ADAPTING FOREST MANAGEMENT TO CLIMATE CHANGE

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Doctoral Thesis

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Memòria presentada per Rubén Javier Mur Torrentó, inscrit al programa de doctorat de Ciències Experimentals i Sostenibilitat, itinerari d'Economia Pública, per optar al grau de Doctor per la Universitat de Girona.

Tesi dirigida pel Doctor Renan-Ulrich Goetz i la Doctora Àngels Xabadia.

Rubén Javier Mur Torrentó
2013

El Dr. Renan-Urlich Goetz, catedràtic de l’àrea de Fonaments de l’Anàlisi Econòmica, i la Dra. Àngels Xabadia Palmada, professora titular de la mateixa àrea de coneixement, ambdós de la Universitat de Girona

DECLAREN:

Que el llicenciat en Ciències Ambientals RUBÉN JAVIER MUR TORRENTÓ ha dut a terme, sota la seva direcció, el treball titulat “ADAPTING FOREST MANAGEMENT TO CLIMATE CHANGE”, que presenta en aquesta memòria que constitueix la seva Tesi per optar al grau de Doctor per la Universitat de Girona, i que compleix amb els requisits per a poder optar a la Menció Internacional.

I per a que consti als efectes oportuns, signen la present a Girona, el 16 de setembre de 2013

Vist-i-plau dels directors de la Tesi

Dr. Renan-Ulrich Goetz Dra. Àngels Xabadia Palmada

A la meva família

Agraïments

Aquesta tesi no ha estat fruit només d'una sola persona. La ciència sempre es basa en un coneixement previ que s'intenta portar un petit pas més enllà, i en aquest cas no ha estat diferent: els meus directors de tesi, el Dr. Renan Goetz i la Dra. Àngels Xabadia, han estat les persones sense les quals no hagués pogut fer aquest treball. Així doncs, cap a ells van els meus primers agraïments, per la seva supervisió, el seu esforç i la seva generositat alhora de compartir tot el que saben durant aquests anys.

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Summary

Climate change is one of the most important challenges of the 21st century. The increase in the concentration of CO_2 in the atmosphere, in temperatures, and changes in the precipitation pattern are expected to alter the dynamics of forest ecosystems as they are likely to affect reproduction, growth, mortality of the trees and the process of natural disturbances like fire or pests. Thus, it seems necessary to adopt policies to increase the resilience of forest ecosystems through management practices. At the same time, forest ecosystems can play an important role to mitigate climate change impacts through the sequestration of carbon.

This thesis aims to integrate a biogeochemical and an economic model in order to determine the optimal management regime of a diameter-distributed forest (stand) in the presence of climate change. It analyses the capacity of Mediterranean forests to adapt to new environmental conditions, to an increase in wildfires, and evaluate the associated costs and benefits. Likewise, it determines forest carbon sequestration costs, so that they can be compared with the costs of other mitigation policies.

Resumen

El cambio climático es uno de los retos más importantes del siglo XXI. El incremento en la atmósfera de la concentración de CO_2, en las temperaturas y en el régimen de lluvias, va a comportar cambios en la dinámica de los ecosistemas forestales, afectando probablemente la reproducción, el crecimiento y la mortalidad, así como los procesos de perturbación naturales tales como los incendios o las plagas. Por tanto parece necesario adoptar políticas que aumenten la resiliencia de los ecosistemas forestales a través de la gestión. Al mismo tiempo, los propios ecosistemas forestales pueden jugar un papel importante para mitigar los impactos del cambio climático a través del almacenamiento de carbono.

La presente tesis integra un modelo biogeoquímico con uno de económico para determinar la gestión óptima de una parcela forestal distribuida diamétricamente en presencia de cambio climático. Esto permite analizar la capacidad de los bosques mediterráneos de adaptarse a las condiciones climáticas cambiantes y al incremento de incendios forestales, evaluando de esta forma los costes y los beneficios asociados. Además, también se determinan los costes de almacenamiento de carbono de manera que puedan ser comparados con ´los costes de otras políticas de mitigación.

Resum

El canvi climàtic es un dels reptes mes importants del segle XXI. L'increment en l'atmosfera de la concentració de CO_2, en les temperatures i en el règim pluvial, comportarà canvis en la dinàmica dels ecosistemes forestals, afectant probablement la reproducció, el creixement i la mortalitat, així com els processos de pertorbació naturals com els incendis o les plagues. Per tant sembla necessari adoptar polítiques que augmentin la resiliencia dels ecosistemes forestals a través de la gestió. Al mateix temps, els propis ecosistemes forestals poden jugar un paper molt important per mitigar els impactes del canvi climàtic mitjançant l'emmagatzematge de carboni.

La present tesis integra un model biogeoquímic amb un d'econòmic per determinar la gestió òptima d'una parcel·la forestal distribuïda diamètricament en presencia de canvi climàtic. Això permet analitzar la capacitat dels boscos mediterranis d'adaptar-se a les condicions climàtiques canviants i a l'increment d'incendis forestals, avaluant d'aquesta manera els costos i els beneficis associats. A més, també es determinen els costos de l'emmagatzematge de carboni amb la finalitat que puguin ser comparats amb els costos d'altres polítiques de mitigació.

Introduction

Since Dr. James Hansen (1988) became aware of the relationship between the emission of certain gases and the increase of the global temperature, climate change has become one of the most important challenges faced by countries in the 21st century. Initially there existed the doubt of whether or not the high concentration of CO_2 and other gases in the atmosphere were related to rising temperatures, but few people dare to refute it. Science collected a large number of evidence demonstrating that climate change is actually taking place. Projections indicate that a warming about a minimum of 0,2 ° C per decade is likely in the near future, and it is estimated that a reduction by 30% of the greenhouse gases (GHG) are required by 2020 to keep rising temperatures below 2 degrees at the end of century (MARM, 2007). As a response to it, policy makers aim to limit global temperature increase but not to avoid it. However, any future climate changes will affect the vital cycles of natural resources.

Spain, due to its geographical location and its socio-economic characteristics, is a very vulnerable country to climate change, as it has been revealed in the most recent assessments and investigations (Hein et al., 2009; Lung et al., 2013; Stellmes et al., 2013). The serious environmental problems that are reinforced by the effect of climate change are: the decrease in water resources, the regression of the coast, the losses of biodiversity and natural ecosystems and the increase in soil erosion processes. There are also other effects of climate change which will also cause serious damage to economic sectors like agriculture or forestry (MARM, 2007).

One of the major difficulties involved in addressing climate change is that it is a global problem. It means that the effects of the GHG are noticed all over the world, regardless of the place of the source of the emission. Therefore, international collective action is absolutely necessary to combat this phenomenon. The most important international agreement in this area is the Kyoto Protocol. There was a commitment to reduce GHG to, on average, 5,2% below the levels of the year base (1990) during the 2008-2012 period. The second period of the Kyoto Protocol (2013-2020) amends to a reduction of at least 18% below the year base (1990), also on average, for the participant countries. The commitments of the Kyoto Protocol, however, are not uniform for the different countries that ratified it. For the majority of countries, the treaty requires a reduction with respect to the emissions in 1990. On the other hand, Australia was authorized for the first period to increase emissions by 8% and Spain by 15%. But despite the fact that Spain could increase its emissions by 15% with respect 1990 level, in 2008 exceeded the base year emissions by 42,7%. At the end of the first commitment period, Spain still was rather above the agreed level in spite of the socioeconomic crisis that reduced large part of the emissions coming from the industrial sector. In fact, Spain had to spend 810€ million in emission rights by the end of the first commitment period (Méndez, 2012).

The economic and environmental analysis of problems related to emissions of GHG in Spain is a research topic of great significance which requires solutions to short and medium term. In particular, in the coming years it will be needed to implement policy measures capable of drastically reducing net emissions of greenhouse gases. In addition, adaptation to climate change is necessary and complementary to mitigation, in order to make the best use of the natural resources from the social point of view. Thus, there are two major motivations to carry out this study:

i. the analysis of strategies to reduce the impact of climate change in the biosphere and geosphere, and of

ii. mitigation policies to reduce emissions of greenhouse gases.

1.1.Objectives

Within this general framework, this thesis aims to analyse the optimal adaptation of the management of natural resources taking into account that climate change affects the vital processes of these resources. The study concentrates on the case of forests, analysing the optimal management of resources considering the case where the resource itself sequesters carbon (mitigation).

Chapters 2 and 3 present a bioeconomic model which aims to determine the optimal management regime of a forest under climate change, that is, the regime that maximises the discounted private net benefits from timber production of a stand of *Pinus sylvestris* (Scots pine), over a long time horizon while taking into account the effects of climate change in the forest ecosystem. This model extends the previous literature by incorporating not only data but also the natural processes that governs the evolution of the forests, and considering diameter-distributed forests in order to allow for both clear cutting and selective logging regimes. These concepts are explained in more detail on Chapters 2, 3 and 4.

This thesis presents three distinct analyses using the general framework approach presented in Chapters 2 and 3. They correspond to Chapters 4, 5 and 6. Chapter 4 is an implementation of the bioeconomic model to examine how the management of

Mediterranean forests have to be adapted under climate change conditions in an optimal way, in order to stimulate forest management policies. In Chapter 5 the model is used to evaluate the fire risk in Mediterranean forests, under climate change conditions. Chapter 6 is an implementation of the model in order to evaluate mitigation policies relating to forestation, reforestation and changes in forest management practices inside the Kyoto Protocol. The proposed studies analyse these questions from a theoretical and from an empirical point of view.

1.2.Why *Pinus sylvestris*?

Pinus sylvestris is one of the arboreal species more widely distributed all over the world (Martínez-Vilalta et al., 2012). In Spain, Scots pine is the third most common arboreal specie, and their forests covers 1.280.000 hectares (Mason and Alía, 2000). *Pinus sylvestris* forests are also the second most common type of forests in Catalonia, with 219.754 hectares, according to the Ecological Forest Inventory of Catalonia[1] (Ibàñez, 2004). It means that in 19% of the Catalan forests, Scots pine represents at least 50% of the total basal area. Furthermore, its timber is also appreciated amongst conifers. As a consequence, Scots pine is the most important commercial species for timber production in Catalonia (Ibàñez, 2004).

Moreover, it is the specie with major amount of carbon sequestered in their biomass (Ibàñez, 2004). Thus, *Pinus sylvestris* could play an important role concerning to mitigation strategies. Finally, there exist some studies that suggest Scots pine as a very vulnerable specie to dry periods (Martínez-Vilalta et al., 2012). In this sense, it is important to analyse the effect of changing environment conditions over that specie.

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[1] http://www.creaf.uab.es/iefc/ (accessed on May 2013)

1.3. Adaptation strategies to climate change

The 36% of the total surface in Spain is forest, out of which 58% is privately managed (IFN3-MFE50, 2009). Historically, the most common exploitation of wood land was the extraction of timber. But that traditional use of the forest has suffered a continuous loss of profitability caused by the increase of the management costs. Moreover, many Mediterranean forests have always being characterized by its low biomass productivity, mostly because of extended water stress periods.

The situation of the Catalan forests can be characterised by the lack of management. For example, in the year 2003 only 20,7% from the 81% of private property forests developed a Technical Plan for Forest Improvement and Management (PTGMF in its Catalan acronym) (Vayreda, 2004). The remaining 19% of the forest has been listed as public utility forests. However, it is not management at all, or the management does not result in benefits (Vayreda, 2004).

In these cases, where management is non-existent, the state of abandonment has caused high density forests with small diameter trees. Thus, trees don't reach higher dimensions due to the lack of space, nutrients and light. Moreover, this diametrical structure entails more vulnerability with respect to perturbations such as forest fires.

Forest fires have been a traditional method to remove understory and vegetation, in order to establish crops and plantings. Still today, controlled fire is an important tool of vegetation control (Agee, 1982). But when forest fire turns into an uncontrolled perturbation, it becomes a destroying element that could cause important consequences to the flora and fauna, the soil, the hydrologic cycle, the landscapes and the value of other forestry products beyond timber (Ruiz del Castillo, 1985).

Under new environmental conditions like climate change, the current forest management should be aimed towards a multifunctional and sustainable context more than ever. These concepts are not new, and less in the field of forestry. Forestry is the science that deals with treating the forests towards certain structures to bring profitability. But it also has had as a priority the persistence and the improvement of the forests. Forestry puts also in practice methods concerning to prevent large fires. There exists a very important relationship between the fire behaviour and the amount of fuel available in the forest and the structure of the forests (Guijarro and Valette, 1995). Both factors are subject to being modified by a proper forest management.

With respect to the forest management regime, an important aspect is its certification. In 1993 the Forest Stewardship Council (FSC) was born, a seal of quality. NGO's form part of the Council with the purpose of protecting and managing forests. Their goal is to achieve a sustainable and ecologically viable management through the establishment of principles and criteria of forest certification. In 1998 Spain signed the FSC in order to commercialize timber harvested from sustainable forests. A similar initiative is the Panaeuropean Forest Council (PEFC), founded in 1999, which promotes sustainable management through certification or quality labels called GFS (Sustainable Forest Management).

Adaptation strategies can be understood as those projects, practices and policies that moderate the climate change impacts or take advantage of this change (EEA, 2007). The definition recognizes that climate change is taking place. The change will have negative and positive consequences, and is matter of adaptation strategies to achieve less vulnerability and more resilience of socioecological systems such as forests (Corbera and Romero, 2010).

1.4. Mitigation strategies to climate change

For the last decades forest ecosystems have started to be considered as sinks of CO_2. It is understood as a carbon sink as it captures gases from the atmosphere. Indeed, trees fix large amounts of carbon to grow, which is removed from the atmosphere. Therefore, planting could temporally be a measure of compensation of the carbon emissions from many industrial activities. Another alternative to increase the capacity of forest sinks is to modify the forest management regime. Carbon sinks were included in the Kyoto Protocol to facilitate the fulfilment of the commitments of reducing emissions. In this way, the Annex I Parties to the Kyoto Protocol may deduct up to a certain amount their emissions removals as a result of these activities on the first commitment period (regulated in article 3.3 and 3.4 of the Kyoto Protocol). For the second commitment period this amount has been increased, and these activities have become mandatory.

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 extraction 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). Specifically, the *Plan Forestal Español* (MMA, 2002) expected absorption by sinks as one of the main lines of action aimed at moderating climate change. According to the Third National Forest Inventory[2], Spanish forests are actually sequestering carbon, and it is possible to increase their potential through the forest management over 20% (MMA, 2002).

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[2] http://www.magrama.gob.es/es/biodiversidad/servicios/banco-datos-naturaleza/informacion-disponible/ifn3.aspx (accessed on May 2013)

However, in the presence of climate change many forest ecosystems could see its carbon fixation capacity substantially reduced. The omission of the climate change effects leads to two major errors. Firstly, the change of the natural processes such as growth, reproduction and mortality of the forest is not considered properly, and secondly, it is not possible to assess the benefits and costs of adaptation to the changing climatic conditions. As a result, costs of carbon fixation, often referred to as mitigation costs, could not be correctly estimated.

A literature review indicates that no study analyses in depth how the optimal management of forests for wood and carbon fixation should adapt to the impact of climate change on biological processes. Due to the complexity of the task that represents the incorporation of the effect of climate change in timber production and carbon fixation mitigation costs, Sohngen et al. (2007) pointed to this aspect as an important issue for future research.

1.5.Considerations about the framework approach

The studies presented in this thesis focus on a detailed analysis of a stand, with the aim of improving the modelling of the forest manager's adaptation and mitigation strategies to climate change, the integration of biogeochemical processes and economic models, and the incorporation in the analysis of the effects of climate change on the evolution of the forest. However, they do not consider strategies at a region level, such as the change of tree species, or a different combination of produced wood products (Alig et al., 2002; Sohngen and Mendelsohn, 2003; Tavoni et al., 2007). While the first two studies (Chapter 4 and 5) focus on adaptation strategies to climate change which are common to the majority of stands - the age of rotation, regeneration, and the pattern of logging, the third study (Chapter 6) focus on mitigation policies. The first and the third study are abstract from changes in natural disturbances, e.g. fire. However, it is the focus of the second study. Despite these limitations, the proposed model and the expected results are useful for subsequent applications in order to analyse future forest policies, and carbon fixation.

This thesis is organized as follows: Chapter 2 specifies the general formulation of the bioeconomic model used in all three studies. Chapter 3 explains all the empirical processes carried out to estimate and specify the equations of the model. Using that general framework approach, Chapters 4, 5 and 6 present the three different analyses that focus on adaptation and mitigation strategies. Chapter 7 presents some discussion about results.

bioeconomic model

The model of this thesis is based on a discretized version of the modelling framework developed by Goetz et al. (2010). It extends the previous model by incorporating aspects which are significant for the study. It considers additionally:

i. The effect of climate change on tree growth and forest evolution.
ii. Processes of natural reproduction.
iii. Density dependent mortality.

The model takes account of a very flexible formulation, in the sense that the solution of the model allow for both clear cutting and selective logging regimes or any management regime in between. Nitschke and Innes (2008) reported that a selective-logging regime should be adopted if the forest ecosystem is characterized by low resilience. Likewise, the authors found that selective logging may be required to adapt the management regime to continuous changes in climatic conditions. Tahvonen et al. (2010) found that selective logging may also be superior to a clear cutting regime from an economic point of view if the planting costs exceed a certain threshold value. Moreover, forests provide a large variety of environmental services that are often linked to selective logging. In Spain, forests exploitations based on clear cutting regimes are more common. Despite that, selective logging regime could be implemented even for those species considered as shade intolerant in some northern countries (boreal zone), due to specific climatic conditions in the summer.

As noted on the previous chapter, the purpose of the model is to determine the optimal management regime of a diameter-distributed forest under climate change, that is, the regime that maximises the discounted private net benefits from timber production, at a stand level, while taking into account the effects of climate change in the forest ecosystem. The equations of the model have been specified for *Pinus sylvestris*. In spite of that, the general approach of the model is general enough to be easily applied to other conifer species.

Before presenting the economic model, it is needed to characterize the underlying processes that describe the dynamics of a coniferous forest. The mathematical specification of the dynamics of the forest is independent of any utilized data, and the biogeochemical processes form an integral part of the assessment model. The biogeochemical model is integrated into the economic model through the mathematical formulation of the biogeochemical processes that govern the evolution of the trees.

2.1. Forest dynamics

Forest is defined by a collection of cohorts of trees $\left(\left(X_0(t), L_0(t)\right), \left(X_1(t), L_1(t)\right), ..., \left(X_n(t), L_n(t)\right)\right)$, where $X_i(t), i = 0,1,...,n$ denotes the number of trees in cohort *i* at time *t*, and $L_i(t), i = 0,1,...,n$ 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. L_m (cm) is defined as the maximum diameter that a tree can reach under perfect environmental conditions, and L_0 (cm), as the diameter when the tree is planted or selected for upgrowth. It is assumed that the evolution of a diameter-distributed forest can be fully characterized by the number and the distribution of the tree diameters. In other words, all trees have the same environmental conditions, the same amount of space, and their genetic resources are identical.

In order to model the dynamics of the forest, the three processes –the forest growth, reproduction, and mortality - are described in the following subsections.

2.1.1. Forest growth

$g\left(E(t), L_i(t), CO_2(t)\right)$ denotes the change in the diameter of a tree over time as a function of its current diameter, and of a collection of environmental characteristics, $E(t)$, that affect the individual life cycle. In the absence of pests these characteristics are given by the local environmental conditions of the tree and by the competition between the trees of the same stand for space, light, and nutrients. Since the model does not consider the exact location of each tree, $E(t)$ measures only the intra-specific competition, given by $E(t) = \sum_{i=0}^{n} \frac{\pi}{4} L_i^2 X_i(t)$. The function $g\left(E(t), L_i(t), CO_2(t)\right)$ was specified as a von Bertalanffy growth curve (1957), generalized by Millar and Myers (1990), which allows the rate of growth of the diameter to vary with that intra-specific competition. Moreover, a widely accepted view in the literature (Heimann and Reichstein, 2008) is that forest growth is stimulated within limits by increasing CO_2 (fertilization effect).

2.1.2. Reproduction

Conifers are not able to reproduce through vegetative reproduction. Thus, in order to correctly model the biological reproduction of *Pinus sylvestris*, it is needed to consider the capacity of a tree to produce seeds, and the probability of the seeds becoming seedlings with diameter $L_0(t)$. *Pinus sylvestris* is capable of spreading between 0,2–1,6 million seeds per hectare and year (Hannerz et al., 2002). Hence, it is assumed that for the given climatic conditions, the availability of water, the quality of the soil, and the amount of understory, the ingrowth depends mainly on the amount of light present on the ground (Pardos et al., 2005) or, in other words, on the density of the forest. As much dense is a forest, more difficult is for a seedling to survive and to reach a diameter of $L_0(t)$. On the other hand, an excess of sun could also increase the seedling mortality. That is the reason why selective logging is feasible for certain species in southern countries of Europe but not in northern. Thus, the biological reproduction is given by $\sum_{i=3}^{n} \rho\left(E(t), L_i(t)\right) X_i(t)$ and is a function of the number of fertile trees[3] of each diameter and of the intra-specific competition, $E(t)$.

In the case where the ingrowth of trees is larger than the optimal number of trees, it is assumed that ingrowth[4] is reduced by management actions. In cases that the optimal number of trees cannot be achieved by natural reproduction, the forest manager can plant trees at time *t* with diameter $L_0(t)$. This control variable is denoted by $P(t)$. Thus, the seedlings are the result of natural reproduction and posterior selection for upgrowth by the forest manager and/or of planting.

2.1.3. Natural mortality

The instantaneous self-thinning rate is denoted by $\mu_1\left(E(t), L_i(t)\right)$ and describes the rate at which the probability of survival of a tree, given the environmental characteristics, $E(t)$,

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[3] It is considered that the first three cohorts are not fertile.

[4] These management actions to reduce ingrowth are not actually modelled.

decreases with time. The greater the diameter of the tree, the lower is its probability of survival. On the other hand, the higher the intra-specific competition, the higher is the probability of dying. Since the model is deterministic, pests are not considered. It permits to concentrate on the interdependence of climate change and the processes of mortality, growth, and reproduction.

2.2. Mathematical problem

It is assumed that the forest is privately owned and managed over a planning horizon of T years. The forest owner wants to maximise the economic profitability of the stands. Thus, using the description of the biophysical relationships, his decision problem[5] can be formally stated as:

$$\max_{U_i(t), i=0,\dots,n, P(t)} \int_0^T e^{rt} \left\{ \pi\left(\bar{X}(t), \bar{L}(t), \bar{U}(t), P(t) \right) \right\} dt, \tag{2.1}$$

subject to

$$\begin{aligned} \frac{dX_0(t)}{dt} &= \left[\sum_{i=3}^{n} \rho\left(E(t), L_i(t)\right) X_i(t) \right] + P(t), \\ \frac{dX_i(t)}{dt} &= -\mu_1\left(E(t), L_i(t)\right) X_i(t) - U_i(t), \quad i = 0,1,\dots n, \\ \frac{dL_i(t)}{dt} &= g\left(E(t), L_i(t), CO_2(t)\right), \quad i = 0,1,\dots n, \\ X_i(0) &= X_i^0, \; U_i(t), P(t) \geq 0, \; U_i(t) \leq X_i(t), \; i = 0,1,\dots n, \end{aligned} \tag{2.2}$$

where *r* denotes the discount rate. The term $\pi(\cdot)$ indicates the net benefit function related to timber production. $X_0(t)$ indicates the ingrowth, that is, the number of seedlings that enter the initial cohort $L_0(t)$ at time *t*, plus the plantation $P(t)$ in the case that the optimal number

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[5] Although not all forest managers prioritize the objective of profit maximisation, it is most likely that nearly all of them include it as an important one among the objectives pursued.

of trees cannot be achieved by the natural reproduction. $U_i(t)$ denotes the number of trees of cohort *i* logged at time *t*. X_i^0 denotes the initial number of trees in cohort *i*. $\bar{X}(t), \bar{L}(t)$ and $\bar{U}(t)$ are the vectors $\bar{X}(t) = \left(X_0(t),...,X_n(t)\right)$, $\bar{L}(t) = \left(L_0(t),...,L_n(t)\right)$, and $\bar{U}(t) = \left(U_1(t),...,U_n(t)\right)$ respectively.

For the numerical solution of the problem (Equation (2.1)) the CONOPT3 solver[6], available within GAMS (Brooke et al., 1992) has been employed. For a given initial distribution and for each 10-year period, the numerical solution provides the optimal planting $P(t)$, and for each diameter class *i* the optimal logging $U_i(t)$, and the optimal values of the variables, $X_i(t)$ and $L_i(t)$. Consequently, the natural reproduction, mortality, and economic variables such as the revenue from timber sales, and the cutting, planting, and maintenance costs can also be determined. A terminal value function has not been specified because the numerical solution is based on an iterative procedure. Getz and Haight (1989) show how to approximate an infinite optimal control problem by repeatedly solving a finite time horizon problem. Following their procedure the decision problem is maximised initially over T years. Thereafter, the values of the control and state variables after 10 years are taken as starting values for a new optimization over T years. In other words, it is maximised from 10 to $T+10$ years, thereafter from 20 to $T+20$ years, etc. This iterative process allows avoiding the terminal value problem of dynamic optimization over the planning horizon of T. That is, the limited length of the planning horizon does not affect the outcome.

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[6] For more information about the steps used by the algorithm CONOPT to solve the problem, visit http://www.conopt.com/Algorithm.htm

Specification of biological and economic components

In this chapter, the main forest ecosystem dynamics are specified, as well as the economic data employed and the diameter distributions of the stands used to numerically illustrate the bioeconomic model presented in Chapter 2.

3.1. Forest growth

In the existing literature, forest dynamics is usually determined either based on empirical data or on data generated with biogeochemical process-based simulation models. While the first approach is widely used in forestry economics, it is not suitable for the analysis of the impact of climate change on the optimal management regime, since it is based on recorded data, i.e., it implicitly assumes that future climatic conditions will be similar to current conditions (Garcia-Gonzalo et al., 2007; Hynynen et al., 2002). In contrast, biogeochemical process-based simulation models can incorporate changes in the climate that may affect the evolution of trees (Mäkelä, 1997). Therefore, the latter alternative has been chosen for this thesis.

3.1.1. GOTILWA and climate change scenarios

To determine the evolution of a diameter-distributed stand of *Pinus sylvestris* and the effects of climate change on the forest ecosystem, the biogeochemical model GOTILWA (Growth Of Trees Is Limited by WAter, http://www.creaf.uab.es/gotilwa%2B/) has been used. 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, and has been employed extensively for scientific research (Sabaté et al., 2002; Vicente-Serrano et al., 2010). 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, vapour pressure deficit, wind speed, global radiation), tree physiology (photosynthetic and stomatal conductance parameters), forest composition (tree structure and diameter at breast high 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 (1995); leaf temperature is determined based on leaf energy balance (Gates, 1962) and transpiration is estimated according to the Penman-Monteith equation (Jarvis and McNaughton, 1986; Monteith, 1965). Autotrophic respiration is divided into maintenance and growth respiration. Maintenance respiration is temperature dependent, 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).

Soil is divided into two layers: an organic layer (LF horizon), which considers heterotrophic respiration, 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. Appendix A provides the most relevant values of the parameters used in GOTILWA.

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 (Keenan et al., 2011; Sabaté et al., 2002), and has been proven as a good terrestrial biogeochemical model to simulate carbon fluxes (Morales et al., 2005).

For the empirical analysis various initial diameter distributions of a forest were chosen 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 cm ≤ l ≤ 50 cm. The density function of the diameter of trees, $\theta(l;\, \gamma;\, \varphi)$, is defined over a closed interval, and thus the integral

$$\int_{l_1}^{1_{1+1}} \theta(l;\, \gamma,\, \varphi)\, dl \tag{3.1}$$

gives the proportion of trees lying within the range $[l_i, l_{i+1})$. For the simulation of forest dynamics, a diameter interval [0, 50] has been chosen, because it is representative of the real diameter distributions of the south European forests. 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, three different pairs (γ, φ) have been used. 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 these shape distributions have been combined with three different initial basal areas, 15 m^2, 25 $m^{2,}$ and 35 m^2, which gives rise to the following 9 initial distributions:

Fig. 3.1: Initial diameter distribution corresponding to parameters (0.5,2), BA =15. Young stand shape.

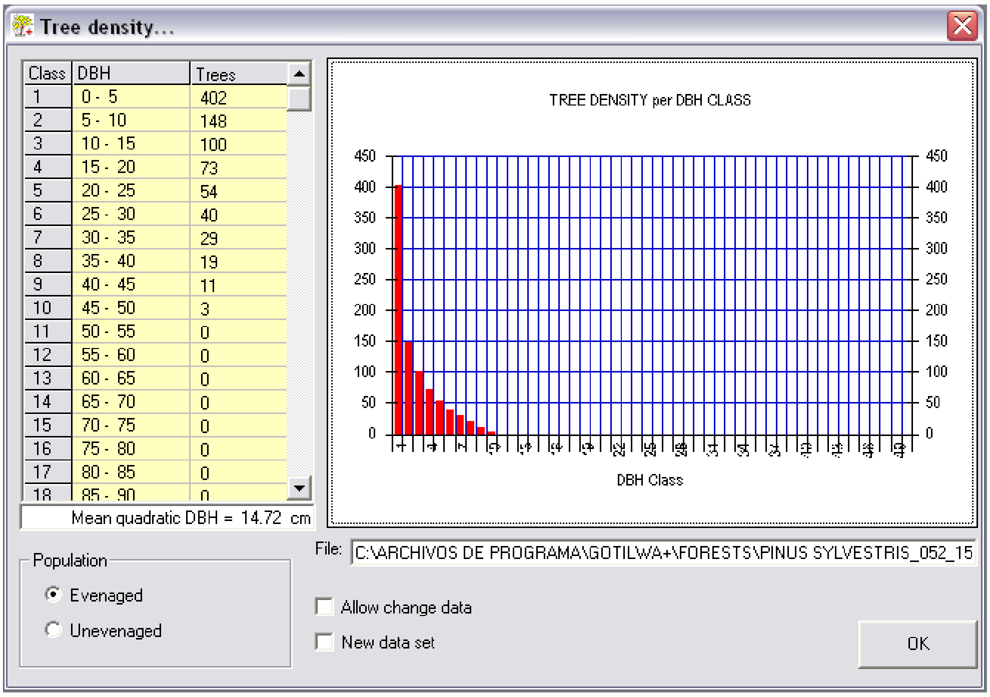


Fig. 3.2: Initial diameter distribution corresponding to parameters (0.5,2), BA =25. Young stand shape.

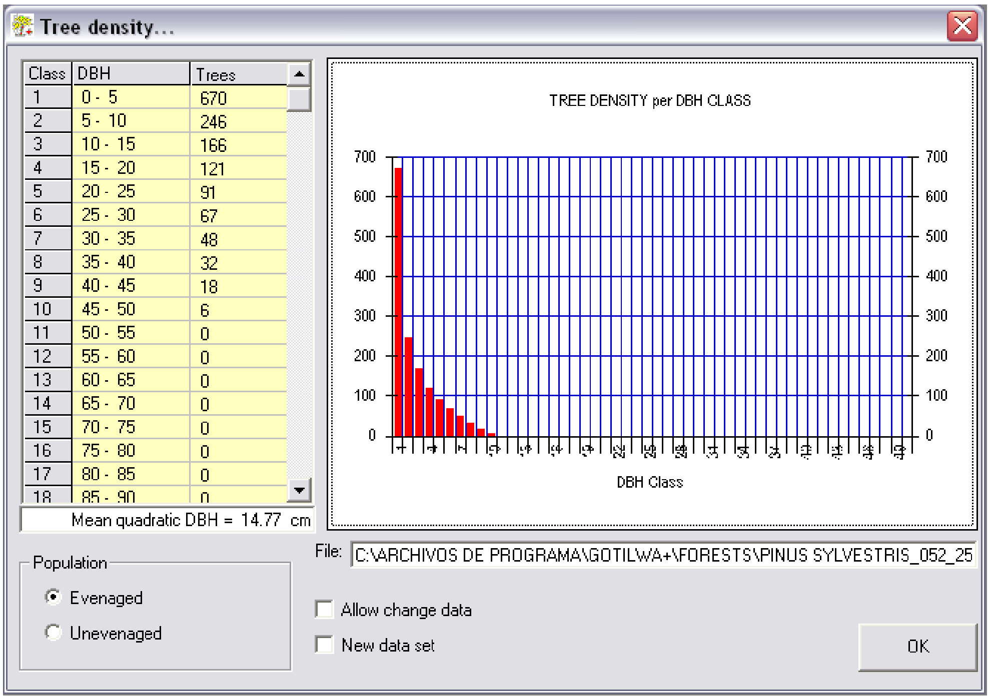


Fig. 3.3: Initial diameter distribution corresponding to parameters (0.5,2), BA =35. Young stand shape.

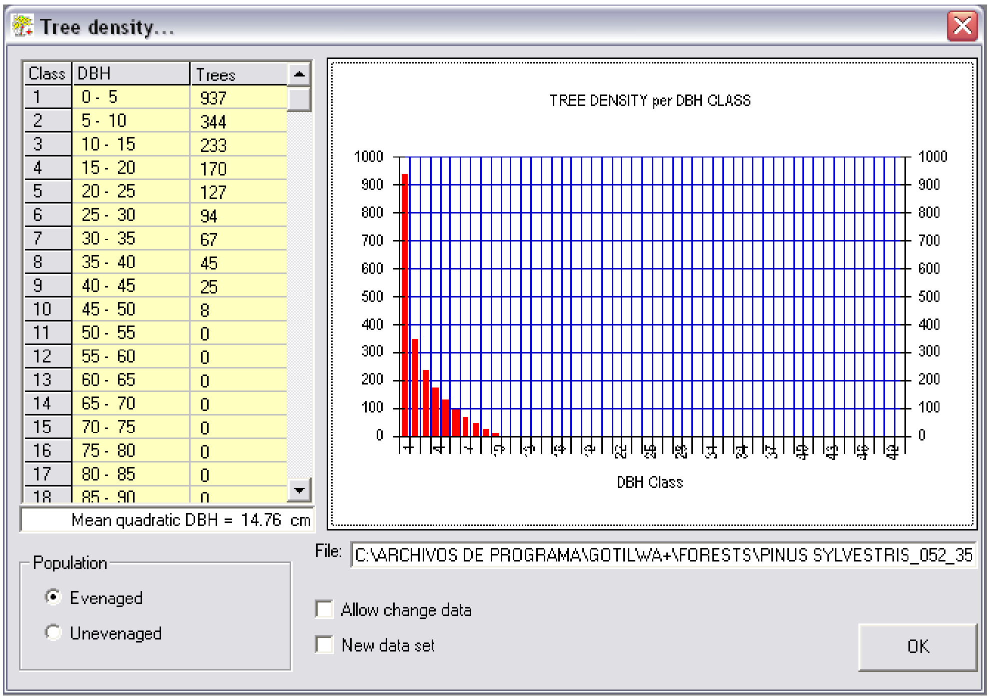


Fig. 3.4: Initial diameter distribution corresponding to parameters (1,1), BA =15. Uniform distribution.

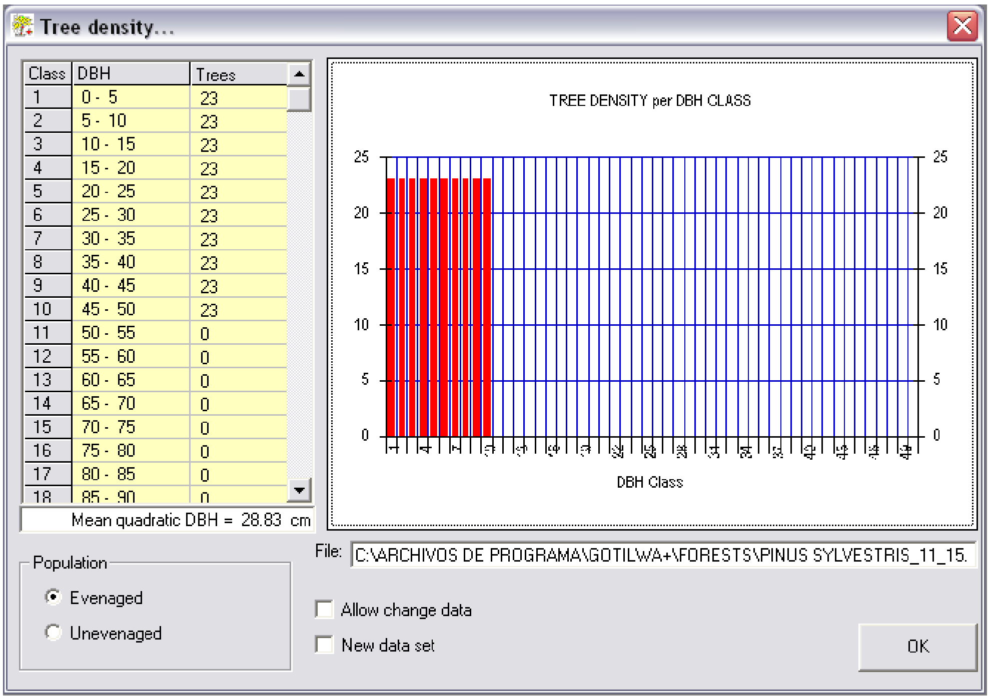


Fig. 3.5: Initial diameter distribution corresponding to parameters (1,1), BA =25. Uniform distribution.

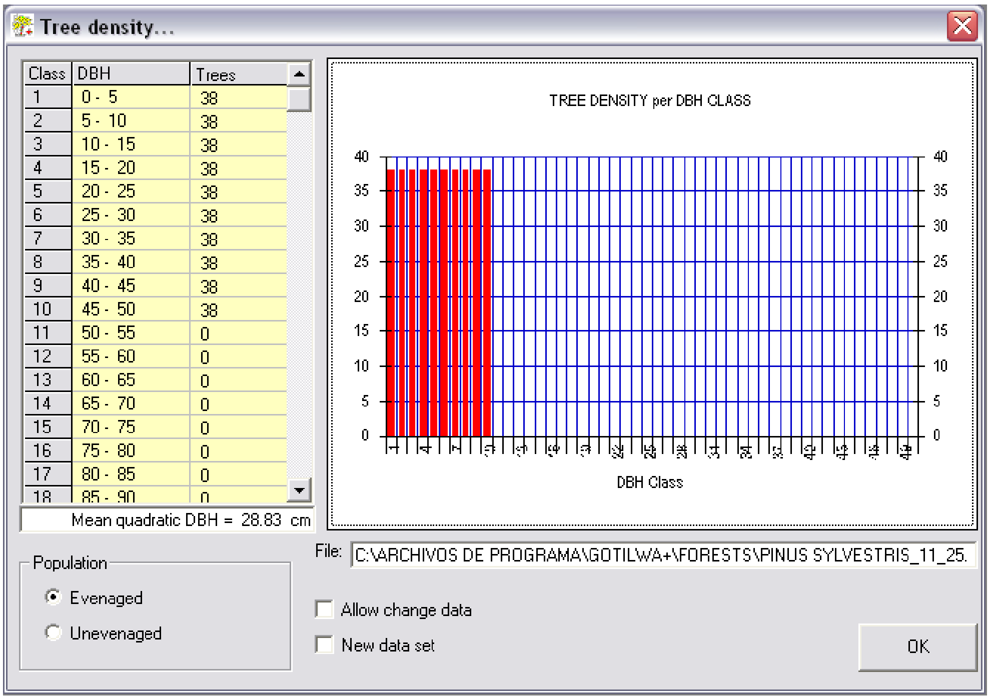


Fig. 3.6: Initial diameter distribution corresponding to parameters (1,1), BA =35. Uniform distribution.

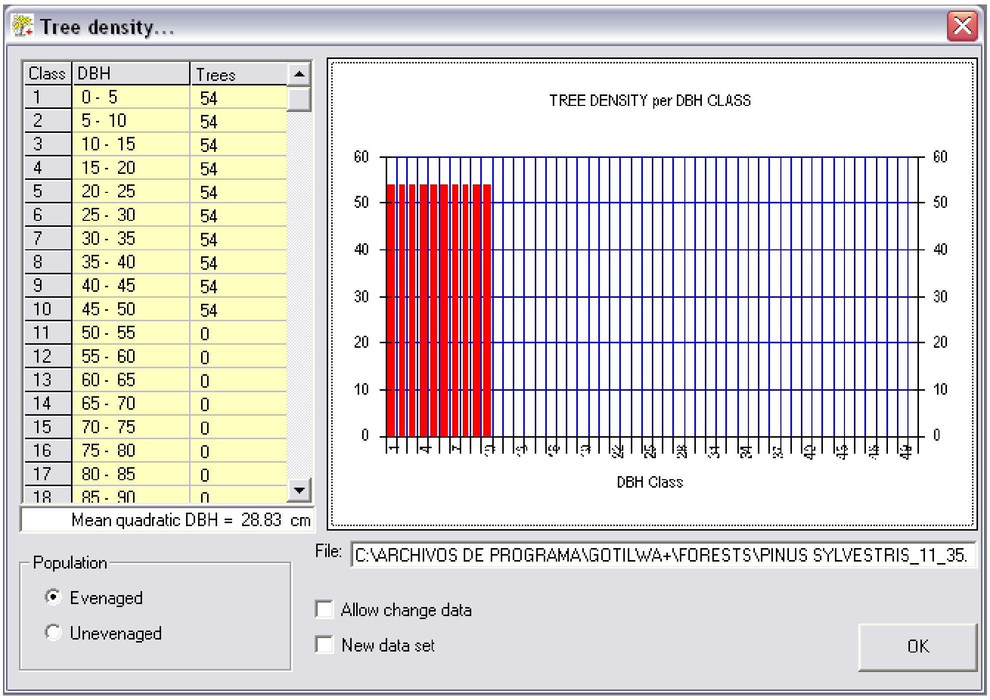


Fig. 3.7: Initial diameter distribution corresponding to parameters (2,2), BA =15. Mature stand shape.

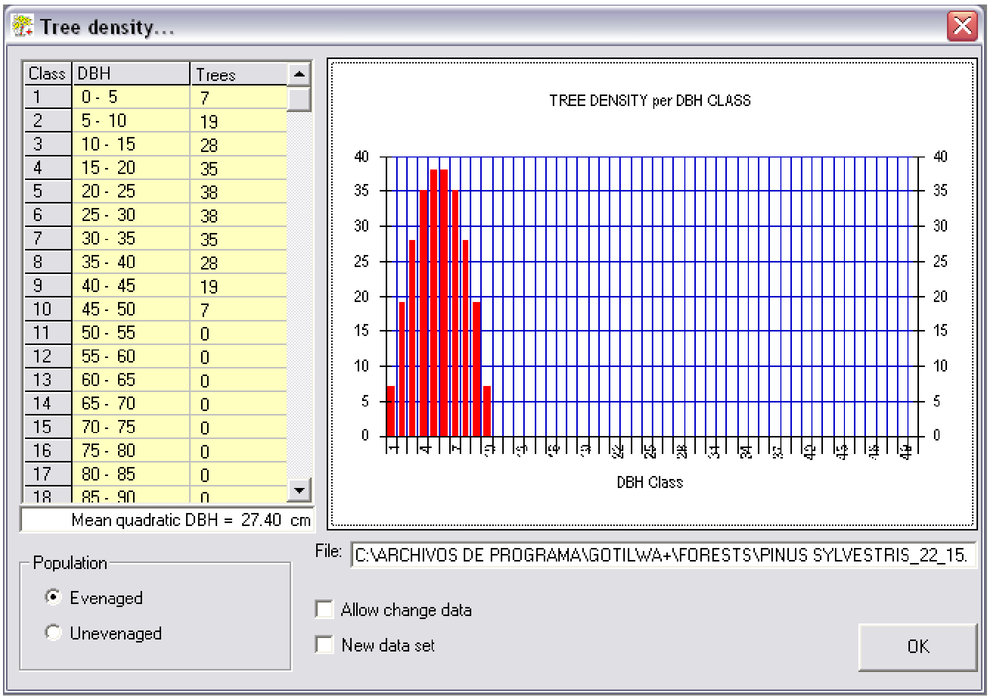


Fig. 3.8: Initial diameter distribution corresponding to parameters (2,2), BA =25. Mature stand shape.

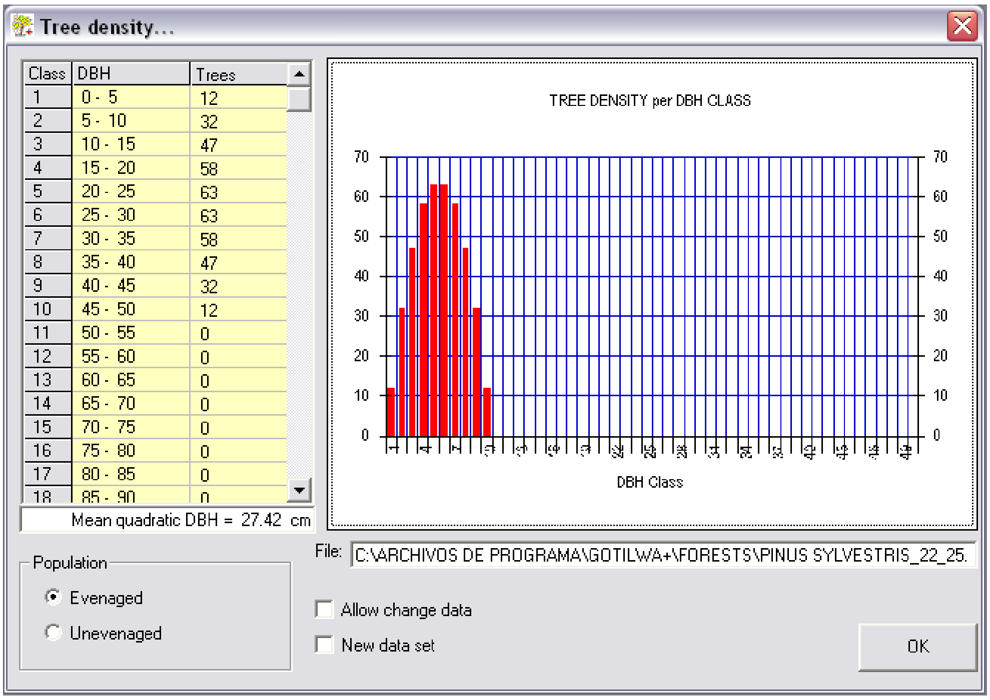
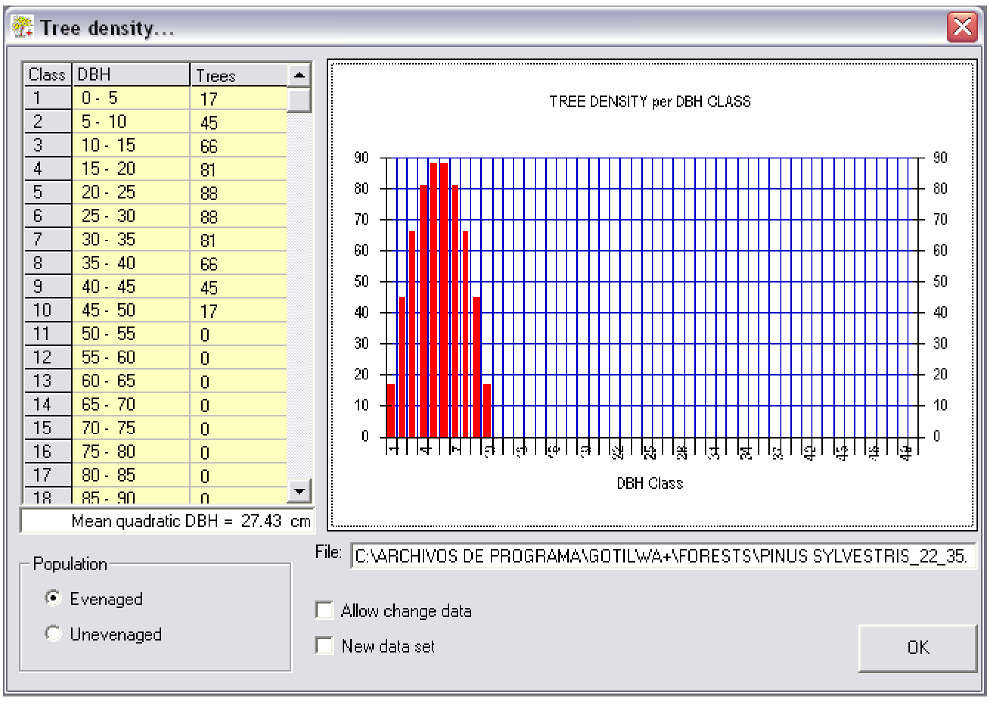


Fig. 3.9: Initial diameter distribution corresponding to parameters (2,2), BA =35. Mature stand shape.



Three different climate scenarios have been considered to analyse their effects on the evolution of the forest growth. The first scenario does not take into account climate change and is denoted by NoCC. 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, and have been used extensively in the previous literature (Davi et al., 2006; Ruosteenoja et al., 2003). These scenarios were defined with the support of the atmosphere-ocean general circulation model ECHAM4 (http://www.mpimet.mpg.de/en/science/models/echam.html) and are both characterized by moderate to high increases in CO_2 emissions from the year 2000 to 2100. The more pessimistic scenario, A2, predicts a greater increase in CO_2 emissions than the scenario in B2. In particular, scenario A2 calculates a CO_2 concentration of 870 ppm by the year 2100, with a temperature increase by around 5°C, while B2 estimates a CO_2 concentration of 621 ppm, and a temperature increase by around 4°C. Nevertheless, within the range of all scenarios considered in the IPCC's Third Assessment Report (2001), neither of the two scenarios is extreme. Given that the smallest available grid size of ECHAM4 is the south of Europe and the north of Africa (Mediterranean Region 5), the expected trajectories of CO_2 concentration in the atmosphere (Figure 3.10), temperature (Figure 3.11) and rainfall (Figure 3.12) until 2200 have been estimated for Catalonia according to the data from this grid[7].

[7] The climate model ECHAM4 predicts for the scenarios B2 and A2 an increase in temperature by 4.39 ºC and 5.41ºC, and a decrease in the average annual precipitation from by 4% and 13% respectively.

Fig. 3.10: Trajectories of the atmospheric CO_2 concentration (ppm).

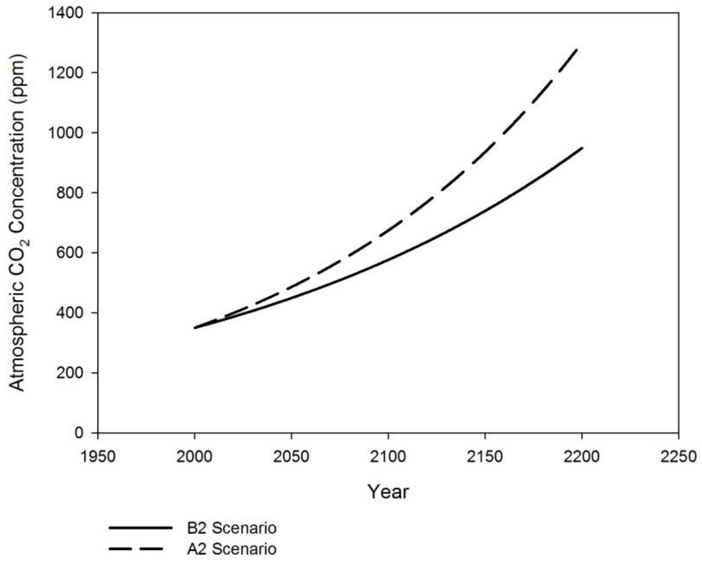


Fig. 3.11: Trajectories of the temperature variation (ºC).

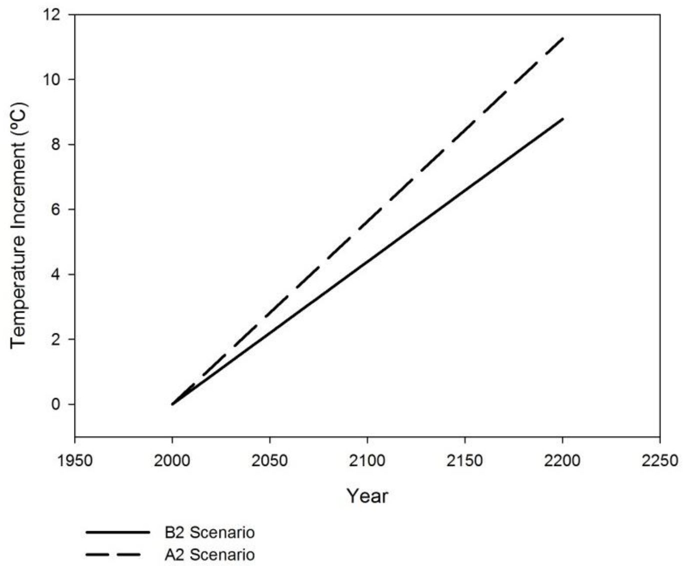
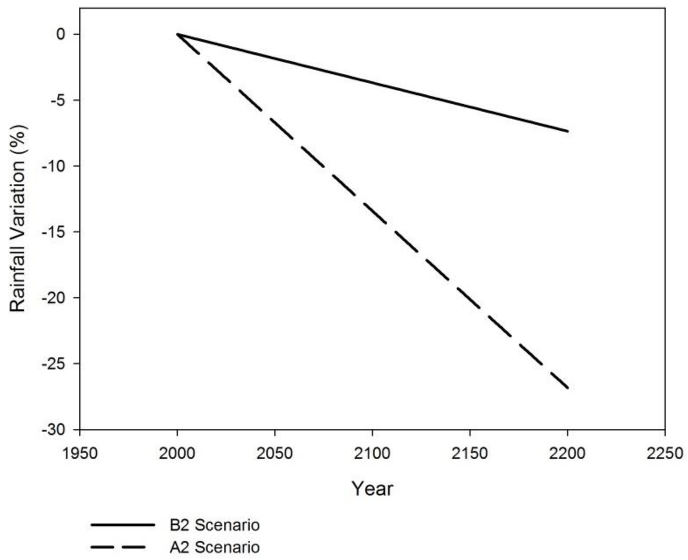


Fig. 3.12: Trajectories of the rainfall variation (%).



3.1.2. Simulation results

The effects of the different climate change scenarios on forest growth have been simulated by feeding GOTILWA with that expected trajectories of CO_2 concentration, temperature and rainfall. Next, the evolution of the forest ecosystem has been simulated over 200 years for the different specified initial diameter distributions and the three different climate scenarios. The data generated from the series of simulations allowed us to estimate the growth function $g\left(E(t), L_i(t), CO_2(t)\right)$. The specification of the function is given by

$$g(\cdot) = (L_m - L_i)(\beta_0 + \beta_1 \cdot CO_2) + (\beta_2 + \beta_3 \cdot CO_2) \cdot BA + (\beta_4 + \beta_5 \cdot CO_2) \cdot BA_i \quad (3.2)$$

where the exogenous variables of the function indicate the average diameter at breast height (cm) of class *i* (L_i), the concentration of carbon dioxide CO_2 (ppm), the basal area (m^2) of the entire stand (BA), and the basal area (m^2) of an "average" tree in cohort *i* (BA_i). The influence of the environment $E(t)$ in the form of intraspecific competition is reflected by the variables BA and BA_i. While an increase in the BA of the stand increases the competition, the latter variable BA_i presents the competitive status of the individual trees, i.e., the larger

BA_i is, the less competition the individual tree faces (Trasobares et al., 2004). Hence, the variable $E(t)$ is measured by the basal area of the stand: $BA = \sum_{i=1}^{n} \frac{\pi}{4} L_i^2 X_i(L_i)$ (density of the stand) and the basal area of the average tree of cohort *i* by $BA_i = \frac{\pi}{4} L_i^2 X_i(L_i)$. The parameters β_0, β_1, β_2, β_3, β_4 and β_5 were estimated based on the data pooled over time and initial diameter distributions. The estimation was carried out using SPSS, by quadratic sequential programming. Different types of functions were analysed, and the best estimation in terms of goodness of fit and parameters signification yielded the following function:

$$g(E, L_i, CO_2) = \underset{(86,47)}{(183,75 - L_i)}\left(\underset{(65,16)}{2,07 \cdot 10^{-2}} + \underset{(27,26)}{1,87 \cdot 10^{-5}} \cdot CO_2\right) + \left(\underset{(-61,65)}{-2,43 \cdot 10^{-4}} + \underset{(26,00)}{7,87 \cdot 10^{-8}} \cdot CO_2\right) \cdot BA + \left(\underset{(41,59)}{6,42 \cdot 10^{-2}} - \underset{(45,94)}{5,86 \cdot 10^{-5}} \cdot CO_2\right) \cdot BA_i. \qquad (3.3)$$

where the numbers in brackets provide the t-values of the estimated parameters.

The simulations with GOTILWA allow the effect of climate change on the biological variables of an unmanaged forest to be illustrated. Figure 3.13 show that the diameter of an initially young tree (diameter 2,5cm) increases by up to 20% with climate change (A2 Scenario) and that of an initially mature tree (32,5cm) by only 2%. The growth of the diameter of mature trees even declines with climate change after 150 years because the competition within the stand has increased. Figures 3.14 and 3.15 show that the average diameter and volume of the stand increases with climate change (A2 Scenario) by about 9% and 8% respectively. However, the former increase starts decreasing slightly after 150 years and the latter after 120 years as the maximum carrying capacity is reached. The case of B2 Scenario follows a similar pattern than A2 Scenario.

Fig. 3.13: Growth of the diameter of young and mature trees from an unmanaged forest (young stand).

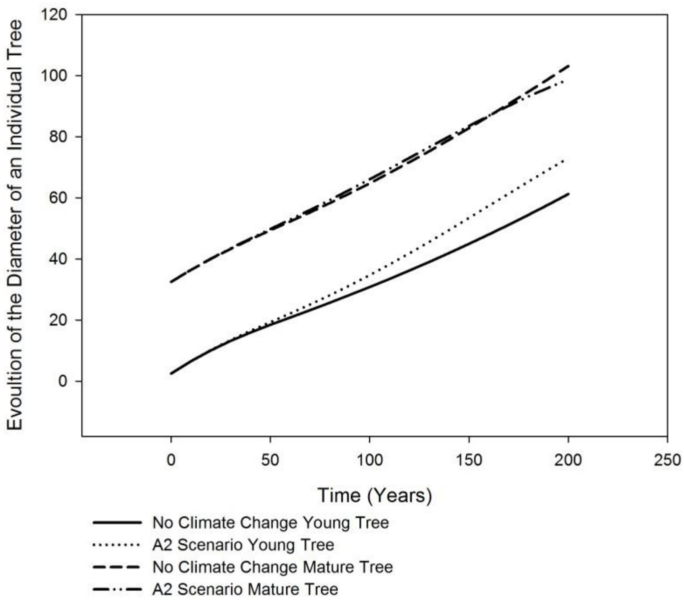


Fig. 3.14: Growth of the diameter of the stand of an unmanaged forest (young stand).

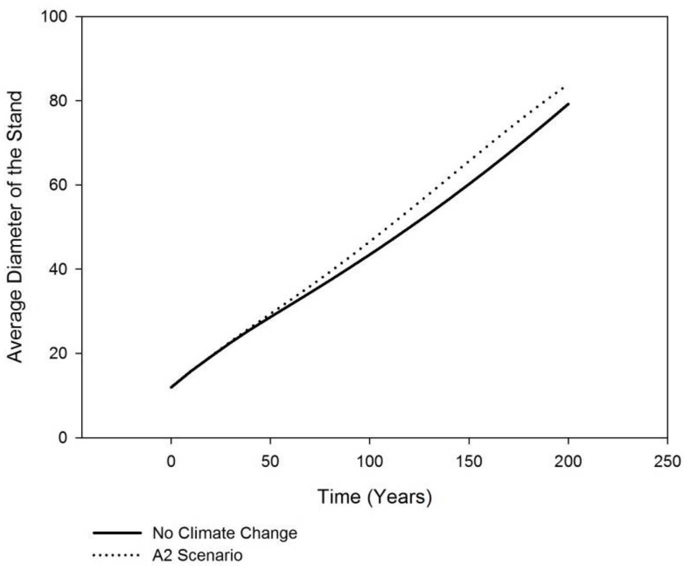
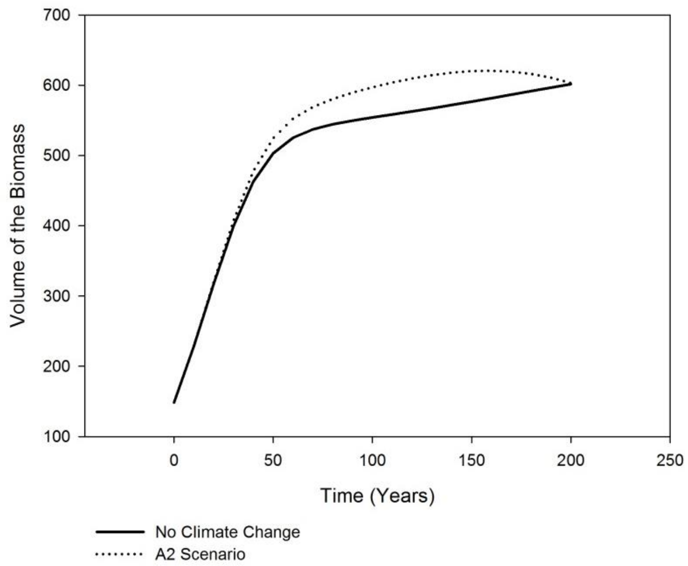


Fig. 3.15: Growth of the volume of the stand of an unmanaged forest (young stand).



3.2.Reproduction

The reproduction function $\rho(\cdot)$ was estimated using data of germinated sprouts of *Pinus sylvestris* in Catalan forests and of the canopy closure, provided by SIBosC database (CREAF-DMAH, 1988-1998). SIBosC is based on the Ecological and Forest Inventory of Catalonia, an inventory set up from 1988 to 1998 by the CREAF (Centre for Ecological Research and Forestry Applications) for the Catalan forests. This database offers a large variety of data about biomass, above- ground production of wood, leaves, branches, and the diameter distribution of the stand. For the reproduction function, data about the basal area of *Pinus sylvestris* stands located in the studied region has been obtained, the total number of trees, and the corresponding number of seedlings with a diameter between 0 and 2,5 cm. Guittet and Laberche, (1974) reported that the rate of mortality of one-year old seedlings after five years was about 83%. Thus, based on the reported data of this study, the number of seedlings that reach the diameter of 2,5 cm has been calculated, to estimate a function where the number of seedlings depends on the basal area of the stand[8]. The estimation was carried out using SPSS,

[8] It is assumed that seedlings grow into the first cohort (2.5–5 cm) after thirteen years.

by the ordinary least squares method. Different types of functions were analysed, and the estimation which has the best goodness of fit was a polynomial function. That estimated function allows the number of surviving seedlings of 2,5 cm to be determined, taking into account the high mortality in the early stages of growth process:

$$\rho(\cdot) = Max\Big[10\cdot\big(\underset{(-2,08)}{-4,86\cdot10^{-6}}\cdot BA^3 + \underset{(2,67)}{3,64\cdot10^{-4}}\cdot BA^2 - \underset{(-4,08)}{8,93\cdot10^{-3}}\cdot BA + \underset{(9,01)}{8,98\cdot10^{-2}}\big),0\Big] \cdot\sum_{i=3}^{n} X_i(t), \tag{3.4}$$

where the numbers in brackets provide the t-values of the estimated parameters. This function is decreasing along its range (0– 41.16 m^2), except for a plateau when the basal area is within 21.67 and 28.25 m^2 per hectare, where it remains approximately stable around 0.18 seedlings per fertile tree.

3.3.Natural mortality

The function μ_1 was calibrated upon the probability of survival described by Gonzalez et al. (2005)[9], and is given by

$$\mu_1 = \vartheta(t)\left(1-\left(1+\exp\left(-3,954+0,035\cdot BA-2,297\frac{L_i}{Age}\right)\right)^{-2}\right) \tag{3.5}$$

Where ϑ presents changes in the mortality rate as climate change takes place and Age denotes the average age of the trees of the stand. Although the latter variable is not present in the model, the average age of the existing trees at the beginning of the exploitation could be calculated through data provided by SIBosC database (CREAF-DMAH, 1988-1998). The average

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[9] These authors estimated the probability of survival for time periods of five years, so the ten-year time periods mortality rate used in this study is an adaptation.

age for the rest of trees 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 an important strand of the literature, an increase in temperature and a decrease in water availability will lead to an increase in forest mortality in southern Europe (Martinez-Vilalta and Piñol, 2002). Similar results were reported for *Pinus sylvestris* in Switzerland (Bigler et al., 2006; Dobbertin and Rigling, 2006). Van Mantgem and Stephenson (2007) find an annual increment in mortality of about 3% for Abies and Pinus in the Sierra Nevada of California. However, a review article shows that the impact of climate change on the mortality of the trees cannot be quantified unambiguously, since the uncertainties are very high (Allen et al., 2009). Therefore, it is not possible to establish an unambiguous relationship between mortality and climate variations.

3.4. Economic components

The net benefit function of timber management consists of the net revenue from the sale of timber at time *t* minus the maintenance costs (clearing, pruning, and grinding the residues) and minus the costs associated with nursing and selecting the appropriate number of seedlings for upgrowth. It is specified by

$$\left[\sum_{i=0}^{n}\Big(p_{TIM}\big(L_i(t)\big)v_M - c_H\big(L_i(t)\big)\Big)v_{TOT}\big(L_i(t)\big)U_i(t)\right] - c_{MT}\left(\sum_{i=0}^{n}X_i(t)\right) - c_N, \quad (3.6)$$

where $p_{TIM}\big(L_i(t)\big)$ and $c_H\big(L_i(t)\big)$ denote the price of timber per m^3 and the harvesting cost, respectively, as a function of the diameter, v_{TOT} indicates 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 is given by $p_{TIM}\left(L_i\right) = Min\left[-23,24 + 13,63\sqrt{L_i},\ 86,65\right]$. It is strictly concave 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 $c_H\left(L_i\right) = 6 + 73,1125 L_i^{0,506}$, and are also provided by Palahí and Pukkala (Palahí and Pukkala, 2003). The total volume v_{TOT} is characterized by the function $v_{TOT}\left(L_i\right) = 0,135 \cdot 10^{-3} L_i^{2,429}$, 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, which reads as $v_M\left(L_i\right) = 0,699 + 0,431 \cdot 10^{-3}\ L_i$.

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 costs of trees planted are specified as $c_N = 0,73P$. The values of the cost functions are consistent with the data 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 (DMAH, 2009).

3.5. Real diameter distributions

The general purpose of the mathematical analysis is to determine the regime that maximises the discounted private net benefits from timber production of a diameter-distributed forest. To apply the model, two real stands of *Pinus sylvestris* located in Alta Garrotxa (Catalonia) have been selected. As it was noticed on Chapter 1, *Pinus sylvestris* was chosen because it is the most important commercial species for timber production in Catalonia, and the Garrotxa is a region with a large expanse of forest stands of this species

(Ibàñez, 2004). For all considered climate scenarios the average precipitation at the locations of the two stands is around 850-1100 mm/year; clearly exceeding the critical level for water stress (400 mm/year).

The two initial real diameter distributions were obtained from the SIBosC database. Stand 1 (Figure 3.16) can be considered as a population of young trees and stand 2 (Figure 3.17) as a population of mature trees. In addition, a hypothetic stand has been considered and presented as a very young stand or new planted stand. Determining the optimal management for one stand each time, it is possible to study the effect of different initial distributions on the optimization results.

Fig. 3.16: Real young stand.

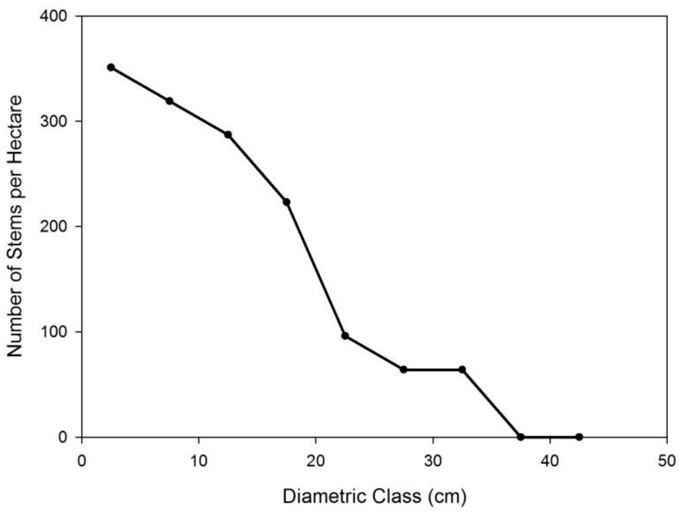
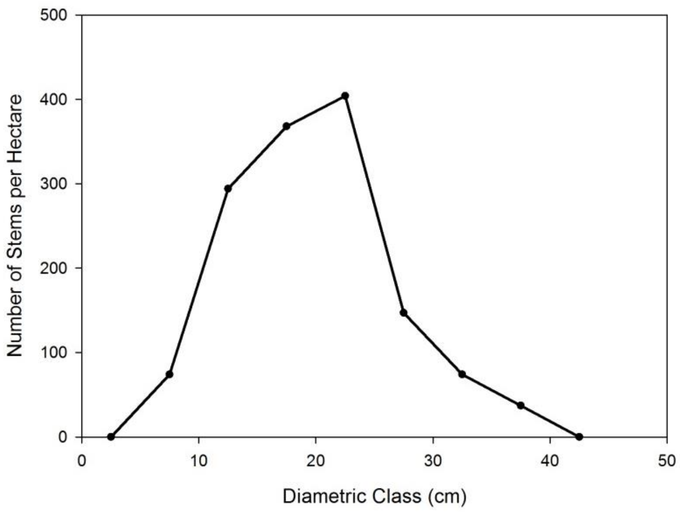


Fig. 3.17: Real mature stand.



All optimizations have been carried out on a per-hectare basis. Initially the optimal management regime has been calculated given a discount rate of 2%, in line with the studies by Palahí and Pukkala (2003) and Díaz-Balteiro and Romero (2003). Afterwards, a sensitive analysis of the discount rate has been conducted on Chapter 4 (adaptation issue) and 6 (mitigation issue).

adapting the optimal management to climate change

It is widely recognized that rising atmospheric CO_2 concentrations are influencing climate on a global scale. As this climate change takes place, it affects the net ecosystem productivity of forests, due to the fertilization effect of carbon, changes in the rate of reproduction, and the increase in disturbances and dieback (Alig et al., 2004; Cramer et al., 2001; Karjalainen et al., 2003; Kellomäki and Kolström, 1993; Scholze et al., 2006). Consequently, one is left to ask to what degree climate change affects the profitability of forest management.

Sohngen et al. (2010) reviewed a great number of studies on mitigation and on the adaptation of forest management regimes to different climatic conditions. They found, as also indicated by Caparrós (2009), that most of the literature does not analyse forest management responses at the stand level to climate change in detail and, most importantly, the way these changes may influence the biological processes of forest ecosystems.

Irland et al. (2001) analysed the impact of climate change on the forest sector and found that the assumed climate changes would in general be beneficial for the US timber products sector for a time horizon of 120 years. These findings are in line with the results of the 2005 Resource Planning Act (RPA) Timber Assessment (Haynes et al., 2007) and with those obtained earlier by Perez Garcia et al. (2002) and by Sohngen and Mendelsohn (1998). For the most part, the authors of these studies simulated the evolution of forests either using a biogeochemical or biogeographic simulation model for determining the inventory of the forest at the end of the planning horizon for a given climate change scenario while interpolating the transitory evolution of the forest for the rest of the planning horizon. While these studies provide valuable insights into the future evolution of forests and their related product markets, they do not take into account that the adaptation of forest management regimes to climate change leads to changes in optimal management regimes. Therefore, Nuutinen et al. (2006) simulated the evolution of the forest for a fixed set of management options in the first stage, and in the second stage the optimal management regime was chosen endogenously. A similar procedure was chosen by Alig et al. (2002). Although this two-stage process or "soft-link" is clearly an advancement, it does not fully integrate the biogeochemical and economic models. The choice of the management regime affects the future evolution of forests as a result of higher or lower competition between individual trees for scarce resources such as light, space and nutrients, and changes in reproduction and mortality. Yet, the simulated evolution of the forest in the first stage was based on a specific management regime and not on a sequence of different management regimes which may adapt best to changing climatic conditions.

To overcome this shortcoming, the biogeochemical model integrated with an economic model presented in the previous chapter is proposed, by incorporating not only data but also the process that governs the evolution of the forest: the forest growth, the tree reproduction and the natural mortality. Moreover, this thesis extends the existing literature by considering diameter-distributed forests where the optimal management regime (clear cutting, selective harvesting, and selection of young trees for upgrowth) is determined endogenously.

The importance of considering market effects is recognized for the correct determination of the net benefits of adaptation to climate change. However, since this thesis concentrates on a detailed stand analysis, changes in timber prices as a result of a change in timber supply or demand are not determined within the model. Nevertheless, market effects have been approximated to the analysis by employing the time path of timber prices, given by a global integrated assessment model (Tavoni et al., 2007).

As indicated in Chapter 1 the analysis is based on a numerical study determining the optimal forest management of two real stands of *Pinus sylvestris*. The purpose of the numerical analysis for this chapter is to determine that optimal logging regime for a time horizon of 200 years. In order to determine what is required for the optimal adaptation of forest management to future climatic conditions, the three climate scenarios defined in Chapter 3, “No Climate Change” (NoCC from now onward) and scenarios A2 and B2, were employed. The next section determines the optimal forest management regime and conducts a sensitivity analysis of the results with respect to key parameters. Detailed results of the optimization process are presented in Appendix B.

4.1. Analysis of the optimization results

The optimal management regime has been calculated for the three climate scenarios considered. The results show that it is optimal to harvest trees selectively. Moreover, and aggregated discounted net benefits obtained on B2 and A2 scenario are higher compared to the NoCC scenario. This is because the CO_2 fertilization effect dominates the competition effect and the negative effects of the rise in temperatures and mortality. The optimal management regime in the presence of climate change leads to a decrease in the diameter and the age of the logged trees, but to an increase in their number. As a result timber yields are higher. These and other additional findings of this section are presented as observations below.

Observation 4.1: *The fertilization effect of CO_2 leads to an increase in the growth of the biomass. Under an optimal management regime, climate change may lead in the long-run to younger and higher density forests with lower average diameter. In the long-run, logged trees are also younger and have a lower average diameter.*

Figures 4.1–4.2 depict the evolution of the number and the average age of the standing trees. In the presence of climate change, the optimal management regime leads to a substantial increase in the number of trees (Fig. 4.1), and to a decrease in the average age (Fig. 4.2). Figures 4.3 and 4.4 show that the total basal area of the stand (Fig. 4.3) increases while the average diameter of the standing trees (Fig. 4.4) is decreased after 200 years of exploitation. The latter implies that timber yields increase with climate change. Figures 4.5 – 4.6 show the number of young trees that are the result of replantation and of natural reproduction. Planting increases (Fig. 4.5), and natural reproduction decreases over time (Fig. 4.6). As shown in Figure 4.1, in the presence of climate change it is optimal to increase the number of trees over time thus leading to a higher stand density and consequently to a reduction in the natural reproduction capacity. Hence, the number of planted trees has to increase in order to compensate the decrease in natural reproduction. Consequently, the prediction in the literature that an increase in CO_2 (fertilization effect) leads to an increase in the growth of the biomass (Heimann and Reichstein, 2008; Norby et al., 2005) also holds for an optimally managed stand. This tendency is even more pronounced for the optimal forest management regime in the presence of the climate change scenario with the highest CO_2 emissions (A2). Results confirm the finding in the literature that climate change increases harvest yields (White et al., 2010). However, in contrast to the findings in most of the literature (White et al., 2010) the observation that the optimal rotation length is extended is not observed, but rather that it is shortened.

Fig. 4.1– 4.6: Evolution of the main biological variables over time for the young stand.

Fig. 4.1.

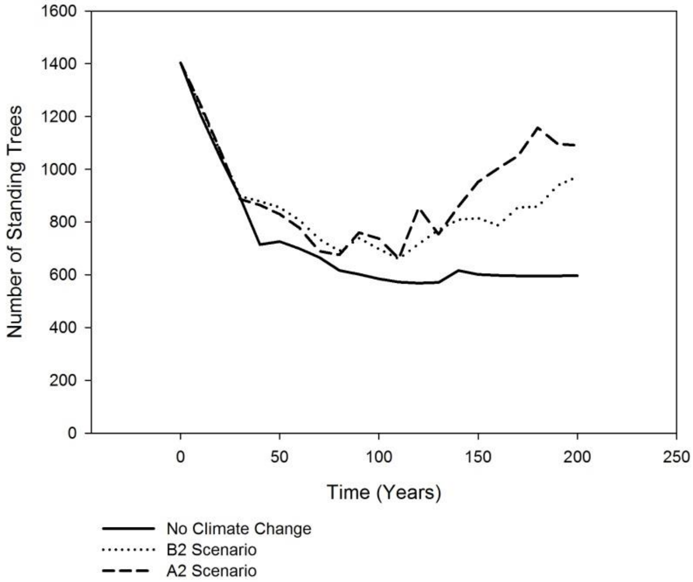


Fig. 4.2.

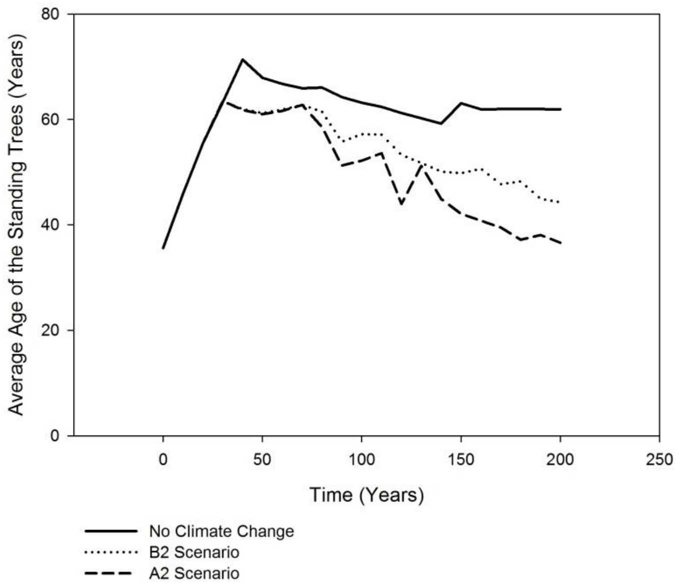
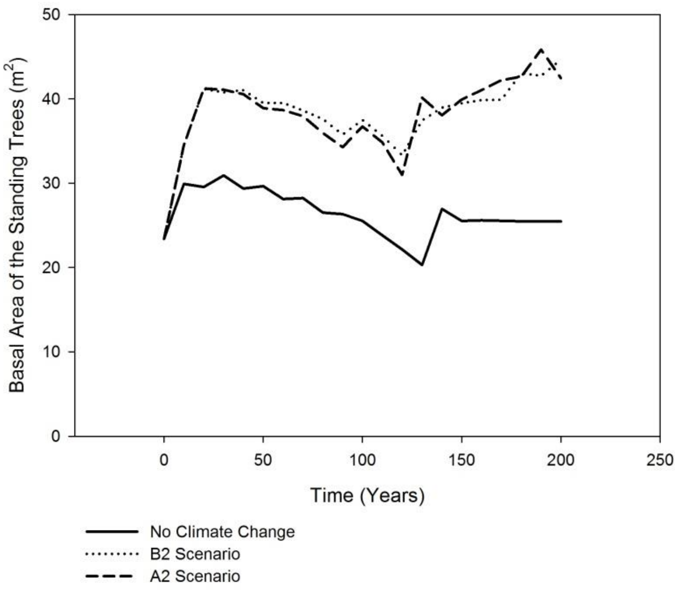
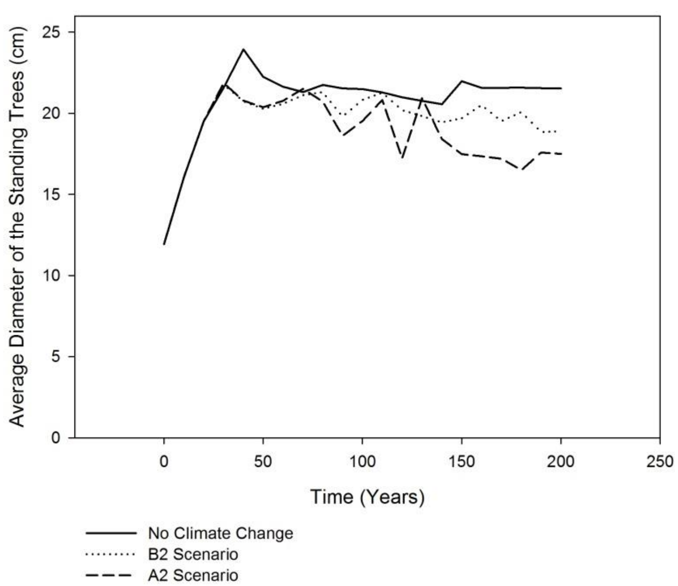


Fig. 4.3.



Basal Area of the Standing Trees (m^2)
50
40
30
20
10
0
0
50
100
150
200
250
Time (Years)
No Climate Change
B2 Scenario
A2 Scenario

Fig. 4.4.



Average Diameter of the Standing Trees (cm)
25
20
15
10
5
0
0
50
100
150
200
250
Time (Years)
No Climate Change
B2 Scenario
A2 Scenario

Fig. 4.5.

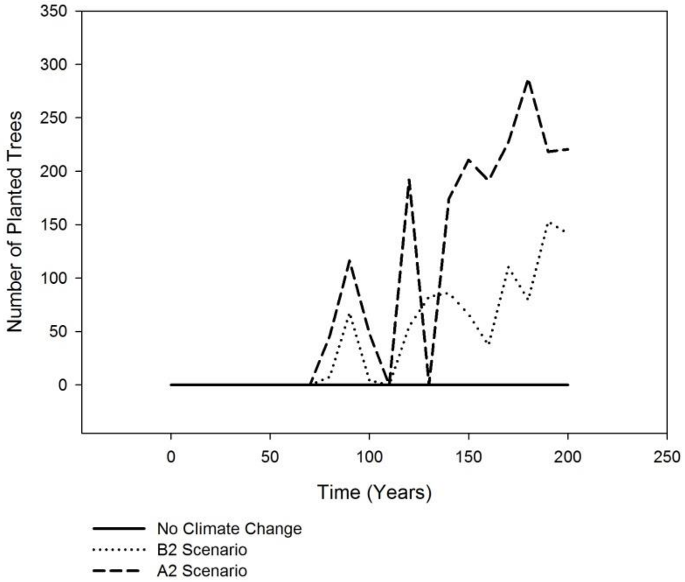
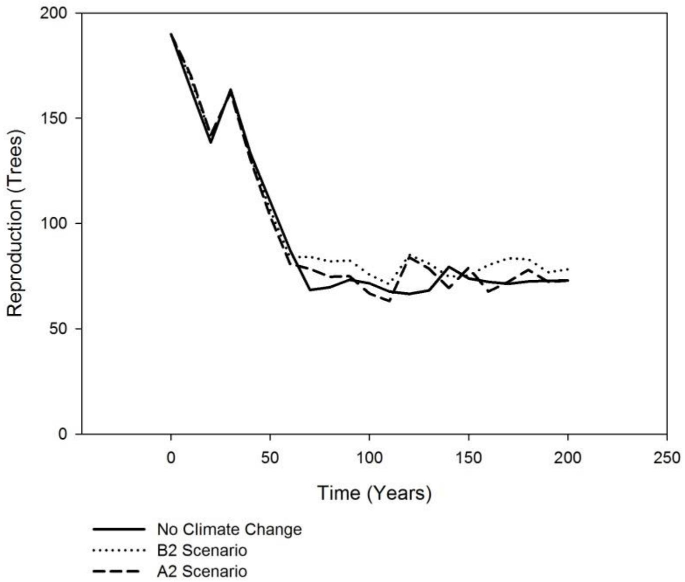

Number of Planted Trees
350
300
250
200
150
100
50
0
0
50
100
150
200
250
Time (Years)
No Climate Change
B2 Scenario
A2 Scenario

Fig. 4.6.


Reproduction (Trees)
200
150
100
50
0
0
50
100
150
200
250
Time (Years)
No Climate Change
B2 Scenario
A2 Scenario

For logged trees it is observed that after approximately 150 years diameter and age decrease with climate change. At that point of time the stand has approached a more uniform diameter distribution (normal forest) – see Figures 4.7 and 4.8. This phenomenon can be explained by the fact that the model allows for selective logging and replanting or natural reproduction. In this way it is possible to increase the yields by increasing the density, and not by extending the rotation length. The previous literature usually did not consider this option since despite the possibility of selective logging, replanting normally required clearing the entire stand beforehand. The graphs for Figures 4.7 and 4.8 show some discontinuities because during certain time periods no trees are cut.

Fig. 4.7 – 4.8: Evolution of the average diameter and age of the logged trees (young stand).

Fig. 4.7.

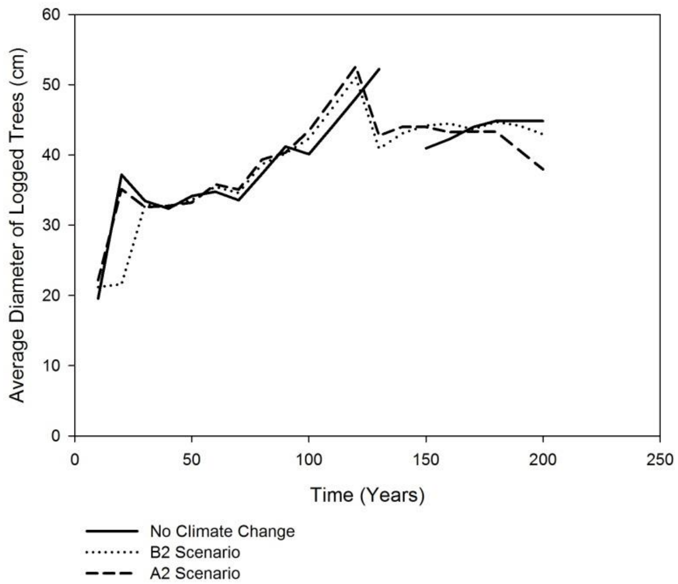
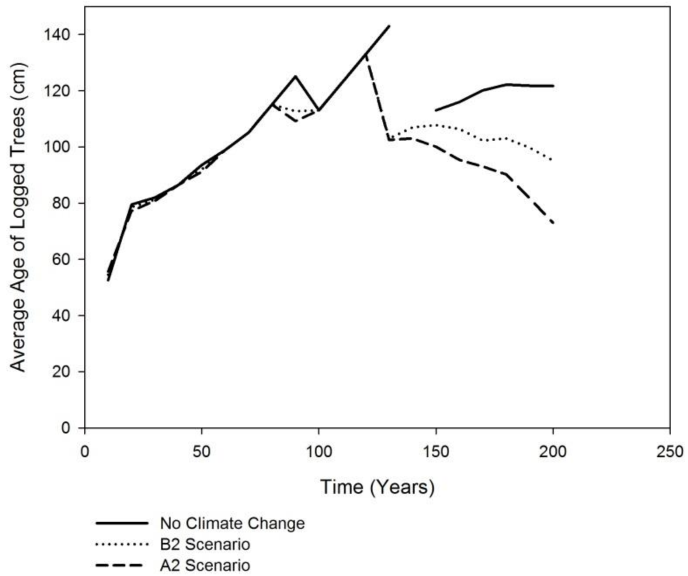


Fig. 4.8.



The results of the optimization for the mature stand show that it evolves according to the same pattern as the young stand. Therefore, findings related to the mature stand are only presented in this section if they follow a different pattern then the findings related to the young stand. The rest of figures concerning about the mature stand are presented in a supplementary online material available on the following link: https://www.dropbox.com/s/ts563fovhk851ye/MaturePlots.pdf

Observation 4.2: *The diameter distribution of the forest tends in the long run to a "steady state equilibrium", characterized by a normalized forest, independently of the initial diameter distribution*[10]*.*

The calculations show that it takes at least 100 years to reach a tree diameter distribution that is relatively stable over time and approaches a normalized forest. Figures 4.9 and 4.10 illustrate the evolution of the number of trees and the average diameter of each cohort for

[10] Give that there is climate change there does not exist a steady state equilibrium. Yet this term is used to indicate the long-run effects which seem to be stable.

climate change scenario B2 in more detail. The diameter distribution at t = 0 shows the initial distribution of the young and mature stands respectively.

Fig. 4.9 – 4.10: Evolution of the diameter distribution over time, in the presence of climate change scenario B2.

Fig. 4.9: Young stand.

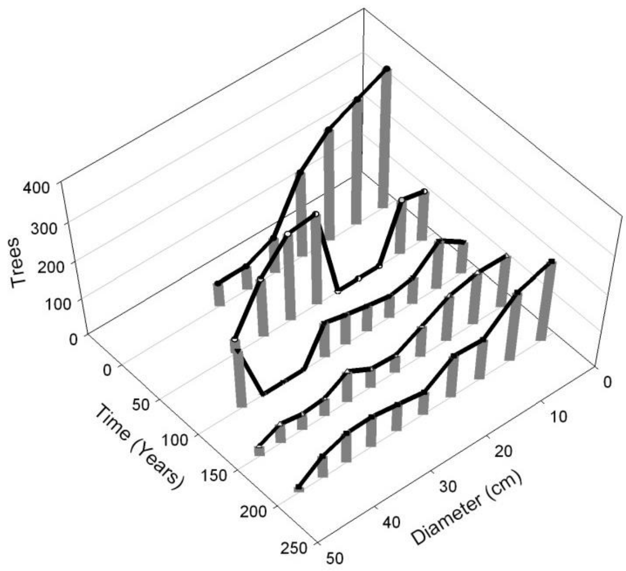
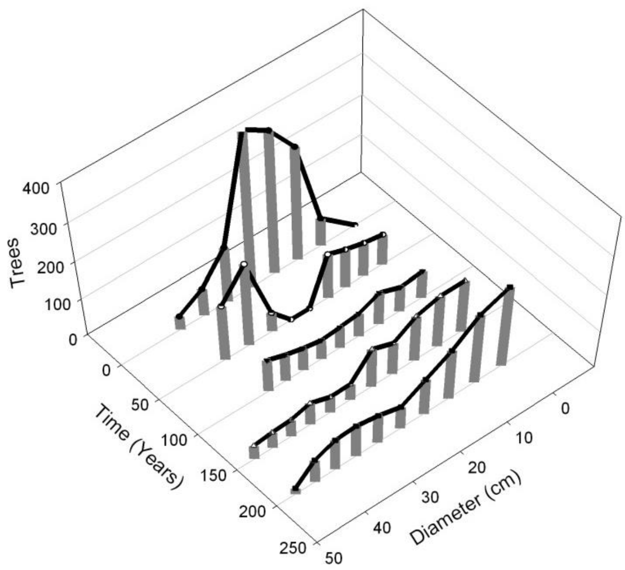


Fig. 4.10: Mature stand.



Observation 4.3: *Under climate change, the fertilization effect of CO_2 leads to higher profits, partially as a result of higher timber extraction. Approximately 70% of this increase can be attributed to the evolution of future timber prices.*

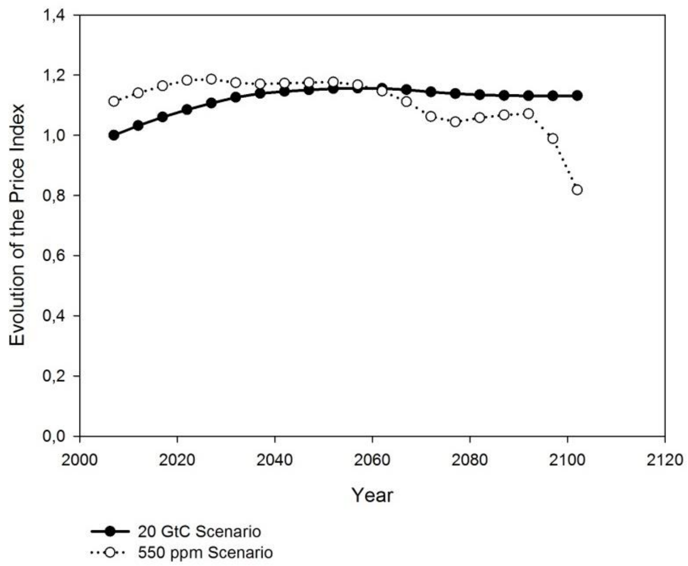
It is important to analyse the effect of climate change on the maximised discounted sum of the net benefits of timber production. Table 4.1 shows for a stand of predominantly young trees and for constant market prices that the maximal discounted net benefits over 200 years are 5895 €/ha in the absence of climate change, and 6524 €/ha and 6652 €/ha for scenarios B2 and A2 respectively. Thus, in the presence of climate change the optimal management regime leads to higher profits, most likely due to the fertilization effect of CO_2. The results suggest that the fertilization effect dominates the negative effects of the increase in intra-specific competition and in mortality. The results of the optimization for the mature stand produce a similar pattern for the logging regime as those of the young stand. However, the profits obtained are of course higher for all considered scenarios, due to the logging of mature trees already during the initial periods of the planning horizon. The discounted net benefits for constant market prices are 9781 €/ha, 10378 €/ha and 10483 €/ha, for the NoCC, B2 and A2 scenarios, respectively.

Although the analysis is conducted at the level of an individual stand, future market effects are taken into account by considering the future evolution of timber prices resulting from changes in supply and demand. Tavoni et al. (2007) link the general equilibrium model - World Induced Technical Change Hybrid (WITCH) - to a global forest sector model. 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. According to all these factors, WITCH provides a price path for carbon abatement that determines the value of carbon sequestration. The WITCH model and the global timber model are solved iteratively until the price path of carbon, price of timber and the amount of sequestered carbon are supported by each of them. The study by Tavoni et al. (2007) 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 conference of the parties posterior to the Kyoto protocol limits the emission reduction credits as a result of forest carbon sequestration for all Annex I countries (Amano and Sedjo, 2006).

The authors consider two climate change scenarios. 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 timber price indices over time are presented in Figure 4.11[11].

[11] The calculated evolution of the global timber prices for the two scenarios formulated by Tavoni et al. (2007) were supplied in a personal communication by B. Sohngen.

Fig. 4.11: Evolution of the timber price over time depending on the two climate change scenarios considered by Tavoni et al. (2007).



The projected price path of the global timber price is in line with the results of the literature (Sohngen et al., 2010; White et al., 2010). Most studies employ a climate scenario often denominated baseline or business as usual, where the CO_2 concentration increases strongly – in that case the A2 scenario – and a second scenario with a significant lower increase in CO_2 – in that case the B2 scenario. Nearly all studies find that the more stringent CO_2 scenario leads to lower global timber prices than the baseline scenario. However, as also observed in Fig. 4.11, the timber prices of the stricter climate scenario may be higher for some time periods due to reduced logging activities or due to dieback effects of the laissez-faire scenario (business as usual).

Based on the pattern of Fig. 4.11 the two paths of the timber price employed in this study have been calculated. It allows the discounted net benefits of the young and mature stand for the three considered climate scenarios to be determined, based on the predicted evolution of timber prices. The results are presented in Table 4.1 and show that the maximised discounted aggregate net benefits increase from 5895€ to 7744€ (scenario B2) or 8408€ (scenario A2). If timber prices were held constant over time the maximised net benefits would decrease from

7744€ to 6524€ in scenario B2 and from 8408€ to 6652€ in scenario A2. The intuition for these results lies in the fact that the timber price initially increases for both scenarios. Timber prices are higher for B2 than for A2 because it requires a stricter climate policy, i.e., trees are initially not cut so that the sequestered carbon is not released. However, a stricter climate policy requires reforestation and afforestation in the initial years leading to substantial decrease in timber prices once these trees are mature. Since the climate policy associated with the A2 scenario does not require planting trees on non-forest land, timber prices stay more or less constant from a certain point in time onwards. The difference in the maximised net benefits between columns 2 and 3 shows the market effect for the different scenarios. The market effect leads to an increase of 1219€ compared to the situation of constant prices in the case of scenario B2 and to an increase of 1755€ in the case of scenario A2. Hence, in the presence of a stringent climate policy (B2) the market effect is moderated compared to a fairly unrestricted climate policy (A2).

Formulated in a different way, tightening climate policy (from A2 to B2) reduces producer rents from 8408€ to 7744€ (loss of 7,9 %). This interpretation is in line with the literature. Alig et al. (2002) found for the US that producer rents compared to the baseline decrease between 3 – 7% as a result of climate change. On the contrary, compared to the baseline, Sohngen et al. (2001) predict an increase in the producer surplus of between 25 – 43 US$ for the US and 6 – 26 US$ for Europe. Unfortunately, the latter study does not report relative values. Solberg et al. (2003) found that producer rents decrease below 1% compared to the base case. The results of the cited studies cannot be compared directly, either with each other or with the present study, since the definition of the baseline is not identical for all of the four studies. Moreover, in the case of this study, timber prices are not determined endogenously, and it remains to be determined to what extent the trajectory of global timber prices are representative for the studied region. Nevertheless, this finding seems to confirm the sign of the previous results.

Table 4.1: Aggregated discounted net benefits (€) over time.

	Constant market equilibrium prices	**Variable market equilibrium prices**
	Young stand	
NoCC	5895,77	5895,77
B2 Scenario	6524,86 (11% increase)	7744,42 (31% increase)
A2 Scenario	6652,65 (13% increase)	8408,17 (43% increase)
	Mature stand	
NOCC	9781,52	9781,52
B2 Scenario	10378,05 (6% increase)	12265,47 (25% increase)
A2 Scenario	10483,83 (7% increase)	12365,43 (26% increase)

Observation 4.4: *The younger is the diameter distribution of the forest, the higher are the loss of aggregated discounted net benefits in case forest manager does not adapt the management to climate conditions.*

The loss of discounted aggregate net benefits (costs) over time have also been evaluated for constant timber prices, if the optimal management regime were not adapted to the changes in the climatic conditions, i.e., maintaining the management regime that corresponds to the NoCC scenario even though climate change is taking place. The calculations show that in the case of a mature stand the adaption benefits are only 0,8% for scenario B2 and 1,5% for scenario A2. The relatively low losses of net benefits for not adapting to climate change can be explained by the already complete development of the mature stand and the minor impacts of management actions. Consequently, one expects that these losses increase with the immaturity of the stand. In fact, for the young stand the losses of the net benefits for not adopting to climate change are 1,4% for scenario B2 and 2,8% for scenario A2. In the case of a very young stand these losses increase to 34% for scenario B2 and to 35% for scenario A2.

These calculations show that additional net benefits can be obtained by adapting the management regime to climate change. The younger the forest is, the higher are these additional net benefits. These results are summarized in Table 4.2.

Table 4.2: Loss of aggregated discounted net benefits (%) over time if the management regime is not adapted to climate change.

	Very young stand	Young stand	Mature stand
NoCC	0,0%	0,0%	0,0%
B2 Scenario	34%	1,4%	0,8%
A2 Scenario	35%	2,8%	1,5%

Observation 4.5: *The negative effect of the increasing mortality due to changing environment conditions will not have large consequences on the discounted net benefits. The increase in the discount rate does not affect the optimal management actions carried out by the manager.*

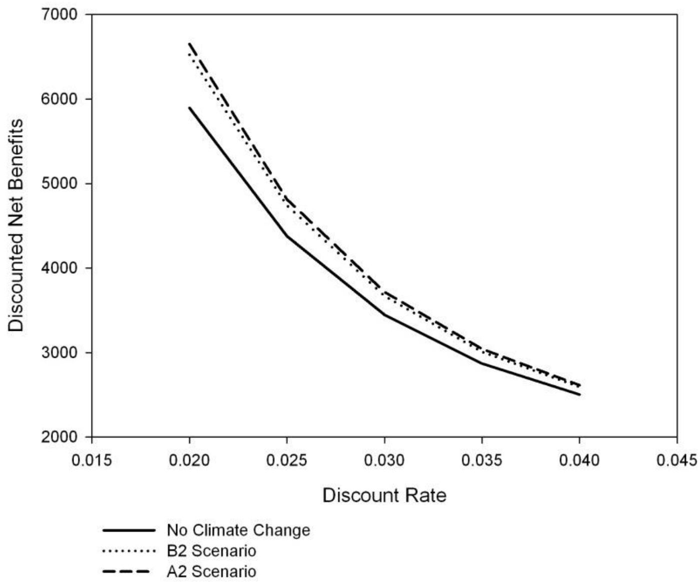
As far as mortality is concerned, the effects of a variation of the initial assumption with respect to mortality have been analysed. The results show that even an increase of 100% of the mortality over 100 years for scenario A2, or over 200 years for scenario B2 has a relatively small effect on the discounted net benefits. For the case of scenario B2, net benefits decrease between 2,0% and 6,6% and for scenario A2 between 2,3% and 7,3%. More detailed results are presented in Table 4.3.

Table 4.3: Aggregated discounted net benefits (€) depending on mortality effect.

		Mortality (μ_1)	**2x μ_1 in 200 years**	**2x μ_1 in 100 years**
B2 Scenario	Young stand	6740,21	6524,86 (-3,2%)	6292,02 (-6,6%)
	Mature stand	10585,90	10378,05 (-2,0%)	10134,49 (-4,3%)
A2 Scenario	Young stand	7175,01	6916,15 (-3,6%)	6652,65 (-7,3%)
	Mature stand	11013,83	10757,95 (-2,3%)	10483,83 (-4,8%)

Finally, the effects of variations in the discount rate from 2% to 4% on the discounted sum of net benefits have been evaluated. It is observed that for all considered scenarios the sum of the discounted net benefits of the optimal forest management for the young stand decreases with an increase in the discount rate. The degree of this decrease varies depending on the initial diameter distribution and the underlying scenario. For instance, the net benefits for the NoCC scenario decrease by 57% with an increase of the discount rate from 2% to 4%, while for the A2 scenario the net benefits decrease by 61%. In other words, the presence of climate change increases the net benefits but its effect decreases as the interest rate increases. The graphical presentation of these results is shown in Figure 4.12. A similar but somehow more moderate reaction can be observed for the stand of mature trees. These results are presented in the supplementary online material available on the following link: https://www.dropbox.com/s/ts563fovhk851ye/MaturePlots.pdf

Fig. 4.12: Sum of discounted net benefits over time as a function of the discount rate.



4.2.Conclusions

The results show that it is optimal to cut trees selectively and that forest stands converge to a "normal forest", however the trajectory is different for each stand since it depends on the initial diameter distribution.

When climate change is incorporated into the model, the adaptation of optimal management achieves substantially higher discounted aggregate net benefits than in the NoCC case (Table 4.1). This is because the fertilization effect dominates the negative effects of an increase in intra-specific competition and in mortality. The fertilization effect of CO_2 leads to an increase in the growth and in the natural reproduction rate; it consequently allows private managers to obtain higher profits. Moreover, in the presence of climate change, the number of standing trees and the timber yields increase, whereas the rotation age decreases.

The expected changes in market prices for timber lead to an increase in the net benefits. However, this increase is more pronounced in the presence of a lax climate policy than in the presence of a strict climate policy. Hence, it is observed that a tighter climate policy leads to a reduction of the producer rents by about 8%.

In the case where the forest manager does not adapt to the change in the climatic conditions the aggregate discounted net benefits decrease by between 1 and 35%. Young stands are far more sensitive to this lack of adaptation than the mature stands (Table 4.2). As the optimal management under climate change tends to yield younger forests and with higher density in the long-run, the policy of not adapting the forest management to climate change may have major implications in the future.

forests under endogenous risk of fire

Within catastrophic events that affect forest ecosystems, fire represents a major disturbance for all forests in the world (Hanewinkel et al., 2011). Forest management decisions may help to reduce the risk of fire which has been recognized to be crucial to attain a sustainable development of forests (González-Olabarría et al., 2008). Consequently, over the last decades wildfires have received considerable attention in the literature.

This line of research was initiated in the early eighties with some works that incorporated the risk of fire into a Faustmann rotation framework in an exogenous way (Martell, 1980; Reed, 1984). Consequent research evolved towards the consideration of the probability of fire occurrence as an endogenous factor, which may be altered through management practices. González et al. (2005) and González-Olabarría et al. (2008) integrated the risk of fire in a bioeconomic model to determine the optimal management of *Pinus nigra* Arn. stands in Catalonia. Pasalodos-Tato et al. (2010) developed a model for the optimal management of *Pinus pinaster* Ait. stands in Galicia subject to the risk of fire. These studies provide valuable insights into the interaction between forest management and fire-risk, but despite being characterized by long temporal horizons, they do not incorporate likely changes in climatic conditions predicted for the next century.

The increasing concentration of greenhouse gases in the atmosphere is influencing the climate on a global scale, and the change is expected to take place in the medium- and long-term future. Apart from modifying biological processes such as growth, reproduction, or tree-mortality (Kellomäki and Kolström, 1993; Scholze et al., 2006), evidence suggests that climate change will increase the incidence and damage of forest fires (Hessl et al., 2004). Therefore, one is left to ask to what extent forest management can be adapted to respond to the increase in wildfire risk as a result of changing climatic conditions.

In this thesis the term fire risk is used to indicate the likelihood of fire occurrence and the intensity of the fire. However, both aspects are limited to the area of the considered stand. In other words, fire occurrence as a result of fire propagation across the landscape is not considered.

The analysis of this chapter is based on a numerical study that determines the optimal forest management of two real stands of *Pinus sylvestris*. In order to determine the optimal adaptation of the forest management regime to the future climatic conditions and the increase in endogenous fire risk, the same three climate scenarios have been considered: NoCC, and B2 and A2, defined by the IPCC (2001). The results show that in the presence of climate change, the net benefits of the optimal logging regime increases since the CO_2 fertilization effect dominates the negative effects in the form of higher competition, a decrease in precipitation and a rise in temperatures, and mortality. Climate change implies a higher density of standing trees, which increases the risk and the resulting damage of fires. Moreover, the consideration of fire risk under climate change leads to a decrease in the diameter of the logged trees since the forest owner wants to compensate the higher fire risk by cutting the trees earlier. Overall, the adaptation of the management regime to fire risk alone is more beneficial for the forest manager than its adaption to climate change alone.

This chapter is organized as follows: next section describes the new features of the bioeconomic model for this analysis. Section 5.3 determines the optimal selective cutting regime for timber when forest fire risk is taken into account.

5.1. Bioeconomic model

The bioeconomic model presented in this chapter is based on the model specified in Chapter 3, but extended by the component of the endogenous risk of forest fire.

5.1.1. Forest fire risk

Apart from self-thinning, it is assumed that trees die due to wildfires. A quantitative definition of fire risk includes two main components: fire occurrence probabilities and fire damages (Finney, 2005). Thus, one can express the potential effect of forest fires in terms of fire occurrence probability and potential tree mortality. The probability of fire occurrence has been adapted from González et al. (2006), and it is given by

$$F_{NoCC} = \left(1 + e^{-\left(-1{,}947 - 0{,}015 Dg + 0{,}012 BA + 2{,}081 Sd/Dg\right)}\right)^{-0{,}83}, \tag{5.1}$$

where Dg denotes the basal area weighted mean diameter and Sd, the standard deviation of the diameter distribution, all controllable through forest management. Fire is a bottom-up disturbance, thus, the very first trees to be potentially affected by a wildfire are the younger age classes. As fire intensity increases, more older age classes would be affected (He and Mladenoff, 1999). As a consequence, as bigger is the weighted mean diameter, lower is the probability of fire occurrence. Concerning to standard deviation, as higher is Sd, higher is the vertical structure, which enhances the probability of fire occurrence. However, the risk of forest fire model defined by Gonzalez et al. (2006) does not take account of climate change, i.e., the effect of the variations in temperature and rainfall on the probability of a fire. Thus, in order to incorporate the effects of climate change in the model, meteorological data from Meteocat[12] have been obtained, for the period 2000–2010 and the historical records of forest fires in the Garrotxa region from the Catalan Forest Fire Prevention Service for the same time period. With this historical data the Drought Code (DC) of the commonly used Fire Weather Index (van Wagner, 1987) has been calculated. The Drought Code represents the moisture content of a deep layer of compact organic matter in the forest floor. Besides the Drought Code, the Duff Moisture Code (DMC) has been used in the literature as a representative index of forest fire risk. However, as the correlation between the two indices is high, there would be no additional gain in information if both were used (Otway et al., 2006). The choice for the DC is motivated by the fact that it has been recommended by the *Forest Fire Prevention Service* of Catalonia and that it depends only on data about temperature and precipitations which is available for Catalonia at a local scale.

Next, the historical data records of the DC and the forest fires have been correlated, in order to determine their relationship. Then, the evolution of the weather for the period 2011–2100 in Garrotxa has been specified, taking into account the variation of temperature and rainfall predicted by scenarios B2 and A2 of the IPCC (2001). These two pieces of information permit estimating the expected number of forest fires[13] per each climate change scenario based exclusively on climatic conditions. Moreover, they allowed determining a coefficient that reflects the increment of that estimated number of forest fires on scenario B2 and A2, capturing the effect of climate change on the probability of fire occurrence. As a result, the

[12] Meteorological Service of Catalonia.

[13] Empirical literature on forest fires relates forest fire probability to many social, economic and natural factors, e.g. fuel type, topography, distance to roads, rural abandonment, etc.

effect of the climate change over the probability of fire occurrence is given by $F_{B2} = \varphi_{B2} \cdot F_{NoCC}$ and $F_{A2} = \varphi_{A2} \cdot F_{NoCC}$, with $\varphi_{B2} = 1{,}1$ and $\varphi_{A2} = 1{,}17$.

The second component of fire risk is damage, which is usually measured in terms of burnt timber. According to González et al. (2007), the potential damage caused by fire is given by

$$P_{dead} = \left(1 + e^{-(0{,}865 - 0{,}329 BA + 4{,}319 BA/(Dq + 0{,}01) + 6{,}718 Sd/(Dq + 0{,}01))}\right)^{-1}, \quad (5.2)$$

where P_{dead} is an indicator of the level of dead trees and Dq denotes the quadratic mean diameter. Based on this indicator, González et al. (2007) calculate the surviving trees by diameter classes, which is given by

$$P_{surv} = \left(1 + e^{-(2{,}224 + 0{,}110 L_i - 7{,}117 P_{dead})}\right)^{-1}. \quad (5.3)$$

Therefore, the wildfire risk, denoted by $\mu_2(\cdot)$, can be computed as the product of the two components, $\mu_2 = F_K \cdot (1 - P_{surv})$, with $K = \{NoCC, B2, A2\}$.

5.1.2. The forest management problem

As in the previous chapter, the model assumes that the forest is privately owned and managed over a planning horizon of T years. The forest owner wants to maximise the economic profitability of the stands. Thus, using the description of the biophysical relationships, his decision problem can be formally as the maximisation of the equation (2.1) stated on Chapter 2, which indicates the net benefit function related to timber production. The maximisation of the function is subject now to

$$
\begin{aligned}
&\frac{dX_0(t)}{dt} = \left[\sum_{i=3}^{n} \rho\left(E(t), L_i(t)\right) X_i(t)\right] + P(t), \\
&\frac{dX_i(t)}{dt} = -\left(\mu_1(E(t), L_i(t)) + \mu_2(E(t), L_i(t)\right) X_i(t) - U_i(t), \quad i = 1, \ldots n, \\
&\frac{dL_i(t)}{dt} = g(E(t), L_i(t)), \quad i = 0, 1, \ldots n, \\
&X_i(0) = X_i^0, \;\; U_i(t), P(t) \geq 0, \;\; U_i(t) \leq X_i(t), \;\; i = 0, 1, \ldots n.
\end{aligned}
\tag{5.4}
$$

The evolution of the number of trees en each cohort $\frac{dX_i(t)}{dt}$ is now taking into account not only the natural mortality of the forest $\mu_1(\cdot)$ but also the mortality coming from the forest fires $\mu_2(\cdot)$.

The initial purpose of the numerical analysis of this chapter is to determine the optimal management regime that maximises the discounted net benefits from timber production of a stand of *Pinus sylvestris* in the presence of climate change over a time horizon of 200 years. These results provide the reference case and allow comparing the optimal management regime when wildfire risk is considered and when it is not taken into account. Detailed results of the optimization process are presented in Appendix C.

5.2. Analysis of the optimization results

The integrated assessment model was solved for the two real stands. As is Chapter 4 analysis, the results show that harvesting trees selectively is optimal for both young and mature stands. Figures 5.1-5.4 depict the evolution of the number of standing trees, the average diameter, the average age and the total basal area of the young stand. In the presence of climate change, as compared to NoCC, the optimal management regime leads to an increase in the number of trees (Figure 5.1), and in the basal area of the stand (Figure 5.4). Figure 5.2 indicates that the average diameter of the trees as well as their average age decrease (Figure 5.3). The calculations also reveal the differences in the standard deviation of the diameter distribution of the scenarios considered (Figure 5.5) are not very significant. Hence, the increase in the basal area of the stand is the result of the increase in the number of trees and not of an increase in the individual diameter. Consequently, albeit the adaptation of the management regime, the structure of the resulting forest under climate change is more sensitive to forest fires since trees are younger and the tree density is higher.

The results of the optimization for the mature stand show that it evolves according to the same pattern as the young stand. These findings are presented in the supplementary online material available on: https://www.dropbox.com/s/ts563fovhk851ye/MaturePlots.pdf

Fig. 5.1 – 5.5: Evolution of the main biological variables over time for the young stand.

Fig. 5.1.

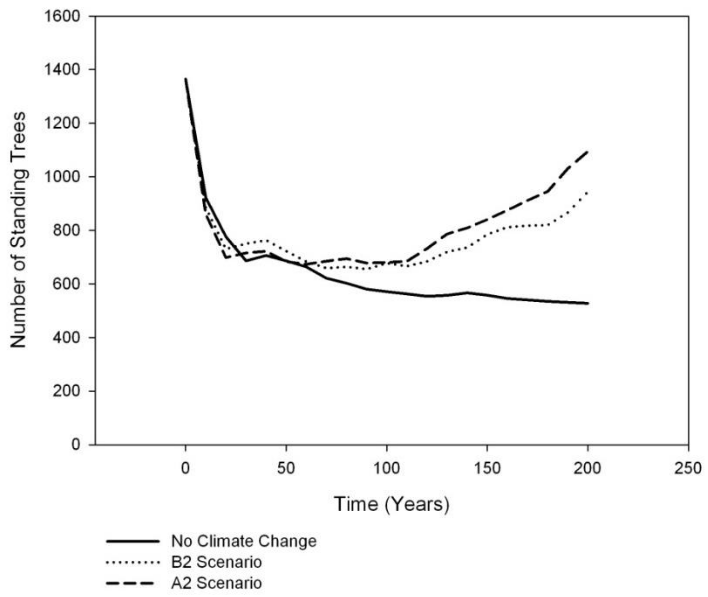


Fig. 5.2.

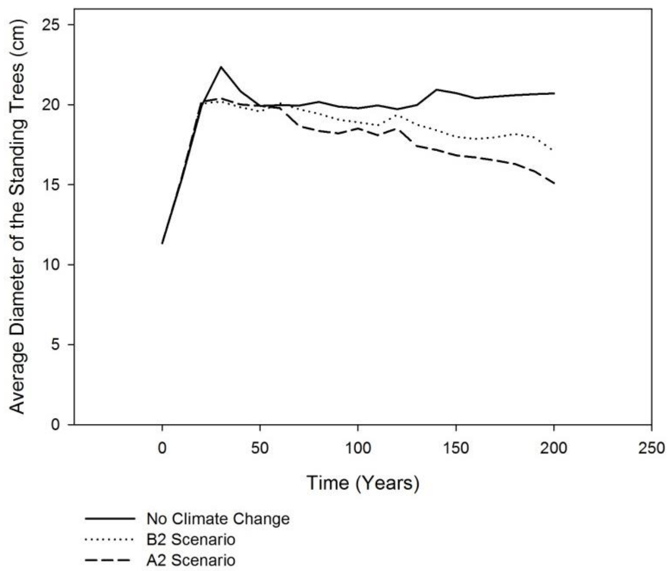

Average Diameter of the Standing Trees (cm)
0
5
10
15
20
25
0
50
100
150
200
250
Time (Years)
No Climate Change
B2 Scenario
A2 Scenario

Fig. 5.3.

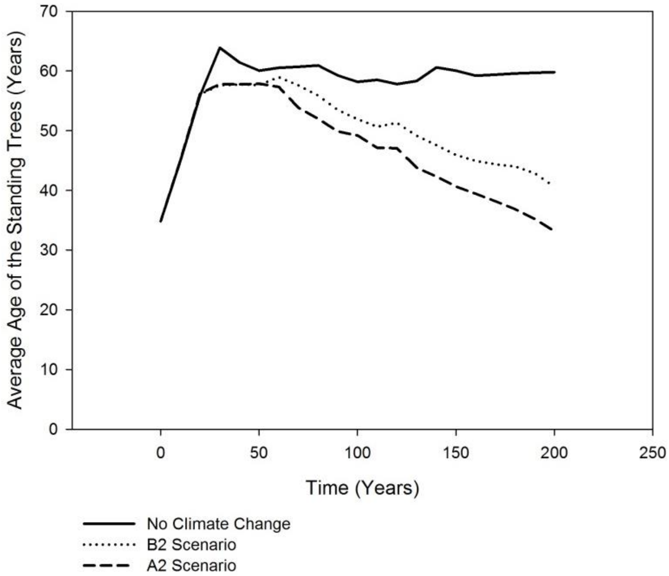

Average Age of the Standing Trees (Years)
0
10
20
30
40
50
60
70
0
50
100
150
200
250
Time (Years)
No Climate Change
B2 Scenario
A2 Scenario

Fig. 5.4.

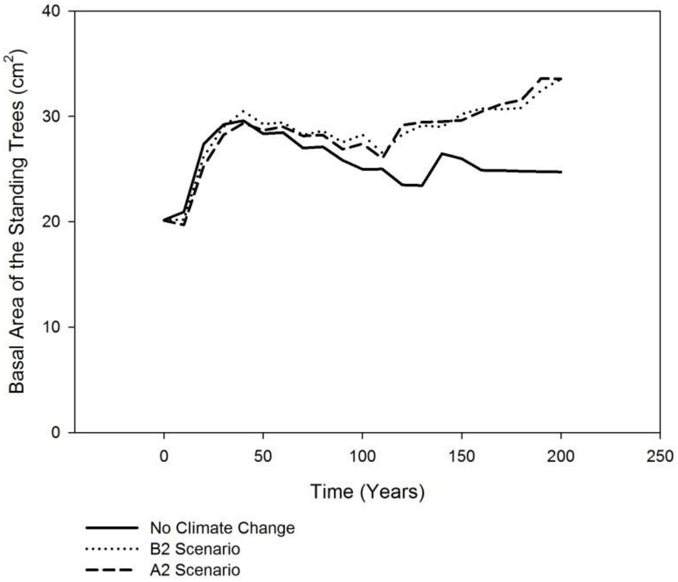
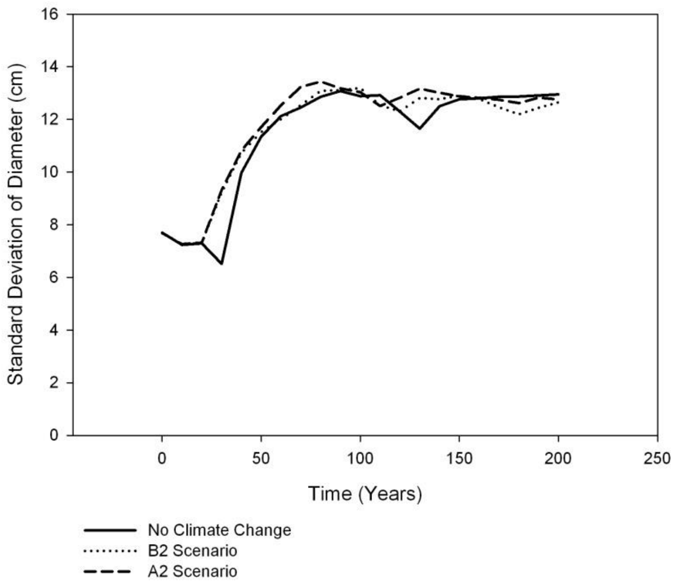

Basal Area of the Standing Trees (cm²)
Time (Years)
No Climate Change
B2 Scenario
A2 Scenario

Fig. 5.5.


Standard Deviation of Diameter (cm)
Time (Years)
No Climate Change
B2 Scenario
A2 Scenario

Additional findings of this section are presented as observations below.

Observation 5.1: *Climate change may increase the probability of forest fire occurrence and the dead trees caused by fire in managed forest for timber. The increment is less significant for preserved stands which are not managed for timber extraction.*

Figure 5.6 depicts the increase in the probability of fire occurrence of the B2 and A2 scenarios compared to the NoCC, calculated as $\frac{F_{B2}(t)-F_{NoCC}(t)}{F_{NoCC}(t)}$ and $\frac{F_{A2}(t)-F_{NoCC}(t)}{F_{NoCC}(t)}$, respectively. It accounts for the effects of the increase in temperature, the decrease in rainfall, and the change in forest structure on forest fire probability. Figure 5.6 shows that climate change tends to increase wildfire probabilities of occurrence in case of managed forests for timber. In case of preserved forests which are not used for timber extraction[14] (partially managed on Figure 5.6), the probability of forest fire occurrence is lower. The same pattern is shown also for the mature stand. Results for the mature stand are presented in: https://www.dropbox.com/s/ts563fovhk851ye/MaturePlots.pdf

Figures 5.7, 5.8 and 5.9 depict the evolution of the dead trees caused by fire for stands managed for timber extraction, for preserved stands, and for stands where the management has not been adapted to fire risk respectively (see observation 5.2 of this chapter). Figure 5.7 shows that climate change leads in the long run to an increase in the fire mortality of about 1%. It is also remarkable how the adaptation of optimal management regime to wildfire reduces the amount of dead trees for young stands during the initial 30 years. On the contrary, this pattern is far less pronounced for mature stands. Figure 5.8 shows that preserved stands demonstrate a far less significant increase in mortality after the initial 50-75 years. Figure 5.9

[14] An optimization is not conducted in this case. However, it is considered that the understory is removed, as well as the litterfall that could act as fuel for the wildfires. There also exists selection of the ingrowth seedlings. In spite of that there is no selection of trees or plantation.

shows that if fire risk is not taken into account, the percentage of dead trees increases. This increment is remarkable high for young stands.

Fig. 5.6: Comparison of the forest fire probability over time for the young stand.

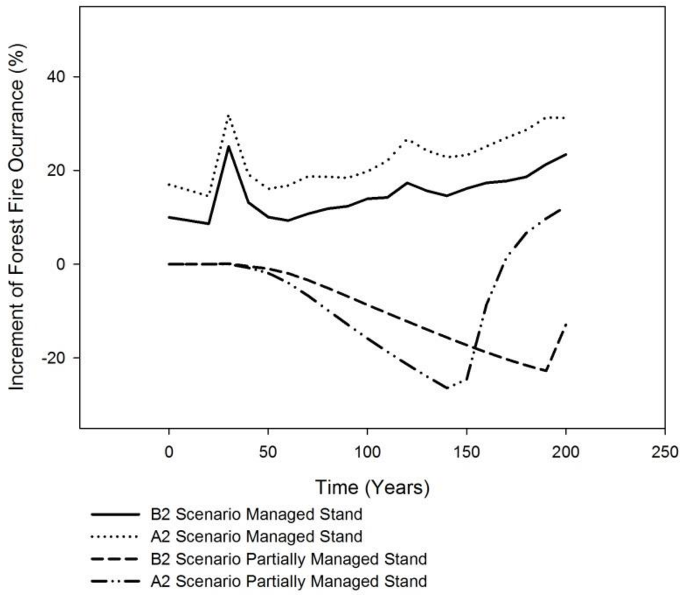


Fig. 5.7: Percentage of dead trees caused by fire for stands managed for timber.

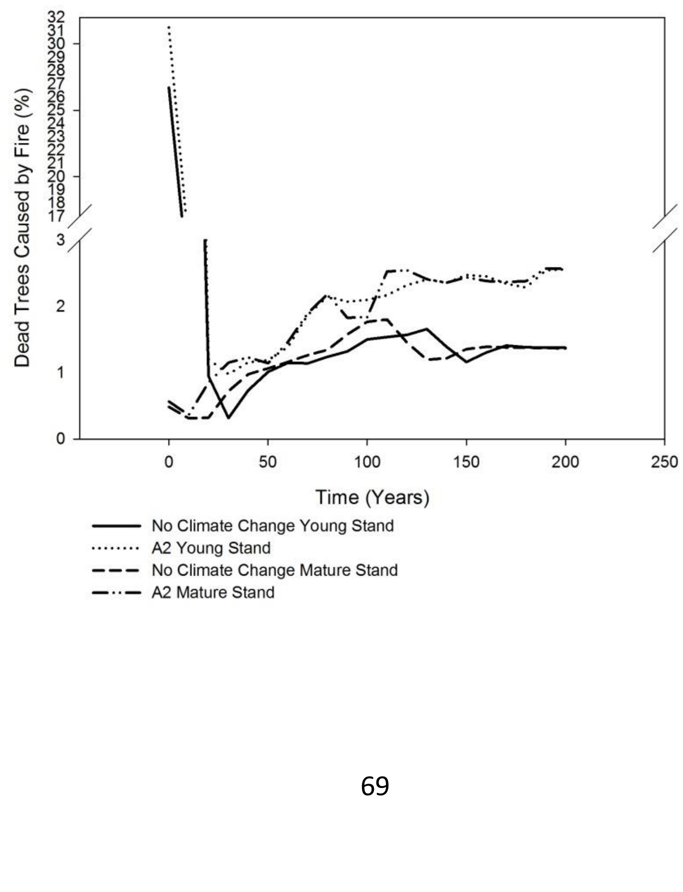


Fig. 5.8: Percentage of dead trees caused by fire for preserved stands.

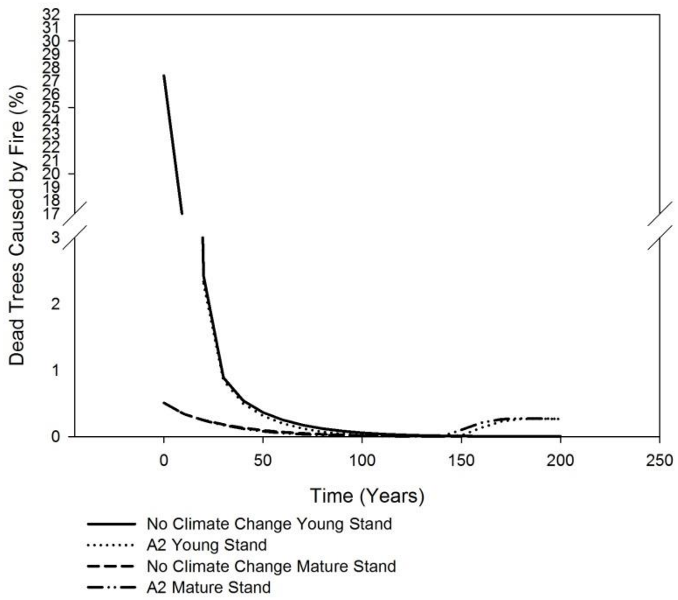
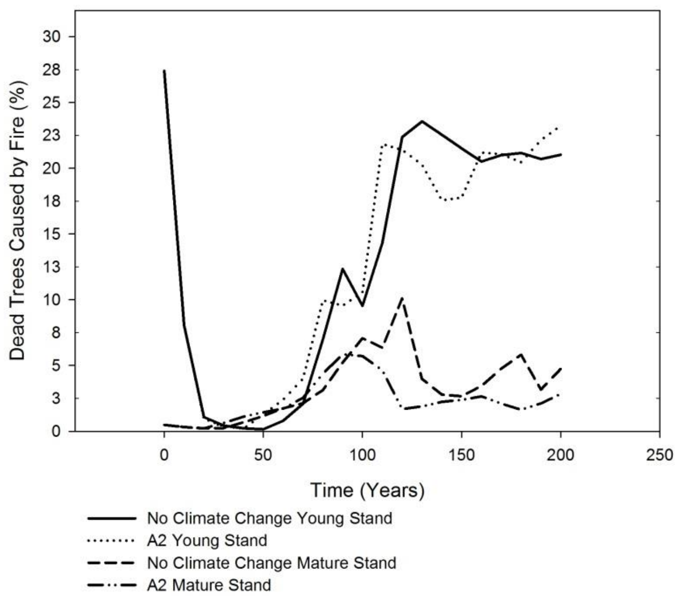


Fig. 5.9: Percentage of dead trees caused by fire for stands where the management regime is not adapted to fire risk.



Observation 5.2: *The adaptation to fire risk is far more important than the adaptation to climate change conditions. The younger the stand, the higher is the importance of the adaptation strategies to fire risk.*

It is important to analyse the effect of climate change on the discounted sum of the net benefits of timber production taking into account the forest fire risk. For the young stand, Table 5.1 shows that the discounted net benefits over 200 years are 5053 €/ha in the absence of climate change (NoCC), and 5540 €/ha and 5561 €/ha for management regimes that adapt to the scenarios B2 and A2 respectively. Thus, the presence of climate change leads to higher profits. The results of the optimization for the mature stand produce a similar pattern for the logging regime as those of the young stand. However, the obtained profits are of course higher for all considered scenarios, due to the logging of mature trees already during the initial periods of the planning horizon. They are given by 9746 €/ha, 10334 €/ha and 10438 €/ha, for the scenarios NoCC, B2 and A2, respectively.

The gains of the discounted net benefits have been also evaluated as a result of the adaptation of the management regime to forest fire risk. Optimizations of the assessment model where the management does not consider the risk of fire were carried out to evaluate the difference in the discounted net benefits. These results are presented in the first column of Table 5.1. Adaptation of optimal management regime to the risk of fire leads to an increase from 4342 to 5053 €/ha, from 4735 to 5540 €/ha, and from 4792 to 5561 €/ha for the scenarios NoCC, B2 and A2 respectively. The corresponding increase in per cent is given by the values in parenthesis in the second column of Table 5.1. For this part of the study, the hypothetic young stand has also been analysed. It is characterized by very young trees and is denoted by VYS (very young stand). Column 2 of Table 5.1 also shows that whether one adapts the management regime to climate change or not, or if climate change does not take place, the benefits of adaptation of the management regime to fire risk are very important for plantations, important to some extent for a young stand, and nearly negligible for a mature stand. Finally, the increase in benefits if the forest management regime is adapted to climate change is compared to not adaptation.

Table 5.1: Aggregated discounted net benefits (€) over time depending on the climate change scenario, the initial diameter distribution and adaptation of the management regime to fire risk.

		No adaptation of the management regime to fire risk	Adaptation of the management regime to fire risk
No adaptation of the management regime to climate change	NoCC	**VYS:** -614,99	**VYS:** 732,52 (+219,1%)
		YS: 4342,04	**YS:** 5053,18 (+16,4%)
		MS: 9672,68	**MS:** 9746,58 (+0,8%)
	B2	**VYS:** -673,06	**VYS:** 1197,84 (+278,0%)
		YS: 4727,30	**YS:** 5512,79 (+16,6%)
		MS: 10198,31	**MS:** 10188,71 (0,0%)
	A2	**VYS:** -614,99	**VYS:** 1245,77 (+302,6%)
		YS: 4782,23	**YS:** 5572,70 (+16,5%)
		MS: 10238,20	**MS:** 10250,83 (+0,1%)
Adaptation of the management regime to climate change	B2	**VYS:** -600,77 [+10,74%]	**VYS:** 1371,74 (+303,8%)[14,52%]
		YS: 4735,84 [+0,2%]	**YS:** 5540,79 (+17,2%)[0,51%]
		MS: 10250,16 [+0,5%]	**MS:** 10334,20 (+1,3%)[1,43%]
	A2	**VYS:** -512,32 [+16,7%]	**VYS:** 1511,98 (+345,8%)[21,37%]
		YS: 4792,16 [+0,2%]	**YS:** 5571,16 (+16,4%)[0%]
		MS: 10337,52 [+1,0%]	**MS:** 10438,24 (+1,9%)[1,83%]

VYS = plantation of very young trees, YS = predominately young trees, MS = predominately mature trees

Table 5.1 shows an increase in the aggregated discounted net benefits from 0,2% to 16,7% (column 1, numbers in square brackets) in those stands where forest fire is not considered but the management regime is adapted to climate change. While for young and mature stands the benefits of adaptation of the management regime to climate change are nearly negligible, they are important for plantations (10,74%, 16,7%). For the case where the management regime takes account of fire risk, the adaptation benefits of the management regime to climate change lead to similar results. The increase in the benefits ranges from 0% to 21% (column 2, numbers in square brackets). If one compares the adaptation benefits of the management regime to climate change versus fire risk, column 2 of Table 5.1 (number in parenthesis vs. numbers in square brackets) indicates that adaptation to fire risk is far more important. It is highly beneficial for plantations and young stands, whereas it matters relatively little for mature stands.

Observation 5.3: *Under climate change conditions, the fertilization effect leads to higher growth of biomass, and in consequence to higher profits. This positive phenomenon predominates over the negative effect of an increase in fire risk, caused by the fertilization effect.*

Table 5.2 isolates the effects of an increase in CO_2 or a change in temperature and precipitation on the net benefits. It shows that the net benefits increase for a young stand from 5053 to 5860 €/ha, or to 6291 €/ha with a rise in CO_2 corresponding to B2 and A2 scenarios respectively, but without change in temperature and precipitation according to the same climate change scenarios. On the contrary, it is seen that the net benefits of a young stand decrease by 5% and 9% if the CO_2 concentration does not change but temperature and precipitation change according to the scenarios B2 and A2. In this way the overall increase of the net benefits of the young stand from 5053 to 5540 €/ha for scenario B2, and 5561 €/ha for scenario A2, can be broken down. The rise of CO_2 according to scenario B2 leads to an increase of the net benefits of a young stand by 16% whereas the changes in temperature and precipitation to a 5,2% decrease. The overall increase of 10% is slightly less than the sum of the individual effects due to the interaction of the two effects. Table 5.2 provides also information about the driving factors of the changes of the net benefits of the mature stand.

Table 5.2: Aggregated discounted net benefits (€) over time where the CO_2 effect and the temperature and precipitation effect have been isolated.

		No CO_2 effect		**CO_2 effect**
No changes in temperature and precipitation		**YS:** 5053,18 **MS:** 9746,58	B2	**YS:** 5860,36 (+16,0%) **MS:** 10554,45 (+8,3%)
			A2	**YS:** 6291,66 (+24,5%) **MS:** 10992,10 (+12,8%)
Changes in temperature and precipitation	B2	**YS:** 4789,96 (-5,2%) **MS:** 9579,56 (-1,7%)		**YS:** 5540,79 (+9,6%) **MS:** 10334,20 (+6,0%)
	A2	**YS:** 4551,22 (-9,9%) **MS:** 9401,89 (-3,5%)		**YS:** 5561,16 (+10,0%) **MS:** 10438,24 (+7,1%)

5.3. Conclusions

The results show that optimally managed forests under climate change are more productive compared to the NoCC scenario. Table 5.2 demonstrates that the fertilization effect of CO_2 is the driving factor which increases the productivity of the stand, through the increase in the growth and in the natural reproduction rate. Thus, in the presence of climate change, the number of standing trees and the timber yields increase, whereas the rotation age decreases.

Nevertheless, climate change will increase the probability of fire occurrence and the trees affected and died by a forest fire, in a parallel way. Calculations show that it is optimal to increase the number of trees in the forest, and decrease the age and diameter at which they are logged. Thus, under climate change (A2 scenario) the resulting forest in the long-run doubled the percentage of dead trees (2,5%) compared to the NoCC scenario (1%). The results also demonstrate that preserved stands are less sensitive to fire risk than younger ones, due to the fact that they reach a mature structure, which is far less sensitive to wildfires. Finally, the results show that the absence of adaptation strategies to fire risk leads to a high increment of the dead trees caused by fire, especially for young stands.

Results demonstrate that adaptation of the management regime to climate change is important for very young stands but decreases rapidly with the initial age of the trees (Table 5.1). The adaption of the management regime to changes in fire risk proved to be more important from an economic point of view than its adaptation to climate change. Moreover, its importance decreases far less rapidly with the initial age of the trees compared to the adaptation of the management regime to climate change (Table 5.1).

forest management for timber and carbon sequestration

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 (Giupponi 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 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 modelling 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 maximising the net benefits of timber is only partly compatible with the objective of maximising 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 maximised. 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 maximises 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 analysing the effect of climate change for the broad range of admissible management regimes is the adequate modelling 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 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 management regime to climate changes are often limited, and the optimal timing and partial harvesting pattern remain not fully-answered questions.

The presence of climate change adds another twist to the trade-off between the optimal management of timber and carbon. While an increase in CO_2 favours 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 carried out 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.

This chapter is organized as follows: next section is a short overview of the literature about the economic implications of climate change in forestry. Section 6.3 describes the new features of the bioeconomic model for the analysis of this chapter. Then the data and functions employed for the numerical analysis are specified. Section 6.4 determines the optimal selective cutting regime for timber and carbon in an empirical setting when climate change is taken into account.

6.1.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) analysed 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. As it has been noticed on Chapter 4, the results 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) analysed the effect of climate change on timber production and carbon sequestration on a global scale, as it was noticed on Chapter 4. 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 results show that carbon sequestration can be an important instrument for controlling greenhouse gases. The authors note, however, that their modelling 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 analyses 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 Río 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) contributed to this discussion by considering also recreational services. Hence, to the best knowledge, and as also noted by Sohngen et al. (2010), 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 it is aimed to improve the forest managers modelling 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, this study concentrates 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 analysed. Moreover, it is considered 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. Finally, the approach of this study does not consider land-use changes driven by changes in supply and demand for forest and agricultural land.

6.2.Bioeconomic model

The bioeconomic model presented in this chapter is based on the model specified on Chapter 3, but with the following differences: carbon dynamics are introduced into the model, and natural reproduction is not taken into account in order to simplify the optimization process.

6.2.1. Carbon dynamics in the forest ecosystem

Besides the stand dynamics described on Chapter 3, for this part of the analysis the mathematical model needs to reflect the evolution of the sequestered carbon. The flow method has been used to account for carbon in the forest ecosystem. It considers carbon sequestration while trees grow and 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

$$\frac{dS(t)}{dt} = h(V(t), S(t), te(t)), \; S(0) = S^0 \tag{6.1}$$

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 $V(t) = \sum_{i=0}^{n} \gamma_0 L_i^{\beta} X_i(t)$, where the parameters γ_0 and β are chosen according to the tree species. The amount of carbon sequestered in the biomass is determined by $B(t) = \sum_{i=0}^{n} \left(1+\gamma_2\right) \gamma_1 L_i^{\beta} X_i(t)$, where γ_1 and γ_2 are constants that relate the above-ground volume with the sequestered carbon in the above-ground, γ_1, and below-ground, γ_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

$$\frac{dW(t)}{dt} = \delta(U_0(t), \ldots U_n(t), W(t), \upsilon(\cdot)) \tag{6.2}$$

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

$$\frac{dC}{dt} = \frac{dB}{dt} + \frac{dS}{dt} + \frac{dW}{dt} \tag{6.3}$$

The system of equations (6.1) - (6.3) 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.

6.2.2. The forest management problem

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

$$\max_{U_i(t),\, i=0,\ldots,n,P(t)} \int_0^T e^{-rt} \left\{ \pi(\bar{X}(t), \bar{L}(t), \bar{U}(t), P(t)) + p_C(t) \left(\frac{d\left(C(t) - C_{p_c=0}(t)\right)}{dt} \right) \right\} dt, \tag{6.4}$$

subject to the system of equations (2.2), on Chapter 2.

The first term in the integral remains equal to the decision problem (Equation (2.1)), stated in Chapter 2. The final point of time of the planning horizon is again denoted by T , and 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. 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 the concept of "additionality" is applied. In the presence of a national emission accounting system this term refers to the difference between the changes in carbon stock of the reference level in comparison with the changes in the carbon stock as a result of human-induced activities.

In the case of project-based emission, accounting for it refers to the additional contribution of a particular project compared to alternative projects or to the non-realization of the project at all.

In the case of afforestation and reforestation the reference level of the carbon stock can be determined fairly straightforwardly as it is simply given by the carbon stock prior to afforestation or reforestation. For the second commitment period, Art 3.4 of the Kyoto protocol has been changed in so far as reporting on forest management is no longer optional but has now become a mandatory activity for all parties (2/CMP.7 2011, The Durban Agreement). In order to account for forest management as a human-induced change, a clear cause and effect relationship between management practices and carbon stock in different compartments of the forest ecosystem is required. Obviously, the determination of the reference level is far more complex now since it is not a constant value but is linked to a trajectory of the carbon stock over time in the absence of a change in forest management. The basic problems are to monitor the evolution of the carbon stock and to determine the reference level in the absence of human-induced activities directed towards the sequestration of carbon. Although annex II of the document 2/CMP.6 (The Cancun Agreement) provides guidelines for the submission of information on forest reference levels, questions related to the actual collection of the data and the underlying concept, as well as the determination of the forest management reference level are at the centre of on-going research.[15]

Based on this concept of additionality, only the sequestered carbon on top of the carbon that corresponds to the management regime which maximises timber net benefits, needs to be taken into account. In other words, if the forest manager decides to participate in a payment or credit scheme only the amount of carbon that is sequestered above a certain level is honoured 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.

6.2.3. Data and specification of functions

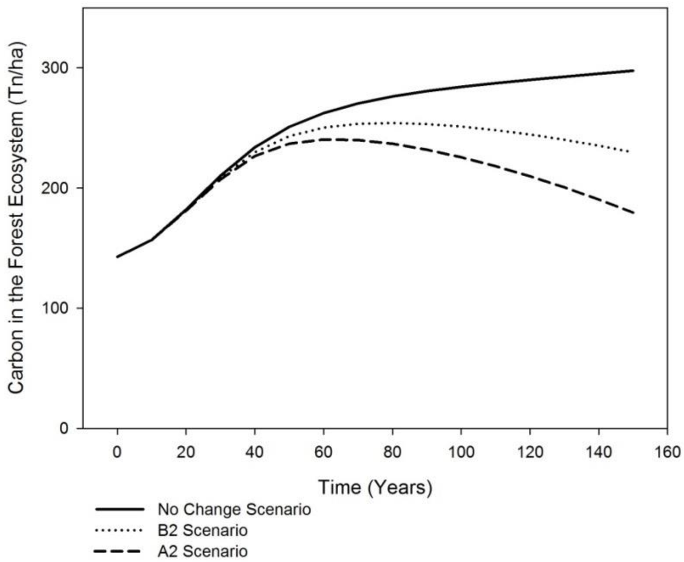
Biogeochemical simulation model

In order to evaluate the effect of climate change on biological variables independent of management decision, the carbon in the forest ecosystem, the diameter of the stand, and the diameter of an individual tree for an unmanaged forest (young stand) have been calculated. This allows validating the plausibility and reliability of the underlying assumptions, parameter values, and the specification of the functions of the model. Figure 3.13 on Chapter 3 shows that the diameter of an initially young tree (diameter 2,5cm) increases with climate change after 150 years up to 18,8% and of an initially mature tree (32,5cm) by only 0,9%. Figure 3.14

[15] Richards et al. (2006) and Ruddell et al. (2007) discuss policy design and implementation related to forest management and Lindner et al. (2008) and Andersson et al. (2009) analyse the rationale for forest management induced changes in GHG and discuss questions related to their measuring and modelling.

illustrates that the average diameter of the stand increases with climate change by about 9,1%. Figure 6.1 illustrates the effect of climate change on carbon in the forest ecosystem. It shows that carbon decreases after 50 years by 3,4% and by 5,6% in the case of scenarios B2 and A2 respectively. After 150 years the decrease is far stronger and has amounted to 23% and 40% for scenarios B2 and A2 respectively.

Fig. 6.1: Evolution of carbon in an unmanaged forest ecosystem (young stand).



The view that forest growth and carbon sequestration is stimulated within limits by increasing CO_2 (fertilization effect) is widely accepted in the literature. Schroeter (2004) found that, in Europe, climate change leads to an increase of forest growth within the range of 18% (B1) to 24% (A2) until 2100. The same study concludes that forests are initially able to sequester in the case of climate scenario B2, and in the case of scenario A2, however forests turns into a carbon source after 50 years (2050). Solberg et al. (2003) considered an increase in forest growth for Europe of 1–2% per year as a result of climate change for a given time horizon of 20 years. Karjalainen et al. (2003) found that climate change will have increased forest growth in Northern and Southern Europe by approximately 10% by the year 2050. With respect to carbon in the forest ecosystem, the authors found that it increases with climate change by 5% by the year 2050. Unfortunately the results of the cited studies cannot be directly compared either with each other or with the results of this study since the underlying assumptions, the location and the reference scenario, etc. are not identical for all the studies. However, this short literature review shows that the results of this study fall within the range of the results of the previous study, and support the underlying assumptions, parameter values, and the specification of the functions of the model.

To model the evolution of carbon within the forest ecosystem, the previous model needs to be complemented by the soil carbon dynamics h function, and the carbon release function δ.

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 (Bonan, 2008; Trumbore et al., 1996). 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 estimating the change in soil carbon over time described by the function $h\left(V(t), S(t), te(t)\right)$. Soil carbon is measured in metric tons per hectare and time period. The estimation was carried out using SPSS, by the ordinary least squares method. Different types of functions were analysed, and the estimations with the best goodness of fit and signification of the parameters yielded the following lineal function specified as:

$$h = \underset{(-42,83)}{43,995} - \underset{(-70,47)}{0,326}S(t) + \underset{(86,41)}{0,059}V(t) - \underset{(-50,88)}{2,54}te(t) \tag{6.5}$$

where the numbers in brackets provide the t-values of the estimated parameters.

Finally, the function $\delta(\cdot)$ needs to be specified. $\delta(\cdot)$ 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, $\sum_{i=0}^{n} \gamma_1 L_i^{\beta} U_i(t)$. On the other hand, the carbon sequestered in wood products is released following an extended logistic decay function (Eggers, 2002). Accordingly, the function

$$\omega(LT(L_i),\tau,t) = 1,2 - \frac{1,2}{1+5e^{-2(t-\tau)/LT(L_i)}} \tag{6.6}$$

indicates the proportion of the sequestered carbon of a tree harvested in year τ 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 $LT(L_i) = 7.759 L_i^{0.358}$. 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

$$\upsilon(LT(L_i),\tau,t) = \frac{12e^{-2(t-\tau)/LT(L_i)}}{\left(1+5e^{-2(t-\tau)/LT(L_i)}\right) LT(L_i)}. \tag{6.7}$$

Given the specifications above, the change of the carbon sequestered in wood products is given by

$$\delta(\cdot) = \sum_{i=0}^{n} \gamma_1 L_i^{\beta} U_i(t) - \int_0^t \sum_{i=0}^{n} \upsilon(LT(L_i),\tau,t) \gamma_1 L_i^{\beta} U_i(\tau)\, d\tau \tag{6.8}$$

Carbon in the biomass

Besides the data specified on section 3.4, the data generated by GOTILWA also allowed calculating the amount of carbon sequestered in the biomass, which is given by $B(L_i) = (1+0,2)0,323 \cdot 10^{-4} L_i^{2,429}$.

The purpose of the numerical analysis for this chapter is initially to determine the optimal selective logging regime that maximises the discounted net benefits from timber production and carbon sequestration of the two real stands of *Pinus sylvestris* for a time horizon of 150 years. The optimal management regime has been calculated for the three climate scenarios considered. Some detailed results of the optimization process are presented in Appendix D.

6.3. Analysis of the optimization results

The integrated assessment model was solved for both a young and a mature forest. The optimal logging regime that maximises 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 CO_2[16], has been calculated. However, only the results of scenario NoCC and scenario A2 for carbon prices of 0€ and 40€ per ton of CO_2 have been presented. The results for scenario B2 and for carbon prices of 10€, 20€ and 30 €/ton of CO_2 are situated between the results obtained for NoCC and A2 with carbon prices of 0€ and 40€. 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 honoured, 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 CO_2, the amount of sequestered carbon that corresponds to the optimal management

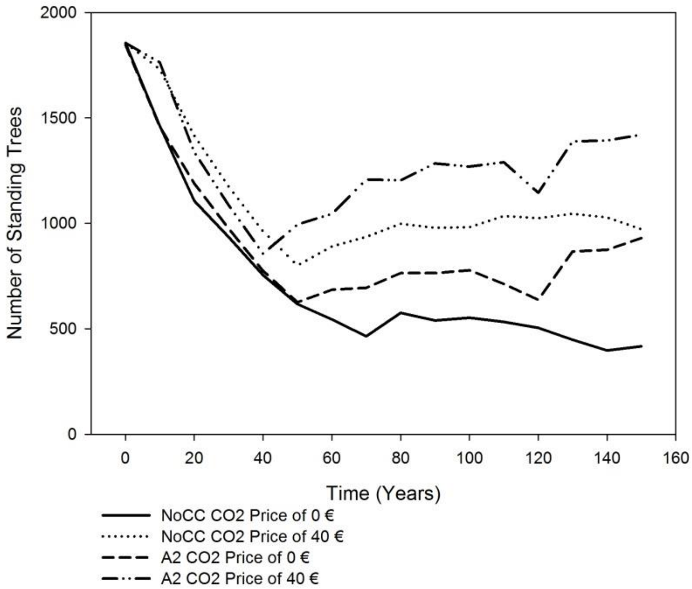
[16] This thesis expresses the carbon price in terms of CO_2. The conversion factor from C to CO_2 is 3,667.

regime defines the trajectory of the reference level $C_{p_c=0}(t)$, i.e., the non-additional carbon. Only carbon sequestered above this reference level can be considered as additional carbon, and will be honoured 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[17].

Figure 6.2 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 NoCC 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).

[17] 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 http://cdm.unfccc.int/methodologies/index.html (accessed 4.3.2013).

Fig. 6.2: Evolution of the number of stems.



Figures 6.3 to 6.5 show the evolution of the average diameter, age and basal area of the standing trees for a carbon price of 0€. It is observed that the average diameter and age decrease with climate change and the basal area increases once the stand has approached a more uniform diameter distribution.

A similar picture can be observed for the average diameter and age of the logged trees, plot on Figures 6.6 and 6.7. Since logging is a discontinuous process, the evolution of the average diameter and age is not necessarily continuous.

These results also hold when the carbon price increases from 0 to 40€, as it is observed on Figures 6.8-6.12.

Fig. 6.3 – 6.5: Evolution of the average diameter, age and basal area of the standing trees (young stand), carbon price = 0.

Fig. 6.3.

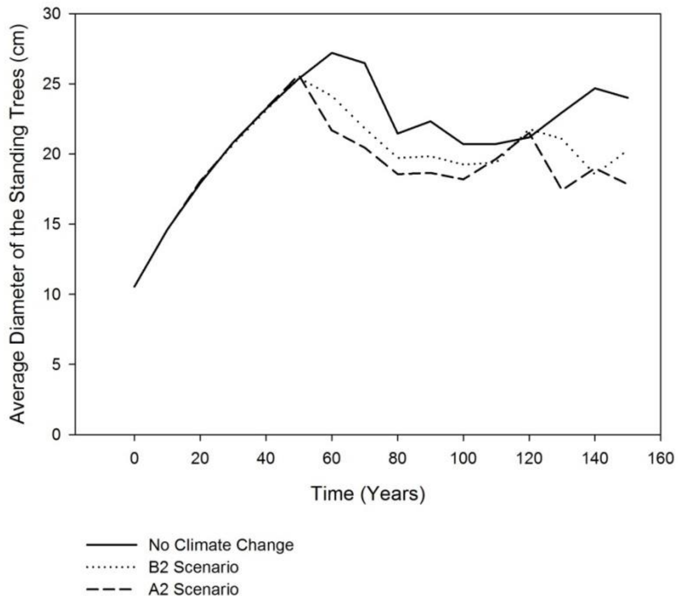


Fig. 6.4.

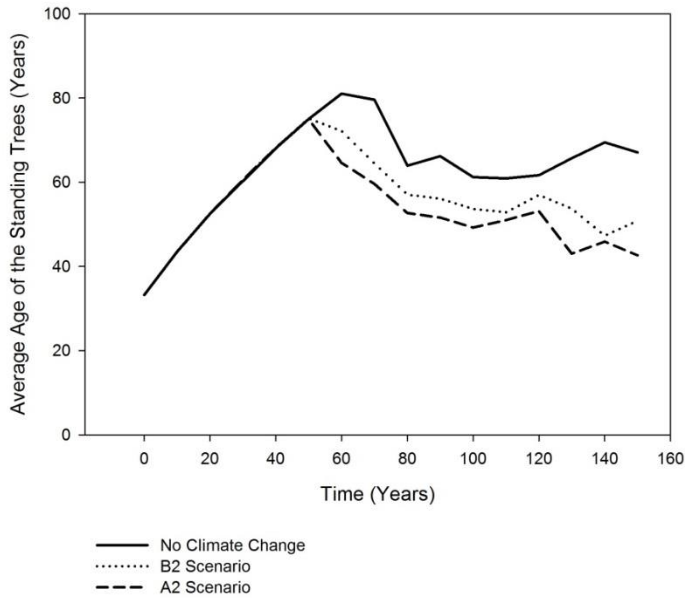


Fig. 6.5.

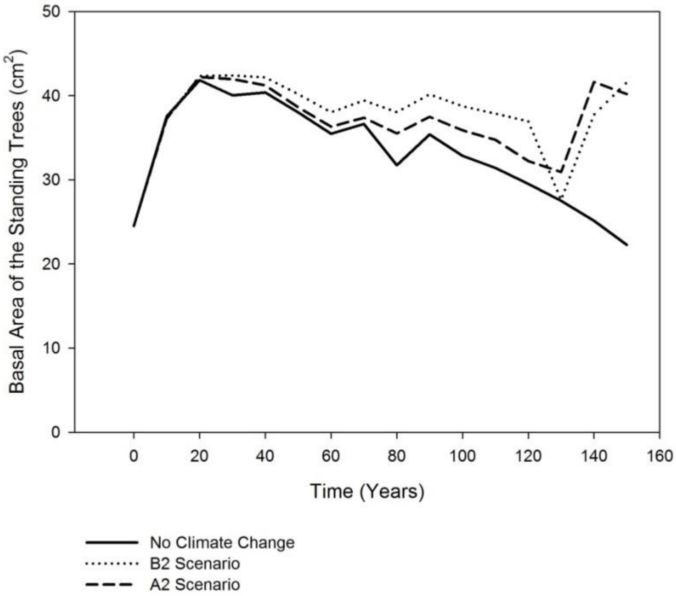


Fig. 6.6 – 6.7: Evolution of the average diameter and age of the logged trees (young stand), carbon price = 0.

Fig. 6.6.

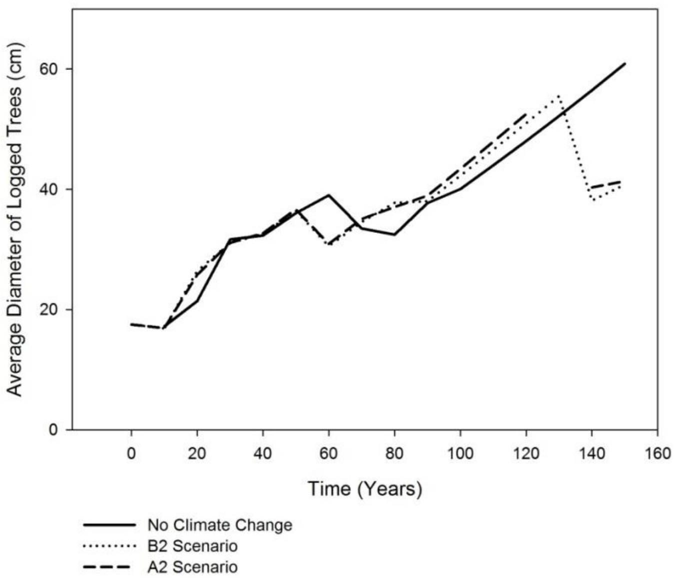


Fig. 6.7.

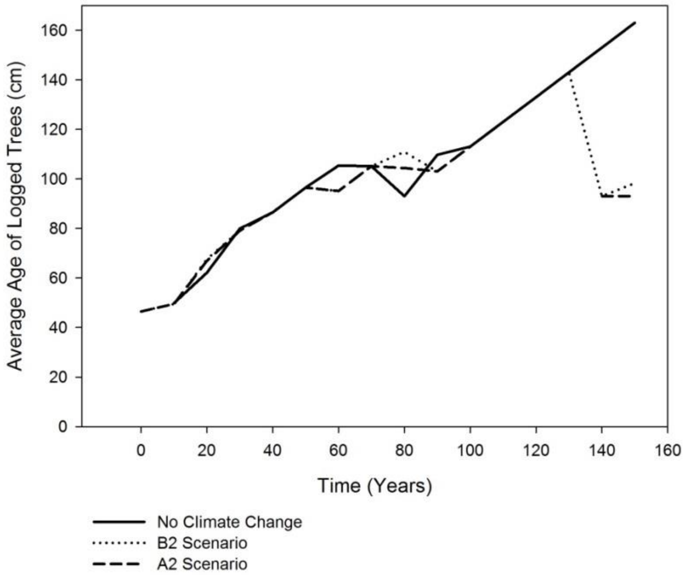


Fig. 6.8 – 6.10: Evolution of the average diameter, age and basal area of the standing trees (young stand), carbon price = 40.

Fig. 6.8.

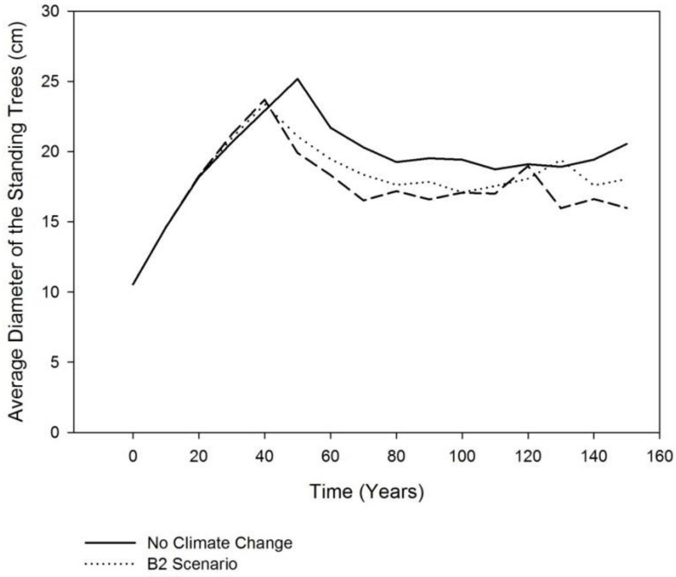


Fig. 6.9.

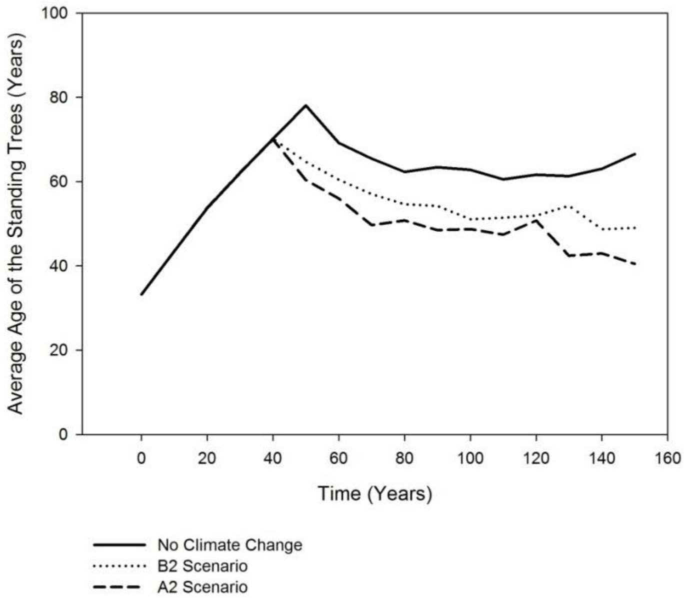


Fig. 6.10.

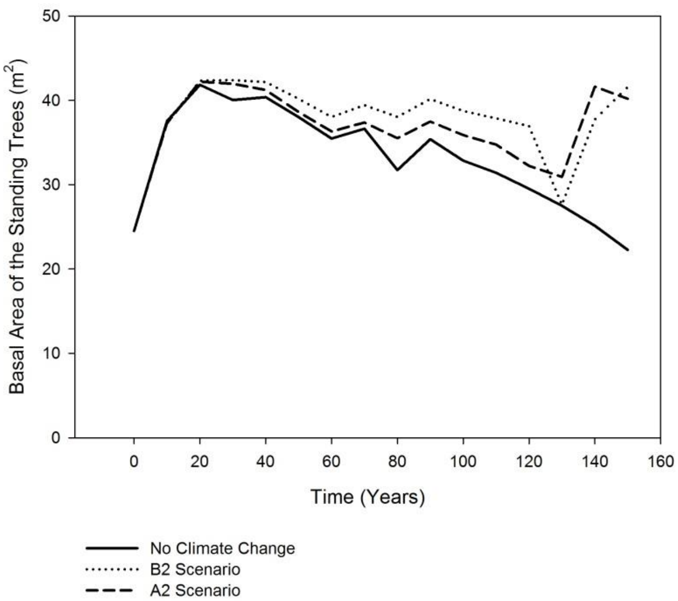


Fig. 6.11 – 6.12: Evolution of the average diameter and age of the logged trees (young stand), carbon price = 40.

Fig. 6.11.

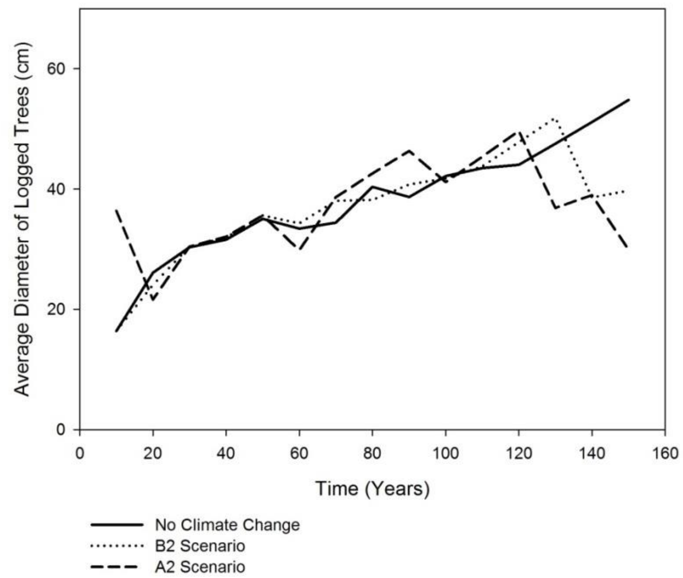
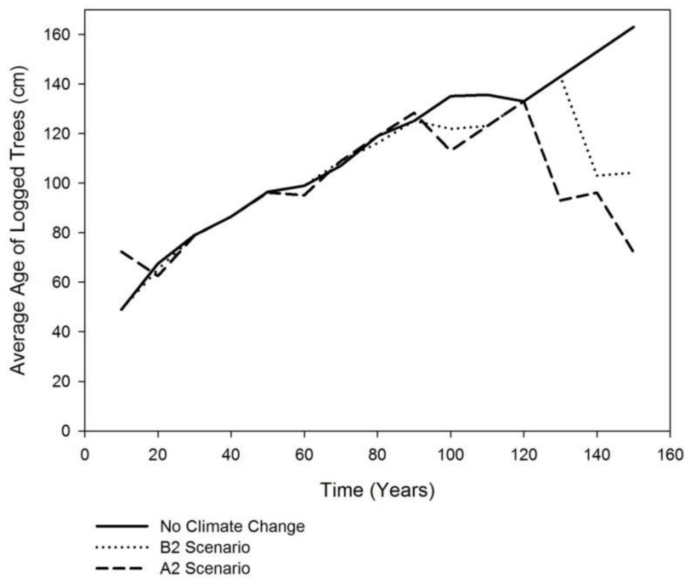
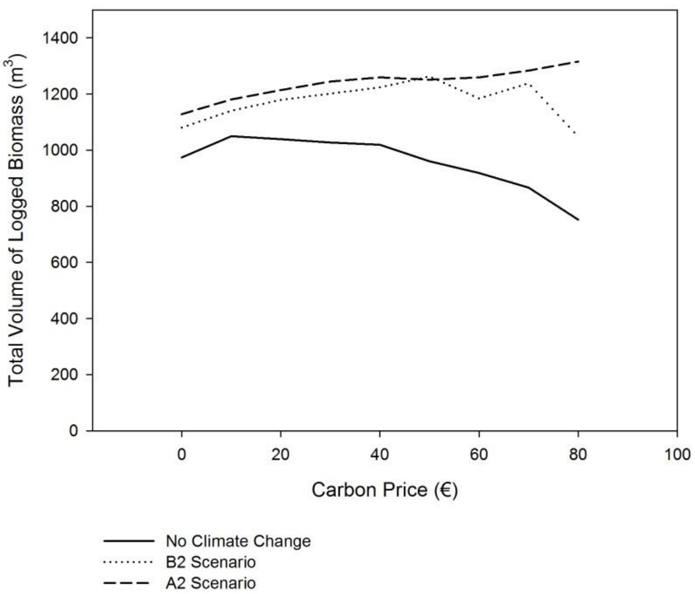


Fig. 6.12.



As in the previous literature, one can also find that climate change increases harvest yields (White et al., 2010). Figure 6.6 shows that the average diameter of the logged trees decreases. However, in contrast to the findings in most of the literature (White et al., 2010), it is not observed that the rotation length is extended, but rather that it is shortened – Figure 6.7. This result can be explained by the fact that the model allows for selective logging and for plantation. It allows the yields to be augmented by increasing the density, and not by extending the rotation length. Most of the previous literature did not consider this option since, despite the possibility of selective logging, replanting usually required the entire stand to be clear cut. Although the age and diameter of the logged trees decrease, the volume of the logged trees increases with climate change as illustrated in Figure 6.13. The decrease in the diameter of the logged trees is more than compensated by the increase in the number of logged trees.

Fig. 6.13: Aggregated volume of the logged trees (young stand) for different carbon prices.

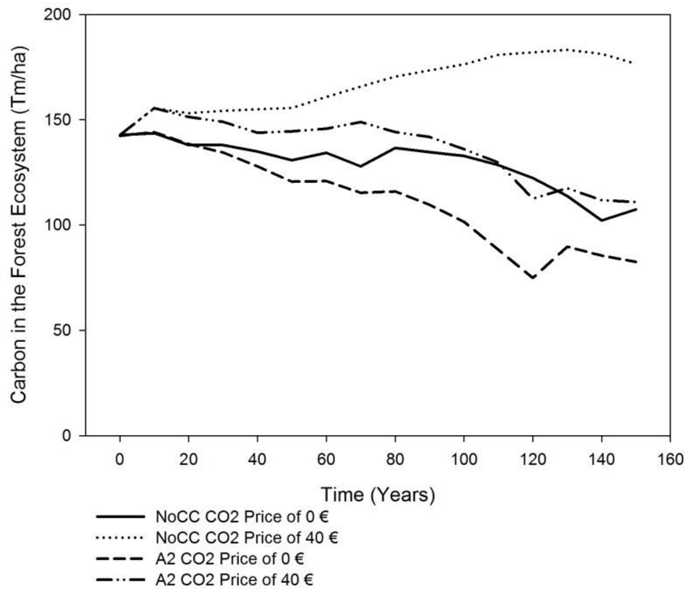


As in the previous chapters, the rest of the basic findings of this section are presented as observations.

Observation 6.1: *Climate change may convert optimally-managed forest ecosystems from carbon sinks to carbon sources. Moreover, it may reduce the effectiveness of carbon payments.*

Figure 6.14 shows the evolution of the carbon stock in the forest ecosystem. In the absence of climate change, the maximisation 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 6.14). 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 per hectare are higher.

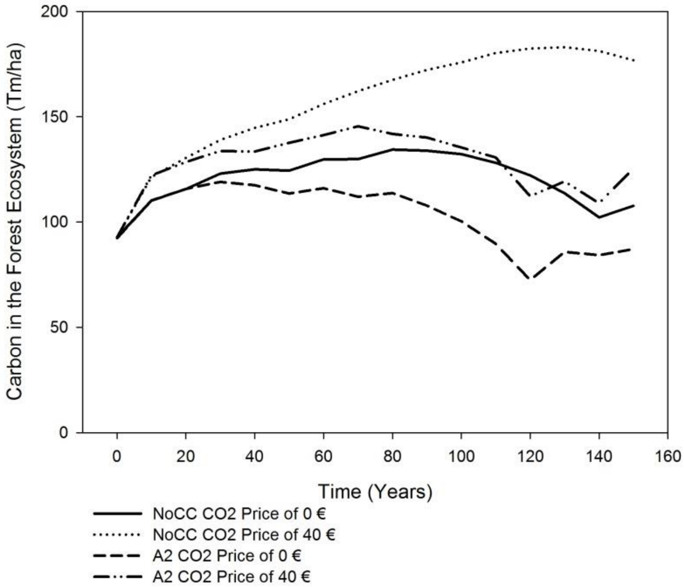
Fig. 6.14: Evolution of carbon in the ecosystem (initial soil carbon 100 tons).



If the initial amount of soil carbon is reduced by 50% (50 tons instead of 100 tons)[18], the ranking of the evolutions of the different climate scenarios is maintained (see Figure 6.15). In this case, however, at the end of the planning horizon only scenario A2, with a 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.

[18] 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.

Fig. 6.15: Evolution of carbon in the ecosystem (initial soil carbon 50 tons).



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 6.14, 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 6.15 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.

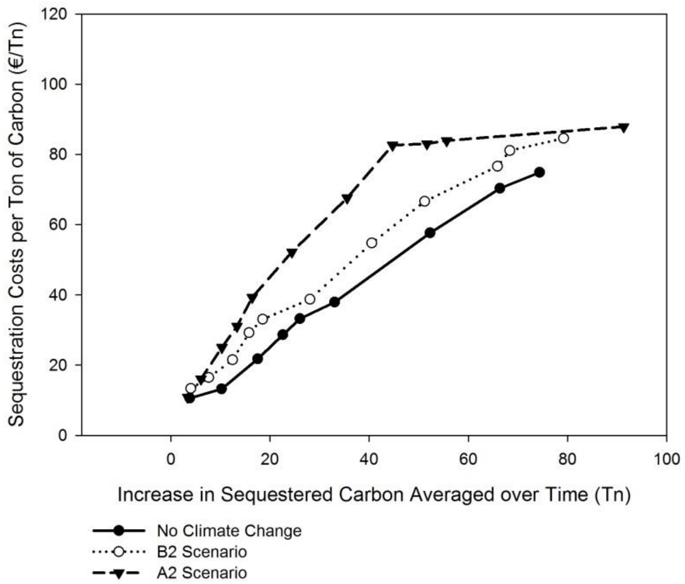
Figures 6.14 and 6.15 both show that the introduction of a carbon price in the presence of climate change increases the amount of sequestered carbon at the end of the planning horizon far less than a situation in which there is no climate change. For instance, as seen in Figure 6.14, an increase in the carbon price from 0€ to 40€ increases the amount of sequestered carbon from 107,40 tons to 176,50 tons for the NoCC scenario. 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 6.14 carbon increases as the carbon price rises for the NoCC scenario 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 the results for a young forest and the climate change scenario A2 have been presented. The calculations for a mature forest show that the pattern of Figures 6.13-6.15 is maintained. These results are presented in the supplementary online material available on: https://www.dropbox.com/s/ts563fovhk851ye/MaturePlots.pdf

Observation 6.2: *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.*

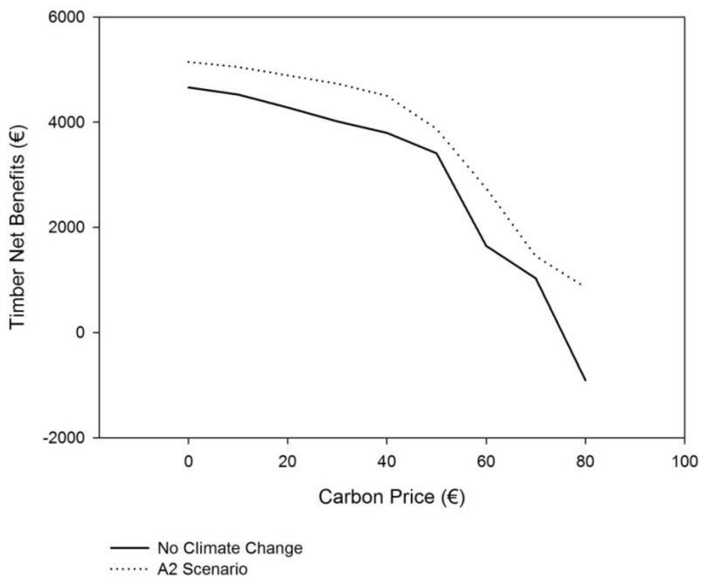
Figure 6.16 shows sequestration costs per averaged ton of carbon over the entire planning horizon. These costs result from the decrease in net benefits from timber production. It demonstrates that the costs increase with climate change by about 34,98% (B2) and 79,49% (A2) for 20 tons of carbon, and by 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 $C_{p_c=0}(t)$, 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. Likewise a higher stand density leads, in the long-run, to a decrease in the average diameter of the standing trees which are less valuable in terms of timber. In other words, the trade-off function is not linear.

Fig. 6.16: Per hectare costs of sequestered carbon per averaged ton over the entire planning horizon (with soil carbon).



Instead of sequestration cost, one can also look at the evolution of the timber net benefits as a function of the sequestered carbon or, equivalently, the carbon price. This relationship is illustrated in Figure 6.17, and demonstrates the trade-off between timber net benefits and sequestration. 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[19]. 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.

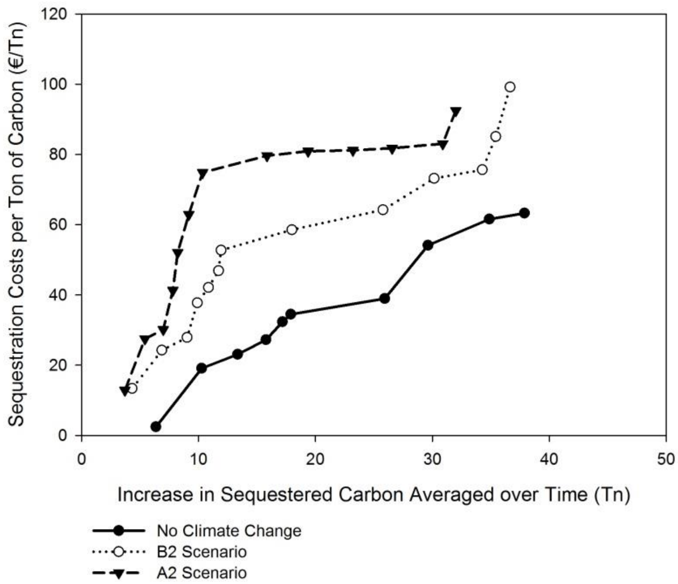
Fig. 6.17: Trade-off between timber net benefits and sequestrated carbon (young stand).



[19] The information about costs of an inventory in Catalonia 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 €/ha. Additionally, the costs for the determination of the soil carbon are 57.60€/ha.

Although Figure 6.18 is similar to Figure 6.17, in Figure 6.18 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.

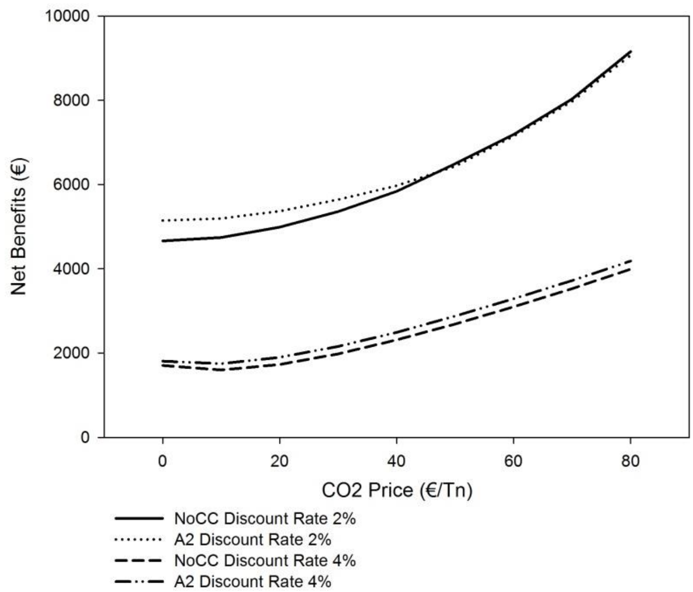
Fig. 6.18: Per hectare costs of sequestered carbon per averaged ton over the entire planning horizon (without soil carbon).



Observation 6.3: *The increase in the discount rate does not affect significantly the optimal management actions carried out by the manager.*

One might suppose that the results obtained depend strongly on the discount rate used. For this purpose, the effects of a variation in the discount rate on the aggregated discounted net benefits have been evaluated. Figure 6.19 shows that the sum of the aggregated discounted 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 NoCC 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% $\left(p_C = 0\right)$. In other words, the presence of climate change increases the net benefits but is not strong enough to alter significantly the effects of a change in the discount rate. A similar reaction, but somehow more moderate, can be observed for the stand of mature trees. These results are presented in the supplementary online material available on the following link: https://www.dropbox.com/s/ts563fovhk851ye/MaturePlots.pdf

Fig. 6.19: Effect of an increase of the discount rate from 2% to 4% on the aggregated discounted net benefits.



Observation 6.4: *Climate change leads to a substantial increase in the discounted sum of net benefits of timber and carbon production. Approximately 90% of this increase can be attributed to the future evolution of timber and carbon prices.*

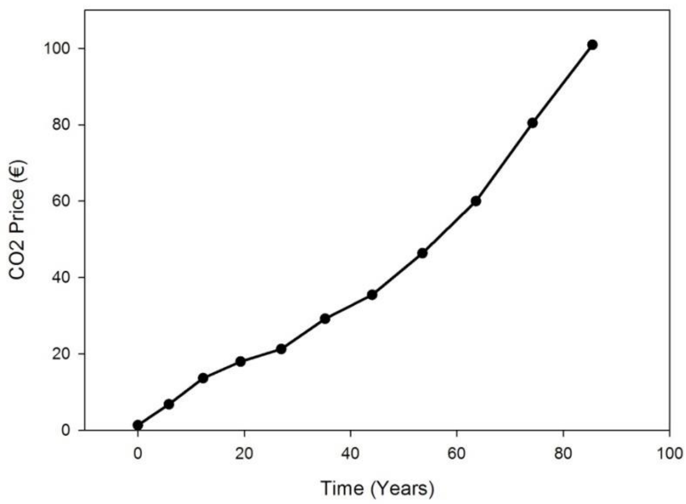
The previous part of the study was conducted without taking into account that climate change most likely will affect future carbon and timber prices. Thus, all prices are constant over time. Despite the fact that the study focuses on the individual stand level, and therefore it is assumed that the actions taken by the landowner do not have an impact on prices, it is possible to analyse the effect of future price changes on the optimal management regime for timber and carbon, and on the cost of carbon sequestration. However, future price changes are not modelled endogenously but exogenously. Consequently, one has to keep in mind that the present approach does not permit to model land-use changes as a result of a change in supply and demand for forest and agricultural land.

As it has been noticed on Chapter 4, 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 for two climate change scenarios, which are comparable to the scenarios considered in this thesis. Hence, the corresponding global equilibrium timber prices for the two scenarios formulated by Tavoni et al. (2007), have been used.

Tavoni et al. (2007) also determined the evolution of the carbon prices. The evolution of the equilibrium carbon price of the forest sector and the general equilibrium model that have been used on this study was calculated by Tavoni et al. (2007) for their second scenario (corresponding to B2 in this thesis). However, they did not calculate it for their first scenario as it assumes there is no policy intervention. Hence, in the absence of specific carbon prices for the first scenario, the evolution of carbon price of the 550 ppm scenario has been linked to climate scenario A2 also.

The resulting evolution of timber prices and carbon prices (in €) are presented in Figures 4.11 (on Chapter 4) and 6.20 respectively. Based on this pattern, the timber price path for each of the two climate change scenarios has been calculated, which allows the discounted net benefits of the young and mature stand to be determined for all climate scenarios considered. The timber and carbon prices reported by Tavoni et al. (2007) cover a period of 100 years. However, since the analysis covers 150 years, it is assumed that the prices are constant from year 100 onwards. This conservative estimate has been used to avoid placing too much weight on the far-distant future.

Fig. 6.20: Evolution of carbon prices over time.



The results presented in table 6.1 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 CO_2. 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 the carbon prices are not fixed, one can observe that, in the case of scenario B2, 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.

The carbon sequestration cost for a mature stand has been also calculated. 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 are presented are presented in supplementary online material: https://www.dropbox.com/s/ts563fovhk851ye/MaturePlots.pdf

Table 6.1: Discounted aggregate net benefits for different climate scenarios, timber, and carbon prices.

		Carbon Prices	
		Constant carbon market equilibrium price of 0 €	**Variable carbon market (550 ppm)**
Timber Prices	**Constant timber market equilibrium prices**	**NoCC:** 4660,10 **B2:** 5050,94 **A2:** 5144,34	**NoCC:** 7211,20 **B2:** 7015,46 **A2:** 7239,32
	Variable timber market equilibrium prices (550 ppm)	**B2:** 6409,01	**B2:** 9503,43
	Variable timber market equilibrium prices (20 GtC)	**A2:** 6751,21	**A2:** 8698,72

6.4. Conclusions

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 the presence of climate change this concept of forest ecosystem as carbon sinks may need to be revised as they may turn into sources of carbon emissions.

The results also 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. 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.

As the previous studies on Chapter 4 and 5, the results of this chapter show that in the presence of climate change the fertilization effect leads the manager to obtain higher profits through the optimal management (Table 6.1).

Discussion and 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 not to avoid it. Since any future climate changes will affect forest ecosystems, it is desirable to adapt the optimal management of forests to changes in the climatic conditions, as well as to analyse the potential of forest ecosystems to develop and reconsider present and future mitigation strategies. Following some discussion about the results of the previous chapters are presented.

Could the private forest be managed?

The analysis on Chapter 4 presents the results of applying to *Pinus sylvestris* stands the bioeconomic model introduced on Chapter 2, which allows to determine the optimal management of a diameter-distributed forest where the growth process of the trees depends not only on individual characteristics but also on the distribution of the individual characteristics over the entire population. The integrated assessment model takes into account the effects of climate change on the growth, mortality, and reproduction of the trees.

The results show that the optimal forest management is based on selective logging regime instead of the clear-cutting regime. Thus, the optimal management allows taking into account the multiple services forests provide apart from timber. It is well known that forests are also a source of important by-products, such as mushrooms, or cork (Raddi, 1997) and they present scenic and recreational values (Scarpa et al., 2000). Moreover, forests maintain biological diversity by providing habitat for a wide range of species (Doyon et al., 2005; Sawadogo et al., 2005). Finally, forests also grant important environmental services, such as protection of floods, avalanches and landslides, the enhancement of the water buffering capacity and the sequestration of carbon (Rojas, 1996), which is matter of study on Chapter 6. In this sense, the results demonstrate that an optimal forest management is compatible with keeping other social services of the forests available.

The results on Chapter 4 also show that the adaptation of optimal management achieves substantially higher discounted aggregate net benefits when climate change is incorporated into the model than in the NoCC case. This is because the fertilization effect of CO_2 leads to an increase in the growth and in the natural reproduction rate; it consequently allows private managers to obtain higher profits. Consequently, the prediction in the literature that an increase in CO_2 (fertilization effect) leads to an increase in the growth of the biomass (Heimann and Reichstein, 2008; Norby et al., 2005) also holds for an optimally managed stand. Moreover, in the presence of climate change, the number of standing trees increases, whereas the rotation age decreases. The expected changes in market prices for timber lead also to an increase in the net benefits. However, this increase is more pronounced in the presence of a lax climate policy than in the presence of a strict climate policy. Hence, it is observed that a tighter climate policy leads to a reduction of the producer rents by about 8%.

In the case where the forest manager does not adapt to the change in the climatic conditions, the aggregate discounted net benefits decrease by between 1 and 35%. Young stands are far more sensitive to this lack of adaptation than the mature stands (Table 4.2). As the optimal management under climate change tends to yield younger forests and with higher density in the long-run, the policy of not adapting the forest management to climate change may have major implications in the future.

Climate change is going to affect the natural mortality rate of forests in some sense. However, a review article shows that the impact of climate change on the mortality of the trees cannot be quantified easily because of its high uncertainties (Allen et al., 2009). Furthermore, some studies show that the capacity of *Pinus sylvestris* to resist dry periods has been overcome in several regions (Martínez-Vilalta et al., 2012), because of its strict stomatal control of transpiration (Irvine et al., 1998; Poyatos et al., 2007). The sensitive analysis of mortality conducted show that even in the case of a high increase of mortality (Table 4.3), the loss of the aggregated discounted net benefits would not be critical.

The assessment model presented in Chapters 2 and 3 could be an interesting tool for managers to modify the current logging regime in anticipation of future climate conditions, and to optimize it in order to encourage maintaining actively managed forests in territories, such as Catalonia, where forests are suffering a severe status of abandonment. Adaptation strategies can be understood as projects, practices and policies that moderate the climate change impacts or take advantage of this change (EEA, 2007). In this sense, these results could allow managers to obtain higher profits under a climate change context in the case water is not a limiting factor. Otherwise, in places where climate change leads to a loss of biomass productivity, policy makers could use adaptation policies to encourage a profitable and sustainable management regime. It means keeping forests safe from practices such as the remove and commercialization of illegal timber, an important problem that is causing deforestation in many countries.

In future research it would be interesting to determine the optimal logging regimes also at locations that are more sensitive to climate change, since the negative effects of the decrease in water availability may have a significant impact on the forest management and, as a consequence, on the profitability of forests. Likewise, it would be interesting to analyse the effects of climate change for species that do not belong to conifers and therefore are less well adapted to dry conditions, such as *Quercus ilex*.

Adapting the management to the risk of fire

One of the major disturbances of forests is wildfires, and their occurrence is expected to increase as a result of changes in temperature and precipitation. According to Bodin and Bo (2007), a change in forest management from optimising for timber, through a management which makes it compatible with a broad range of other forest services, in combination with measures to insure forests against meteorological manifestations of a climate change, presents fundamentally new challenges. Therefore, the proposed model in Chapter 5 aims to overcome these uncertainties taking into account the fire risk in order to determine the optimal forest management regime in the presence of climate change.

As noted also in Chapter 4, the results show that the optimally managed forest adapted to climate change is more productive compared to the NoCC scenario. Nevertheless, climate change will increase the probability of fire occurrence and the trees affected and died by a forest fire, in a parallel way. Calculations show that it is optimal to increase the number of trees in the forest, and decrease the age and diameter at which they are logged. Thus, under climate change (A2 scenario) the resulting forest in the long-run doubled the percentage of dead trees (2,5%) compared to the NoCC scenario (1%). However, under the optimal management the number of dead trees caused by fire decrease dramatically during the initial 30 years for young stands, and even at the end of the planning horizon the relative value of dead trees is still lower compared to the beginning.

The results also demonstrate that preserved stands (stands not managed for timber extraction) are less sensitive to fire risk than younger ones, due to the fact that they reach a mature structure, which is far less sensitive to wildfires. Thus, the policy of forest preservation could be an interesting alternative to decrease the fire risk for some considered stands. However, the presence of fine and coarse fuel is potentially higher on aged stands (He and Mladenoff, 1999). Consequently, as preserved stands could reach a very mature structure, it is still necessary to manage these stands for removing the understory and fuel, which are the main factor of the fire intensity (He and Mladenoff, 1999).

The adaption of the management regime to changes in fire risk proved to be more important from an economic point of view than its adaptation to climate change. Moreover, its importance decreases far less rapidly with the initial age of the trees compared to the adaptation of the management regime to climate change (Table 5.1). Likewise, the increment of dead trees caused by fire is higher in the case where the manager does not adapt their management to fire risk compared to the increase of dead trees due to climate change. These results highlight the importance of adopting forest management policies, especially in Catalonia where forests with a very young diameter distribution structure are very common. The optimal management determined could encourage forest owners to obtain higher profits through adaptation policies and at the same time diminish the fire risk of the young forests.

In future research it would be interesting to determine the optimal logging regimes at locations that are more sensitive to climate change. Likewise, it would be interesting to analyse the differences between a real unmanaged forest, taking account of understory and litterfall, and an optimal managed forest. For this purpose it would be necessary to estimate a new growth curve, and to modify equations of fire occurrence and fire damage taking into account the presence of understory. Finally, it would be also interesting to analyse the effect of climate change over the damage (F_K), since the analysis conducted on Chapter 5 only takes into account the effect of climate change over the damage indirectly; through structural variables such as the quadratic mean diameter (Dq) and the basal area (BA).

Could forests help to mitigate climate change?

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 *Pinus sylvestris* 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 Report (2007).

The results in Chapter 6 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 Chapter 6 provide the basis to determine the optimal size of carbon sequestration contracts, once the monitoring and control costs are known.

The results obtained in Chapter 6 also show that changes in the management regime that account for 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 CO_2 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.

Appendix A: GOTILWA Parameters

Fig. A.1 – A.5: Values of GOTILWA parameters.

Fig. A.1.

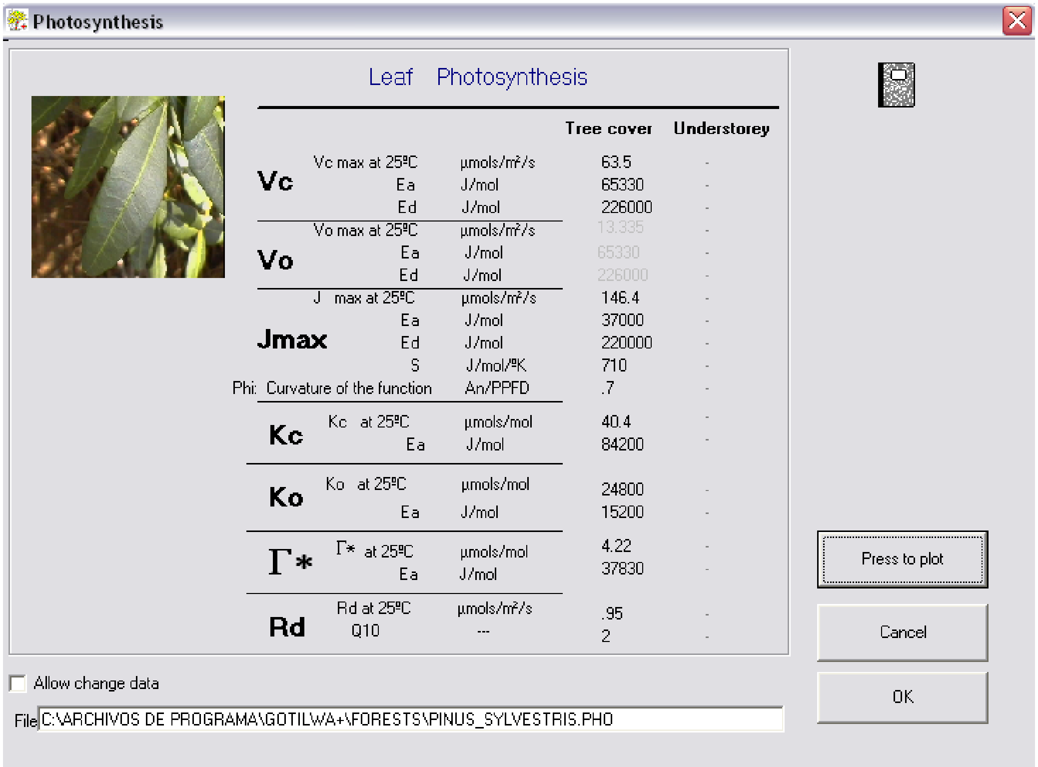
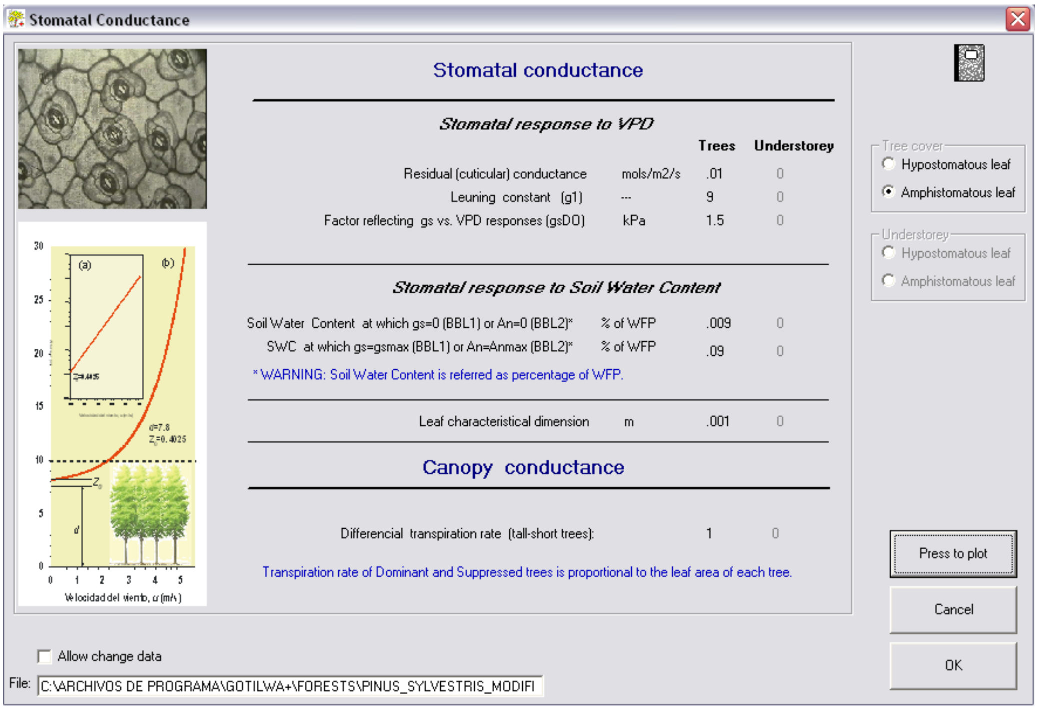


Fig. A.2.


Stomatal Conductance
Stomatal conductance
Stomatal response to VPD
Trees
Understorey
Residual (cuticular) conductance
mols/m2/s
.01
0
Leuning constant (g1)

9
0
Factor reflecting gs vs. VPD responses (gsD0)
kPa
1.5
0
Stomatal response to Soil Water Content
Soil Water Content at which gs=0 (BBL1) or An=0 (BBL2)*
% of WFP
.009
0
SWC at which gs=gsmax (BBL1) or An=Anmax (BBL2)*
% of WFP
.09
0
* WARNING: Soil Water Content is referred as percentage of WFP.
Leaf characteristical dimension
m
.001
0
Canopy conductance
Differencial transpiration rate (tall-short trees):
1
0
Transpiration rate of Dominant and Suppressed trees is proportional to the leaf area of each tree.
Tree cover
Hypostomatous leaf
Amphistomatous leaf
Understorey
Hypostomatous leaf
Amphistomatous leaf
Press to plot
Cancel
OK
Allow change data
File: C:\ARCHIVOS DE PROGRAMA\GOTILWA+\FORESTS\PINUS_SYLVESTRIS_MODIFI
Velocidad del viento, u (m/s)

Fig. A.3.

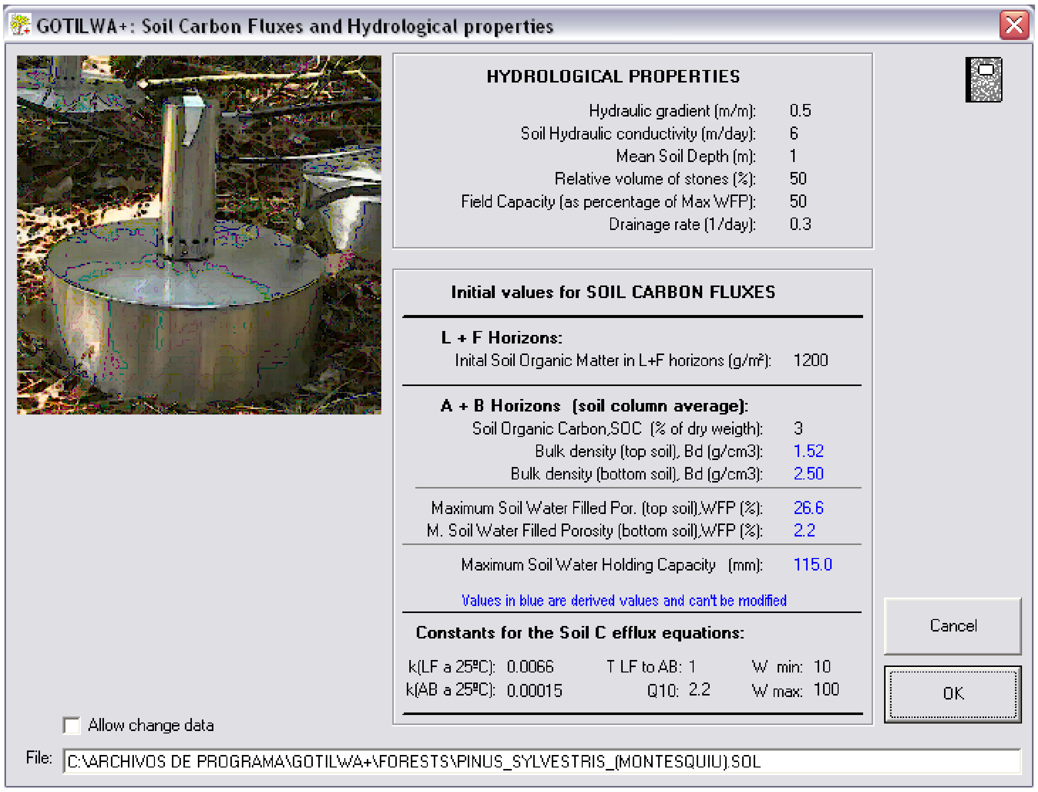

GOTILWA+: Soil Carbon Fluxes and Hydrological properties
HYDROLOGICAL PROPERTIES
Hydraulic gradient (m/m): 0.5
Soil Hydraulic conductivity (m/day): 6
Mean Soil Depth (m): 1
Relative volume of stones (%): 50
Field Capacity (as percentage of Max WFP): 50
Drainage rate (1/day): 0.3
Initial values for SOIL CARBON FLUXES
L + F Horizons:
Inital Soil Organic Matter in L+F horizons (g/m²): 1200
A + B Horizons (soil column average):
Soil Organic Carbon,SOC (% of dry weigth): 3
Bulk density (top soil), Bd (g/cm3): 1.52
Bulk density (bottom soil), Bd (g/cm3): 2.50
Maximum Soil Water Filled Por. (top soil),WFP (%): 26.6
M. Soil Water Filled Porosity (bottom soil),WFP (%): 2.2
Maximum Soil Water Holding Capacity (mm): 115.0
Values in blue are derived values and can't be modified
Constants for the Soil C efflux equations:
k(LF a 25ºC): 0.0066
T LF to AB: 1
W min: 10
k(AB a 25ºC): 0.00015
Q10: 2.2
W max: 100
Cancel
OK
Allow change data
File: C:\ARCHIVOS DE PROGRAMA\GOTILWA+\FORESTS\PINUS_SYLVESTRIS_(MONTESQUIU).SOL

Fig. A.4.

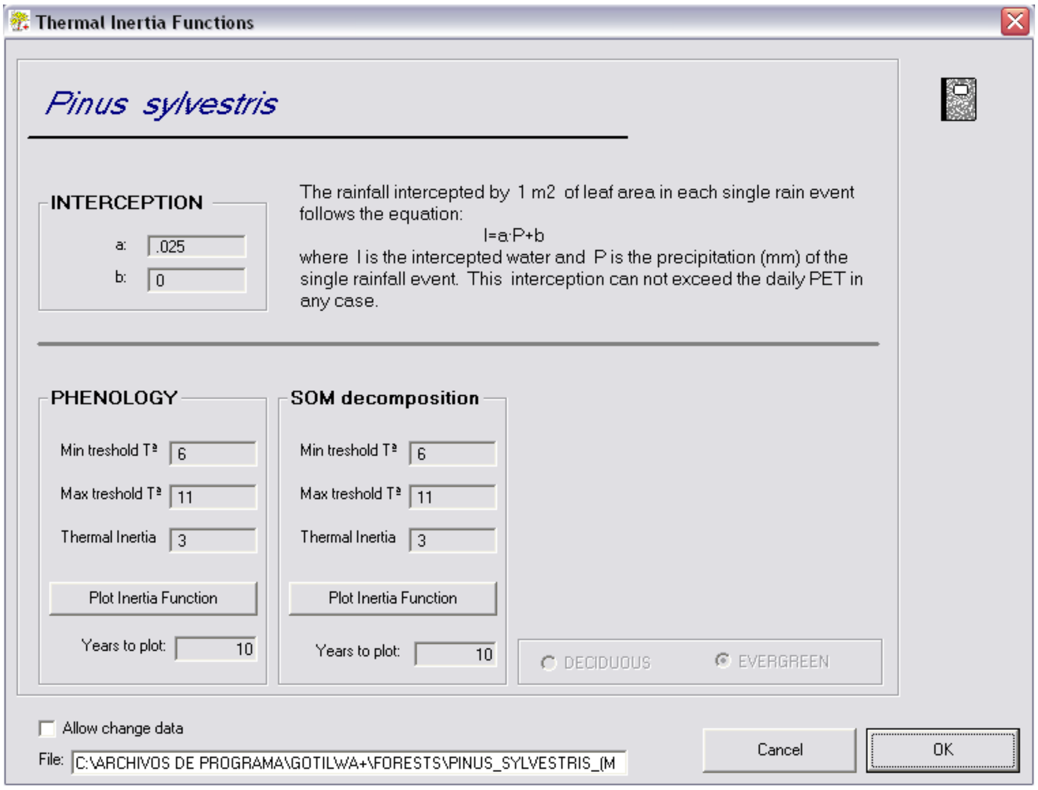
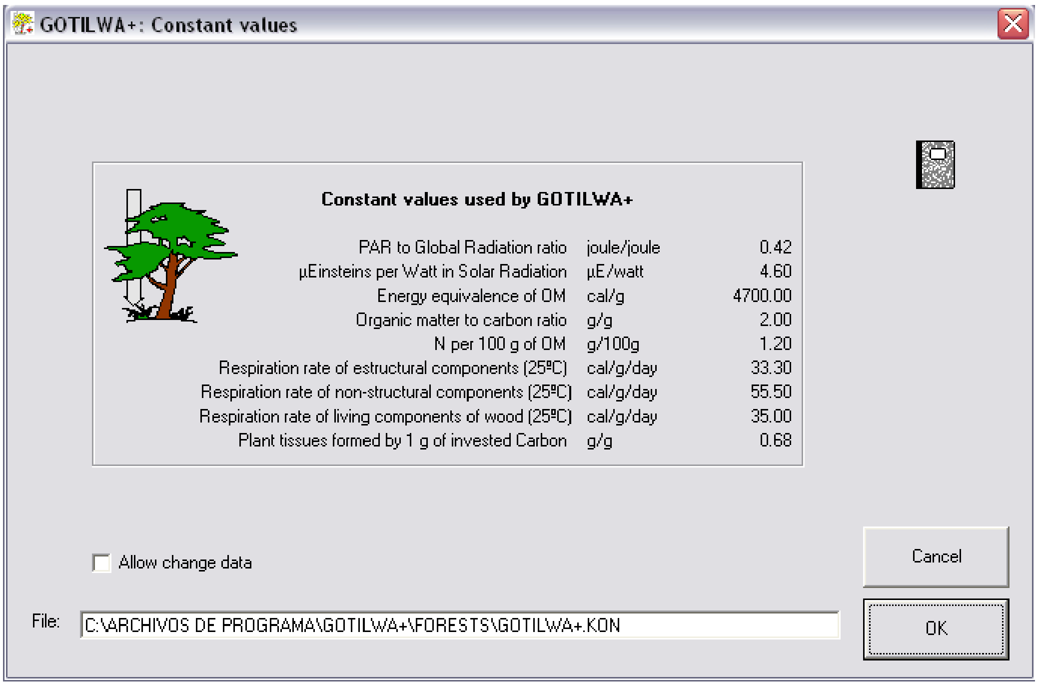

Thermal Inertia Functions
Pinus sylvestris
INTERCEPTION
a: .025
b: 0
The rainfall intercepted by 1 m2 of leaf area in each single rain event follows the equation:
I=a·P+b
where I is the intercepted water and P is the precipitation (mm) of the single rainfall event. This interception can not exceed the daily PET in any case.
PHENOLOGY
Min treshold Tª 6
Max treshold Tª 11
Thermal Inertia 3
Plot Inertia Function
Years to plot: 10
SOM decomposition
Min treshold Tª 6
Max treshold Tª 11
Thermal Inertia 3
Plot Inertia Function
Years to plot: 10
DECIDUOUS
EVERGREEN
Allow change data
File: C:\ARCHIVOS DE PROGRAMA\GOTILWA+\FORESTS\PINUS_SYLVESTRIS_(M
Cancel
OK

Fig. A.5.


GOTILWA+: Constant values
Constant values used by GOTILWA+
PAR to Global Radiation ratio joule/joule 0.42
µEinsteins per Watt in Solar Radiation µE/watt 4.60
Energy equivalence of OM cal/g 4700.00
Organic matter to carbon ratio g/g 2.00
N per 100 g of OM g/100g 1.20
Respiration rate of estructural components (25ºC) cal/g/day 33.30
Respiration rate of non-structural components (25ºC) cal/g/day 55.50
Respiration rate of living components of wood (25ºC) cal/g/day 35.00
Plant tissues formed by 1 g of invested Carbon g/g 0.68
Allow change data
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Cancel
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Appendix B: Chapter 4 Optimization Results

*The reproduction expresses the number of seedlings that can be selected for upgrowth for the forest manager. The number of trees in period t+10 is given by the number of trees in period t minus the number of dead trees in period t and the number of logged trees in period t+10, plus the number of seedlings selected for upgrowth.

Table B.1: Young Stand. BA : 23,40 m^2. NoCC Scenario.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Net revenue from timber sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1404	0	0	190	62	0,00	-690,65	0,00	-690,65
10	1208	134	0	164	62	594,62	-564,25	0,00	24,92
20	1045	101	0	138	54	2742,21	-469,79	0,00	1529,27
30	893	99	0	164	47	1800,08	-390,58	0,00	778,14
40	715	131	0	133	36	2092,67	-308,95	0,00	807,83
50	726	86	0	110	39	1715,76	-313,75	0,00	520,89
60	699	99	0	87	37	2054,31	-302,11	0,00	534,04
70	666	83	0	68	36	1524,17	-288,42	0,00	308,97
80	617	81	0	70	32	2189,13	-268,99	0,00	393,84
90	602	53	0	73	30	2019,75	-263,25	0,00	295,55
100	585	60	0	72	29	2099,62	-256,67	0,00	254,39
200	597	44	0	73	28	2236,39	-261,38	0,00	37,63
				Discounted sum over 200 years		8276,38	-2380,62	0,00	5895,77

Table B.2: Young Stand. BA : 23,40 m^2. B2 Scenario.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Net revenue from timber sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1404	0	0	190	62	0,00	-690,65	0,00	-690,65
10	1237	105	0	169	67	552,77	-477,52	0,00	75,25
20	1068	103	0	142	60	1786,76	-324,51	0,00	1462,25
30	897	110	0	163	54	1046,12	-216,87	0,00	829,24
40	879	128	0	132	56	957,21	-173,74	0,00	783,46
50	855	100	0	106	58	698,47	-138,31	0,00	560,16
60	806	97	0	84	56	663,37	-106,50	0,00	556,87
70	735	100	0	84	51	508,40	-79,38	0,00	429,02
80	690	85	8	82	47	534,91	-61,19	-1,14	472,58
90	739	53	68	82	54	319,28	-53,71	-8,30	257,26
100	697	74	4	76	50	426,81	-41,62	-0,42	384,77
200	972	83	142	78	110	70,22	-8,20	-1,97	60,05
				Discounted sum over 200 years		9105,72	-2546,16	-34,70	6524,86

Table B.3: Young Stand. BA : 23,40 m^2. A2 Scenario.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Net revenue from timber sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1404	0	0	190	62	0,00	-690,65	0,00	-690,65
10	1246	96	0	170	70	596,85	-482,17	0,00	114,67
20	1072	106	0	142	65	1728,67	-326,03	0,00	1402,64
30	887	120	0	162	58	1106,95	-213,98	0,00	892,97
40	864	127	0	130	62	962,00	-170,53	0,00	791,47
50	829	103	0	103	65	690,29	-133,79	0,00	556,50
60	777	91	0	81	65	641,46	-102,41	0,00	539,06
70	689	104	0	78	58	556,70	-74,56	0,00	482,15
80	675	80	46	75	58	531,78	-59,98	-6,90	464,91
90	760	48	116	75	74	291,06	-55,26	-14,29	221,51
100	737	72	48	67	72	453,55	-43,95	-4,86	404,74
200	1090	106	220	73	214	57,72	-9,42	-3,07	45,23
				Discounted sum over 200 years		9293,15	-2561,31	-79,20	6652,65

Table B.4: Mature Stand. BA : 47.81 m^2. NoCC Scenario.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Net revenue from timber sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1089	309	0	192	54	2501,20	-494,22	0,00	2006,98
10	893	142	0	159	45	1610,20	-320,37	0,00	1289,84
20	724	154	0	127	36	1192,30	-210,41	0,00	981,90
30	704	111	0	103	36	1092,93	-168,02	0,00	924,91
40	698	72	0	85	37	861,09	-136,63	0,00	724,46
50	655	91	0	69	34	772,28	-105,51	0,00	666,78
60	623	66	0	72	32	667,18	-82,72	0,00	584,47
70	598	65	0	72	30	478,63	-65,50	0,00	413,13
80	580	61	0	70	28	515,21	-52,29	0,00	462,92
90	571	51	0	67	26	480,31	-42,35	0,00	437,97
100	583	30	0	70	26	309,48	-35,34	0,00	274,13
200	601	43	0	73	28	42,84	-5,01	0,00	37,83
				Discounted sum over 200 years		11636,79	-1855,27	0,00	9781,52

Table B.5: Mature Stand. BA : 47.81 m^2. B2 Scenario.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Net revenue from timber sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1087	311	0	191	54	2485,03	-493,02	0,00	1992,01
10	891	142	0	158	46	1609,73	-319,54	0,00	1290,19
20	854	149	0	126	49	1160,99	-250,20	0,00	910,79
30	816	115	0	101	49	1152,74	-195,27	0,00	957,47
40	789	78	0	83	50	952,86	-154,75	0,00	798,11
50	726	96	0	84	46	853,70	-116,57	0,00	737,14
60	700	64	0	86	46	634,34	-92,31	0,00	542,03
70	660	80	0	81	43	642,17	-71,55	0,00	570,62
80	662	63	28	76	43	587,14	-58,86	-4,12	524,16
90	645	50	0	74	41	526,64	-47,13	0,00	479,52
100	634	44	0	74	41	368,44	-38,04	0,00	330,40
200	975	85	143	75	110	71,33	-8,24	-1,98	61,11
				Discounted sum over 200 years		12439,60	-2025,10	-36,45	10378,05

Table B.6: Mature Stand. BA : 47.81 m^2. A2 Scenario.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Net revenue from timber sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1084	314	0	191	54	2482,96	-491,52	0,00	1991,44
10	888	142	0	158	48	1610,03	-318,56	0,00	1291,47
20	849	150	0	126	52	1174,62	-248,47	0,00	926,15
30	807	116	0	100	54	1163,19	-192,98	0,00	970,21
40	776	77	0	81	56	949,28	-152,07	0,00	797,20
50	704	98	0	81	52	892,53	-113,02	0,00	779,51
60	700	64	30	82	56	620,71	-92,24	-6,78	521,69
70	695	77	45	76	57	643,03	-75,11	-8,30	559,63
80	662	66	15	68	54	650,79	-58,85	-2,30	589,63
90	715	40	78	72	62	434,81	-51,96	-9,55	373,29
100	757	39	72	78	73	351,12	-45,14	-7,23	298,75
200	1093	89	260	66	239	77,22	-9,46	-3,61	64,15
				Discounted sum over 200 years		12610,75	-2042,84	-84,09	10483,83

Table B.7: Very Young Stand. BA : 0.88 m^2. NoCC Scenario.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Net revenue from timber sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1800	0	0	0	45	0,00	-990,05	0,00	-990,05
10	1755	0	0	0	41	0,00	-781,91	0,00	-781,91
20	1340	374	0	0	37	16,33	-436,04	0,00	-419,70
30	1303	0	0	242	52	0,00	-344,37	0,00	-344,37
40	1018	233	0	182	48	323,40	-206,16	0,00	117,24
50	818	334	0	119	39	750,89	-131,85	0,00	619,04
60	691	207	0	74	32	626,46	-91,11	0,00	535,34
70	733	0	0	71	40	0,00	-79,21	0,00	-79,21
80	510	253	0	57	20	1193,82	-47,12	0,00	1146,70
90	431	116	0	105	12	605,69	-34,20	0,00	571,49
100	422	0	0	84	11	0,00	-27,64	0,00	-27,64
200	515	30	0	62	23	34,00	-4,41	0,00	29,58
			Discounted sum over 200 years			4009,29	-3293,45	0,00	715,84

Table B.8: Very Young Stand. BA : 0.88 m^2. B2 Scenario.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Net revenue from timber sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1800	0	0	0	45	0,00	-990,05	0,00	-990,05
10	1755	0	0	0	43	0,00	-781,91	0,00	-781,91
20	1394	318	0	0	42	15,77	-460,27	0,00	-444,50
30	1352	0	0	253	63	0,00	-361,98	0,00	-361,98
40	1127	271	0	176	66	400,75	-233,55	0,00	167,20
50	912	324	0	119	56	791,82	-148,68	0,00	643,14
60	754	222	0	72	44	742,78	-99,35	0,00	643,43
70	779	3	0	76	57	11,13	-84,26	0,00	-73,14
80	553	245	0	61	29	1320,21	-50,25	0,00	1269,97
90	473	112	0	95	19	676,68	-36,51	0,00	640,17
100	549	0	0	69	23	0,00	-33,61	0,00	-33,61
200	762	44	0	74	82	39,90	-6,28	-1,17	32,20
			Discounted sum over 200 years			4746,59	-3434,97	-12,13	1296,83

Table B.9: Very Young Stand. BA : 0.88 m^2. A2 Scenario.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Net revenue from timber sale (€/ha	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1800	0	0	0	45	0,00	-990,05	0,00	-990,05
10	1755	0	0	0	44	0,00	-781,91	0,00	-781,91
20	1404	307	0	0	46	15,82	-464,59	0,00	-448,77
30	1358	0	0	254	71	0,00	-364,05	0,00	-364,05
40	1143	286	0	174	78	433,69	-237,98	0,00	195,70
50	920	320	0	116	66	809,95	-150,04	0,00	659,90
60	746	223	27	67	53	779,59	-98,32	0,00	681,28
70	787	2	0	77	72	7,50	-85,13	-4,10	-82,63
80	557	235	0	61	37	1348,31	-50,57	0,00	1297,74
90	484	97	0	84	26	623,92	-37,13	0,00	586,79
100	542	0	0	65	33	0,00	-33,25	0,00	-33,25
200	945	81	0	64	208	62,75	-7,94	-2,93	51,24
			Discounted sum over 200 years			4929,59	-3460,25	-35,53	1426,03

Table B.10: Young Stand. BA : 23,40 m^2. B2 Scenario. 550 ppm Timber Price Scenario.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Net revenue from timber sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1341	63	0	178	58	3,81	-648,17	0,00	-644,36
10	1277	6	0	166	74	159,14	-497,77	0,00	-338,63
20	1065	138	0	143	58	3003,06	-323,40	0,00	2679,67
30	948	100	0	164	57	1121,98	-230,93	0,00	891,06
40	911	144	0	132	57	1358,57	-180,86	0,00	1177,71
50	813	173	0	91	47	1247,73	-131,02	0,00	1116,71
60	731	126	0	70	42	661,26	-96,31	0,00	564,95
70	759	0	0	89	54	0,00	-82,05	0,00	-82,05
80	596	198	0	68	33	1174,52	-53,57	0,00	1120,95
90	507	125	0	81	22	631,01	-38,45	0,00	592,56
100	566	0	0	64	26	0,00	-34,49	0,00	-34,49
200	747	47	86	75	78	43,74	-6,15	-1,20	36,40
			Discounted sum over 200 years			10228,51	-2469,91	-14,18	7744,42

Table B.11: Young Stand. BA : 23,40 m^2. A2 Scenario. 20 GtC Timber Price Scenario.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Net revenue from timber sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1404	0	0	190	62	0,00	-690,65	0,00	-690,65
10	1307	35	0	163	81	24,99	-513,89	0,00	-488,90
20	1124	102	0	141	74	2334,08	-346,12	0,00	1987,95
30	1016	137	0	164	71	1695,46	-250,73	0,00	1444,73
40	969	141	0	132	72	1273,13	-194,38	0,00	1078,75
50	903	127	0	102	71	931,13	-147,05	0,00	784,08
60	827	108	0	90	67	812,32	-109,41	0,00	702,91
70	747	106	4	86	62	672,40	-80,75	-0,56	590,96
80	791	72	91	85	70	555,93	-70,27	-11,22	471,98
90	821	66	82	81	80	407,54	-59,96	-8,24	337,55
100	739	83	0	71	68	612,21	-44,06	0,00	568,15
200	1223	103	324	73	279	93,41	-10,92	-3,70	77,99
			Discounted sum over 200 years			11238,68	-2740,20	-74,08	8408,17

Table B.12: Mature Stand. BA : 47.81 m^2. B2 Scenario. 550 ppm Timber Price Scenario.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Net revenue from timber sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1192	206	0	143	68	2205,15	-554,46	0,00	1650,69
10	945	180	0	161	51	2892,25	-341,68	0,00	2550,57
20	858	196	0	130	48	1940,12	-251,49	0,00	1688,63
30	846	94	0	106	51	1160,44	-203,23	0,00	957,21
40	784	117	0	80	49	1047,89	-153,57	0,00	894,31
50	652	162	0	66	34	1768,31	-105,13	0,00	1663,19
60	621	63	0	70	33	566,98	-82,49	0,00	484,49
70	659	0	0	86	43	0,00	-71,42	0,00	-71,42
80	538	163	0	73	26	1546,84	-49,13	0,00	1497,71
90	509	76	0	64	22	214,75	-38,59	0,00	176,15
100	551	0	0	62	29	0,00	-33,70	0,00	-33,70
200	765	46	107	73	83	38,51	-6,30	-1,48	30,73
			Discounted sum over 200 years			14321,24	-2038,12	-17,64	12265,47

Table B.13: Mature Stand. BA : 47.81 m^2. A2 Scenario. 20 GtC Timber Price Scenario.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Net revenue from timber sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1075	323	0	106	62	690,13	-486,56	0,00	203,57
10	991	121	0	135	61	2869,54	-361,40	0,00	2508,14
20	941	123	0	123	63	1944,04	-279,25	0,00	1664,79
30	864	138	0	100	59	1612,51	-207,94	0,00	1404,57
40	809	97	0	92	57	1396,41	-158,71	0,00	1237,70
50	743	100	0	86	53	1080,00	-119,32	0,00	960,69
60	754	79	57	84	58	800,61	-99,39	-10,45	688,48
70	765	76	60	78	62	734,04	-82,66	-9,04	640,35
80	784	64	67	73	64	726,90	-69,58	-8,25	647,26
90	754	56	16	78	63	546,87	-54,82	-1,66	490,02
100	821	50	102	85	81	275,48	-49,17	-8,43	216,04
200	1221	102	324	72	279	93,77	-10,90	-3,70	78,36
				Discounted sum over 200 years		14678,40	-2203,68	-89,66	12365,43

Table B.14: Young Stand. BA : 23,40 m^2. B2 Scenario. Not Adaption to Climate Change.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Net revenue from timber sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1404	0	0	0	62	0,00	-690,65	0,00	-690,65
10	1208	134	0	0	65	487,80	-462,88	0,00	24,92
20	1042	101	0	0	57	1852,94	-315,16	0,00	1537,79
30	887	98	0	0	52	1005,23	-213,96	0,00	791,27
40	704	131	0	131	41	981,05	-137,76	0,00	843,29
50	709	84	0	110	46	653,68	-113,92	0,00	539,76
60	678	95	0	87	45	656,17	-89,50	0,00	566,67
70	638	83	0	68	44	427,33	-69,31	0,00	358,02
80	581	81	0	70	39	514,81	-52,33	0,00	462,48
90	568	44	0	73	39	325,39	-42,12	0,00	283,27
100	541	60	0	72	38	354,70	-33,21	0,00	321,49
200	479	34	0	0	49	62,63	-4,17	0,00	58,45
				Discounted sum over 200 years		8777,73	-2346,90	0,00	6430,83

Table B.15: Young Stand. BA : 23,40 m^2. A2 Scenario. Not Adaption to Climate Change.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Net revenue from timber sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1404	0	0	0	62	0,00	-690,65	0,00	-690,65
10	1208	134	0	0	67	487,80	-462,88	0,00	24,92
20	1040	101	0	0	61	1855,40	-314,33	0,00	1541,07
30	881	98	0	0	58	1006,49	-212,40	0,00	794,09
40	693	131	0	129	46	993,10	-135,68	0,00	857,42
50	694	82	0	110	53	648,25	-111,46	0,00	536,78
60	659	92	0	87	53	655,00	-87,08	0,00	567,92
70	610	83	0	68	52	448,09	-66,62	0,00	381,46
80	545	81	0	70	46	544,07	-49,65	0,00	494,42
90	534	34	0	73	49	273,82	-40,08	0,00	233,74
100	498	60	0	72	46	385,89	-31,14	0,00	354,75
200	367	27	0	0	64	62,78	-3,50	0,00	59,29
			Discounted sum over 200 years			8784,68	-2315,94	0,00	6468,74

Table B.16: Mature Stand. BA : 47.81 m^2. B2 Scenario. Not Adaption to Climate Change.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Net revenue from timber sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1089	309	0	0	54	2501,20	-494,22	0,00	2006,98
10	893	142	0	29	46	1610,20	-320,37	0,00	1289,84
20	722	154	0	127	39	1200,26	-209,95	0,00	990,31
30	700	111	0	103	40	1110,82	-167,06	0,00	943,76
40	691	71	0	85	43	869,45	-135,35	0,00	734,09
50	642	91	0	69	40	811,61	-103,69	0,00	707,91
60	607	64	0	72	38	682,71	-80,88	0,00	601,83
70	576	65	0	72	37	526,79	-63,39	0,00	463,39
80	551	61	0	70	35	574,03	-50,06	0,00	523,97
90	535	51	0	67	32	540,65	-40,12	0,00	500,53
100	547	22	0	70	35	264,33	-33,53	0,00	230,80
200	482	33	0	0	49	61,50	-4,19	0,00	57,31
			Discounted sum over 200 years			12122,04	-1827,17	0,00	10294,87

Table B.17: Mature Stand. BA : 47.81 m^2. A2 Scenario. Not Adaption to Climate Change.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Net revenue from timber sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1089	309	0	0	54	2501,20	-494,22	0,00	2006,98
10	893	142	0	29	48	1610,20	-320,37	0,00	1289,84
20	720	154	0	127	41	1202,86	-209,48	0,00	993,38
30	696	111	0	103	44	1117,00	-166,08	0,00	950,92
40	684	70	0	85	48	862,35	-134,06	0,00	728,29
50	630	91	0	69	46	826,57	-101,86	0,00	724,71
60	592	61	0	72	45	670,48	-79,03	0,00	591,45
70	553	65	0	72	44	546,70	-61,28	0,00	485,42
80	521	61	0	70	41	599,35	-47,86	0,00	551,49
90	498	51	0	67	39	567,73	-37,94	0,00	529,79
100	512	15	0	70	44	186,35	-31,77	0,00	154,58
200	370	25	0	0	64	60,43	-3,51	0,00	56,92
				Discounted sum over 200 years		12125,66	-1800,29	0,00	10325,37

Table B.18: Very Young Stand. BA : 0.88 m^2. B2 Scenario. Not Adaption to Climate Change.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Net revenue from timber sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1800	0	0	0	45	0,00	-990,05	0,00	-990,05
10	1755	0	0	0	43	0,00	-781,91	0,00	-781,91
20	1339	374	0	0	40	-26,88	-435,39	0,00	-462,27
30	1299	0	0	0	58	0,00	-342,88	0,00	-342,88
40	1008	233	0	182	56	247,23	-203,67	0,00	43,57
50	800	334	0	119	46	627,21	-128,83	0,00	498,38
60	666	207	0	74	38	593,54	-88,02	0,00	505,53
70	703	0	0	71	49	0,00	-75,96	0,00	-75,96
80	471	253	0	57	23	1269,69	-44,35	0,00	1225,34
90	404	101	0	3	15	634,12	-32,74	0,00	601,38
100	391	0	0	41	13	0,00	-26,34	0,00	-26,34
200	423	23	0	62	39	56,08	-3,82	0,00	52,26
				Discounted sum over 200 years		4122,04	-3264,65	0,00	857,39

Table B.19: Very Young Stand. BA : 0.88 m^2. A2 Scenario. Not Adaption to Climate Change.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Net revenue from timber sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1800	0	0	0	45	0,00	-990,05	0,00	-990,05
10	1755	0	0	0	44	0,00	-781,91	0,00	-781,91
20	1337	374	0	0	43	-26,42	-434,73	0,00	-461,15
30	1295	0	0	0	65	0,00	-341,37	0,00	-341,37
40	998	233	0	182	63	254,36	-201,16	0,00	53,20
50	783	334	0	119	53	650,14	-125,83	0,00	524,30
60	642	207	0	74	43	620,71	-85,01	0,00	535,70
70	672	0	0	71	57	0,00	-72,81	0,00	-72,81
80	432	253	0	57	26	1352,68	-41,76	0,00	1310,92
90	386	77	0	3	19	518,75	-31,83	0,00	486,91
100	370	0	0	41	17	0,00	-25,45	0,00	-25,45
200	329	15	0	62	52	44,92	-3,28	0,00	41,64
			Discounted sum over 200 years			4165,44	-3237,87	0,00	927,57

Table B.20: Young Stand. BA : 23,40 m^2. B2 Scenario. NoCC Mortality Scenario (µ1).

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Net revenue from timber sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1404	0	0	190	62	0,00	-690,65	0,00	-690,65
10	1242	100	0	169	65	540,11	-479,95	0,00	60,17
20	1077	100	0	143	57	1797,37	-328,15	0,00	1469,22
30	916	104	0	163	50	1014,04	-221,98	0,00	792,06
40	898	130	0	134	51	968,39	-178,07	0,00	790,31
50	881	100	0	108	52	712,91	-142,87	0,00	570,04
60	829	107	0	86	48	724,08	-109,68	0,00	614,40
70	774	93	0	87	45	470,22	-83,65	0,00	386,56
80	727	89	0	88	40	547,69	-64,44	0,00	483,25
90	749	58	33	87	43	366,85	-54,50	-4,09	308,26
100	747	76	29	83	41	426,12	-44,58	-2,91	378,63
200	1024	94	124	56	67	82,58	-8,73	-1,73	72,11
			Discounted sum over 200 years			9356,48	-2590,82	-25,45	6740,21

Table B.21: Young Stand. BA : 23,40 m^2. B2 Scenario. A2 Mortality Scenario (μ1).

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Net revenue from timber sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1404	0	0	190	62	0,00	-690,65	0,00	-690,65
10	1238	105	0	169	69	597,74	-477,66	0,00	120,09
20	1051	117	0	139	63	1737,87	-318,45	0,00	1419,42
30	873	115	0	161	56	1078,27	-210,34	0,00	867,94
40	852	126	0	129	60	946,40	-167,94	0,00	778,46
50	821	100	0	103	63	682,94	-132,40	0,00	550,53
60	768	93	0	80	62	639,63	-101,26	0,00	538,37
70	686	99	0	78	57	517,09	-74,26	0,00	442,82
80	637	82	12	73	52	526,37	-56,79	-1,74	467,84
90	713	47	102	74	67	255,93	-51,83	-12,50	191,60
100	649	72	0	65	59	427,81	-38,88	0,00	388,93
200	838	71	153	64	153	60,31	-6,94	-2,13	51,24
			Discounted sum over 200 years			8825,19	-2487,17	-46,00	6292,02

Table B.22: Young Stand. BA : 23,40 m^2. A2 Scenario. NoCC Mortality Scenario (μ1).

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Net revenue from timber sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1404	0	0	190	62	0,00	-690,65	0,00	-690,65
10	1258	85	0	172	66	568,72	-488,04	0,00	80,68
20	1094	98	0	145	59	1754,22	-334,40	0,00	1419,82
30	925	110	0	162	52	1049,32	-224,45	0,00	824,87
40	904	131	0	133	52	981,13	-179,48	0,00	801,64
50	881	104	0	106	53	718,94	-143,02	0,00	575,92
60	827	107	0	85	49	741,46	-109,41	0,00	632,05
70	770	93	0	85	46	497,07	-83,25	0,00	413,82
80	738	89	17	86	42	573,00	-65,38	-2,60	505,01
90	797	58	73	83	48	389,11	-58,06	-8,98	322,08
100	841	78	86	80	49	465,39	-50,49	-8,70	406,20
200	1117	140	280	25	76	105,90	-9,72	-3,89	92,29
			Discounted sum over 200 years			9886,67	-2654,71	-56,96	7175,01

Table B.23: Young Stand. BA : 23,40 m^2. A2 Scenario. B2 Mortality Scenario (μ1).

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Net revenue from timber sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1404	0	0	190	62	0,00	-690,65	0,00	-690,65
10	1250	93	0	171	68	573,19	-483,93	0,00	89,26
20	1084	98	0	144	62	1754,22	-330,79	0,00	1423,43
30	907	115	0	163	55	1077,64	-219,61	0,00	858,03
40	887	129	0	133	57	970,51	-175,52	0,00	794,99
50	859	103	0	106	59	703,63	-139,00	0,00	564,63
60	806	99	0	83	57	692,35	-106,49	0,00	585,86
70	734	99	0	84	52	523,30	-79,29	0,00	444,01
80	716	85	35	82	51	552,75	-63,45	-5,28	484,02
90	784	54	91	81	60	347,61	-57,06	-11,15	279,39
100	807	74	76	76	62	455,14	-48,26	-7,67	399,21
200	1109	112	200	37	144	91,00	-9,63	-2,79	78,58
			Discounted sum over 200 years			9595,00	-2613,91	-64,93	6916,15

Appendix C: Chapter 5 Optimization Results

*The reproduction expresses the number of seedlings that can be selected for upgrowth for the forest manager. The number of trees in period t+10 is given by the number of trees in period t minus the number of dead trees in period t and the number of logged trees in period t+10, plus the number of seedlings selected for upgrowth.

Table C.1: Young Stand. BA : 23,40 m^2. NoCC Scenario.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Dead trees caused by fire (%)	Forest fire occurrence (%)	Net benefit (€/ha)
0	1365	39	0	182	54	26,71	29,42	-32,02
10	922	21	0	124	35	11,84	27,39	86,84
20	776	0	0	112	34	0,94	26,28	-225,97
30	686	56	0	127	32	0,32	25,03	770,92
40	706	72	0	107	36	0,73	29,02	695,27
50	686	85	0	86	35	1,01	29,61	684,60
60	664	67	0	72	34	1,15	29,34	464,61
70	621	72	0	73	31	1,14	28,54	506,26
80	603	52	0	74	30	1,24	28,10	340,67
90	581	59	0	71	27	1,32	27,45	354,96
100	571	45	0	69	26	1,50	27,13	309,77
200	528	37	0	65	23	1,38	27,20	211,37
							Discounted sum over 200 years	5053,18

Table C.2: Young Stand. BA : 23,40 m^2. B2 Scenario.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Dead trees caused by fire (%)	Forest fire occurrence (%)	Net benefit (€/ha)
0	1365	39	0	182	54	28,01	32,36	-27,65
10	886	20	0	120	34	13,65	29,94	88,49
20	730	0	0	105	33	1,15	28,55	-212,41
30	750	45	0	120	41	0,93	31,32	633,40
40	763	60	0	102	46	1,03	32,84	651,92
50	722	87	0	82	45	1,05	32,59	747,38
60	683	67	0	79	44	1,04	32,07	544,22
70	659	71	19	77	42	1,20	31,62	551,54
80	664	54	33	76	45	1,46	31,43	384,45
90	655	60	30	71	44	1,53	30,84	417,58
100	677	43	48	72	48	1,75	30,91	296,96
200	943	68	169	74	106	1,54	33,57	57,42
							Discounted sum over 200 years	5540,79

Table C.3: Young Stand. BA : 23,40 m^2. A2 Scenario.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Dead trees caused by fire (%)	Forest fire occurrence (%)	Net benefit (€/ha)
0	1364	40	0	182	54	29,64	34,41	-19,70
10	861	19	0	117	33	14,87	31,71	84,94
20	698	0	0	100	33	1,28	30,09	-203,18
30	715	41	0	115	42	1,01	33,02	590,55
40	722	60	0	97	48	1,13	34,57	685,26
50	683	79	0	78	49	1,14	34,36	688,77
60	673	60	30	75	53	1,34	34,27	523,26
70	685	66	65	72	57	1,84	33,88	520,39
80	694	53	61	70	62	2,14	33,33	416,17
90	677	60	51	66	60	2,10	32,50	446,77
100	680	43	55	70	64	2,14	32,49	318,67
200	1094	87	326	64	244	2,41	35,68	71,58
							Discounted sum over 200 years	5561,16

Table C.4: Mature Stand. BA : 47.81 m^2. NoCC Scenario.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Dead trees caused by fire (%)	Forest fire occurrence (%)	Net benefit (€/ha)
0	1093	305	0	193	53	0,49	27,35	2018,82
10	892	142	0	159	44	0,36	25,10	1289,43
20	736	148	0	127	36	0,36	25,91	936,17
30	716	109	0	103	37	0,67	29,42	898,02
40	704	73	0	85	37	0,87	29,96	732,40
50	657	88	0	71	34	0,96	29,33	637,74
60	616	70	0	72	30	1,10	28,48	622,14
70	593	56	0	73	30	1,23	27,86	373,87
80	570	58	0	70	27	1,35	27,06	437,75
90	557	47	0	67	25	1,61	26,56	403,12
100	549	40	0	66	23	1,80	26,62	377,56
200	522	36	0	64	23	1,36	27,16	38,14
							Discounted sum over 200 years	9746,58

Table C.5: Mature Stand. BA : 47.81 m^2. B2 Scenario.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Dead trees caused by fire (%)	Forest fire occurrence (%)	Net benefit (€/ha)
0	1096	302	0	193	53	0,57	30,09	2012,76
10	897	140	0	159	46	0,41	27,67	1256,99
20	857	144	0	126	49	0,73	32,79	875,20
30	814	112	0	102	48	0,94	33,43	925,48
40	779	80	0	83	49	1,05	33,15	811,33
50	712	92	0	83	44	1,02	32,19	699,53
60	673	69	0	83	42	1,09	31,57	637,03
70	670	66	30	79	44	1,38	31,24	445,62
80	645	63	14	73	41	1,42	30,44	525,12
90	614	53	0	69	38	1,38	30,09	510,08
100	622	37	22	74	40	1,47	30,76	312,89
200	951	73	174	73	107	1,46	33,36	61,64
							Discounted sum over 200 years	10334,20

Table C.6: Mature Stand. BA : 47.81 m^2. A2 Scenario.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Dead trees caused by fire (%)	Forest fire occurrence (%)	Net benefit (€/ha)
0	1094	304	0	192	53	0,60	32,01	2003,80
10	893	141	0	159	47	0,43	29,42	1271,90
20	857	144	0	126	52	0,81	34,98	878,99
30	810	113	0	101	53	1,02	35,52	936,33
40	769	79	0	82	54	1,12	35,14	816,58
50	694	92	0	81	50	1,09	34,04	721,45
60	684	63	31	80	53	1,40	33,86	584,03
70	691	66	56	75	58	1,83	33,32	457,84
80	684	62	53	68	58	2,16	32,47	536,35
90	636	55	12	66	51	1,84	32,03	557,06
100	631	37	31	71	54	1,83	32,71	314,46
200	1099	85	326	62	245	2,30	35,56	74,12
							Discounted sum over 200 years	10438,24

Table C.7: Very Young Stand. BA : 0.88 m^2. NoCC Scenario.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Dead trees caused by fire (%)	Forest fire occurrence (%)	Net benefit (€/ha)
0	1802	0	0	2	45	19,05	20,19	-991,71
10	1414	0	0	1	31	16,15	18,24	-572,07
20	1153	1	0	0	30	5,30	17,51	-355,35
30	1062	0	0	190	36	0,60	18,09	-264,42
40	992	27	0	177	47	0,23	18,86	-171,61
50	861	220	0	127	45	0,55	29,09	253,75
60	775	163	0	95	41	0,83	30,75	322,16
70	699	123	0	71	37	0,98	30,13	344,90
80	631	94	0	70	32	1,03	28,84	345,45
90	589	73	0	71	29	1,17	27,64	323,89
100	566	57	0	70	27	1,38	26,64	298,09
200	504	34	0	62	22	1,35	26,92	38,19
							Discounted sum over 200 years	732,52

Table C.8: Very Young Stand. BA : 0.88 m^2. B2 Scenario.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Dead trees caused by fire (%)	Forest fire occurrence (%)	Net benefit (€/ha)
0	1802	0	0	2	45	20,95	22,21	-991,71
10	1379	1	0	0	32	16,65	19,46	-551,85
20	1117	1	0	0	30	5,59	19,20	-342,88
30	1024	0	0	183	38	0,62	19,81	-252,97
40	980	0	0	169	54	0,24	20,81	-196,83
50	879	214	0	119	56	0,69	33,20	282,83
60	775	161	0	89	52	0,87	33,99	369,33
70	729	116	41	67	52	1,13	33,52	372,44
80	734	89	89	70	54	1,58	32,36	364,26
90	723	74	60	69	53	1,75	30,76	382,71
100	692	64	32	69	48	1,68	29,45	400,81
200	927	55	160	77	103	1,65	33,77	51,33
							Discounted sum over 200 years	1371,75

Table C.9: Very Young Stand. BA : 0.88 m^2. A2 Scenario.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Dead trees caused by fire (%)	Forest fire occurrence (%)	Net benefit (€/ha)
0	1802	0	0	2	45	23,62	29,42	-991,71
10	1355	1	0	0	32	20,68	27,39	-538,69
20	1084	1	0	0	31	20,36	26,28	-330,20
30	990	0	0	177	40	20,95	25,03	-242,86
40	985	0	0	167	61	28,37	29,02	-198,02
50	885	201	0	117	66	35,77	29,61	274,22
60	771	157	0	86	63	36,00	29,34	384,18
70	768	111	93	68	69	35,75	28,54	364,47
80	770	87	105	69	74	34,12	28,10	380,08
90	751	74	78	65	73	32,39	27,45	413,55
100	706	65	46	68	66	31,17	27,13	443,18
200	1079	82	305	66	237	36,14	26,84	61,75
							Discounted sum over 200 years	1511,99

Table C.10: Partially Managed Young Stand. BA : 23,40 m^2. NoCC Scenario.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Dead trees caused by fire (%)	Forest fire occurrence (%)	Net benefit (€/ha)
0	1404	0	0	81	62	27,41	29,66	0
10	1038	0	0	96	46	15,98	28,74	0
20	922	0	0	111	49	2,42	29,22	0
30	961	0	0	30	69	0,89	30,75	0
40	914	0	0	0	85	0,54	31,23	0
50	824	0	0	0	95	0,36	31,01	0
60	726	0	0	0	97	0,25	30,45	0
70	628	0	0	0	90	0,17	29,50	0
80	537	0	0	0	79	0,12	28,29	0
90	457	0	0	0	67	0,08	26,95	0
100	389	0	0	0	56	0,06	25,58	0
200	102	0	0	0	11	0,00	14,54	0
							Discounted sum over 200 years	0

Table C.11: Partially Managed Young Stand. BA : 23,40 m^2. B2 Scenario.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Dead trees caused by fire (%)	Forest fire occurrence (%)	Net benefit (€/ha)
0	1404	0	0	81	62	27,41	29,66	0
10	1038	0	0	96	48	15,98	28,74	0
20	920	0	0	110	53	2,33	29,23	0
30	956	0	0	23	76	0,86	30,77	0
40	894	0	0	0	96	0,50	31,08	0
50	793	0	0	0	109	0,33	30,71	0
60	682	0	0	0	109	0,21	29,84	0
70	571	0	0	0	99	0,14	28,49	0
80	471	0	0	0	84	0,09	26,84	0
90	387	0	0	0	68	0,05	25,09	0
100	319	0	0	0	55	0,03	23,36	0
200	66	0	0	5	8	0,03	12,66	0
							Discounted sum over 200 years	0

Table C.12: Partially Managed Young Stand. BA : 23,40 m^2. A2 Scenario.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Dead trees caused by fire (%)	Forest fire occurrence (%)	Net benefit (€/ha)
0	1404	0	0	81	62	27,41	29,66	0
10	1038	0	0	96	50	15,98	28,74	0
20	919	0	0	110	56	2,31	29,22	0
30	951	0	0	23	84	0,85	30,75	0
40	881	0	0	0	108	0,50	30,99	0
50	769	0	0	0	122	0,31	30,41	0
60	645	0	0	0	120	0,20	29,24	0
70	524	0	0	0	105	0,12	27,51	0
80	418	0	0	0	85	0,07	25,51	0
90	333	0	0	0	67	0,04	23,47	0
100	266	0	0	0	52	0,02	21,52	0
200	71	0	0	9	14	0,26	16,33	0
							Discounted sum over 200 years	0

Table C.13: Partially Managed Mature Stand. BA : 47.81 m^2. NoCC Scenario.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Dead trees caused by fire (%)	Forest fire occurrence (%)	Net benefit (€/ha)
0	1398	0	0	0	110	0,51	30,54	0
10	1280	0	0	0	142	0,34	30,98	0
20	1134	0	0	0	157	0,25	30,88	0
30	974	0	0	0	150	0,18	30,15	0
40	822	0	0	0	130	0,13	29,01	0
50	691	0	0	0	108	0,09	27,71	0
60	582	0	0	0	89	0,07	26,38	0
70	493	0	0	0	73	0,05	25,10	0
80	420	0	0	0	60	0,03	23,88	0
90	360	0	0	0	50	0,02	22,71	0
100	310	0	0	0	41	0,02	21,60	0
200	90	0	0	0	9	0,00	12,72	0
						Discounted sum over 200 years		0

Table C.14: Partially Managed Mature Stand. BA : 47.81 m^2. B2 Scenario.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Dead trees caused by fire (%)	Forest fire occurrence (%)	Net benefit (€/ha)
0	1398	0	0	0	110	0,51	30,54	0
10	1280	0	0	0	147	0,34	30,98	0
20	1129	0	0	0	168	0,25	30,85	0
30	958	0	0	0	162	0,18	30,00	0
40	794	0	0	0	141	0,12	28,65	0
50	653	0	0	0	116	0,08	27,11	0
60	537	0	0	0	94	0,06	25,53	0
70	443	0	0	0	75	0,04	24,00	0
80	367	0	0	0	61	0,02	22,52	0
90	306	0	0	0	49	0,02	21,11	0
100	257	0	0	0	40	0,01	19,77	0
200	64	0	0	7	8	0,09	13,99	0
						Discounted sum over 200 years		0

Table C.15: Partially Managed Mature Stand. BA : 47.81 m^2. A2 Scenario.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Dead trees caused by fire (%)	Forest fire occurrence (%)	Net benefit (€/ha)
0	1398	0	0	0	110	0,51	30,54	0
10	1280	0	0	0	153	0,34	30,98	0
20	1124	0	0	0	178	0,24	30,79	0
30	943	0	0	0	173	0,17	29,80	0
40	768	0	0	0	149	0,12	28,24	0
50	619	0	0	0	121	0,08	26,48	0
60	497	0	0	0	96	0,05	24,70	0
70	401	0	0	0	76	0,03	22,98	0
80	324	0	0	0	61	0,02	21,33	0
90	264	0	0	0	48	0,01	19,77	0
100	216	0	0	0	39	0,01	18,30	0
200	69	0	0	9	14	0,27	16,11	0
						Discounted sum over 200 years		0

Table C.16: Young Stand. BA : 23,40 m^2. NoCC Scenario. Not Adaption to Fire Risk.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Dead trees caused by fire (%)	Forest fire occurrence (%)	Net benefit (€/ha)
0	1404	0	0	0	62	27,41	29,66	-690,65
10	824	134	0	0	31	8,05	27,33	194,63
20	647	76	0	0	23	1,08	25,18	1223,03
30	544	73	0	0	19	0,43	23,12	634,86
40	392	129	0	0	12	0,22	19,78	964,84
50	346	33	0	64	11	0,15	18,64	135,32
60	365	33	0	66	14	0,80	25,78	196,06
70	331	83	0	63	12	2,09	27,05	432,31
80	309	65	0	68	10	6,99	26,17	418,12
90	342	0	0	64	12	12,34	25,87	-29,66
100	292	60	0	73	9	9,53	23,68	359,78
200	271	8	0	73	7	21,03	24,24	6,98
						Discounted sum over 200 years		4342,04

Table C.17: Young Stand. BA : 23,40 m^2. B2 Scenario. Not Adaption to Fire Risk.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Dead trees caused by fire (%)	Forest fire occurrence (%)	Net benefit (€/ha)
0	1404	0	0	0	62	27,41	29,66	-690,65
10	853	105	0	0	34	8,14	27,38	248,37
20	671	76	0	0	26	0,97	25,22	1122,53
30	552	86	0	0	22	0,38	23,01	722,82
40	412	115	0	78	15	0,20	20,03	873,31
50	415	59	0	76	17	1,30	26,39	302,44
60	435	32	0	78	21	2,15	27,77	201,50
70	383	100	0	75	17	3,63	26,94	583,40
80	382	42	0	77	17	8,80	26,05	291,74
90	376	30	0	74	17	9,97	25,25	158,02
100	318	74	0	87	12	10,18	23,94	527,75
200	386	11	0	117	20	21,27	25,42	8,31
							Discounted sum over 200 years	4735,84

Table C.18: Young Stand. BA : 23,40 m^2. A2 Scenario. Not Adaption to Fire Risk.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Dead trees caused by fire (%)	Forest fire occurrence (%)	Net benefit (€/ha)
0	1404	0	0	0	62	27,41	29,66	-690,65
10	862	96	0	0	35	8,15	27,38	288,87
20	675	79	0	0	28	0,95	25,22	1065,06
30	543	97	0	0	23	0,37	22,88	791,30
40	413	105	0	77	18	0,20	20,07	793,50
50	399	72	0	75	19	1,28	26,35	398,29
60	421	27	0	75	24	2,40	27,64	166,00
70	358	104	0	75	19	3,99	26,67	638,85
80	366	30	0	74	21	9,95	25,94	211,65
90	345	35	0	71	21	9,55	24,93	205,07
100	288	72	0	114	14	10,55	24,05	552,18
200	371	14	0	155	34	23,23	25,83	6,72
							Discounted sum over 200 years	4792,16

Table C.19: Mature Stand. BA : 47.81 m^2. NoCC Scenario. Not Adaption to Fire Risk.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Dead trees caused by fire (%)	Forest fire occurrence (%)	Net benefit (€/ha)
0	1089	309	0	0	53	0,48	27,35	2006,98
10	888	142	0	0	43	0,31	25,11	1290,93
20	688	154	0	29	33	0,21	23,38	992,49
30	572	111	0	107	27	0,24	24,35	955,11
40	579	71	0	103	28	0,67	28,71	734,72
50	559	91	0	85	27	1,15	29,20	684,91
60	545	64	0	69	25	1,74	28,45	579,55
70	513	65	0	72	23	2,12	27,14	428,87
80	489	61	0	72	20	3,13	25,85	481,00
90	474	51	0	70	17	5,22	25,11	457,57
100	472	27	0	67	17	7,07	25,47	259,67
200	467	28	0	73	17	4,74	26,55	28,51
							Discounted sum over 200 years	9672,68

Table C.20: Mature Stand. BA : 47.81 m^2. B2 Scenario. Not Adaption to Fire Risk.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Dead trees caused by fire (%)	Forest fire occurrence (%)	Net benefit (€/ha)
0	1087	311	0	0	53	0,48	27,36	1992,01
10	886	142	0	0	45	0,31	25,13	1291,23
20	690	149	0	126	36	0,21	23,45	960,76
30	663	115	0	124	36	0,62	28,81	995,68
40	669	76	0	101	39	1,09	29,98	802,58
50	628	96	0	83	36	1,40	29,14	760,16
60	603	62	0	84	35	1,61	28,28	543,95
70	561	80	0	86	31	0,00	26,96	595,87
80	541	63	0	97	28	2,96	26,12	556,21
90	544	48	0	76	27	4,64	26,51	489,54
100	521	44	0	74	24	4,41	27,23	353,51
200	587	49	0	110	54	1,06	26,12	36,31
							Discounted sum over 200 years	10250,16

Table C.21: Mature Stand. BA : 47.81 m^2. A2 Scenario. Not Adaption to Fire Risk.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Dead trees caused by fire (%)	Forest fire occurrence (%)	Net benefit (€/ha)
0	1084	314	0	0	52	0,48	27,35	1991,44
10	884	142	0	0	46	0,31	25,13	1292,49
20	685	150	0	126	38	0,21	23,42	975,83
30	655	116	0	122	39	0,63	28,77	1007,89
40	658	75	0	100	44	1,11	29,89	800,23
50	609	98	0	81	40	1,44	28,96	802,03
60	578	62	0	106	40	1,71	28,03	533,90
70	556	77	0	100	38	2,54	26,87	596,75
80	535	66	0	91	34	4,38	25,95	621,67
90	527	38	0	98	34	5,85	26,34	395,99
100	519	39	0	99	34	5,71	27,42	335,54
200	323	40	0	60	39	2,83	22,74	33,34
							Discounted sum over 200 years	10337,52

Table C.22: Very Young Stand. BA : 0.88 m^2. NoCC Scenario. Not Adaption to Fire Risk.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Dead trees caused by fire (%)	Forest fire occurrence (%)	Net benefit (€/ha)
0	1802	0	0	0	45	19,02	20,18	-991,71
10	1414	0	0	0	34	16,14	18,24	-572,31
20	778	374	0	0	20	2,67	17,54	-251,77
30	738	0	0	0	25	0,73	17,58	-176,01
40	475	233	0	93	17	0,22	16,80	197,89
50	217	334	0	100	7	6,52	27,50	741,86
60	171	115	0	74	6	10,30	21,89	403,28
70	213	0	0	71	7	24,08	24,80	-35,60
80	226	0	0	57	8	24,67	25,70	-29,82
90	219	0	0	3	8	24,00	25,53	-24,19
100	161	0	0	41	6	18,11	23,03	-18,00
200	221	5	0	53	23	12,22	22,99	13,48
							Discounted sum over 200 years	-614,99

Table C.23: Very Young Stand. BA : 0.88 m^2. B2 Scenario. Not Adaption to Fire Risk.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Dead trees caused by fire (%)	Forest fire occurrence (%)	Net benefit (€/ha)
0	1802	0	0	0	45	19,02	20,18	-991,71
10	1414	0	0	0	33	16,14	18,24	-572,31
20	835	318	0	0	20	2,95	17,62	-265,92
30	790	0	0	108	25	0,71	17,73	-188,77
40	597	271	0	116	21	1,98	26,93	213,35
50	355	324	0	119	11	10,21	27,25	671,61
60	279	134	0	72	7	14,39	25,83	442,50
70	290	0	0	76	8	24,98	26,03	-40,48
80	286	0	0	61	8	24,80	26,26	-32,96
90	268	0	0	95	8	23,68	25,84	-26,25
100	291	0	0	69	10	23,52	25,80	-22,39
200	260	11	0	74	13	17,15	23,62	13,18
						Discounted sum over 200 years		-600,78

Table C.24: Very Young Stand. BA : 0.88 m^2. A2 Scenario. Not Adaption to Fire Risk.

Year	Number of trees	Logged trees	Planted trees	Reproduction	Dead trees	Dead trees caused by fire (%)	Forest fire occurrence (%)	Net benefit (€/ha)
0	1802	0	0	0	45	19,02	20,18	-991,71
10	1414	0	0	0	34	16,14	18,24	-572,31
20	845	307	0	0	22	2,99	17,63	-267,89
30	797	0	0	143	28	0,69	17,76	-190,64
40	620	286	0	121	25	3,02	28,06	236,63
50	374	320	0	116	14	11,44	26,92	684,73
60	296	123	0	67	9	15,44	26,20	417,74
70	295	0	0	77	10	24,88	26,08	-40,80
80	289	0	0	61	11	24,73	26,37	-33,16
90	268	0	0	84	11	23,34	25,85	-26,25
100	279	0	0	65	13	22,83	25,71	-21,92
200	203	13	0	64	17	18,86	23,24	10,59
						Discounted sum over 200 years		-512,33

Appendix D: Chapter 6 Optimization Results

*The reproduction expresses the number of seedlings that can be selected for upgrowth for the forest manager. The number of trees in period t+10 is given by the number of trees in period t minus the number of dead trees in period t and the number of logged trees in period t+10, plus the number of seedlings selected for upgrowth.

*For the optimization process of this analysis, a different but comparable real Young Stand has been used.

Table D.1: Young Stand. BA : 24,22 m^2. NoCC Scenario. Carbon Price of 0€.

Year	Number of trees	Logged trees	Planted trees	Carbon in the forest ecosystem (Tm/ha)	Net revenue from timber sale (€/ha)	Net revenue from carbon sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1855	0	0	142,71	0,00	0	1036,25	0,00	-1036,25
10	1462	306	0	143,55	418,37	0	599,32	0,00	-180,95
20	1107	280	0	137,92	1432,14	0	339,31	0,00	1092,83
30	935	114	0	137,91	961,08	0	227,29	0,00	733,78
40	755	131	0	134,86	944,55	0	147,70	0,00	796,85
50	617	99	0	130,76	870,09	0	100,04	0,00	770,05
60	544	49	5	134,29	472,50	0	73,71	1,12	397,68
70	464	126	73	127,81	572,36	0	53,50	13,26	505,60
80	575	34	167	136,56	113,38	0	51,93	24,98	36,47
90	539	77	73	134,62	42,46	0	10,19	1,45	30,82
100	552	60	102	132,77	0,00	0	1036,25	0,00	-1036,25
150	417	6	39	107,40	418,37	0	599,32	0,00	-180,95
				Discounted sum over 200 years	7517,56	0	2789,39	68,07	4660,10

Table D.2: Young Stand. BA : 24,22 m^2. NoCC Scenario. Carbon Price of 40€.

Year	Number of trees	Logged trees	Planted trees	Carbon in the forest ecosystem (Tm/ha)	Net revenue from timber sale (€/ha)	Net revenue from carbon sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1855	0	0	143	0,00	0,00	1036,25	0,00	-1036,25
10	1731	37	0	155	21,06	339,97	765,70	0,00	-404,68
20	1416	190	0	153	1703,69	464,77	470,40	0,00	1698,06
30	1175	146	0	154	1045,25	181,14	300,33	0,00	926,06
40	962	133	0	155	881,14	151,82	192,72	0,00	840,24
50	800	98	0	156	784,27	135,87	128,72	0,00	791,42
60	890	79	222	161	433,60	47,75	118,65	49,43	313,27
70	936	79	190	166	405,30	254,64	103,03	34,72	522,19
80	998	55	191	170	401,41	5,29	91,12	28,58	287,00
90	979	70	132	173	359,52	78,49	73,05	16,24	348,72
100	981	56	139	176	319,78	71,34	60,11	13,97	317,04
150	972	40	68	177	207,77	-16,43	22,08	2,55	166,71
				Discounted sum over 200 years	7500,53	2041,98	3521,85	183,23	5837,43

Table D.3: Young Stand. BA : 24,22 m^2. A2 Scenario. Carbon Price of 0€.

Year	Number of trees	Logged trees	Planted trees	Carbon in the forest ecosystem (Tm/ha)	Net revenue from timber sale (€/ha)	Net revenue from carbon sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1846	9	0	142,36	9,12	0,00	1028,93	0,00	-1019,82
10	1458	302	0	144,11	324,80	0,00	597,47	0,00	-272,68
20	1190	184	0	138,38	1579,21	0,00	372,22	0,00	1206,99
30	976	140	0	134,37	1095,91	0,00	238,90	0,00	857,01
40	775	136	0	127,79	1025,03	0,00	151,80	0,00	873,24
50	625	97	0	120,57	914,30	0,00	101,16	0,00	813,14
60	685	91	193	120,83	373,16	0,00	90,33	42,92	239,91
70	694	100	165	115,25	538,30	0,00	75,03	30,09	433,19
80	764	59	190	115,90	320,95	0,00	67,77	28,39	224,79
90	764	85	159	109,54	447,87	0,00	55,55	19,55	372,77
100	778	68	158	101,48	426,85	0,00	46,44	15,90	364,51
150	930	80	258	82,45	159,56	0,00	20,99	9,66	128,90
		Discounted sum over 200 years			8285,04	0,00	2959,82	180,88	5144,34

Table D.4: Young Stand. BA : 24,22 m^2. A2 Scenario. Carbon Price of 40€.

Year	Number of trees	Logged trees	Planted trees	Carbon in the forest ecosystem (Tm/ha)	Net revenue from timber sale (€/ha)	Net revenue from carbon sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1855	0	0	142,71	0,00	0,00	1036,25	0,00	-1036,25
10	1763	5	0	155,50	102,17	367,24	787,03	0,00	-317,62
20	1338	300	0	151,28	1620,22	278,93	435,14	0,00	1464,00
30	1087	153	0	148,96	1108,29	126,32	272,12	0,00	962,49
40	856	144	0	143,77	1010,89	54,05	168,81	0,00	896,14
50	994	75	283	144,51	638,97	209,93	164,34	76,64	607,92
60	1044	123	272	145,72	441,87	84,70	143,07	60,42	323,08
70	1208	61	343	148,87	462,50	231,88	141,01	62,55	490,83
80	1204	78	231	144,11	686,72	-10,88	115,17	34,54	526,13
90	1284	57	296	141,78	548,16	75,95	102,88	36,38	484,86
100	1269	90	259	135,95	470,10	39,79	83,08	26,08	400,73
150	1420	149	435	110,87	160,68	8,20	35,98	16,30	116,60
		Discounted sum over 200 years			8586,23	1471,50	3697,92	387,80	5972,01

Table D.5: Mature Stand. BA : 47.81 m^2. NoCC Scenario. Carbon Price of 0€.

Year	Number of trees	Logged trees	Planted trees	Carbon in the forest ecosystem (Tm/ha)	Net revenue from timber sale (€/ha)	Net revenue from carbon sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1127	271	0	158,89	2651,00	0,00	516,00	0,00	2135,00
10	929	142	0	151,43	1611,85	0,00	335,00	0,00	1276,86
20	728	154	0	146,11	1195,21	0,00	211,63	0,00	983,58
30	575	117	0	140,30	1154,90	0,00	139,65	0,00	1015,25
40	520	91	63	139,74	657,40	0,00	105,61	20,99	530,80
50	525	83	113	136,78	706,90	0,00	87,24	30,68	588,97
60	531	66	99	132,78	665,36	0,00	72,26	22,09	571,00
70	554	46	95	133,97	379,43	0,00	61,30	17,41	300,72
80	547	58	80	129,90	494,89	0,00	49,82	12,02	433,05
90	521	47	49	124,33	454,99	0,00	39,31	5,96	409,72
100	466	42	11	115,76	446,00	0,00	29,63	1,07	415,29
150	503	47	66	122,11	97,95	0,00	11,65	2,48	83,82
		Discounted sum over 200 years			11179,72	0,00	1732,80	124,82	9322,09

Table D.6: Mature Stand. BA : 47.81 m^2. NoCC Scenario. Carbon Price of 40€.

Year	Number of trees	Logged trees	Planted trees	Carbon in the forest ecosystem (Tm/ha)	Net revenue from timber sale (€/ha)	Net revenue from carbon sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1228	170	0	163,77	2498,59	0,00	576,56	0,00	1922,03
10	1032	130	0	160,49	1450,41	260,43	379,43	0,00	1331,40
20	832	140	0	159,77	1056,01	257,79	243,16	0,00	1070,63
30	841	94	151	161,87	879,52	324,45	201,78	60,73	941,45
40	890	72	177	164,80	796,32	286,81	176,27	58,51	848,35
50	960	68	202	170,56	562,05	328,42	157,71	54,76	678,00
60	979	69	162	174,39	606,60	274,63	132,35	36,14	712,74
70	989	58	147	177,59	573,52	136,72	109,90	26,81	573,54
80	999	51	143	179,12	548,76	150,27	91,26	21,34	586,43
90	1031	45	159	181,19	448,77	149,68	77,76	19,54	501,16
100	1024	50	129	181,11	414,15	132,51	63,27	13,03	470,36
150	933	60	115	171,26	126,67	-12,72	21,06	4,29	88,60
		Discounted sum over 200 years			11171,99	2291,47	2376,30	319,10	10768,07

Table D.7: Mature Stand. BA : 47.81 m^2. A2 Scenario. Carbon Price of 0€.

Year	Number of trees	Logged trees	Planted trees	Carbon in the forest ecosystem (Tm/ha)	Net revenue from timber sale (€/ha)	Net revenue from carbon sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1131	267	0	158,95	2655,67	0,00	518,55	0,00	2137,12
10	933	142	0	151,54	1611,43	0,00	336,68	0,00	1274,74
20	728	154	0	145,05	1203,78	0,00	211,78	0,00	992,00
30	569	118	0	136,86	1188,41	0,00	138,40	0,00	1050,00
40	598	93	155	133,32	675,82	0,00	118,60	51,37	505,85
50	646	82	171	127,39	749,75	0,00	104,23	46,35	599,18
60	672	69	145	119,38	759,91	0,00	88,74	32,19	638,99
70	705	54	140	116,62	457,14	0,00	76,23	25,51	355,39
80	700	64	118	107,21	636,27	0,00	62,06	17,69	556,53
90	655	57	71	94,04	642,14	0,00	47,84	8,75	585,55
100	689	38	123	86,70	407,24	0,00	41,13	12,38	353,73
150	810	61	168	87,10	169,09	0,00	18,00	6,28	144,81
				Discounted sum over 200 years	11905,24	0,00	1869,04	235,98	9800,22

Table D.8: Mature Stand. BA : 47.81 m^2. A2 Scenario. Carbon Price of 40€.

Year	Number of trees	Logged trees	Planted trees	Carbon in the forest ecosystem (Tm/ha)	Net revenue from timber sale (€/ha)	Net revenue from carbon sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1231	167	0	164,11	2472,20	0,00	577,95	0,00	1894,26
10	1030	133	0	160,35	1489,15	254,46	378,66	0,00	1364,96
20	814	152	0	156,57	1155,91	197,47	237,62	0,00	1115,75
30	907	92	239	155,93	886,34	300,16	219,40	96,17	870,93
40	1011	71	249	156,74	808,72	317,14	204,34	82,43	839,10
50	1061	88	236	156,41	732,66	251,45	177,83	63,88	742,40
60	1139	71	262	156,01	697,63	249,10	159,33	58,39	729,02
70	1168	69	233	151,97	773,98	78,27	135,01	42,59	674,65
80	1258	59	294	149,31	625,26	148,62	121,99	44,08	607,80
90	1153	76	142	138,75	725,46	74,87	89,40	17,48	693,45
100	1204	57	258	129,36	595,67	10,13	77,56	26,04	502,21
150	1380	122	382	111,86	202,49	-6,38	34,58	14,29	147,25
				Discounted sum over 200 years	12277,76	1787,54	2628,80	530,98	10905,52

Table D.9: Young Stand. BA : 24,22 m^2. NoCC Scenario. Carbon Price of 0€. Initial Soil Carbon of 50 Tons.

Year	Number of trees	Logged trees	Planted trees	Carbon in the forest ecosystem (Tm/ha)	Net revenue from timber sale (€/ha)	Net revenue from carbon sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1855	0	0	92,71	0,00	0,00	1036,25	0,00	-1036,25
10	1466	302	0	110,16	401,22	0,00	601,64	0,00	-200,42
20	1105	281	0	115,66	1431,12	0,00	338,67	0,00	1092,45
30	936	112	0	122,99	971,93	0,00	227,62	0,00	744,31
40	756	131	0	125,00	942,85	0,00	147,89	0,00	794,96
50	618	99	0	124,38	867,08	0,00	100,18	0,00	766,90
60	540	49	0	129,77	492,91	0,00	73,20	0,00	419,70
70	509	100	96	129,87	451,99	0,00	57,33	17,50	377,16
80	566	52	135	134,39	282,07	0,00	51,25	20,28	210,53
90	546	80	91	133,86	322,09	0,00	40,80	11,16	270,13
100	559	61	103	132,23	290,34	0,00	34,12	10,43	245,79
150	419	6	38	107,66	41,08	0,00	10,22	1,42	29,44
		Discounted sum over 200 years			7530,96	0,00	2795,66	68,71	4666,59

Table D.10: Young Stand. BA : 24,22 m^2. NoCC Scenario. Carbon Price of 40€. Initial Soil Carbon of 50 Tons.

Year	Number of trees	Logged trees	Planted trees	Carbon in the forest ecosystem (Tm/ha)	Net revenue from timber sale (€/ha)	Net revenue from carbon sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1855	0	0	92,71	0,00	0,00	1036,25	0,00	-1036,25
10	1718	50	0	121,31	28,09	320,44	757,54	0,00	-409,01
20	1419	188	0	130,43	1703,19	460,47	471,54	0,00	1692,12
30	1176	146	0	138,95	1046,53	176,01	300,75	0,00	921,79
40	963	133	0	144,64	881,14	149,24	192,93	0,00	837,45
50	801	98	0	148,77	778,04	136,12	128,95	0,00	785,20
60	859	80	192	156,00	442,03	46,13	114,07	42,64	331,45
70	946	65	216	162,07	420,03	163,86	104,28	39,48	440,13
80	972	68	169	167,44	386,43	53,24	88,39	25,35	325,93
90	983	65	155	172,18	336,32	89,89	73,47	18,98	333,77
100	991	56	145	175,77	320,02	79,48	60,85	14,57	324,08
150	976	40	74	176,77	205,95	-16,44	22,19	2,78	164,53
		Discounted sum over 200 years			7493,24	1989,08	3511,30	180,94	5790,09

Table D.11: Young Stand. BA : 24,22 m^2. A2 Scenario. Carbon Price of 0€. Initial Soil Carbon of 50 Tons.

Year	Number of trees	Logged trees	Planted trees	Carbon in the forest ecosystem (Tm/ha)	Net revenue from timber sale (€/ha)	Net revenue from carbon sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1846	9	0	92,33	9,82	0,00	1028,37	0,00	-1018,55
10	1457	302	0	110,24	336,60	0,00	596,79	0,00	-260,19
20	1192	181	0	115,71	1579,79	0,00	373,20	0,00	1206,58
30	975	139	0	119,01	1093,03	0,00	238,55	0,00	854,48
40	774	136	0	117,42	1025,22	0,00	151,60	0,00	873,61
50	624	98	0	113,52	917,69	0,00	101,01	0,00	816,67
60	661	90	170	116,04	372,25	0,00	87,40	37,84	247,02
70	683	98	174	111,97	529,28	0,00	73,90	31,72	423,66
80	762	57	196	113,74	313,20	0,00	67,54	29,28	216,38
90	722	87	121	107,75	459,11	0,00	52,49	14,89	391,73
100	724	65	138	100,31	413,06	0,00	43,17	13,92	355,97
150	682	44	137	87,07	120,73	0,00	15,14	5,13	100,46
	Discounted sum over 200 years				8208,40	0,00	2930,25	158,35	5119,80

Table D.12: Young Stand. BA : 24,22 m^2. A2 Scenario. Carbon Price of 40€. Initial Soil Carbon of 50 Tons.

Year	Number of trees	Logged trees	Planted trees	Carbon in the forest ecosystem (Tm/ha)	Net revenue from timber sale (€/ha)	Net revenue from carbon sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1855	0	0	92,71	0,00	0,00	1036,25	0,00	-1036,25
10	1741	27	0	122,11	15,07	360,63	772,69	0,00	-396,99
20	1334	304	0	128,47	1620,03	271,96	433,32	0,00	1458,67
30	1086	153	0	133,69	1104,49	128,26	271,80	0,00	960,96
40	855	144	0	133,44	1012,51	53,71	168,56	0,00	897,66
50	997	74	285	137,59	641,93	212,69	164,84	77,32	612,46
60	1060	121	284	141,27	435,67	95,02	145,69	63,11	321,89
70	1196	64	320	145,42	488,21	221,19	139,23	58,45	511,72
80	1198	76	232	141,79	671,53	-11,10	114,42	34,81	511,21
90	1265	57	283	140,06	539,85	84,18	100,89	34,76	488,38
100	1252	87	254	135,32	455,77	48,13	81,58	25,58	396,73
150	1425	297	710	125,46	21,11	62,49	36,16	26,57	20,86
	Discounted sum over 200 years				8344,95	1555,97	3677,80	393,54	5829,59

Table D.13: Young Stand. BA : 24,22 m^2. NoCC Scenario. Variable Carbon Market.

Year	Number of trees	Logged trees	Planted trees	Carbon in the forest ecosystem (Tm/ha)	Net revenue from timber sale (€/ha)	Net revenue from carbon sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1842	13	0	142,20	13,24	0,00	1025,63	0,00	-1012,38
10	1411	346	0	134,59	1058,70	-43,90	570,43	0,00	444,37
20	924	414	0	130,32	729,34	-148,33	273,40	0,00	307,62
30	778	105	0	133,08	609,11	-41,41	185,82	0,00	381,88
40	672	91	0	137,07	550,30	173,79	131,81	0,00	592,27
50	753	56	184	136,72	509,57	279,15	120,99	49,99	617,73
60	918	53	259	150,45	166,50	404,30	122,83	57,57	390,40
70	948	97	187	160,89	250,28	697,21	104,63	34,17	808,68
80	996	172	293	175,94	109,03	417,76	90,90	43,90	391,99
90	1185	41	314	192,93	156,23	679,71	92,56	38,52	704,86
100	1358	171	461	215,68	14,02	812,39	91,06	46,47	688,88
150	1470	141	106	281,87	76,97	156,58	37,78	3,97	191,80
Discounted sum over 200 years					4257,65	6477,51	3125,61	398,34	7211,20

Table D.14: Young Stand. BA : 24,22 m^2. B2 Scenario. Variable Carbon Market.

Year	Number of trees	Logged trees	Planted trees	Carbon in the forest ecosystem (Tm/ha)	Net revenue from timber sale (€/ha)	Net revenue from carbon sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1827	28	0	141,58	29,23	0,00	1012,88	0,00	-983,65
10	1406	337	0	135,10	955,42	-46,25	567,73	0,00	341,44
20	962	399	0	130,73	771,63	-174,37	286,23	0,00	311,03
30	821	98	0	129,95	880,20	-29,53	196,69	0,00	653,98
40	660	153	36	134,78	387,46	186,26	129,64	11,91	432,17
50	838	54	231	131,86	448,19	349,85	135,37	62,61	600,06
60	1063	60	343	141,18	205,84	437,90	146,23	76,42	421,08
70	1229	71	310	142,83	427,63	524,01	144,24	56,57	750,82
80	1181	239	296	151,90	214,14	404,81	112,37	44,25	462,32
90	1306	239	490	170,61	35,07	778,32	105,23	60,23	647,93
100	1599	197	672	194,84	6,32	958,21	114,63	67,73	782,17
150	2116	245	1026	285,12	1,53	288,04	65,17	38,42	185,98
Discounted sum over 200 years					5040,26	6033,75	3425,15	633,41	7015,46

Table D.15: Young Stand. BA : 24,22 m^2. B2 Scenario. 550 ppm Timber Price Scenario.

Year	Number of trees	Logged trees	Planted trees	Carbon in the forest ecosystem (Tm/ha)	Net revenue from timber sale (€/ha)	Net revenue from carbon sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1550	305	0	137,24	18,34	0,00	794,23	0,00	-775,90
10	1483	0	0	146,53	0,00	0,00	611,77	0,00	-611,77
20	1242	156	0	134,17	2812,07	0,00	393,59	0,00	2418,48
30	1040	132	0	134,56	1019,32	0,00	257,84	0,00	761,48
40	821	156	0	126,14	1480,55	0,00	161,30	0,00	1319,25
50	692	166	85	118,74	982,85	0,00	111,18	23,12	848,55
60	638	154	141	109,62	734,09	0,00	84,59	31,43	618,06
70	851	0	248	123,24	0,00	0,00	92,55	45,31	-137,86
80	589	220	21	95,61	1094,36	0,00	52,96	3,21	1038,19
90	439	142	24	65,30	722,02	0,00	34,60	3,01	684,41
100	421	0	0	66,27	0,00	0,00	27,61	0,00	-27,61
150	653	76	102	95,56	142,60	0,00	14,53	3,84	124,23
		Discounted sum over 200 years			9268,56	0,00	2722,31	137,24	6409,01

Table D.16: Y.Stand. BA : 24,22 m^2. B2 Scenario. Variable Carbon Market. 550 ppm Timber Price Scenario.

Year	Number of trees	Logged trees	Planted trees	Carbon in the forest ecosystem (Tm/ha)	Net revenue from timber sale (€/ha)	Net revenue from carbon sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1550	305	0	137,24	18,34	0,00	794,23	0,00	-775,90
10	1448	35	0	138,24	855,04	-34,28	591,35	0,00	229,41
20	1184	183	0	126,42	2233,44	-112,78	369,74	0,00	1750,92
30	994	135	0	125,92	1021,11	-69,71	244,04	0,00	707,36
40	807	128	0	120,12	1264,61	53,82	158,35	0,00	1160,08
50	728	142	105	119,58	696,79	191,13	116,82	28,57	742,53
60	1003	89	407	122,97	438,31	481,44	136,28	90,64	692,82
70	1359	0	428	144,33	0,00	400,85	165,06	78,18	157,61
80	1104	157	44	132,19	977,10	614,56	103,15	6,65	1481,86
90	947	286	226	145,99	24,83	1443,88	70,30	27,70	1370,70
100	1509	0	656	171,09	0,00	1010,65	105,46	66,14	839,06
150	1687	197	647	235,58	7,50	289,94	46,10	24,23	227,11
	Discounted sum over 200 years				8005,56	5147,84	3194,74	455,23	9503,43

Table D.17: Young Stand. BA : 24,22 m^2. A2 Scenario. Variable Carbon Market.

Year	Number of trees	Logged trees	Planted trees	Carbon in the forest ecosystem (Tm/ha)	Net revenue from timber sale (€/ha)	Net revenue from carbon sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1753	102	0	138,55	108,15	0,00	951,20	0,00	-843,05
10	1474	201	0	131,23	1190,93	-73,50	606,29	0,00	511,15
20	1034	460	0	126,37	651,66	-181,39	312,16	0,00	158,10
30	852	133	0	124,33	801,40	-50,71	204,78	0,00	545,92
40	694	109	0	120,77	863,11	62,08	135,92	0,00	789,27
50	915	107	370	129,03	162,77	437,74	149,23	100,40	350,87
60	1132	84	345	132,88	272,95	436,75	158,17	76,72	474,81
70	1224	110	297	134,97	361,13	500,64	143,52	54,25	664,00
80	1191	273	381	147,10	129,14	505,43	113,64	57,05	463,88
90	1386	214	578	166,92	14,82	870,27	114,15	71,04	699,90
100	1692	167	743	191,79	9,51	1025,43	124,56	74,86	835,52
150	2436	22	2000	320,51	242,85	215,72	81,72	74,87	301,98
Discounted sum over 200 years					4829,32	6849,50	3599,08	840,42	7239,32

Table D.18 Young Stand. BA : 24,22 m^2. A2 Scenario. 550 ppm Timber Price Scenario.

Year	Number of trees	Logged trees	Planted trees	Carbon in the forest ecosystem (Tm/ha)	Net revenue from timber sale (€/ha)	Net revenue from carbon sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1855	0	0	142,71	0,00	0,00	1036,25	0,00	-1036,25
10	1504	263	0	147,61	184,53	0,00	624,30	0,00	-439,77
20	1263	149	0	144,28	1815,84	0,00	402,65	0,00	1413,20
30	1013	165	0	137,09	1625,98	0,00	249,72	0,00	1376,26
40	795	148	0	128,76	1336,99	0,00	156,00	0,00	1180,99
50	691	102	52	122,22	1040,92	0,00	111,09	14,12	915,71
60	732	122	212	118,22	605,01	0,00	96,36	47,08	461,57
70	741	97	165	112,85	614,01	0,00	80,01	30,05	503,94
80	818	58	199	114,29	355,23	0,00	72,79	29,82	252,62
90	819	88	168	108,00	541,19	0,00	59,79	20,66	460,74
100	835	70	167	99,89	515,35	0,00	50,07	16,86	448,42
150	1003	81	260	86,24	187,95	0,00	22,91	9,72	155,32
Discounted sum over 200 years					10045,89	0,00	3086,51	208,17	6751,21

Table D.19: Y.Stand. BA : 24,22 m^2. A2 Scenario. Variable Carbon Market. 550 ppm Timber Price Scenario.

Year	Number of trees	Logged trees	Planted trees	Carbon in the forest ecosystem (Tm/ha)	Net revenue from timber sale (€/ha)	Net revenue from carbon sale (€/ha)	Maintenance cost (€/ha)	Planting cost (€/ha)	Net benefit (€/ha)
0	1855	0	0	142,71	0,00	0,00	1036,25	0,00	-1036,25
10	1439	329	0	142,17	436,99	-34,18	586,26	0,00	-183,45
20	1222	125	0	132,08	2257,91	-131,08	385,56	0,00	1741,26
30	987	164	0	125,06	1369,11	-93,74	241,97	0,00	1033,39
40	799	127	0	118,56	1201,75	24,55	156,77	0,00	1069,53
50	878	118	247	119,55	547,88	190,12	142,47	66,94	528,59
60	1099	93	381	122,73	487,03	336,60	152,41	84,75	586,47
70	1342	68	415	128,90	449,92	510,73	162,24	75,72	722,69
80	1516	74	403	133,01	537,02	285,83	157,86	60,39	604,60
90	1344	251	278	135,87	439,82	372,33	109,45	34,11	668,60
100	1636	245	863	164,52	26,58	838,47	118,60	87,00	659,45
150	1999	267	1319	255,91	0,29	389,12	59,61	49,38	280,42
Discounted sum over 200 years					8339,26	4702,01	3667,64	674,91	8698,72

Appendix E: Symbols

Symbol	Definition
i	Cohort
t	Calendar time
T	End of the planning horizon
L_i	Average diameter at breast height in cohort i
L_0	Minimum “vital” diameter of trees
L_m	Maximum diameter that trees can reach
$X_i(t)$	Number of trees in the cohort at time t
$E(t)$	Competition between individuals (basal area)
$g(\cdot)$	Change in diameter of the tree over time
$\rho(\cdot)$	Reproduction function of a fertile tree
$\mu_1(\cdot)$	Instantaneous mortality rate
$\mu_2(\cdot)$	Wildfire mortality
$\pi(\cdot)$	Net benefit function
$P(t)$	Number of planted young trees with diameter L_0
$X_0(t)$	Ingrowth
$U_i(t)$	Logged trees
$X_i^0(t)$	Initial number of trees in cohort i
$\theta(l)$	Beta density function
BA and BA_i	Basal area and basal area in cohort i respectively
p_{TIM}	Price of timber per m^3
c_H	Harvesting cost
c_N	Cost of planting young trees
v_{TOT}	Total volume of a tree
v_M	Marketable part of the volume of timber of each tree
F	Probability of fire occurrence
Dg	Basal area weighted mean diameter
Sd	Standard deviation of the diameter distribution
Dq	Quadratic mean diameter
P_{dead}	Indicator of the level of trees affected by a wildfire
P_{surv}	Surviving trees

$B(t)$	Amount of sequestered carbon in the biomass
$V(t)$	Aboveground volume of the biomass
$S(t)$	Amount of sequestered carbon in the soil
$W(t)$	Amount of carbon stored in wood products
$C_{p_c=0}(t)$	Carbon reference level
$\delta(\cdot)$	Rate of change of carbon sequestered in wood products
LT	Permanence time of carbon in wood products
$\omega(\cdot)$	Release function of carbon in wood products
υ	Share of the sequestered carbon in the biomass that is released between *t* and *t+LT* from the wood product expressed in terms of year *t*
p_C	Carbon price

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