Forest Management for Timber and Carbon Sequestration in the Presence of Climate Change: The Case of Pinus Sylvestris

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Abstract

Climatic changes will affect the dynamics of a forest ecosystem. Consequently, carbon sequestration costs can only be estimated correctly if changes in climatic conditions are considered. This article determines the changes in mitigation costs of an optimal forest management regime in the presence of climatic changes and varying prices, and takes account of substitution processes between timber production and carbon sequestration at the stand level. The study demonstrates that in the presence of climate change the sequestration costs per ton of carbon increase with higher amounts of carbon sequestered per hectare. This finding can be used to identify a threshold for the amount of sequestered carbon per hectare below which the costs of carbon sequestration are hardly influenced by climate change.

Key words: Forest management, climate change, carbon sequestration, selective logging, mitigation cost.

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1. Introduction

Carbon sequestration in forests has attracted the attention of researchers for the last 20 years. From an economic point of view the studies have focused on determining the costs of carbon sequestration in order to compare it with other policy options that offset or avoid carbon emissions (Guipponi et al. 2007). Given the long forest rotation periods, most of the previous studies on carbon sequestration consider time horizons within the range of 50-100 years. Yet, in the medium- and long-term future, climate change will have taken place, and it will therefore have affected soil carbon dynamics and processes such as tree reproduction, growth, and mortality (Sabaté et al. 2002). Consequently, the costs of carbon sequestration that are often referred to as mitigation costs can only be evaluated correctly if changes in the climatic conditions are considered.

Changing climatic conditions require that the management regime be continuously adapted to new environmental conditions. In turn, these adaptive measures alter the future evolution of the forest, so the data that describe the evolution of the forest ecosystem have to be updated continuously. For this purpose biogeochemical models are frequently employed to update the evolution of the forest. However, a change in the future evolution of the forest ecosystem affects the choice of the optimal management regime. Therefore, the mutual interdependency of the biogeochemical and economic models requires that the biological data used in the economic model be continuously updated. The integration of these two models can be achieved if the economic model is based not only on data but also on the processes that govern the evolution of the forest
ecosystem. We follow this modeling approach and present an integrated economic and biophysical model to compute the costs of carbon sequestration in the presence of climate change.

Healey et al. (2000) and van Kooten and Bulte (1999) indicated that the objective of maximizing the net benefits of timber is only partly compatible with the objective of maximizing the net benefits of sequestered carbon. The former calls for growing a reduced number of high value trees, while the latter requires that the standing biomass be maximized. This finding is supported by Thornley and Cannell (2000), who show that management regimes that maintain a continuous canopy cover and mimic, to some extent, regular natural forest disturbances are likely to achieve the best combination of high wood yield and carbon storage. The results of their study suggest that the analytical framework to determine the optimal forest management regime that maximizes the net benefits from timber production and carbon sequestration should allow for management regimes that range from no harvest to selective harvest and to the complete harvest of the stand.

One of the problems in analyzing the effect of climate change for the broad range of admissible management regimes is the adequate modeling of partial harvesting. Models are often based on the premise that a partially harvested stand evolves like a younger version of itself, but newly planted trees or natural reproduction would modify the evolution pattern of the stand, and therefore only commercial thinning would be allowed and no regeneration could take place until the entire stand had been harvested (one example is the Forest and Agricultural Sector Optimization Model, FASOM). Moreover, studies usually consider a fixed set of management intensity classes for each stand. In this respect, the measures available to the forest manager to adapt the
The presence of climate change adds another twist to the trade-off between the optimal management of timber and carbon. While an increase in CO₂ favors biomass growth (fertilization effect), i.e., timber production and carbon sequestration, an increase in temperature leads to a rise in the release of carbon fixed in the soil (soil carbon release effect).

Previous work has empirically determined the mitigation costs at the stand level for the current climate (Goetz et al. 2010) but not the net benefits of adaptation, and not the variation in the mitigation costs due to the effects of climate change in the carbon dynamics and in the processes that govern growth and mortality. This study helps to revise sequestration costs as it takes account of the effect of climate changes on the forest ecosystem, and it considers the trade-off between carbon sequestration and timber production at the stand level, which allows the amount of carbon per hectare that minimizes sequestration costs per ton of carbon to be determined.

Studies by Irland et al. (2001) and by Haynes et al. (2007) showed that timber and land markets will adjust to the effect of climate change in ways that act to limit its economic consequences. Therefore, the present study will not only take account of the effect of climate change on the forest ecosystem, but also of the way the future evolution of global timber and carbon markets will affect the optimal forest management regime of a stand.

The article is organized as follows: we first describe the features of the bioeconomic model. We then specify the data and functions employed for the numerical analysis. The next section determines the optimal selective cutting regime for timber and carbon in an
empirical setting when climate change is taken into account. The last section presents some conclusions.

2. Literature review

One strand of the literature includes management choices at the stand level, afforestation and reforestation. Consequently, the analysis focuses on a geographical region. For instance, Irland et al. (2001) analyzed four forest growth scenarios based on the paired application of two global climate models and two biogeochemical process models. The application of these models establishes the trajectory of the changes in the vegetation carbon for each of the four scenarios. In turn, these changes allow the corresponding timber yields that are then employed in the FASOM to be determined. The calculations with this model demonstrated that the assumed climate changes will in general be beneficial for the US timber products sector. These findings are consistent with the results of the 2005 Resource Planning Act (RPA) timber assessment (Haynes et al. 2007).

A different strand of literature extended the analysis of the impact of climate changes on the forest sector by considering not only timber products but also carbon sequestration (Alig et al. 2002). Following the approach by Irland et al. (2001) the authors show that the overall increase in forest productivity in the United States leads to an increase in long-term timber inventory and to an increase in economic welfare for all climate change scenarios considered. However, climate change leads to changes in the mix of timber products, land use, and the geographical distribution of tree species. In this respect, the results of Alig et al. (2002) are consistent with the results of both Irland et al. (2001) and Haynes et al. (2007). Although Alig et al. (2002) do not include carbon
in the objective function, they report the evolution of sequestered carbon in the forest. Compared to the baseline, the amount of sequestered carbon remains more or less identical for the first 20 years. Thereafter, it declines between 1% and 1.7% during the next 30 years before carbon storage increases relative to the baseline.

Sohngen and Mendelsohn (2003) and Tavoni et al. (2007) analyzed the effect of climate change on timber production and carbon sequestration on a global scale. For this purpose they link the Dynamic Integrated Climate Economy (DICE) model or the World Induced Technical Change Hybrid (WITCH) model to a global timber model. According to the employed damage function for climate change (the specified CO$_2$ stabilization target), DICE, and also WITCH, provide a price path for carbon abatement that determines the value of carbon sequestration. The DICE (WITCH) model and the global timber model are solved iteratively until the price path of carbon and the amount of sequestered carbon are supported by each of them. The results show that carbon sequestration can be an important aspect of controlling greenhouse gases. The authors note, however, that their modeling approach considers the effects of climate change on the damage function but not on the evolution of the forest. Due to the complexity of the task of incorporating the effect of climate change on timber production and carbon sequestration, the authors leave it for future research.

The literature that analyzes carbon sequestration and forest management at the stand level does not include climate change either. It focuses on the effect of different management instruments on the supply of carbon (Bravo et al. 2008, del Rio et al. 2008). Van Kooten et al. (1995), Pohjola and Valsta (2007), and Goetz et al. (2010) extended this approach by determining the optimal management strategy for certain management instruments. Caparrós et al. (2003) contribute to this discussion by
considering also recreational services. Hence, to the best of our knowledge, and as Sohngen et al. (2007) have also noted, the incorporation of the effect of climate change on the forest ecosystem has not yet been completed and motivates part of the present study.

This short literature review shows that the previous economic studies focused on the effect of climate change on the global timber and carbon market, while this study is based on a detailed stand-level analysis in which we aim to improve the forest managers’ modeling of adaptive measures to climate change, integrate biogeochemical process and economic models, and determine the optimal design of carbon mitigation policies at the stand level. In particular, we concentrate on climate change adaptation strategies that are common to most stands: rotation age, regeneration, and harvesting pattern. However, other adaptation strategies that are mainly indicated for stands in specific regions, such as the change in the tree species, or in the mix of timber products, are not analyzed. Moreover, we consider changes in natural disturbances such as pests, diseases or fires only implicitly through changes in the mortality rate but not explicitly to keep the model tractable.

3. Bioeconomic model

3.1 Size-structured forest dynamics

The bioeconomic model presented in this article is based on a discretized version of the modeling framework developed by Goetz et al. (2010). The original problem is a distributed optimal control problem that is discretized with the help of the so-called Escalator Boxcar Train technique (de Roos 1988). It allows a system of integral partial differential equations to be transformed into a system of ordinary integral differential
equations. A distinguished feature of EBT is that individual trees with similar diameters are grouped together into a cohort. Throughout their life cycle the trees stay together in the same cohort and do not move from one cohort to the other. Following this idea, we define a forest as a collection of cohorts of trees

\[ X_0(t), L_0(t), X_1(t), L_1(t), \ldots, X_n(t), L_n(t), \] where \( X_i(t), i = 0,1,\ldots,n \) denotes the number of trees in cohort \( i \) at time \( t \), and \( L_i(t), i = 0,1,\ldots,n \) denotes the average diameter at breast height of the trees. Thus, the forest is fully characterized by the number of trees and the diameter distribution of the trees.

The stand development over time is described by the following system of equations:

\[
\begin{align*}
\frac{dX_i(t)}{dt} &= -\mu(E(t), L_i(t))X_i(t) - U_i(t) + P_i(t), \quad i = 0,1,\ldots,n, \\
\frac{dL_i(t)}{dt} &= g(E(t), L_i(t)), \quad i = 0,1,\ldots,n, \\
X_i(0) &= X_i^0, \quad U_i(t), P_i(t) \geq 0, \quad U_i(t) \leq X_i(t), \quad i = 0,1,\ldots,n,
\end{align*}
\]

where \( U_i(t) \) denotes the number of trees of cohort \( i \) logged at time \( t \). \( P_i(t) \) indicates the ingrowth, that is, the number of seedlings that enter the initial cohort \( L_0(t) \) at time \( t \). The seedlings are the result of natural reproduction and posterior selection for upgrowth by the forest manager. Thus, \( P_i(t) = 0, \quad i > 0 \). \( X_i^0 \) denotes the initial number of trees in cohort \( i \). The change in diameter of the tree over time is described by the function \( g(E(t), L_i) \), and the instantaneous mortality rate by the function \( \mu(E(t), L_i) \). This describes the rate at which the probability of survival of an \( L_i \)-sized tree decreases with time. The generic function \( E(t) \) (environment) stands for the factors other than diameter that affect tree growth. It allows taking into account the competition between individual trees for scarce resources such as space, light, nutrients and water.

### 3.2 Carbon dynamics in the forest ecosystem
Besides the stand dynamics we need to describe the evolution of the sequestered carbon. For this end we use the flow method, which accounts for carbon sequestration while trees grow and for carbon release when trees are cut. The change in carbon content is determined by the change in carbon sequestered in the soil $dS/dt$, the change in carbon in the above- and below-ground biomass $dB/dt$, and the change in carbon stored in the wood products $dW/dt$.

The dynamics of soil carbon $S(t)$ can be described by the equation

$$\frac{dS(t)}{dt} = h(V(t), S(t), te(t)), \quad S(0) = S^0.$$  

(2)

It characterizes to what extent the above-ground volume of the biomass $V(t)$, the current soil carbon, and the temperature $te(t)$ affect the change in soil carbon with respect to time. The specification of the above-ground volume of the biomass is determined by $V(t) = \sum_{i=0}^{n} \gamma_0 \gamma_i^\beta X_i(t)$, where the parameters $\gamma_0$ and $\beta$ are chosen according to the tree species. The amount of carbon sequestered in the biomass is determined by $B(t) = \sum_{i=0}^{n} 1 + \gamma_2 \gamma_1^\beta X_i(t)$, where $\gamma_1$ and $\gamma_2$ are constants that relate the above-ground volume with the sequestered carbon in the above-, $\gamma_1$, and below-ground, $\gamma_2$, biomass.

Once trees are harvested $dB/dt$ decreases, and it is negative if the increase in the amount of sequestered carbon in the standing trees is below the amount of sequestered carbon in the harvested trees.

Finally, in order to correctly account for the evolution of the overall carbon in the forest ecosystem, one has to consider the fact that sequestered carbon in harvested trees...
is not released immediately. Instead, it is stored in wood products and gradually set free over time. The dynamics of carbon stored in wood products is determined by:

\[ \frac{dW(t)}{dt} = \delta(U_0(t), \ldots U_n(t), W(t), \varphi(\cdot)) \]  

(3)

It depends on the logged trees, the amount of carbon stored and the release function of sequestered carbon in wood products to be specified in the next section.

Hence, the overall change in the carbon stored in the forest ecosystem is given by

\[ \frac{dC}{dt} = \frac{dB}{dt} + \frac{dS}{dt} + \frac{dW}{dt}. \]

The system of equations (1) - (3) provides sufficient mathematical structure to portray the processes that govern the evolution of the forest ecosystem. Once the parameters of these equations have been specified empirically, they can be incorporated into the economic decision model. Hence the biogeochemical processes and the economic model are integrated to a large extent.

### 3.3 The forest management problem

Given the description of the biophysical relationships, the forest manager’s decision problem can now be stated as

\[ \max_{U_1(t), \ldots U_n(t), \varphi(\cdot)} \int_0^T e^{-\gamma t} \left\{ \pi(X(t), L(t), U(t), P(t)) + p_c(t) \left( \frac{d}{dt} C(t) - C_{p=0}(t) \right) \right\} dt, \]  

(D)

subject to the system of equations (1) - (3).¹

The final point of time of the planning horizon is denoted by \( T \). The term \( \pi(\cdot) \) indicates the net benefit function related to timber production, which consists of the net revenue from the sale of timber at time \( t \) minus the maintenance costs (clearing, etc.).

¹ Although not all forest managers prioritize the objective of profit maximization, it is most likely that nearly all of them include it as an important one among the objectives pursued.
pruning, and grinding the residues) and minus the costs associated with nursing and
selecting the appropriate number of seedlings for upgrowth. $\bar{X}(t), \bar{L}(t), \bar{U}(t)$ and $\bar{P}(t)$
are the vectors $\bar{X}(t) = X_0(t), ..., X_n(t)$, $\bar{L}(t) = L_0(t), ..., L_n(t)$, $\bar{U}(t) = U_0(t), ..., U_n(t)$
and $\bar{P}(t) = P_0(t), 0, ..., 0$, respectively.

The second term in the integral denotes the benefits of carbon sequestration. It is
given by the net storage of carbon times the price of carbon $p_c(t)$. In order to calculate
the proper amount of carbon that qualifies for carbon credits we apply the concept of
“additionality”. That is, if the manager decides to participate in a payment or credit
scheme, only the sequestered carbon on top of the carbon that corresponds to the
management regime that maximizes timber net benefits, needs to be taken into account.
In other words, only the amount of carbon that is sequestered above a certain level is
honored by the carbon price mentioned above. The value of this reference level evolves
over time and is a function of the parameters used, in particular the evolution of the
timber price and of the climate scenario employed—and it is denoted by $C_{p_c=0}(t)$. The
trajectory of $C_{p_c=0}(t)$ is determined by a previous optimization process for each climate
change scenario and set of parameter values.

In order to solve the model numerically, the issue of seedlings selected for upgrowth
needs to be addressed. As mentioned above, EBT is designed such that the trees stay in
the cohort they were initially assigned to. New seedlings are always added to cohort 0.
However, since trees are growing according to the function $g(E(t), L_i(t))$, this cohort
would consist, over time, of young and old trees. Hence it could not be considered
homogeneous anymore, and it is necessary to create a new cohort at regular time
intervals. In this article, a new cohort is initialized every 10 years. Consequently, it is
also necessary to renumber the cohorts. This renumbering operation transforms the class $i$ to the class $i+1$ and initializes a new class 0 that receives the “new” trees.

### 3.4 Data and specification of functions

#### 3.4.1 Biogeochemical simulation model

The general model presented (problem (D)) cannot be solved without defining the species and the location. This study analyzes a stand of Pinus sylvestris located in Catalonia. For the numerical solution all parameters and functions need to be specified. Part of the specification was realized with the support of the biogeochemical model GOTILWA (Growth Of Trees Is Limited by WAter http://www.creaf.uab.es/gotilwa%2B/), in particular to assess the effects of climate change on the forest ecosystem. The model requires the specification of 11 input files and over 90 parameters related to the site, soil composition, tree species, photosynthesis, stomatal conductance, inventory, canopy hydrology, and climate. With these inputs it simulates the evolution of the above- and below-ground biomass, and of soil carbon. For the simulations we specified nine different inventories so that the data generated are as general as possible.

The effects of the different climate change scenarios on forest growth were simulated by feeding GOTILWA with the characteristic time series of CO$_2$, temperature, and rainfall that relates to a specific scenario. In particular, we consider three different climate scenarios, and analyze their effects on the optimal management regime. The first scenario does not take into account climate change, and we refer to it as the baseline (BL). The other two climate change scenarios considered, denoted by A2 and
B2, have been taken from the IPCC’s Third Assessment Report (2001) on climate change. They are both characterized by moderate to high increases in CO₂ emissions from the year 2000 to 2100. The more pessimistic scenario, A2, predicts a higher increase in CO₂ emissions than the scenario in B2. In particular, scenario A2 calculates a CO₂ concentration of 870 ppm by the year 2100, with a temperature increase within the range of 2.0-5.4°C, while B2 estimates a CO₂ concentration of 621 ppm, and a temperature increase within the range of 1.4-3.8°C. Nevertheless, within the range of all scenarios considered in the report, neither of the two scenarios is extreme.

For this study we use the reported evolution of the CO₂ concentration in the atmosphere, as well as the estimated variations in temperature and rainfall in the Mediterranean region which includes Catalonia (Ruosteenoja et al. 2003) to estimate a time series for CO₂, temperature and rainfall for each of the three different climate change scenarios until 2150. Next, we simulate the evolution of the forest ecosystem over 150 years for the different specified initial diameter distributions and the three different climate scenarios.

To model the evolution of the forest we need to specify the following functions: the evolution of the diameter $g$, the mortality $\mu$, soil carbon dynamics $h$, and the carbon release function $\delta$. The view that forest growth and carbon sequestration is stimulated within limits by increasing CO₂ (fertilization effect) is widely accepted in the literature (Heimann and Reichstein 2008). The general form of the function $g$ is given by

$$g(E, L_i = L_m - L_i \beta_0 + \beta_1 CO_2 + (\beta_2 + \beta_3 CO_2) \cdot BA + (\beta_4 + \beta_5 CO_2) \cdot BA_i$$, where the exogenous variables of this function are given by the diameter at breast height ($L_i$), the

\footnote{These two scenarios have been used extensively in previous literature (Ruosteenoja et al. 2003; Davi et al. 2006).}
The basal area $^{3}$ of the entire stand ($BA$), and the basal area of a tree of cohort $i$ ($BA_i$). The latter two variables present the influence of the environment $E$ in the form of intraspecific competition. The data obtained from the simulations with GOTILWA were used to estimate the values of the parameters $L_m$ and $\beta_i$. The estimations with the best fit yielded the following growth function:

$$
g = 183.748 - L_i \cdot 0.21 \cdot 10^{-1} + 0.19 \cdot 10^{-4} \cdot CO_2 + -0.24 \cdot 10^{-3} + 0.79 \cdot 10^{-7} \cdot CO_2 \cdot BA$$

$$+ 0.64 \cdot 10^{-1} - 0.58 \cdot 10^{-4} \cdot CO_2 \cdot BA_i.$$  

3.4.2 The probability survival function

The function $\mu$ is based on the probability of survival described by Gonzalez et al. (2005)$^4$, and it is given by

$$\mu = \vartheta(t) \left( 1 - \left( 1 + \exp \left( -3.954 + 0.035 \cdot BA - 2.297 \cdot \frac{L_i}{Age} \right) \right) \right)^{-2},$$

where $Age$ denotes the average age of the trees of the stand and $\vartheta$ presents changes in the mortality rate as climate change takes place. Although the variable $Age$ is not present in the model, it can be deduced from the variable time during the numerical solution process. Besides changes in forest growth, climate changes are likely to affect the pattern of natural disturbances, such as fires, insects, and diseases, which in turn will affect the mortality rate. According to Battles et al. (2008), tree mortality is likely to increase with climate change. However, a literature review shows that the impact of climate change on the mortality of trees cannot be quantified unambiguously (Allen et al. 2009). Therefore, we

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$^3$ The basal area of the stand is given by the sum of the diameter of the trunk of all trees at a height of 1.30 m.

$^4$ González et al. (2005) estimated the probability of survival for time periods of five years, so we adapted the mortality rate to the ten-year time periods used in this study.
did not establish a functional relationship between mortality and climate variations. Instead, we chose the factor \( \mathcal{g} \) so that the probability of dying in scenario A2 is doubled in 100 years and in scenario B2 it is doubled in 200 years.

### 3.4.3 Carbon in the soil and in wood products

With respect to soil carbon, recent studies have shown that it decreases with an increase in the temperature (Trumbore et al. 1996; Bonan 2008). This finding is particularly important because temperate and boreal forests sequester about four times more carbon in the soil than they do in the vegetation while they grow (Heath et al. 2005). Moreover, there is a dynamic equilibrium between soil and biomass carbon, therefore forest management affects the evolution of carbon in soil. The data generated with GOTILWA allowed us to estimate the change in soil carbon over time described by the function \( h V(t), s(t), t e(t) \). Soil carbon is measured in metric tons per hectare and time period. The specified function reads as

\[
h = 43.995 - 0.326 s(t) + 0.059 V(t) - 2.54 t e(t).
\]

Finally, we need to specify the function \( \delta(\cdot) \), which describes the rate of change of carbon sequestered in wood products. On one hand, carbon in wood products increases with the amount of carbon sequestered in the above-ground biomass of harvested trees,

\[
\sum_{i=0}^{n} y_i L_i^\beta U_i(t).
\]

On the other hand, the carbon sequestered in wood products is released following an extended logistic decay function (Eggers 2002). Accordingly, the function

\[
\omega(LT(L_t), \tau, t) = 1.2 - \frac{1.2}{1 + 5 e^{-2(t-\tau)/LT(L_t)}}
\]

indicates the proportion of the sequestered carbon of a tree harvested in year \( \tau \) that remains sequestered in wood products in year \( t \). The lifetime of wood products \( LT \) essentially depends on the diameter of the logged tree, since it determines the potential use of the timber, such as pulp, pallets,
construction or furniture. It has been estimated using data in Profft et al. (2009), and is given by $LT(L_i) = 7.759L_i^{0.358}$. The derivative of $1 - \omega(LT(L_i), \tau, t)$ with respect to time gives the releasing of carbon sequestered in wood products, which is given by the function $\nu(LT(L_i), \tau, t) = \frac{12e^{-2(t-\tau)/LT(L_i)}}{1 + 5e^{-2(t-\tau)/LT(L_i)}}$. Given the specifications above, the change of the carbon sequestered in wood products is given by

$$\delta() = \sum_{i=0}^{n} \gamma_i L_i^\beta U_i(t) - \int_0^t \nu(LT(L_i), \tau, t) \gamma_i L_i^\beta U_i(\tau) d\tau.$$ 

3.4.4 Benefits and cost functions

The net benefit function of timber management $\pi \cdot$ is specified by

$$\left[ \sum_{i=0}^{n} p_{TIM} L_i t v_{m} - c_h L_i t v_{TOT} L_i t U_i(t) - c_M \left( \sum_{i=0}^{n} X_i t \right) - c_y, \right]$$

where $p_{TIM} L_i t$ and $c_h L_i t$ denote the price of timber per m$^3$ and the harvesting cost, respectively, as a function of the diameter. $V_{TOT}$ measures how the total volume of a tree varies with the diameter. The function $p_{TIM}$ was specified based on a study by Palahí and Pukkala (2003) and reads as $p_{TIM} L_i = \text{Min}[-23.24 +13.63\sqrt{L_i}, 86.65]$. The function is strictly convex and increases up to a diameter of 65 cm. Thereafter, the timber price is constant.

The harvesting costs $c_h$ are described by the function $c_h(L_i) = 6 + \exp[-4.292 -0.506\ln L_i]$, and are also taken from Palahí and Pukkala (2003). The total volume $V_{TOT}$ is characterized by the allometric relationship $V_{TOT} L_i = 0.135 \cdot 10^{-3} L_i^{2.42}$ which was estimated based on data generated by GOTILWA.

The marketable part of the volume of timber of each tree is an increasing function of the
diameter, given by $v_d = 0.699 + 0.431 \cdot 10^{-3} L_d$. The data generated also allowed us to estimate the amount of carbon sequestered in the biomass, which is given by

$$B(L) = 1 + 0.2 \cdot 0.323 \cdot 10^{-4} L_i^{2.429}. $$

Finally, the parameters of the maintenance cost function were estimated using data provided by the consulting firm Tecnosylva (http://tecnosylva.com), which prepares forest management plans throughout Spain. The maintenance costs $c_{MT}$ are given by

$$c_{MT} = 10 + 0.015 \sum_{i=0}^{n} X_i + 0.186 \cdot 10^{-4} \left( \sum_{i=0}^{n} X_i \right)^2.$$

The nursing costs of seedlings selected for upgrowth are given by $c_N = 0.73P_0$. The values of the cost functions employed are consistent with the data (year 2005) provided by the *Forestal Catalana*, a body of the Catalan government, which aims to promote the organization, preservation, and protection of forests by publishing prices and costs that are typical for Catalonia (*Departament de Medi Ambient i Habitatge* 2009).

Further details about the conceptual rationale of the fertilization and soil carbon release effect, data sources, and data quality as well as the validation of the modeling approaches are provided online in the form of supplementary information.

4. Results

4.1 Constant prices

The purpose of the numerical analysis is initially to determine the optimal selective logging regime that maximizes the discounted net benefits from timber production and carbon sequestration of a stand of Pinus sylvestris (Scots pine) for a time horizon of 150 years.
For the numerical solution of the problem we employed the CONOPT3 solver, available within GAMS (Brooke et al. 1992). For a given initial distribution and for each 10-year period, the program determines the optimal value of the decision variables, that is, the optimal logging $U(t)$ and number of seedlings selected for upgrowth $P_0(t)$, which in turn determine the optimal values of the biophysical variables, such as $X(t)$, $L(t)$, and $S(t)$. Consequently, economic variables such as the benefits from timber management and carbon storage can be determined as well. Getz and Haight (1989) show how to approximate an infinite optimal control problem by repeatedly solving a finite time horizon problem. Following their procedure we determined the solution for the first 150 years. Thereafter, the values of resulting state and co-state variables of the 10th year were taken to be the initial values of the state and co-state variables of the subsequent optimization over 150 years. After each new iteration, the values of the state and co-state variables of the 10th year were taken to be the initial values of the state and co-state variables for the subsequent optimization. This iterative process allows us to avoid the end-value problem, that is, the limited length of the planning horizon does not affect the outcome.

All optimizations were carried out on a per hectare basis. With respect to the discount rate, we assumed initially a value of 2%, in line with the studies by Palahí and Pukkala (2003) and Díaz-Balteiro and Romero (2003). Later on the discount rate is modified to analyze its effect on the principal results of the study.

The integrated assessment model was solved for both a young and a mature forest. Although the size distribution of the two stands is different, the initial basal area of the two distributions is equal to 25m², so that the resulting optimal management regimes can be compared. We calculated the optimal logging regime that maximizes profits.
from timber sales and carbon sequestration for the three climate scenarios considered, and for different carbon prices that range from 0€ to 40€/ton of CO₂. However, in the following text we present only the results of scenario BL (baseline, absence of climate change) and scenario A2 for carbon prices of 0€ and 40€ per ton of CO₂. The results for scenario B2 and for carbon prices of 10€, 20€ and 30€/ton of CO₂ are situated between the results obtained for BL and A2 with carbon prices of 0€ and 40€, and are therefore not presented in order to save space. A carbon price of 0€ is interesting as it considers the case where the forest is managed exclusively for timber benefits because forest carbon sequestration is not honored, or because the manager decided not to participate in any carbon payment or credit scheme. Hence, given a carbon price of 0€ per ton of CO₂, the amount of sequestered carbon that corresponds to the optimal management regime defines the trajectory of the reference level \( C_{p=0}(t) \), i.e., the non-additional carbon. Only carbon sequestered above this reference level can be considered as additional carbon, and will be honored with the given carbon price. It is important to note that this reference trajectory is specific for each scenario and set of parameter values. These values are required for each climate scenario or any change in the parameter values, to determine the corresponding trajectory of the reference level in a separate optimization process.⁶

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⁵ Following the literature, we express the carbon price in terms of CO₂. The conversion factor from C to CO₂ is 3.667.

⁶ In practice, forest managers rely on forest inventories of tree and soil carbon to detect whether or not additional carbon has been sequestered. Experience has been gathered with credits obtained via the Clean Development Mechanism. Further information can be found at
Figure 1 shows the evolution of the number of stems in a young forest. As this stand matures the number of trees has to be reduced to provide space for the remaining trees to grow. In the absence of any payment or credit scheme ($p_C = 0$), climate change (scenario A2), in comparison with the baseline scenario, leads at the end of the planning horizon to an increase in the number of trees by 123.19% (from 417 to 931). This evolution is due in part to the rise of carbon in the atmosphere (fertilization effect), which facilitates forest growth, and consequently it is optimal to increase the investment in the forest ecosystem. However, an increase in the number of trees leads to stronger competition among the trees for scarce resources. Yet, the overall increase in the number of trees shows that the competition effect is dominated by the fertilization effect. The same pattern can be observed in the presence of a carbon payment or credit scheme ($p_C = 40$), but to a lower degree. The number of trees increases only by 46.14% (from 972 to 1420). Moreover, the fertilization effect also makes the weighted average diameter of logged trees larger in the presence of climate change, while the average age of the logged trees is nearly unchanged. A similar picture can be observed for the average diameter and the average age of the standing trees. These results also hold when the carbon price increases from 0€ to 40€. To save space these results are not presented in form of a graph.

Observation 1: Climate change may convert optimally-managed forest ecosystems from carbon sinks to carbon sources. Moreover, it may reduce the effectiveness of carbon payments.\(^7\)

Figure 2 shows the evolution of the carbon stock in the forest ecosystem. In the absence of climate change, the maximization of the pure timber net benefit leads at the end of the planning horizon to a decrease in the carbon stock of 35.30 tons of carbon whereas a carbon price of 40€ leads to an increase of 33.80 tons (23.68%). Hence, in the absence of climate change a carbon price of 40€ allows 69.10 tons more of carbon (64.34%) to be sequestered at the end of the planning horizon than a carbon price of 0€. However, when climate change (scenario A2) takes place, the amount of carbon at the end of the planning horizon decreases for all of the depicted carbon prices. In fact, the carbon price has to be above 90€ in order to prevent the release of carbon in the long run (not shown in figure 2). Climate change makes timber production more productive and therefore the cost of carbon sequestration given by foregone timber benefits increases. Expressed in simple terms, the expenditures for contracting the same amount of sequestered carbon are higher.

If the initial amount of soil carbon is reduced by 50% (50 tons instead of 100 tons)\(^8\), the ranking of the evolutions of the different climate scenarios is maintained (see figure 3). In this case, however, at the end of the planning horizon only scenario A2, with a

\(^7\) This and the subsequent observations highlight the basic findings of the section.

\(^8\) The amount of carbon in the biomass is maintained in order to allow for a comparison between the results of the modified and non-modified model.
carbon price of 0€, leads to a decrease in the amount of sequestered carbon in the forest ecosystem, whereas all the other scenarios and price constellations lead to an increase.

The fertilization effect leads to an increase in net ecosystem productivity, which enhances the capacity of the forest to retain carbon in the biomass. However, the increase in the net ecosystem productivity is accompanied by a rise in global temperatures, which in turn exacerbates the decomposition of carbon in the soil. Consequently, more carbon is released to the atmosphere. Thus, as shown in figure 2, for up to approximately 15 years the increase in sequestered carbon in the biomass offsets completely, \((p_c = 0)\), or partially, \((p_c = 40)\), the decrease in soil carbon due to the increase in temperatures (A2) before the amount of carbon in the forest ecosystem starts to decrease. If the initial amount of soil is lower, figure 3 shows that this turning point is reached for a carbon price of 0€ after 28 years and for a carbon price of 40€ after 70 years. Therefore, forests may become a source of carbon emissions if the initial amount of soil carbon is high and the price of carbon is low. If the initial amount of soil carbon is low and the carbon price is sufficiently high, forests may not become a carbon source.

Figures 2 and 3 both show that the introduction of a carbon price in the presence of climate change increases the amount of sequestered carbon at the end of the planning horizon far less than a situation in which there is no climate change. For instance, as seen in figure 2, an increase in the carbon price from 0€ to 40€ increases the amount of sequestered carbon from 107.40 tons to 176.50 tons for the baseline case. This rise corresponds to an increase of 64.34%. However, an identical change in the carbon price when climate change is considered (scenario A2) entails the sequestration of only 28.43
tons of carbon above the reference value at the end of the planning horizon, that is, from 82.45 tons to 110.87 tons (an increase of 34.48%). In figure 3 carbon increases as the carbon price rises for the baseline case by 64.19%, whereas it increases for the A2 scenario by only 44.07%. These results show that climate change reduces the effectiveness of any carbon payment or credit scheme in comparison to a situation without climate change.

So far we have presented the results for a young forest and the climate change scenario A2. Our calculations for a mature forest show that the pattern of figures 1-3 is maintained. Likewise, the consideration of the climate change scenario B2 does not yield additional insight since the results fall between the results of the baseline and of scenario A2. In order to save space, these results are not presented here.

**Observation 2:** Climate change increases carbon sequestration costs per ton and hectare beyond a certain threshold defined in terms of tons of carbon per hectare. If soil carbon is not accounted for, carbon sequestration costs per ton may easily double and the threshold at which climate change becomes important is lower.

Figure 4 shows sequestration costs per averaged ton of carbon over the entire planning horizon. These costs result from the decrease in net benefits from timber production. It demonstrates that the costs increase with climate change by about 34.98%.

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9 In the case of afforested land, the opportunity costs of the land have to form part of the carbon sequestration costs. However, because we are considering a change in the management regime of a standing forest, the opportunity costs of the land affect the aggregate discounted net benefit of timber but not vice versa. In other words, the opportunity costs of the land are independent of the forest management regime and therefore do not need to be taken into account when the costs for additionally sequestered carbon are calculated.
(B2) and 79.49% (A2) for 20 tons of carbon, and by about 20.00% (B2) and 66.32%
(A2) for 40 tons of carbon. However, for smaller amounts of sequestered carbon (5
tons), the costs are more or less the same for the different climate scenarios. An increase
in carbon above the trajectory of the reference level $C_{p=0}(t)$, can only be achieved at
the expense of lower timber benefits. In the presence of climate change, this trade-off
changes as it is nearly equal for small amounts of sequestered carbon but higher for
larger amounts. The intuition for this result is that for small amounts of carbon one has
to give up only a small amount of timber since the net productivity is higher with
climate change. However, if one wants to sequester a higher amount of carbon one has
to plant more trees and the net productivity decreases due to intra-specific competition.
In other words, the trade-off function is not linear. These results show the importance of
a detailed stand analysis that considers the trade-off between timber production and
carbon sequestration since the sequestration costs per ton of carbon are up to five to
seven times higher for larger amounts of sequestered carbon per hectare than for smaller
amounts. Moreover, they suggest that in the presence of climate change it is convenient
to contract small amounts of carbon per hectare rather than large ones, if monitoring and
control costs are negligible. Obviously, the optimal amount of carbon sequestration per
hectare to be contracted will depend on the magnitude of the monitoring and control
costs per hectare. The results obtained provide the basis to determine the optimal size of
carbon sequestration contracts.

Although figure 5 is similar to figure 4, in figure 5 soil carbon has not been
accounted for. For instance, the sequestration of 10 tons of carbon averaged over time
costs 19.10€ (BL), 37.73€ (B2, increase by 97.50%) and 74.82€ (A2, increase by 291.73%) if soil carbon is not taken into account. When soil carbon is accounted for, the sequestration costs are 13.18€ (BL), 18.92€ (B2, increase by 43.59%) and 25.01€ (A2, increase by 89.77%). These results demonstrate that accounting for soil carbon is important since sequestration costs decrease by 49.85% and 66.58% for scenarios B2 and A2, respectively. Moreover, the threshold at which climate change becomes important has to move to the left as a result of the decrease in the sequestration costs.

Observation 3: The decrease in the net benefits with an increase in the discount rate is not affected by climate change.

One might suppose that the results obtained depend strongly on the discount rate used. For this purpose we evaluated the effects of variations in the discount rate on the discounted sum of net benefits. Figure 6 shows that the sum of the discounted aggregated net benefits for the young stand decreases with an increase in the discount rate from 2% to 4%. For instance, the net benefits for scenario BL decrease by 173.25% \( (p_c = 0) \) with an increase in the discount rate from 2% to 4%, while for scenario A2 the net benefits decrease by 184.59% \( (p_c = 0) \). In other words, the presence of climate change increases the net benefits but does not interact with the effect of a change in the discount rate. A similar but somehow more moderate reaction can be observed for the stand of mature trees. For the sake of brevity, however, these results are not presented here.
4.2 Varying prices

The previous part of the study was conducted without taking into account that climate change most likely will affect future carbon and timber prices. Thus, all prices are constant over time. Despite the fact that the study focuses on the individual stand level, and therefore it is assumed that the actions taken by the landowner do not have an impact on prices, it is possible to analyze the effect of future price changes on the optimal management regime for timber and carbon, and on the cost of carbon sequestration.

Tavoni et al. (2007) linked a forest sector model and a general equilibrium model of the economy to determine the evolution of supply, demand, and prices of timber and carbon for two climate change scenarios, which are comparable to the scenarios considered in this article.

When evaluating the magnitude of the price changes of timber and carbon one has to keep in mind that future prices depend on a large array of factors such as population growth, technological progress, the evolution of the world gross product, discovery of new fossil energy deposits, social and institutional developments, land-use change, development of agricultural prices, afforestation and reforestation, etc. The study by Tavoni et al. (2007) took all these factors into account and misses out only the feedback effect of climate change on the supply of timber and sequestered carbon at the stand level and the induced changes in land use, reforestation and afforestation. Given the high number and the magnitude of all the factors mentioned above, one may expect that the consideration of climate change at the stand level would affect carbon and timber market prices to a limited extent only. Although climate change has important economic
consequences for the forest manager and for the magnitude of the carbon sequestration, it does not automatically mean that it is important for the future evolution of timber and carbon prices, especially if the effect of climate change on the forest ecosystem is only one of many driving forces. This view is also supported by the fact that the Kyoto protocol limits the emission reduction credits as a result of forest carbon sequestration for all Annex I countries. For example, for the different EU 15 member states this cap is in the range of 1–4% of their required reduction effort (Amano and Sedjo 2006).

The first scenario, called “business as usual”, assumes that carbon emissions increase up to 20 GtC/year by the year 2100, and the second that a mitigation policy stabilizes the concentration of CO$_2$–eq. at a level of 550 ppm by the year 2100. The A2 climate scenario predicts an increase in the emissions in the range of 23 to 35 GtC by the year 2100, which is slightly above the first scenario postulated by Tavoni et al. (2007). The concentration of CO$_2$–eq. of scenario B2 ranges from 470 to 670 ppm (Nifenecker 2008) and covers the second scenario formulated by Tavoni et al. (2007).

The evolution of the equilibrium carbon price of the forest sector and the general equilibrium model that we used was calculated by Tavoni et al. (2007) for their second scenario (B2 in this study). However, they did not calculate the evolution of the carbon prices for their first scenario as it assumes there is no policy intervention. Hence, in the absence of specific carbon prices for the first scenario, we linked the evolution of carbon price of the 550 ppm scenario to climate scenario A2 also. With respect to timber prices, we used the corresponding global equilibrium timber prices for the two scenarios formulated by Tavoni et al. (2007).$^{10}$

$^{10}$Although the authors did not report the evolution of the timber prices in the paper, this information was supplied by one of them (B. Sohngen).
Observation 4: Climate change leads to a substantial increase in the discounted sum of net benefits of timber and carbon production. Approximately half of this increase can be attributed to the future evolution of timber and carbon prices.

The resulting evolution of timber prices (in %) and carbon prices (in €) are presented in figures 7 and 8 respectively. Based on this pattern, we calculated the timber price path for each of the two climate change scenarios, which allows us to determine the discounted net benefits of the young and mature stand for all climate scenarios considered. The timber and carbon prices reported by Tavoni et al. (2007) cover a period of 100 years. However, since our analysis covers 150 years, we assume that the prices are constant from year 100 onwards. We used this conservative estimate to avoid placing too much weight on the far-distant future.

Figures 7 and 8 here

The results presented in table 1 show that the discounted aggregate net benefits for constant timber and carbon prices increase from 4660€ to 5051€ (scenario B2, increase by 8.39%) or 5144€ (scenario A2, increase by 10.39%). Since all prices are constant, this increase can be attributed exclusively to climate change driven by the fertilization effect of CO₂. The increase in net benefits would be even more pronounced if timber were allowed to adjust to the new market equilibrium conditions. In the case of the climate change scenario B2, the net benefits would increase to 6409€ (increase by 1358€) and in the case of scenario A2 to 6751€ (increase by 1607€). Additionally, if we allow the carbon prices to adjust, we find in the case of scenario B2 that the net benefits
would increase from 6409€ to 9503€ (increase by 3094€) and in the case of scenario A2 from 6751€ to 8699€ (increase by 1948€). The net benefits are slightly lower in scenario A2 because it is associated with a less restrictive climate policy, and therefore timber prices are lower over the first 60 years than they are for scenario B2. These calculations show that the increases in net benefits due to climate change are substantial but significantly lower than the increases due to changes in the equilibrium prices for timber and carbon.

We also calculated the carbon sequestration cost for a mature stand. The results show that the sequestration costs for the young and the mature stand in the presence of climate change are very close. The results, however, are not presented here for the sake of brevity.

Table 1 here

5. Conclusions

Scientists have collected a large amount of evidence demonstrating that climate change is taking place. In response, policy makers have attempted to limit the global temperature increase but do not aim to avoid it. Since any future climate changes will affect the vital cycles of trees and the dynamics of soil carbon, it is desirable to adapt the optimal management of forest ecosystems to changes in the climatic conditions in order to make the best use of them from a social point of view.

Climate mitigation policies traditionally consider forest ecosystems as potential sinks for carbon emissions. However, in the presence of climate change this concept may need to be revised as forest ecosystems may turn into sources of carbon emissions. The optimal management regime of a stand of Scots pine in Catalonia is characterized by an
increase in the net ecosystem productivity, most likely due to the fertilization effect of
carbon in the atmosphere. However, the increase in global temperatures intensifies the
decomposition of soil carbon, which may lead, under certain conditions, to a negative
carbon balance over time. Hence, depending on the location, the specific forest
ecosystem, and the economic conditions, the balance between carbon emissions and
carbon sequestration may tip one way or the other. This result puts forward the idea that
forest carbon sequestration may be an interesting short- and medium-term mitigation
policy, but to a lesser degree for certain forest ecosystems and locations in the long
term. This result also supports a view that was stated in the IPCC’s Fourth Assessment

The results show that carbon sequestration costs are likely to increase with climate
change once the contracted amount of sequestered carbon per hectare exceeds a certain
threshold. Consequently, the sequestration costs per ton of carbon may easily triple,
quadruple or quintuple with an increase in the contracted amount of sequestered carbon
per hectare as a result of the substitution processes between timber production and
carbon sequestration. This finding highlights the importance of a detailed stand analysis
for an accurate estimate of sequestration costs on a larger scale. The threshold level
depends on whether or not soil carbon is included in the carbon accounting method. The
costs of the contracted amount of sequestered carbon per hectare below the threshold
seem to be insensitive to climate change. The results presented in the article provide the
basis to determine the optimal size of carbon sequestration contracts, once the
monitoring and control costs are known.

The results obtained also show that management regime changes that account for the
joint production of timber and carbon sequestration can be considered as part of a
competitive carbon mitigation policy in comparison with reforestation and afforestation projects for carbon purposes alone, and as abatement strategies outside the forest sector. This competitiveness depends strongly on the evolution of the prices for emission allowances within the European Trading Scheme, which have remained within the range of 10–30€/ton of CO₂ over the last four years. The competitiveness of forest carbon sequestration in the presence of climate change depends on the availability of low-cost carbon monitoring technologies and of land to dilute the increasing costs of carbon sequestration per hectare.

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References


Forest and Agricultural Sector Optimization Model, FASOM,
http://agecon2.tamu.edu/people/faculty/mccarl-bruce/papers/503.pdf, pages 2-7,
Getz, W., Haight, R., 1989. Population harvesting: demographic models of fish, forest
and animal resources. Princeton University Press, Princeton.
management and carbon sequestration in size-structured forests: The case of
González, J., Pukkala, T., Palahí, T., 2005. Optimizing the management of Pinus
sylvestris L. stand under risk of fire in Catalonia (north-east of Spain). Annals of
effectiveness of GHG mitigation measures in the European agro-forestry sector.
Environmental Science & Policy, 10: 474-490.
Timber Assessment Update. Portland, OR: U.S, Department of Agriculture,
Forest Service, Pacific Northwest Research Station: 212.
Heath, J., Ayres, E., Possell, M., Bardgett, R., Black, H., Grant, H., Ineson P., Kerstiens,
G., 2005. Rising atmospheric CO2 reduces sequestration of root-derived soil
on Climate Change. Port Chester, NY, Cambridge University Press.
on Climate Change. Port Chester, NY, Cambridge University Press.
K., Sohngen, B., Assessing socioeconomic impacts of climate change on U. S.
forests, wood-product markets and forest recreation. BioScience 59(9): 753 -
764.
Nifenecker, H. 2008. The Energy Issue and the Possible Contribution of the Various
Nuclear Energy Production Scenarios. in V. Ghetta, D. Gorse, D. Maziere and
V. Pontikis, (Eds), Materials Issues for Generation IV Systems, Springer
spruce stands in Finland. Forest Policy and Economics 9: 789-798.
sylvestris L.) stands in Spain based on individual-tree models. Annals of Forest
Science 60(2): 105-114.
carbon sequestration in wood products." European Journal of Forest Research
128: 399–413.
Richards, K.,Stokes C., 2004. A review of forest carbon sequestration cost studies: A
regions: an intercomparison of model-based projections for the new IPCC


Figure 1: Evolution of the number of stems

Figure 2: Evolution of carbon in the ecosystem (initial soil carbon 100 tons)
Figure 3: Evolution of carbon in the ecosystem (initial soil carbon 50 tons)

Figure 4: Per hectare costs of sequestered carbon per averaged ton over the entire planning horizon (with soil carbon)
Figure 5: Per hectare costs of sequestered carbon per averaged ton over the entire planning horizon (without soil carbon)
Figure 6: Effect of an increase of the discount rate from 2% to 4% on the discounted sum of net benefits

Figure 7: Evolution of timber prices over time
Figure 8: Evolution of carbon prices over time
Table 1: Discounted Aggregate Net Benefits for Different Climate Scenarios, Timber, and Carbon Prices

<table>
<thead>
<tr>
<th>Timber Prices</th>
<th>Carbon Prices</th>
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<tbody>
<tr>
<td>Constant carbon market equilibrium price of 0 €</td>
<td>BL: 4660,10</td>
</tr>
<tr>
<td></td>
<td>BL: 7211,20</td>
</tr>
<tr>
<td></td>
<td>B2: 5050,94</td>
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<tr>
<td></td>
<td>B2: 7015,46</td>
</tr>
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<td></td>
<td>A2: 5144,34</td>
</tr>
<tr>
<td></td>
<td>A2: 7239,32</td>
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<td>Variable timber market equilibrium price (550 ppm)</td>
<td>B2: 6409,01</td>
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<tr>
<td></td>
<td>B2: 9503,43</td>
</tr>
<tr>
<td>Variable timber market equilibrium price (20 GtC)</td>
<td>A2: 6751,21</td>
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<td></td>
<td>A2: 8698,72</td>
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</table>
**BIOGEOCHEMICAL PROCESS MODEL AND THE EMPLOYED DATA**

Existing growth and yield tables refer to stands that are managed to meet timber production objectives and they do not, as a rule, follow the growth of merchantable volumes in a stand much after a reasonable harvest age. In the Forest and Agricultural Sector Optimization Model, for instance, all timber yields are assumed to remain constant after 90 years (Adams et al. 1996). However, if trees that have passed this age still accumulate carbon, pressure will mount to lengthen harvest rotations. Since yield tables do not record data beyond a reasonable harvesting age for timber, the authors who describe the Forest and Agricultural Sector Optimization Model (http://agecon2.tamu.edu/people/faculty/mccarl-bruce/papers/503.pdf, pages 2-28, accessed 10.1.2012) believe that the optimal age for rotating trees to meet a carbon sequestration objective is not a settled question by any means. The shortcomings of the existing yield tables can be overcome by using biogeochemical process models such as CENTURY (http://www.nrel.colostate.edu/projects/century5/reference/index.htm, accessed 10.1.2012) or TEM (http://ecosystems.mbl.edu/TEM/index.html, accessed 17.12.2011), which simulate the evolution of forest ecosystems over a long time horizon, generating data that describe their biogeochemical processes.

To determine the evolution of a diameter-distributed stand of *Pinus sylvestris* and the effects of climate change on the forest ecosystem, we used the biogeochemical model GOTILWA (Growth Of Trees Is Limited by WAter, http://www.creat.uab.es/gotilwa%2B/). This model simulates growth and explores how the life cycle of an individual tree is influenced by the climate, the characteristics of the tree itself, and environmental conditions. The model is defined by 11 input files specifying more than 90 parameters relating to site conditions, including soil characteristics and hydrological parameters, climatic conditions (maximum and
minimum temperatures, rainfall, vapor pressure deficit, wind speed, global radiation), tree physiology (photosynthetic and stomatal conductance parameters), forest composition (tree structure and DBH class distribution), and management criteria.

The biogeochemical processes are defined in different models that interact to describe the growth and evolution of the stand over time. The photosynthesis equations employed to calculate gross production are based on the work by Farquhar and von Caemmerer (1982); stomatal conductance uses Leuning’s approach (Leuning 1995); leaf temperature is determined based on leaf energy balance (Gates 1962) and transpiration is estimated according to the Penman-Monteith equation (Monteith 1965; Jarvis and McNaughton 1986). Autotrophic respiration is divided into maintenance and growth respiration. Maintenance respiration is temperature dependent in accordance with a $Q_{10}$ approach, and is calculated as a proportion of total respiring biomass. With respect to growth respiration, the model assumes that the formation of new tissue from net carbon uptake has a respiration cost due to the transport of carbon. The part of the available carbohydrates that is not consumed during the process of growth respiration is allocated first to generate new leaves and fine roots to compensate for their turnover. The remaining carbon, if any, is allocated to the pool of mobile carbon in leaves and woody tissue, in accordance with the pipe model (Shinozaki et al. 1964).

In the sub-model that calculates heterotrophic respiration, soil is divided into two layers: an organic layer (LF horizon) and an inorganic layer (AB horizon). Soil organic matter originates from plant litter above ground, and coarse and fine roots. The model also calculates the amount of organic matter that decomposes and is subsequently lost as atmospheric CO$_2$ efflux, with a specific decomposition rate in each layer as a function of soil temperature and moisture. The most important values of the chosen parameters of GOTILWA are provided at the end of this document.
With these inputs the model simulates the evolution of the above- and below-ground biomass, and of soil carbon. GOTILWA has been used widely in research (Sabaté et al. 2002; Keenan et al. 2011), and has been proven as a good terrestrial biogeochemical model to simulate carbon fluxes (Morales et al. 2005).

To proceed with the empirical study it was necessary to choose various initial diameter distributions of a forest so that the generated data are as general as possible. These distributions were specified as a transformed beta density function \( \theta l \) since it is defined over a closed interval and allows a wide variety of different shapes of the initial tree diameter distributions to be defined (Mendenhall et al. 1990). The stand inventory consists of trees with diameters within the interval \( 0 \text{ cm} \leq l \leq 50 \text{ cm} \). The density function of the diameter of trees, \( \theta l; \gamma; \varphi \), is defined over a closed interval, and thus the integral

\[
\int_{l_1}^{l_{n+1}} \theta l; \gamma; \varphi \; dl
\]

gives the proportion of trees lying within the range \([l_{i}, l_{i+1})\). For the simulation of forest dynamics, we concentrate on the diameter interval \([0, 50] \), because thereafter the tree growth rate is very small. This interval was divided initially into 10 sub-intervals of identical length, with the result that the diameters of the trees of each cohort differ at most by 5 cm, and their size can be considered homogeneous. To generate a variety of initial distributions, we used three different pairs \((\gamma, \varphi)\). The combination \((0.5, 2)\) corresponds to a young stand shape, \((1, 1)\) to a normal distribution stand where the frequency is homogeneous for all considered cohorts, and \((2, 2)\) to a mature stand shape. Afterwards we combined these shape distributions with three different initial basal areas, 15 m², 25 m², and 35 m², which gives rise to 9 initial distributions.
Finally, information about prices and costs were obtained from the government supported website Forestal Catalana: http://www20.gencat.cat/docs/dmah/Home/FC/Lorganisme/Banc%20de%20preus/Tarifes.pdf. For our study we used the data for 2005.

With respect to biomass and soil carbon inventories, the information about its costs has been provided by Forestal Catalana as a personal communication. According to this information the inventory of one hectare stand is assumed to be valid for three additional adjacent hectares. The inventory involves two qualified workers: a technical expert (30.75€/h) and an assistant (20.85€/h), carrying out 0.8 stands per hour. It represents a cost of 64.5€ for four hectares or 16.12€ per hectare. Additionally, the costs for the determination of the soil carbon are 57.6€ per hectare.

The methodologies of forest inventories have been studied and formalized by the UNFCCC. Past experiences allow establishing a baseline, estimating additional carbon benefits and determining the costs of forest inventories. More details can be found at:

http://cdm.unfccc.int/methodologies/index.html

**BIOPHYSICAL BACKGROUND**

The primary effect of the response of plants to atmospheric CO$_2$ enrichment is to increase resource use efficiency (Drake et al. 1997). Elevated CO$_2$ concentration leads to a high presence of CO$_2$ at the surface of the chloroplast. It means reducing stomatal conductance and transpiration and improving water-use efficiency. At the same time, it stimulates higher rates of photosynthesis and increases light-use efficiency. Thus, per unit of carbon absorbed the plant usually requires less light, less water, and less
nitrogen. A long-term exposure to elevated CO$_2$ concentrations entails two opposite effects. On one hand, the plant reduces key enzymes of the photosynthetic carbon reduction cycle, increasing nutrient use efficiency (Drake et al. 1997). On the other, the response functions of plants and ecosystems tend to adjust, making fertilization effect smaller with time (Körner 2000). These effects obviously have major consequences for agriculture and forestry in a presence of climate change characterized by rising atmospheric CO$_2$ concentrations.

*Carbon sequestration:*

In recent years temperate forests have been sequestering carbon. Nabuurs et al. (2003) found that from 1950 until 1999 European forests have been accumulating carbon both in tree biomass and the soil compartment. Ciais et al. (2008) found that this accumulation process has been compatible with timber exploitation over these five decades. This fact has been due to the substantial increase in net primary production, led by the increase in atmospheric CO$_2$ concentrations and nitrogen deposition, as well as the improvement of silvicultural practices (Nabuurs et al. 2003).

*Carbon Pools Evolution:*

Carbon is incorporated in different parts of the tree: foliage, fine roots, branches and coarse roots, and boles. Once these parts of the tree turn into litter they decompose at the rates of 0.5, 0.5, 0.14, and 0.037% per year respectively (Nabuurs et al. 2003). The rate of transformation from litter to the fast soil organic pool occurs at a fairly constant rate (0.55, 0.27, 0.55 and 0.55% respectively). The part of the decomposing carbon that does not enter the fast soil organic pool is emitted to the atmosphere. At the same time,
0.33% of carbon stored in the fast soil organic pool is transferred to the slow soil organic pool each year (Perruchoud et al. 1999).

Although these rates are fairly constant they depend to some extent on environmental factors such as canopy cover, microbial biomass, and especially on temperature or rainfall (Inglima et al. 2009; Phillips et al. 2011). In this sense, soil respiration has been an important issue in the literature, specifically for arid, semi-arid and Mediterranean regions, where the availability of water is more uncertain and the results of respiration remain a not completely determined question (Matías et al. 2012).


Matías, L., Castro, J., Zamora, R., 2012. Effect of simulated climate change on soil respiration in Mediterranean-type ecosystem: rainfall and habitat type are more important than temperature or the soil carbon pool. Ecosystems 15, 299-310.

The most relevant parameters chosen for the presented study used in GOTILWA simulations

7
### Hydrological Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydraulic gradient (m/day)</td>
<td>0.5</td>
</tr>
<tr>
<td>Soil Hydraulic conductivity (m/day)</td>
<td>6</td>
</tr>
<tr>
<td>Mean Soil Depth (m)</td>
<td>1</td>
</tr>
<tr>
<td>Relative volume of stones (%)</td>
<td>50</td>
</tr>
<tr>
<td>Field Capacity (as percentage of Max VPT)</td>
<td>50</td>
</tr>
<tr>
<td>Drainage rate (m/day)</td>
<td>0.3</td>
</tr>
</tbody>
</table>

### Initial values for Soil Carbon Fluxes

**L + F Horizons:**

- Initial Soil Organic Matter in L + F horizon (g/hr): 1200

**A + B Horizons (soil column average):**

- Soil Organic Carbon, SOM (as % by weight): 3
- Bulk density (top soil), Bd (g/cm³): 1.52
- Bulk density (bottom soil), Bd (g/cm³): 2.50
- Maximum Soil Water Filled Porosity, top soil (VPT): 25.6
- Maximum Soil Water Filled Porosity, bottom soil (VPT): 2.2
- Maximum Soil Water Holding Capacity (mm): 115.0

Values in blue are derived values and cannot be modified.

### Constants for the Soil C efflux equations:

- H/LF = 2500
- LF to AB: 1
- W min: 10
- MAP: 200
- W max: 100

### Thermal Inertia Functions

#### Pinus sylvestris

**Interception**

- a: 0.03
- b: 0

The rainfall intercepted by 1 m² of leaf area in each single rain event follows the equation:

\[ I = \frac{Pr}{b} \]

where \( I \) is the intercepted water and \( Pr \) is the precipitation (mm) of the single rainfall event. This interception can not exceed the daily PET in any case.

**Phenology**

- Min threshold T: 2
- Max threshold T: 8
- Thermal inertia: 3

**SOM decomposition**

- Min threshold T: 6
- Max threshold T: 11
- Thermal inertia: 3

**Plot Inertia Function**

- Years to plot: 10

**Plot Inertia Function**

- Years to plot: 13

**Evergreen**
<table>
<thead>
<tr>
<th>Constant values used by GOTOILWA+</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMF to Global Radiation ratio</td>
</tr>
<tr>
<td>μEinstein per Watt in Solar Radiation</td>
</tr>
<tr>
<td>Energy equivalence of OM</td>
</tr>
<tr>
<td>Organic matter to carbon ratio</td>
</tr>
<tr>
<td>N per 100 g of OM</td>
</tr>
<tr>
<td>Respiration rate of structural components (2PC)</td>
</tr>
<tr>
<td>Respiration rate of non-structural components (2PC)</td>
</tr>
<tr>
<td>Respiration rate of living components of wood (2PC)</td>
</tr>
<tr>
<td>Plant tissues formed by 1 g of invested Carbon</td>
</tr>
</tbody>
</table>

Allow change data

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