This assumption implies that each species or type of use has different optimal growth areas, which is a reasonable assumption in most cases. For large scale reforestations price effects can also explain this functional forms.

[7] 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 $Z = rPV_z = r\int_0^\infty z(t)e^{-rt}dt$.

priate extension of this formula if carbon sequestration (Englin and Callaway, 1993; Van Kooten et al., 1995), biodiversity-scenic values (Hartman, 1976) or carbon sequestration and biodiversity-scenic values are internalyzed (Caparrós et al., 2003). The model can thus be seen as having two stages: first the optimal amount of land devoted to a given species is decided and then the optimal rotation. Solving this implies to start at the second stage (optimal rotation) and then move on to the first stage. We will do this two stage process in the application, but since the different variations to be done to the Faustmann's formula are already well understood (they are described in the Appendix in the framework of our application) we will assume here that the function $F_i(f_i)$ already describes optimal rotation values for each species.

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.

$$\begin{aligned} \dot{f}_1 &= u_1 \qquad (1) \\ \dot{f}_2 &= u_2 \qquad (2) \end{aligned}$$

And initial conditions: $f_1(0) = 0$ and $f_2(0) = 0$. Although it is not necessary for the model itself, to apply the model to the 'afforestation and reforestation' alternative within the Kyoto Protocol we have to assume that $f_1(0) = f_2(0) = 0$, since only areas not covered by forests in 1990 are eligible.

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

$$MaxH_c = \Pi + \lambda_1 u_1 + \lambda_2 u_2, \qquad (3)$$

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

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

Π 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 λ_1 and λ_2:

$$\begin{aligned} \lambda_1 &= K_1'(u_1) \qquad (6)\\ \lambda_2 &= K_2'(u_2) \qquad (7)\end{aligned}$$

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:

$$\begin{aligned} \frac{F_1'(f_1)}{r} - K_1'(0) &= \frac{F_0'(L - f_1 - f_2)}{r} \qquad (8)\\ \frac{F_2'(f_2)}{r} - K_2'(0) &= \frac{F_0'(L - f_1 - f_2)}{r} \qquad (9)\end{aligned}$$

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:

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

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 pastureland.

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

$$\begin{aligned} \dot{\lambda}_1 &= K_1''(u_1)\dot{u}_1 \qquad (11)\\ \dot{\lambda}_2 &= K_2''(u_2)\dot{u}_2 \qquad (12)\end{aligned}$$

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

$$\begin{aligned} \dot{u}_1 &= \frac{rK_1'(u_1) - [F_1'(f_1) - F_0'(L - f_1 - f_2)]}{K_1''(u_1)} \qquad (13)\\ \dot{u}_2 &= \frac{rK_2'(u_2) - [F_2'(f_2) - F_0'(L - f_1 - f_2)]}{K_2''(u_2)} \qquad (14)\end{aligned}$$

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.

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 $\frac{\partial \dot{f}_i}{\partial u_i} = 1$, the determinant of the Jacobian matrix for the system formed by (1)(2)(13) and (14) evaluated at the equilibrium point simplifies to:

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

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

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

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'[8]. 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 $(K_1'^{-1})'(Y) > 0$.

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:

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

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

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**]

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 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[9] the stable branch southeast of the long-term equilibrium (i.e. to reduce the amount of forest type 1, a negative u_1).

2.3 Commercial, 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-scenic values.

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[9] 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.

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 timber values (W) are 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 $\left(\frac{f_1^*}{f_2^*}\right)_{WC} < 1$, 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 $\left(\frac{f_1^*}{f_2^*}\right)_{WB} > 1$. This is the situation that a central planner should take into account today (if we assume that carbon sequestration plays no role for the time being). Finally, the value of $\left(\frac{f_1^*}{f_2^*}\right)_{WCB}$ depends on the relative importance of carbon and biodiversity-scenic values.

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 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 apply the model just described to a multiple-use forests in Spain.

3 Application

Since we need to specify particular functions to apply the model we will first discuss the model with the particular functions to be used in the application. We will then apply the model 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. Forests (mainly cork-oaks) cover currently about 53% of the total surface of the area and eucalyptus have also been used in the past in this area for reforestations[10]. Since we are analyzing the ‘afforestation and reforestations’ alternative within the Kyoto Protocol we have to focus on areas that were not covered by trees in 1990. This leaves us with about 80,000 hectare.

We are going to compare reforestations with cork-oaks and with eucalyptus on pastureland. The first species is an extremely slow growing species which yields a highly diverse ecosystem when mature, and which is a key element of the Mediterranean forest, one of the hot-spots for biodiversity in the world (Huntsinger and Bartolome, 1992). Eucalyptus, on the other hand, is a fast growing species (with rotations of about 10 years) and yields more a plantation than a true forest. In addition, with current economic incentives (see below) both species are more or less as attractive to the forest owner, so that it is a good example to study the changes in existing incentives brought forward by the internalization of carbon sequestration.

3.1 Quadratic functions

We 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 assume quadratic 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 these type of functions is very convenient for the discussion on the three different types of benefits generated by the forests under consideration. Finally, the quadratic form is well suited to adapt the data obtained through a choice experiment for biodiversity-scenic values (see table 2 below).

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 $K_i''(u_i) > 0$:

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

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[10] Right now plantations with eucalyptus are not allowed in this area due to environmental restrictions. Within our model this implies that taking into account the values for W and B the government has decided to preclude the use of eucalyptus, but not using market values. We are thus studying the impact of relaxing this environmental constraint. Alternatively, our results can be seen as applying to areas where this environmental contraint is not in place.

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.

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:

$$\dot{u}_1 = \frac{rk_{11} + rk_{12}u_1 - [a_{11} + a_{12}f_1 - a_{01} - a_{02}(L - f_1 - f_2)]}{k_{12}} \tag{20}$$

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

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.

3.2 Adding carbon sequestration to current incentives

We will start by focusing 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 government. Subsidies are actually very important in the area under consideration since the Spanish government, within the framework of the EU Common Agricultural Policy reforms, has established a strong incentive for afforestations (applicable to cork-oaks but not to eucalyptus). These are considered environmentally-friendly subsidies and are not likely to disappear in the near future[11]. If these subsidies were set optimally, they should already incorporate the carbon and biodiversity-scenic values discussed above[12]. Nevertheless, this perfect internalization is probably not a

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[11] In the whereas (29) of the Council Regulation 1257/1999 (OJEC, 1999) it is said that "in the coming years, a prominent role should be given to agri-environmental instruments to support the sustainable development of rural areas and to respond to society's increasing demand for environmental."

[12] In the whereas (38) of the Council Regulation 1257/1999 (OJEC, 1999) it is said that "the afforestation of agricultural land is especially important from the point of view of soil use and the environment and as a contribution to increasing supplies for certain forestry products ...". The application of this norm in Spain can be found in the Real Decreto 6/2001 (BOE, 2001). The reasons for the subsidies enumerated in the Real Decreto are: diversify agricultural production, income and employment; reduce erosion and desertification; favour the conservation of soil, fauna and flora; protect hydrological and ecological balance and reduce fire hazards.

realistic assumption. Hence, we will discuss our results taking out these subsidies (to avoid any double counting) but also keeping the current subsidies. The latter is probably the most relevant scenario, since it is unlikely that the current subsidies for cork-oaks would be eliminated if a general scheme to internalize carbon would be established. Thus, we have two different functions for W (see Table A.4 in the Appendix), one including only commercial values (W/S) and one including all the incentives currently faced by the agent ($W = W/S + S$). The latter include subsidies for cork-oaks but also taxes for both species (i.e. S shows net subsidies).

Although we will use higher carbon prices in some points of our discussion, we will focus on the impact of carbon prices ranging between 0 € and 70 € t/C (about 20 € t/CO_2). This covers the price range that has been historically observed in the different emerging carbon trading schemes (CCPO, 2006). Future prices might be significantly higher according to simulation models, so that the range analyzed can be seen as conservative. In all the discussion below we use a discount rate of 5%, since we are more interested in the sensitivity of our results to other parameters (although the discount rate is a crucial parameter, like in most forestry studies).

The first relevant message that comes out from our application is that without the current subsidies no reforestation with cork-oaks would take place, even if carbon sequestration is integrated. With the CFM a carbon price of more than 400 € t/C (about 110 € t/CO_2) would be necessary to see some reforestation with cork-oaks; with the TYAM the carbon price would need to be even higher. That is, for reasonable carbon prices $(a_{11} - rk_{11}) > (a_{01} + a_{02}L)$ does not hold, and this was a necessary assumption made in the previous section to show that $f_1^* > 0$. Thus, current subsidies are necessary to make cork-oaks a meaningful alternative.

If we re-write the model previously presented with only one tree species (eucalyptus) and pasture, we can study the impact that carbon sequestration incentives would have on eucalyptus if the current incentives for cork-oak would not exist (this is essentially the same model as the one presented in Van Kooten (2000), although with quadratic functions). This would yield an equilibrium with 61% of the surface devoted to Eucalyptus with the CFM method and 44% with the TYAM, with a price of 70 € t/C.

For the more realistic scenario where current incentive for cork-oaks coexist with additional incentives for carbon sequestration, we will start by investigating a situation were Eucalyptus are banned due to environmental regulations and then analyze the impact of allowing for competition with Eucalyptus.

Figure 2 shows the phase diagram[13] when only reforestations with cork-

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[13] This phase diagram is not the same as the one shown in Figure 1 since we are rewriting the whole model with only one species, taking thus into account explicetly the space constraint. The steps to draw the phase diagram are essentially the same, so that we will not repeat the whole process (see also Van Kooten (2000)). Let us just add that the $\dot{f} = 0$ isocline follows the f_1 axis as before and that the $\dot{u} = 0$ isocline intersects the u_1 axis at $\frac{(a_{11} - rk_{11}) - a_{01} - a_{02}L}{k_{12}}$ and the f_1 axis at $\frac{(a_{11} - rk_{11}) - a_{01} - a_{02}L}{-(a_{12} + a_{02})}$.

oaks are allowed, without any carbon price and with a carbon price of 70€t/C internalized with the two methods considered (CFM and TYAM, see Appendix). As can be seen, internalizing carbon sequestration essentially implies to shift outwards the $\dot{u} = 0$ isocline, and this will increase the number of hectares reforested per year and increase the steady-state value of the surface devoted to cork-oak. That is, if we add carbon sequestration incentives to current subsidies and continue to ban Eucalyptus the cork-oak area will increase significantly.

[**Figure 2**]

We now turn to our main model and allow for competition with eucalyptus. As Figure 3 shows, with the current incentives (market values plus net subsidies and a carbon price equal to zero) the equilibrium quantities[14] imply a considerable increase in the surface devoted to eucalyptus, although the surface devoted to cork-oak is actually larger than the surface devoted to eucalyptus (28% of the surface would be covered with cork-oaks and 26% with eucalyptus). That is, if we keep the current subsidies we are actually in a situation that is very close to the one assumed in section 2.3 (i.e. that the equilibrium ratio between the two species is close to one).

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-oaks also increases (as shown in the Appendix we calculate the optimal rotation for eucalyptus taking into account the incentives for carbon sequestration, while we assume that the silviculture for cork-oaks is not changed due to the carbon incentives). Figure 3 shows the equilibrium quantities devoted to cork-oak and eucalyptus for different carbon prices. As shown, with a price of 70 €/t C (20 €/t CO_2) almost all the surface available is devoted to forest (44% cork-oaks and 47% eucalyptus).

[**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 70 €/t C considered forests cover 66% of the surface (see Figure 3). Nevertheless, the important difference is that now the increase of forest surface takes place using mainly cork-oaks (with the 70 €/t C price, cork-oaks cover 37% of the surface while eucalyptus cover 29%). In addition, it has to be taken into account that these results are for the particular equivalence-factor estimated by Moura-Costa and Wilson (2000): $\varepsilon = 0.0182$. This implies, in our case, that less money goes into the area due to the internalization of carbon sequestration (compared to the CFM). To have the same amount of money going into the area, the equivalence factor had to be set equal to 0.04[15]. In this case, for a carbon price of 70 €/t C up to 46% of the area is reforested with cork-oaks (32% is covered by

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[14] While the equilibrium value is not affected by the value of k_{i2} (the parameter describing how reforestation cost per ha increase with surface), the amount of land reforested each year is highly sensitive to this parameter (which is not well know in our application). Given this sensitivity and the imposibility to draw phase diagrams when both species are considered (with decreasing marginal values for pasture) we have decided to focus on equilibrium values.

[15] The precise value of the equivalence factor is highly controversial. In addition, and as stated in the introduction, we are using the TYAM as an example of different accounting methods were the forest owner gets paid for the standing carbon (not for growth).

eucalyptus).

To evaluate the impact on climate change we still need to know what is better, a hectare devoted to cork-oaks or a hectare devoted to eucalyptus. The answer actually depends on the importance given to products outside of the forest (right now the Kyoto framework does not allow to consider carbon stored in harvested wood products, since the decision on this subject matter has been left for future negotiation rounds). If only carbon at the forest is considered, it might well be that on the long run a hectare devoted to cork-oaks is more beneficial, since the amount ultimately stored per hectare is higher, even if we allow the rotation for eucalyptus to adapt to the carbon incentive (see figure 4).

[**Figure 4**]

3.3 Adding visitor's preferences

We have estimated biodiversity-scenic values, only for visitors to the Alcornocales Natural Park, using stated preferences techniques. Our approach arguably estimates mainly scenic values, although these values are probably difficult to separate from the biodiversity values perceived by visitors as associated to the ecosystem favored by species like cork-oaks (this is the reason why we use the term biodiversity-scenic values).

We did a survey with 900 face-to-face interviews to visitors (focus groups and 115 pre-test interviews were also done). A booklet of 8 pages was given to the interviewees to explain the current situation of the ANP and the impact of a reforestation with cork-oaks or with eucalyptus, for more details on the survey see Caparrós et al. (2006). Table 1 shows that visitors see a reforestation (on pasture land) with cork-oaks as 'positive' or 'very-positive' (95%) while they see a reforestation with eucalyptus as 'negative' or 'very-negative' (90%).

[**Table 1**]

Table 2 shows the models estimated based on a choice and a ranking experiment done to value reforestations with cork-oaks (450 interviews were done with each method). We show the estimations obtained with the choice experiment (CE-cork-oak model) and the estimations obtained pooling the data of the choice experiment and the first rank in the contingent ranking (CP-cork-oak model). The data from the choice and the first rank can be pooled since in Caparrós et al. (2006) it was shown that estimations based on the option chosen and on the first rank are statistically indistinguishable. In the Appendix we show the attributes and the levels used. The data are analyzed using a nested logit model, since the IIA hypothesis was violated (McFadden, 1981). We use the CE-cork-oak model (similar results are obtained using the CP model) to estimate the median willingness to pay for a reforestation using cork-oaks (using Krinsky and Robb's (1986) bootstrapping technique); setting all the attributes but the surface constant. We then estimate the total revenues that could be obtained if the relevant population (visitors) would pay the additional tax. That is, we are assuming that the tax would be set at the limit accepted by 50% of the population but that all the population (visitors) would pay the tax (a one time payment).

[Table 2]

As in the last section, we acknowledge that there is a potential risk for double-counting since one of the reason for the current subsidies for cork-oak reforestations are biodiversity-scenic values. Nevertheless, current subsidies are not at all related to the number of visitors and can be applied to any area, so that they should mainly incorporate passive use values and not direct use values by recreational visitors. Thus, adding values estimated for visitors should not imply double counting.

Following the choice or the ranking experiment, half of the interviewees were asked, using an open ended contingent valuation, about a reforestation with cork-oak trees (CV-cork-oak model) and the other 450 subjects were asked about a reforestation with eucalyptus (CV-eucalyptus model). In both cases we made two different questions: one to reforest the equivalent of 20% of current forest surface[16] and one to reforest 40% of current surface (this was needed to estimate a declining marginal value function). Since the results shown in table 1 (which correspond to the main survey) were already obtained in the pre-test, 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 3 shows the results obtained for these valuation questions (the wording used can be found in the Appendix).

[Table 3]

These are arguably the less reliable values obtained with the different valuation techniques used since: (i) they were made after the choice/ranking experiment, (ii) each respondent faced two different CV questions for two different amounts of land, and (iii) we had to use a relatively ‘strange’ wording: WTP to avoid a reforestation with eucalyptus. The reason for the first two caveats was that the choice/ranking experiment was actually the main part of the study and we did not want to further complicate the design of our survey instrument (asking only a subsample about each amount of land reforested). The main reason for the wording was that we wanted an estimation of the money that could be made available to compensate forest owners for not using their (hypothetical) right to plant eucalyptus. In addition, our focus group and our pre-test had shown that a WTA question for reforestations with eucalyptus was not well understood or not taken seriously. Although the CV-eucalyptus model has several caveats the results are probably conservative since: (i) open ended questions tend to yield lower values, (ii) presenting the question after the choice/ranking experiment probably yielded lower values due to a ‘giving fatigue’ and (iii) the WTP to avoid question is more conservative than the corresponding WTA question. This is confirmed by the fact that our estimates for cork-oak reforestations values are considerably larger using the choice experiment than using the contingent

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[16] This was described as needed to counteract current deforestation trends (as in the choice experiment).

valuation data.

Taking into account these biodiversity-scenic values, but taking out current subsidies, a carbon price of 260 € t/C (about 70€ t/CO_2) would be needed to start seeing reforestations with cork-oak using the CFM method (the carbon price must be even higher with the TYAM). Thus, as before, with the carbon price-range between 0€ and 70 € t/C (about 20€ t/CO_2) only reforestations with eucalyptus would take place.

Figure 5 shows the impact of the internalization of the biodiversity-scenic values on the results shown in figure 4 if the current subsidies would be maintained (we use the CE-cork-oak and the CV-eucalyptus models, and the median in both cases). As shown, the equilibrium values for cork-oaks are much higher, even without any value for carbon sequestration. As a result, none of the mechanisms for carbon internalization (CFM or TYAM) imply much additional reforestations with cork-oaks, while the CFM would still imply a strong increase in the surface devoted to eucalyptus.

[**Figure 5**]

To perform a sensitivity analysis, we first take out the negative value estimated for the reforestations with eucalyptus. The general shape of figure 5 remains unchanged, but with more eucalyptus and slightly less cork-oaks (for a zero carbon price 45% of the surface is reforested with cork-oaks and 20% with eucalyptus). If we take the biodiversity-scenic value for cork-oaks out (and keep the value for eucalyptus) the shape would still be very similar, but starting with 33% of cork-oaks and 15% of eucalyptus for a zero carbon price. In all three cases the most remarkable change with the carbon price is the increase in the share devoted to eucalyptus when carbon is internalized using the CFM.

Summing up our results, figure 6 shows the impact of partial or total internalization of the different environmental benefits considered in this article (keeping current subsidies in all cases and with a carbon price of 70 €/t C). Whenever biodiversity-scenic values are internalized the amount of surface devoted to cork-oaks is substantially higher than the surface devoted to eucalyptus. If only biodiversity-scenic values are internalized, eucalyptus completely disappears (this is essentially what happens right now due to environmental regulations). On the contrary, if only carbon sequestration is internalized with the CFM, the surface reforested with eucalyptus is larger than the surface reforested with cork-oaks, while the opposite is true if the TYAM is used. Therefore, the TYAM can be seen as a more conservative way to internalize carbon sequestration which, although implying a lower impact on new forest surface, increases the surface essentially using cork-oaks. This is especially important in areas where biodiversity-scenic values are not properly internalized (actually, most areas).

[**Figure 6**]

4 Conclusion

This paper has presented and solved qualitatively an optimal control model to analyze reforestations with two different species, including in the analysis commercial values, carbon sequestration values and biodiversity-scenic values. We have discussed the implications of partial or total internalization of environmental values (i.e. carbon sequestration and biodiversity-scenic values), showing 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. We have compared the equilibrium outcomes with two different carbon crediting methods: the Carbon Flow Method and the Ton Year Accounting Method; showing 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. Our results have also shown that visitors value reforestations with cork-oaks positively while they consider that reforestations with eucalyptus have a negative impact on their welfare. Furthermore, we have shown that if biodiversity-scenic values (for visitors) were internalized the equilibrium values would imply a significantly larger amount of surface devoted to cork-oaks than the amount devoted to eucalyptus (except for high carbon prices internalized using the CFM).

The implications of our results are that if biodiversity-scenic values are properly internalized it may be better to use the CFM, since it tends to increase forest surface more. However, if biodiversity-scenic values are not fully internalized by markets, as is in fact the case, it may be more appropriate to used a more conservative method like the TYAM, that will increase less forest surface but that will not favor fast growing alien species such as 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 in the Alcornocales Natural Park (South-west of Spain). We use growth functions for three site qualities (high, medium and low). Cork oak growth functions are taken from Sánchez et al. (2005), as well as the initial height and diameter at breast high conditions for different site qualities. Eucalyptus growth functions are our own estimations based on data provided by ENCE[17] for permanent inventory plots in Huelva Mountains (also in the South-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:

$$v_i(t) = k\ t^a\ \ e^{-bt} \tag{22}$$

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 α is a carbon expansion factor ($\alpha = e_f \phi$), e$_f$ an expansion factor from timber biomass to total biomass (including roots) and ϕ the tons of carbon per m^3 of timber biomass. We use a carbon content factor (ϕ) of 0.20 for eucalyptus and an expansion factor of 1.5.

The rotation for cork-oaks is exogenously given. The reason is that cork (bark) is its main woody output (extraction does not imply tree felling) and the striping rotation corresponds to the time required for reaching natural cork stoppers thickness (Montero et al., 2005). In the 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 (starting after 144 years), 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 with the silvicultural treatments and the yields in Montero et al. (2005). Costs and prices are taken from Campos *et al.* (2005).

For cork oak, the specific site carbon sequestration function is estimated for a hectare of cork oak stands, considering Montero et al. (2006) functions that relate cork oak diameter at breast high with different biomass fractions dry weight (trunk, branches, leaves and roots), the carbon content in cork oak biomass (ϕ=0.472; Ibañez et al. (2002)) and the number of standing cork trees along the cork oak rotation cycle. The particular carbon sequestration functions have the same form as eq. (22), but instead of timber volume ($v_i(t)$), the dependent variable is carbon sequestration, measured in carbon tons ($c_i(t)$) per hectare (see Table A.1):

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

---

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

Prices for timber, cork and firewood, as well as costs, are assumed to remain constant at 2002 average prices (see Table A.2). Carbon sequestration benefits are analyzed considering a set of carbon prices ranging from 0 to 70 euros per ton of carbon (approximately between 0 and 20 €/ton of CO_2).

[Table A.2]

A.2 Carbon sequestration accounting methods and optimal rotation

Carbon sequestration revenues are estimated considering two alternative carbon accounting methods: carbon flow and ton year accounting. In both cases we assume that the rotation for eucalyptus is optimized taking into account the carbon incentives while the rotation for cork-oaks stays constant.

A.2.1 Carbon flow method (CFM)

CFM assumes that landowners get paid as carbon is sequestered by biomass growth and pay when carbon is released through harvesting. The amount of carbon released by harvesting depends on the final use of timber. Van Kooten, et al. (1995) suggest to introduce a parameter (β) 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). We use a β value of 0.2.

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):

$$PV_{CFM} = \frac{P_F v(T)e^{-rT} - P_c\alpha\,(1-\beta)\,v(T)e^{-rT} + P_c\alpha \int_0^T v\prime(t)e^{-rt}dt}{(1-e^{-rT})} \tag{24}$$

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 per cubic meter, P_C represents the value of the credit/tax per carbon ton that is removed from or released into the atmosphere. The FOC is:

$$\begin{aligned} & (P_F + P_c\alpha\beta)v\prime(T) \qquad (25) \\ = \quad & \frac{r}{(1-e^{-rT})}\left[(P_F + P_c\alpha\beta)v(T) + rP_c\alpha\int_0^T v(t)e^{-rt}dt\right] - rP_c\alpha v(T). \end{aligned}$$

As stated above, cork oak rotation is given by the normative silvicultural model. Given the complexity of the cork oak management (Montero *et al.*, 2005), with several silvicultural treatments, we have estimated year to year carbon uptake and release. We have then estimated annual carbon flows assuming that a β fraction of extracted biomass goes into long-term carbon storage structures, and fitted a carbon stock function (Table A.1).

A.2.2 Ton year accounting method (TYAM)

For the TYAM we assume that the government (or a third party via an emission trading system) derives to growers carbon credits adjusted on the basis of the *equivalence factor* (ε) 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 ε to be 0.0182 t CO_2.

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

$$PV_{TYAM} = \frac{P_F v(T) e^{-rT} + P_c \alpha \varepsilon \int_0^T v(t) e^{-rt} dt}{(1 - e^{-rT})} \tag{26}$$

where the second term of eq (26) represents the carbon benefits that forest owners get 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 (1976) formula since the standing forest has a value. The FOC used to determine the optimal rotation for the eucalyptus is now (Cunha-e-Sá and Rosa, 2006):

$$\begin{aligned} & P_F v\prime(T) + P_c \alpha \varepsilon v(T) \\ = & \frac{r}{(1 - e^{-rT})} \left[P_F v(T) + P_c \alpha \varepsilon \int_0^T v(t) e^{-rt} dt \right] \end{aligned} \tag{27}$$

For estimating carbon benefits in case of cork oak we use the fitted cork oak carbon sequestration function (Table A.1) , and the equivalence factor ε.

A.3 Stated preferences survey

Table A.3 describes the attributes (and the levels) used in the choice/ranking experiment, for more details see Caparrós et al. (2006).

[Table A.3]

The choice/rankings were followed by two contingent valuation question (changing the amount of land reforested). For eucalyptus the wording used was: "¿What would be the maximum amount that you would be ready to pay more this year as taxes to avoid a reforestation with eucalyptus that would increase the forest area in 20%? (please suppose that only eucalyptus were used, that artificial plantations is used, that no recreational areas are created and that the employment remains constant)."

A.4 Estimation of the quadratic functions

To estimate the quadratic functions for commercial values we have three point estimates (per species), one for each site-quality, since different rates of growth yield different commercial values. Unfortunately, we do not really know the precise surface covered by each of these site-qualities, so that we have simply assumed that one third of the area is of each quality. Thus, our results should be seen more as an illustration than as a detailed study (overall trends will be correct, but precise values not so much). For carbon sequestration we also have three point estimates, since the three different growth functions yield different results. For biodiversity-scenic values, we first estimate the value for cork-oaks reforestation using the estimations of the choice experiment (or the pooled data), where the surface reforested enters explicitly in the function estimated (we assume one autochthonous species (cork-oak), artificial reforestation no recreational areas and no additional employment). For eucalyptus (and for cork-oak using the contingent valuation data) we estimate the quadratic function based on the two points estimates given by the subsequent questions (assuming in addition that the function passes through the origin). Table A.4 shows the quadratic functions estimated.

[**Table A.4**]

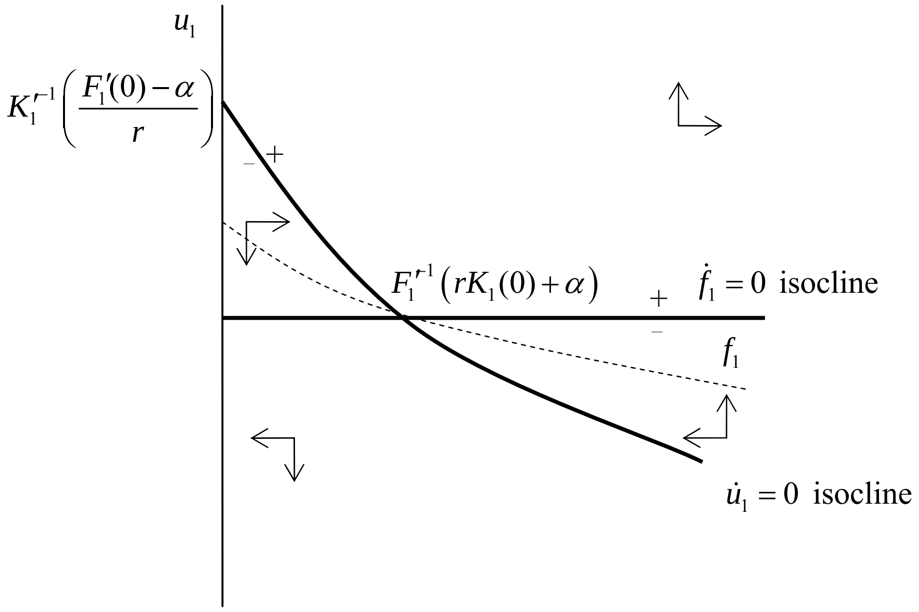

Figure 1. Phase-diagram with general functions.

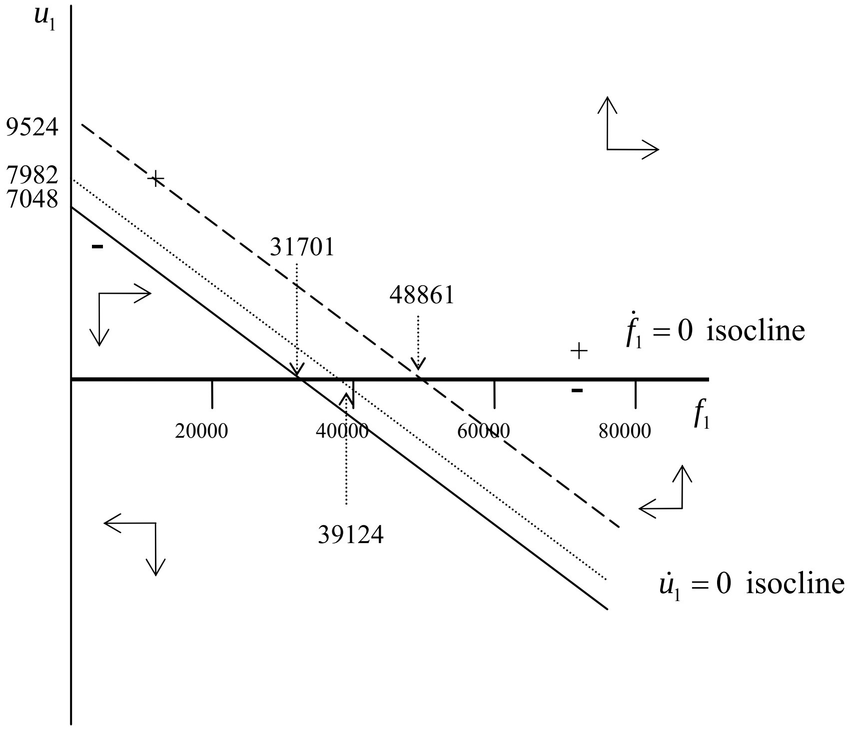

Figure 2. Phase-diagram for reforestations with cork-oaks. For the $\dot{u}_1 = 0$ isocline the full line is with commercial values plus subsidies; the dashed line adds carbon sequestration values internalized using the CFM method; and the dotted line adds carbon sequestration values internalized using the TYAM method. Carbon price: 70€t/C.

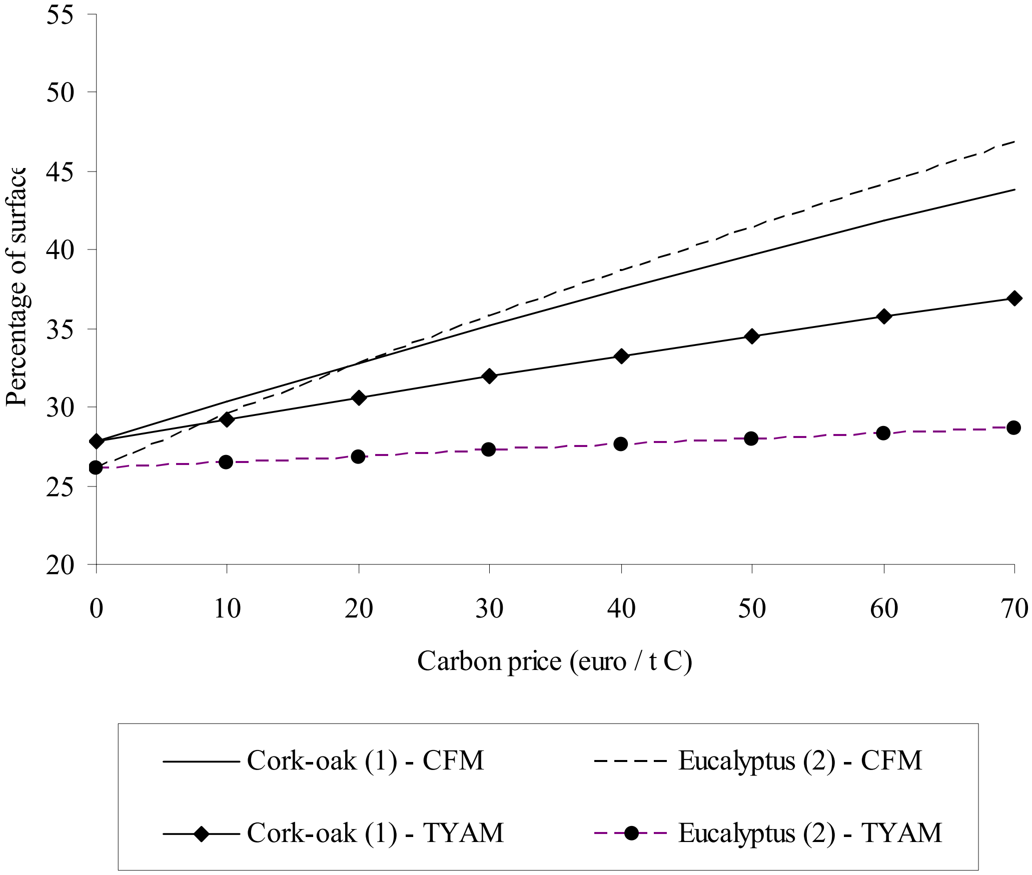

Figure 3. Equilibrium values of surface reforested with cork-oaks and eucalyptus for different carbon prices (for the CFM and the TYAM). Cork-oak and eucalyptus biodiversity-scenic values for visitors are not internalized.

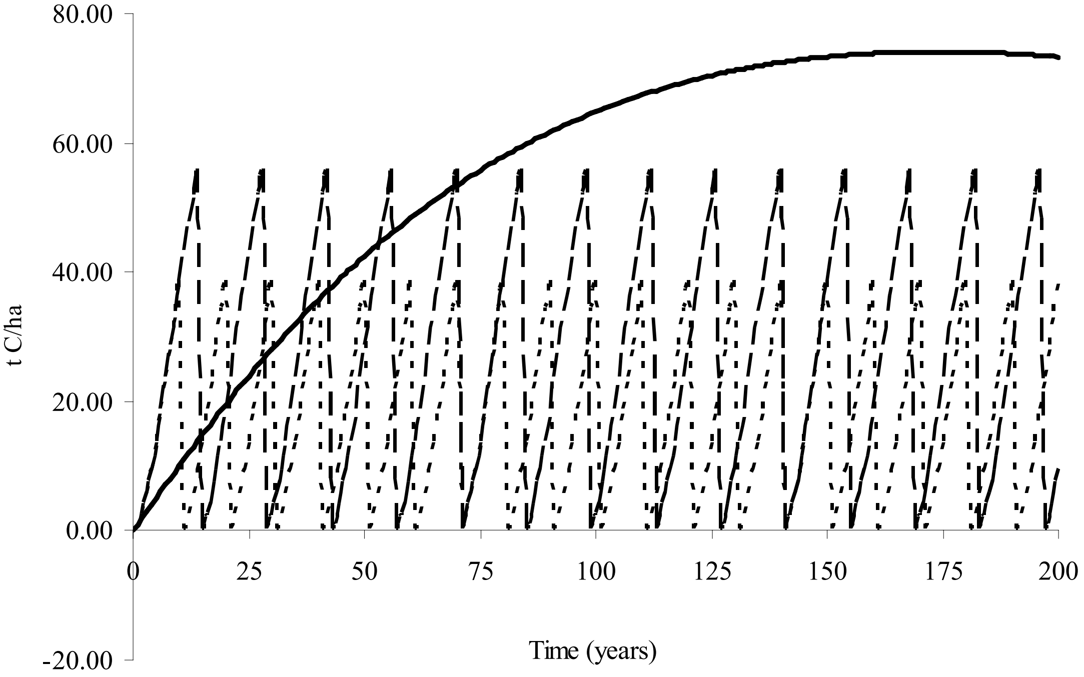

Figure 4. Carbon in forest biomass for cork-oak (full line), for eucalyptus with a rotation of 10 years (dashed line) and for eucalyptus with a rotation of 14 years (dotted line).

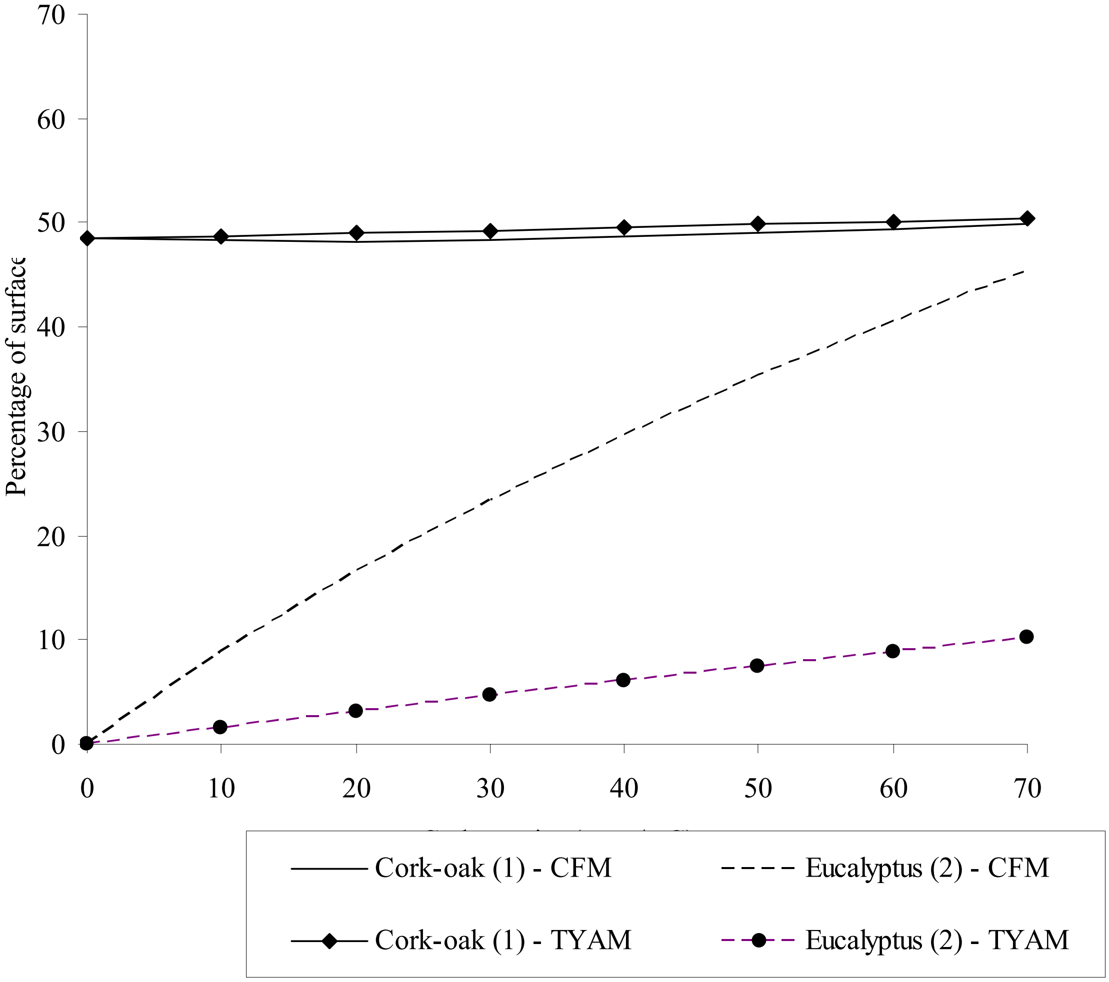

Figure 5. Equilibrium values of surface reforested with cork-oaks and eucalyptus for different carbon prices (for the CFM and the TYAM). Cork-oak and eucalyptus biodiversity-scenic values for visitors are internalized as discussed in the text.

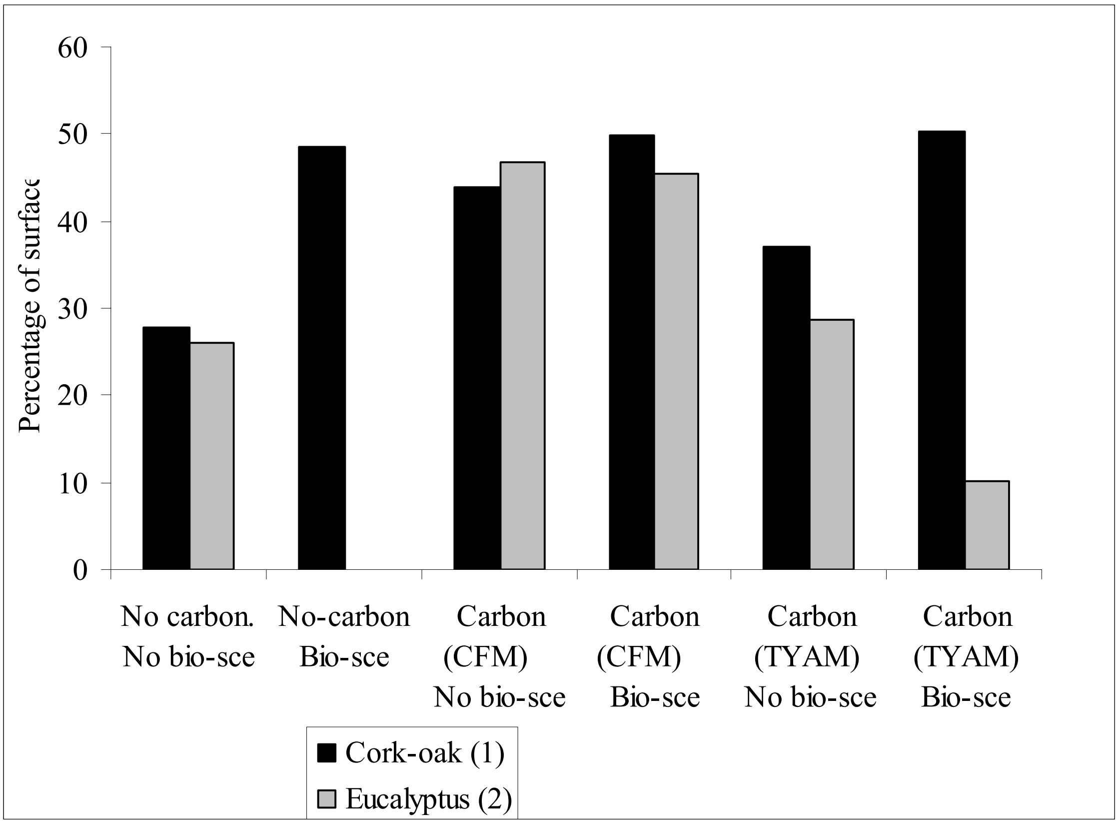

Figure 6. Equilibrium values of surface reforested with cork-oaks and eucalyptus under total or partial internalization of different environmental values (carbon price: 70€t/C).

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. Choice and Pooled Nested Logit Models

Attributes	Choice model (CE)	Pooled model (CP)
	Parameter	Parameter
BIO	0.3811^{***}	0.3767^{***}
	(0.0263)	(0.0209)
TEC	0.3769^{***}	0.3250^{***}
	(0.0349)	(0.0330)
REC	0.3231^{***}	0.3423^{***}
	(0.0588)	(0.0932)
EMP	0.0125^{***}	0.0135^{***}
	(0.0013)	(0.0009)
SUR	0.0666^{***}	0.0576^{***}
	(0.0069)	(0.0054)
SUR^2	-0.0007^{***}	-0.0006^{***}
	(0.0001)	(0.0001)
BID	-0.0223^{***}	-0.0195^{***}
	(0.0024)	(0.0014)
IV (α_{REF})[a]	1.5494^{***}	1.5161^{***}
	(0.8278)	(0.0976)
N	3,600	7194
LogL (β)	-2598.12	-5250.86
LogL (0)	-4906.10	-9797.64
ρ^2	0.4698	0.4638

Standard errors are shown in brackets; N: number of observations.

IV (α_{REF}): inclusive value parameter of the REF branch.

(a) The pooled model combines the choice experiment data and the first rank of the ranking experiment.

(b) Although IV(α_{REF})>1, Herriges and Kling (1996) sufficient condition for local utility maximisation is fulfilled.

***p < .01

Table 3. 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 (€)	18.00	15.00	20.00	20.00
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	2.5062	2.0757	0.0835	0.995	0.9623	1.0467	0.0060	0.651
	(0.3996)	(0.0857)	(0.0048)		(0.3600)	(0.0967)	(0.0007)	
Medium	1.8528	2.0757	0.0835	0.995	0.8157	1.0241	0.0060	0.667
	(0.2955)	(0.0857)	(0.0048)		(0.2800)	(0.0891)	(0.0007)	
Low	1.3057	2.0757	0.0835	0.995	1.0223	0.8106	0.0032	0.679
	(0.2081)	(0.0857)	(0.0048)		(0.3558)	(0.0897)	(0.0006)	

Note: Standard errors are in parenthesis.

* A β 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	125.1	92.5	65.1
Harvesting costs	m^3	10.8			

Note: Standard errors are in parenthesis.
* For cork-oak regeneration felling starts after 144 years, in case no carbon is accounted for eucalyptus rotation length is 10 years.
** Timber volume in a €0 price per sequester carbon ton context.

Table A.3. Attributes and levels of the choice/ranking experiments

Attributes	Levels
Biodiversity [a] (BIO)	1; 2; 3; 4
Technique used (TEC)	Natural regeneration; artificial plantation
Number of new recreational areas (REC)	0; 2
Permanent equivalent employees (EMP)	20; 40; 60; 80
Forest surface ensured (SUR)	90% of present surface (10% reduction); 100% of present surface (same surface); 120% of present surface (20% increase); 140% of present surface (40% increase);
Increase in taxes for this year (BID)	6 €; 12 €; 24 €; 48 €

Note: the status quo levels were: no trees, no technique, no additional recreational areas, no employees, an 80% of the current forest surface ensured (20% reduction) and no additional taxes.

[a] Number of autochthonous tree species used, including cork oak.

Table A.4. 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
Current incentives	W	140.0000	-0.0011		250.1451	-0.0014		10	258.2849	-0.0022	
Commercial (Timber, firewood and/or cork)	W/S	140.0000	-0.0011	1.0000	-230.0918	-0.0014	0.9568		266.5725	-0.0022	0.9974
Net subsidies	S				480.2369				-8.2876		
Biodiversity-scenic values											
Choice experiment	B				148.5000	-0.0034	1.0000				
Pooled choice experiment	B				149.5000	-0.0034	1.0000				
Contingent valuation	B				65.0000	-0.0022	1.0000		-50.0000	0.0014	1.0000
Carbon sequestration (CFM)	C										
Price 10 €/tC	C				10.0455	-0.0001	0.9966	11	13.9874	-0.0001	0.9974
Price 20 €/tC	C				20.0909	-0.0002	0.9966	11	27.7986	-0.0002	0.9974
Price 30 €/tC	C				30.1364	-0.0002	0.9966	12	41.6095	-0.0003	0.9974
Price 40 €/tC	C				40.1819	-0.0003	0.9966	13	55.5304	-0.0004	0.9974
Price 50 €/tC	C				50.2273	-0.0004	0.9966	14	69.6338	-0.0006	0.9974
Price 60 €/tC	C				60.2728	-0.0005	0.9966	15	83.9680	-0.0007	0.9974
Price 70 €/tC	C				70.3183	-0.0006	0.9966	15	98.5658	-0.0008	0.9974
Carbon sequestration (TYAM)	C										
Price 10 €/tC	C				3.7911	0.0000	0.9985	10	2.7009	0.0000	0.9974
Price 20 €/tC	C				7.5822	-0.0001	0.9985	10	5.3568	0.0000	0.9974
Price 30 €/tC	C				11.3733	-0.0001	0.9985	11	7.9807	-0.0001	0.9974
Price 40 €/tC	C				15.1645	-0.0001	0.9985	11	10.5843	-0.0001	0.9974
Price 50 €/tC	C				18.9556	-0.0001	0.9985	11	13.1776	-0.0001	0.9974
Price 60 €/tC	C				22.7467	-0.0002	0.9985	12	15.7696	-0.0001	0.9974
Price 70 €/tC	C				26.5378	-0.0002	0.9985	12	18.3683	-0.0001	0.9974
					k_{11}	k_{12}			k_{21}	k_{22}	
Reforestation costs	K				2419.2848	0.0284	0.7230		2295.6915	0.0284	0.7230

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