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Effects of changes in land-use, age-structure and management on carbon dynamics of European forests

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Academic dissertation

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ABSTRACT

In European forests, carbon storage has increased uninterruptedly during the last 60 years, but the contribution of multiple factors affecting the carbon dynamics is not clear. The main aim of this research was to study effects of changes in land-use, age-structure and management on carbon dynamics of European forests. The specific research tasks were: i) to reconstruct the age-structure of European forests beginning in 1950, by combining available national inventory data with state-of-the-art backcasting, and to study how the mean forest age has changed since the 1950´s (Paper I); ii) to evaluate the role of afforestation on the development of mean forest age and effects of changes in forest area and structure (both age-structure and age/volume relationship) on the development of forest carbon stocks in two European case study countries (Paper II); iii) to quantify the effects of rotation length on the carbon stocks of forests (trees, soil) and wood products, and to estimate the effects of changing rotation length on climate change mitigation (Paper III), and iv) to quantify the average CO_2 emissions from wildfires in Mediterranean countries, and estimate the potential of prescribed burning to mitigate CO_2 emissions (Paper IV).

Results show that in European forests, the share of old forests (>100 years) has decreased from 21% in 1950 to 16% in 2010, and the mean age has decreased from 62 to 59 years (Paper I). However, there exists large variation in these results at country level. In two case study countries, Finland and Czech Republic, the development of mean age was affected by afforestation, although it did not change the observed trend of mean age. In both countries, the increase of mean growing stock volume had a larger effect on the increase of forest biomass carbon stock than afforestation (Paper II). In this work, it was also found that the average carbon stocks of tree biomass could be increased by increasing the rotation length. However, this may in some cases decrease carbon stocks of soil and wood products (Paper III). In Mediterranean countries, the use of prescribed burning could also decrease the emissions from forest fires, affecting considerably also the carbon balance of the LULUCF sector (Paper IV).

Despite the uncertainties related to employed data and models, this work provided valuable insights on the effects of changes in land-use, age-structure and management on the carbon dynamics of European forests. In overall, the increase of forest carbon stocks can be largely explained by the smaller harvests compared to forest growth, but the contribution of different factors varies significantly between the countries. Findings of this work call for more systematic and accurate estimation of the carbon dynamics and balance of European forests, and factors explaining them, in order to better estimate and utilize the possibilities offered by European forests for climate change mitigation.

Keywords: European forests, carbon stock, forest age structure, forest management, climate change mitigation

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Kitee, February 2015
Terhi Vilén

LIST OF ORIGINAL ARTICLES

This dissertation consists of a summary and the four following articles, which are referred to by their Roman numerals in the text. The articles I, III and IV are reprinted with the kind permission of the publishers, while article II is the author's version of the submitted manuscript.

I Vilén T., Gunia K., Verkerk P.J., Seidl R., Schelhaas M.J., Lindner M, Bellassen V. (2012). Reconstructed forest age structure in Europe 1950-2010. Forest Ecology and Management 286: 203-218.
http:dx.doi: 10.1016/j.foreco.2012.08.048

II Vilén T., Cienciala E., Schelhaas M.J., Verkerk P.J., Lindner, M., Peltola, H. (2014). Effects of afforestation, changes in growing stock volume and forest age structure on the forest biomass carbon stock between 1950 and 2010: a comparative study for Finland and the Czech Republic. Submitted manuscript.

III Kaipainen T., Liski J., Pussinen A., Karjalainen T. (2004). Managing carbon sinks by changing rotation length in European forests. Environmental Science & Policy 7 (3): 205-219.
http:dx.doi: 10.1016/j.envsci.2004.03.001

IV Vilén T., Fernandes P.M. (2011). Forest fires in Mediterranean countries: CO_2 emissions and mitigation possibilities through prescribed burning. Environmental Management 48: 558-567.
http:dx.doi: 10.1007/s00267-011-9681-9

Terhi Vilén (former Kaipainen) was the main and responsible author of the all four articles. Co-authors have participated in the work mainly by commenting the manuscript and supporting data analysis. In addition, Katja Gunia produced the maps and Hans Verkerk conducted the statistical comparison of the backcasting methods in Article I and Paulo M. Fernandes analyzed the forest fire data from Portugal and based on that, produced the prescribed burning scenarios for the Article IV.

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LIST OF TERMS AND ABBREVIATIONS

Afforestation	Establishment of a forest or stand of trees in an area where there was no forest
BEF	Biomass Expansion Factor
CAI	Current Annual Increment, the growth observed in a tree or stand in a specific one-year period, m^3 ha^{-1} yr^{-1}
Carbon sink	A carbon sink is a natural or artificial reservoir that accumulates and stores some carbon-containing chemical compound. The process by which carbon sinks remove carbon dioxide (CO_2) from the atmosphere is known as carbon sequestration.
Carbon stock	The quantity of carbon contained in a "pool", meaning a reservoir or system which has the capacity to accumulate or release carbon. In the context of forests it refers to the amount of carbon stored in the world's forest ecosystem, mainly in living biomass and soil, but to a lesser extent also in dead wood and litter.
Combustion factor	Fraction of biomass exposed to fire that is actually consumed
CO_2	Carbon dioxide
Deforestation	Long-term or permanent removal of forest cover and conversion to a non-forested land use
Eligible carbon sink	The largest sinks eligible under Article 3.4 of the Kyoto Protocol
Emission factor	Weight of released CO_2 per weight of dry matter burned
FOLU	Forestry and Other Land Use
GHG	Greenhouse Gas
IPCC	Intergovernmental Panel on Climate Change
Kyoto Protocol	An international agreement linked to the United Nations Framework Convention on Climate Change, which commits its Parties by setting internationally binding emission reduction targets.
LULUCF	Land Use, Land-Use Change and Forestry
Normal forest	Idea of a norm or standard forest structure against which existing forest structures can be compared. A normal forest is a forest composed of even-aged fully-stocked stands representing a balance of age classes such that for a specified rotation period, one age class can be harvested in each year. At the end of the rotation, the stands that were harvested first in the cycle would be ready for harvesting again.
NPP	Net Primary Production
UNFCCC	United Nations Framework Convention on Climate Change
Wood density	Mass of wood per unit volume, Mg m^3

1 INTRODUCTION

1.1 Background of the research

Rising concentrations of atmospheric CO_2 is widely agreed to result in a globally changed climate in the future (Cubasch et al. 2013; Peters et al. 2013). Terrestrial ecosystems like forests have a critical role in the global carbon cycle and in mitigating anthropogenic climate change, as they sequester CO_2 and other greenhouse gases from atmosphere. The current global carbon stock of forests is estimated to be 861 ± 66 Pg C and their annual net carbon sink 1.1 ± 0.8 Pg C (Pan et al. 2011). However, between 1750 and 2011, forestry and other land use (FOLU) accounted about a third of global anthropogenic CO_2 emissions, mainly due to deforestation (IPCC 2014), and human induced land-use changes are the second largest contributor to atmospheric CO_2 emissions, following the fossil fuel combustion (Van der Werf et al. 2009).

European forests have been an almost uninterrupted carbon sink during the last six decades (Nabuurs et al. 2003; Ciais et al. 2008; Bellassen et al. 2011). That is partly due to a drastic change that has happened in the European forests; between 1950 and 2000 the forest area increased by 30% (Gold 2003) due to abandonment of low-productive agricultural lands and active afforestation in some countries. Land-abandonment, i.e. forest transition (Mather and Needle 1998) has affected remarkably the carbon sequestration especially in Eastern Europe, where transformation from socialist to market economy has led to the abandonment of large areas of formerly cultivated croplands (e.g. Schierhorn et al. 2013; Masný and Zaušková 2014). However, also in other parts of Europe, low productive agricultural lands have been abandoned due to agricultural adjustment to land-quality, which has made the abandonment areas available for reforestation through natural regeneration or planting (Mather and Needle 1998).

In addition to increased forest area, also the net annual increment has increased substantially (cf. Spiecker et al. 1996) and the growing stock in European forests has almost doubled (Gold et al. 2006). There are multiple factors affecting the forest carbon sink, such as age-structure, forest management and environmental factors, but the contributions of different factors is not yet clear (Magnani et al. 2007; Ciais et al. 2008; De Schrijver et al. 2008; de Vries et al. 2008). However, it is postulated that the global forest carbon sink is mainly driven by changes in atmospheric CO_2 concentration and in nitrogen deposition (Bellassen and Luyssaert 2014). Recently, first signs of the saturation of the European forest carbon sink have been recognized although the carbon sink was projected to last still for decades (Nabuurs et al. 2013). After six decades of increasing stem volume increment, the increment rate is decreasing (Forest Europe et al., 2011), land-use is intensifying and natural disturbances are increasing (Seidl et al. 2014), which increase also the CO_2 emissions. Thus, to sustain the carbon sink, growth and carbon stocks of forests in the future, we may need to adapt forest management. This could also help to decrease the risk of natural disturbances leading to large CO_2 emissions.

Several forest management strategies can be used in adapting to and mitigation of climate change (Brown et al. 1996). Existing carbon stocks can be maintained by avoiding deforestation and degradation and through decreasing the risk of disturbances. Carbon sequestration can be enhanced by afforestation and reforestation, and by forest management activities that increase the forest growth and the carbon stocks in existing forests. Those forest management activities include, e.g. use of proper site-specific species, improved seed and seedling material in regeneration, fertilization and proper thinning regimes and rotation lengths. However, since in addition to in situ carbon stocks, also off situ carbon, i.e. carbon in wood products and substitution of fossil fuels and carbon intensive materials have influence on climate change mitigation. The life cycle of the wood products also affects to the potential of climate change mitigation, e.g. logwood used in construction creates a long-term carbon stock while the biomass from younger forests are primarily used for products with shorter life span. Thus, it is not easy to decide the best strategy to manage forests to mitigate climate change (Bellassen and Luyssaert 2014).

In European forestry, forest management has been recognized as one of the key drivers of the current and future carbon sink (Ciais et al. 2008; Eggers et al. 2008; Kellomäki et al. 2008). However, the current and future forest structure, carbon sink and mitigation potential are much dependent on the timing and intensity of management and harvest interventions. The use of relatively heavy thinnings and nitrogen fertilization with shorter rotations will in general increase the forest growth rate and amount of harvested timber and forest biomass (e.g., Routa et al. 2011a, b, 2012; Pyörälä et al. 2014). On the other hand, use of less heavy thinnings and longer rotations may be more optimal in storing carbon in managed forest ecosystems (e.g., Routa et al. 2011a, b, 2012; Pyörälä et al. 2014). Furthermore, after clear felling, the rate of decomposition of slash on the ground is higher than accumulation of carbon in the vegetation and soil and forests act as a carbon source for some years before they turn into sinks again due to carbon sequestration of the regrowing vegetation and accumulation of carbon in the soil and coarse woody debris (e.g. Janisch and Harmon 2002; Jarvis et al. 2005; Zerva et al. 2005). In maturing stands the carbon gain is again reduced along with the declining growth and over-mature stands may even lose carbon (Jarvis et al. 2005). On the other hand, old-growth forests can also accumulate carbon for centuries (Luyssaert et al. 2008) if disturbances do not occur. In the future, the concurrent elevation of mean annual temperature and atmospheric CO_2 together with changes in precipitation are likely to affect forest growth and carbon sequestration and stocks, too.

Also the United Nations Framework Convention on Climate Change (UNFCCC 1997) recognized the huge potential of forests could offer for carbon sequestration and storage as well. In Kyoto in 1997, the European Community together with 37 industrialized countries committed to decrease their greenhouse gas (GHG) emissions by an average of 5% from the base year 1990 emissions in the first commitment period of the Protocol, 2008-2012. During the second commitment period, from 2013 to 2020, Parties committed to reduce GHG emissions by at least 18 percent below 1990 levels. Already in Kyoto in 1997, the conference of the parties to the climate convention (UNFCCC 1997) identified also a limited set of activities in forests that will be permitted in order to help countries to achieve their agreed emission reductions. Such activities included direct human-induced land-use change and forestry activities limited to afforestation, reforestation and deforestation under the Article 3.3 of the Protocol and additional human induced land-use change and forestry activities under the article 3.4. In 2011, the Conference of the Parties (COP17, in Durban) also considered the Article 3.4 forest management activities to be mandatory for the parties of the Conference in the second commitment period starting in 2013 (FCCC 2012).

The appropriate choice of rotation length (time from the establishment of a forest stand to its final felling) is considered to be an effective forest management activity for controlling the carbon stocks of forests (Cooper 1983; Karjalainen 1996; Liski et al. 2001;

Harmon and Marks 2002; Pussinen et al. 2002). Rotation length affects the carbon stocks of both trees and soil and, through the effects on the quantity and the quality of harvested timber, also on the carbon stock of wood products. A change in rotation length is also seen as a forest management activity that countries may choose to apply under Article 3.4 of the Kyoto Protocol to help them meet their commitments for reduction of greenhouse gas emissions (UNFCCC 1997, 2001a; IPCC 2000). However, estimates of the effects of rotation length on the carbon stocks of forests are scarce, especially those that account for the dynamics between the different stocks of forest carbon in different forest types.

In addition to maintaining the growth and forest carbon stock, it is essential to modify forest management in order to avoid large scale disturbances that have been increasing all over Europe (Schelhaas et al. 2003; Seidl et al. 2011; Seidl et al. 2014). Storms and fires are the most important abiotic disturbances in European forests. In the period 1950-2000, an annual average of 35 million m^3 wood was damaged by disturbances (i.e. 8% of the total fellings in Europe), from which storms were responsible for 53% of the total damage and fire for 16% (Schelhaas et al. 2003). Since 1990, several storms have caused large damages in European forests, resulting to considerable carbon releases (Lindroth et al. 2009). Currently, each year about 500 000 ha of forest is affected by fire in Europe (European Commission 2011) and large fires are a remarkable source of greenhouse gases especially in the Mediterranean region (Barbosa et al. 2008). Prescribed burning can be used to manage fuel loads in forests (e.g., Fernandes and Botelho 2004; Fernandes et al. 2004). It decreases the intensity of wildfires by disrupting the horizontal and vertical continuity of the fuel complex (Fernandes and Botelho 2003). As a by-product, prescribed burning could also result in a net reduction of CO_2 emissions from forest fires. Fire emissions have been thoroughly studied in different parts of the world, but few studies have considered prescribed burning in the context of carbon emissions mitigation.

To improve the estimation of the forest carbon balance and to attribute the forest carbon sink to different factors, data on land-use change, development of age structure and effects of forest management is needed. That data is also important in quantifying the additionality of management measures compared to the long-term carbon dynamics resulting from age-structure, which is an essential issue in the context of the climate change mitigation. Namely, the Kyoto Protocol requires the forest management practices under Article 3.4 to be additional, i.e. the net sequestration or greenhouse gas emission savings should be larger compared to a baseline situation.

1.2 Aims of the research

The main aim of this research was to study effects of changes in land-use, age-structure and management on carbon dynamics of European forests. The specific aims for different sub-research tasks in Papers I-IV were:

•to reconstruct the age-structure of European forests from 1950, by combining available national inventory data with state-of-the-art backcasting and to study how the forest mean age has changed since the 1950´s (Paper I),

•to evaluate what is the role of afforestation on the development of forest mean age and what are the implications of the change in the forest area and structure (both age-structure and age/volume relationship) on the development of forest carbon stocks in selected European countries (Paper II),

•to quantify the effects of rotation length on the carbon stocks of forests (trees, soil and wood products), and to estimate the efficiency of change in rotation length in mitigating the climate change (Paper III), and

•to quantify the average CO_2 emissions from wildfires in Mediterranean countries and to estimate the potential of prescribe burning to mitigate emissions (Paper IV)

2 MATERIALS AND METHODS

2.1 Reconstructing the forest age-structure in Europe 1950 – 2010 (Paper I)

Approach

In this study, country level historical age-class data was combined with a backcasting method to reconstruct the age-class structure for 25 European countries from 1950 to 2010. Based on the results, dynamic maps of forest age-class distributions on 0.25° x 0.25° grid were generated, and the change in the forest age structure analyzed.

Data

National forest inventory reports and international statistics (UNECE and FAO 1985, 1990, 2000; Schelhaas et al. 2006; Forest Europe et al. 2011) were utilized to gather historical and current forest age-class distribution data from 1950 to present. To make the different inventories comparable, a uniform distribution of forest area within age-classes was assumed, data was divided into one-year age-classes and forest area was reallocated into comparable age-classes. Since only a small number of countries have inventory data from 1950 onwards, missing data and gaps between the inventories had to be reconstructed.

The backcasting approach by Seidl et al. (2011) was used to fill in the gaps between the inventory years as well as reconstruct the missing data from the last inventory until 1950. This approach is a simple age-class distribution backcasting method borrowing from the matrix model concept of EFISCEN (Schelhaas et al. 2007). Starting from reported age class distributions (class width n years) at the end of the study period (MCPFE 2007) and assuming uniform distribution of forest area within each age class, 1/n of each age-class area is transferred to the previous age class per backcasted year. Area from the first age class is routed to higher age classes assuming a country-specific age pattern of stand-replacing harvests, as used in the continental scale EFISCEN simulations by Verkerk et al. (2011). Annual changes in forest area are accounted for by updating the area routed from/to the first age class, i.e. decreases in forest area are assumed to result from land-use change after stand-replacing harvest and increases are assumed to stem from afforestation. In this study, reconstructions were done on country level, pooled for all tree species.

Analysis

The reconstructed country level age-class distributions were then used to calculate the age-class distribution in 1950 and 2010, the share of young and old forests, and the development of mean age from 1950 to 2010 in 25 European countries: EU 27 (excluding Greece, Cyprus, Malta and Spain) and Norway and Switzerland. The reconstruction assumes a uniform distribution of forest area within each age class. To compare assimilating historical data into backcasting to using only a single inventory year as backcasting starting point, the age structure over Europe was calculated both 1) using inventory data when available and only filling the gaps by means of backcasting and 2) reconstructing the age structure using only the latest inventory data as a starting point and applying backcasting over the full study period. For subsequent mapping and analysis of continental scale forest age trends the former approach (backcasting with data assimilation) was used.

2.2 Estimating the effect of afforestation and increased mean volumes of growing stock to the development of forest carbon stock (Paper II)

Approach

To study the effects of afforestation, development of mean growing stock volumes and forest structure on the development of forest carbon stock, two case study countries, Finland and Czech Republic, were used. In this work, forest inventory data and national forestry statistics (Paper II, Table 1) were utilized to calculate how the forest area and age-structure have developed in the case study countries. The effect of afforestation on the forest area and forest mean age were studied by combining land-use modelling data from Historic Land Dynamics Assessment (HILDA) v. 2.0 dataset (Fuchs et al. 2013) and forest age-class reconstruction approach by Vilén et al. (2012).

Data

The effects of afforestation on the development of forest area and forest age were studied using gross afforestation data from the HILDA dataset, assuming constant annual afforestation rates for each decade in our study period (i.e. decadal values were divided by 10 to get annual values). Since the age-class is usually reported for even-aged, productive forests, it does not include all forests like the HILDA dataset does. To avoid overestimating the effect of afforestation, we calculated the relationship between the total forest areas from age-class data and HILDA-dataset and used that relationship as a correction factor to adjust the afforestation areas (see Paper II, Tables 2 and 3). These afforestation areas were then traced from 1950 onwards and excluded from age-class data that were reconstructed using the approach by Vilén et al. (2012) to find out how the forest area and age structure would have developed without afforestation. Then, these reconstructions were used to calculate the development of forest area, age-structure and mean age in Finland and the Czech Republic with and without afforestation.

Historical inventory data was used to study how the age-dependent mean volumes have changed since the 1950. For both case study countries, the growing stock (i.e. stem volume per age-class) was first converted into biomass using basic wood density (IPCC 2003). When species level data was available, species specific dry wood values were used, but if the data was aggregated, average dry wood values were used. Then, stem biomass was converted into total forest biomass (including stem, branches, coarse roots, fine roots and foliage) using biomass expansion factors (BEFs, Lehtonen et al. 2004; Vilén et al. 2005) and total biomass was then converted into carbon stock using a carbon content of 0.5 (IPCC 2003).

Analysis

To find out how afforestation and change of mean volume of growing stock have affected the change of forest biomass carbon stock, we compared the development of forest biomass carbon stock during the last 60 years, which was calculated using both historical inventory data (baseline) and three alternative scenarios: I) age-class structure that was reconstructed assuming no afforestation between 1950 and 2010, mean volume of growing stock from inventory data; II) forest area and age structure from inventory data and the age-specific mean volumes of growing stock from the base year ~1950; and III) age-class structure that was reconstructed assuming no afforestation between 1950 and 2010 and age-specific mean volumes of growing stock from the base year ~1950.

In this scenario analysis, aggregated data for all species was used for both case studies and growing stock data was converted into carbon stock using same conversion factors than in the baseline scenario based on historical inventory data. Results of these scenarios were then compared to the baseline situation, i.e. carbon stock of forest biomass based on historical inventory data, to separate the effects of afforestation and increased growing stock volume on the past development of the carbon stock of forest biomass.

2.3 Studying the effects of rotation length on the carbon stocks of forests (Paper III)

Approach

CO2FIX V2.0 model (Nabuurs et al. 2002; Masera et al. 2003) was used to calculate average carbon stocks over different rotation lengths in Finland, Germany, UK and Spain. In these countries, only tree species having economic importance were studied: Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) forests in Finland and in Germany, Sitka spruce (*Picea sitchensis*) in UK, and Scots pine and Maritime pine (*Pinus pinaster*) in Spain. CO2FIX was parameterized for the simulations as advised in the manual of the model (Masera et al. 2003; Nabuurs et al., 2002), and single cohort, even-aged forests were simulated.

To estimate the effects of changing rotation length from the currently used, differences in the average carbon stocks between the currently recommended and 20-year longer rotation lengths were studied. The annual carbon sinks or sources were estimated by dividing the total difference by 20 years, which is theoretically the shortest time required to reach the new age-class distribution with the increased rotation length. To evaluate the efficiency of increasing rotation length with regard to Article 3.4 of the Kyoto Protocol, only carbon in trees was accounted and the area where rotation length need to be changed to reach the maximum eligible sink (of the first commitment period of Kyoto Protocol) in the countries studied, were estimated (UNFCCC 2001b).

Data

Current annual increment (CAI) was taken from local growth and yield tables (Paper III; Table 1), wood densities were derived from the CO2FIX manual (Nabuurs et al. 2002) and 50% carbon content was assumed for all biomass. To calculate other biomass compartments, i.e. foliage, branches and roots (fine roots are excluded at CO2FIX), the model needs their growth rates relative to the growth of the stem. These relative growth rates were determined by first calculating the biomass of each compartment using biomass equations (Marklund 1988; Ter-Mikaelian and Korzukhin 1997; Gracia et al. 2004) and yield tables, and then calculating the periodic growth and comparing that to the periodic growth of the stem. Turnover coefficients needed for CO2FIX to calculate litter production were derived for foliage from Kellomäki et al. (1992) and for branches and roots from Liski et al. (2002). Thinning regimes were taken from national guidelines for forest management or, if these were not available, they were derived from yield tables (Wiedemann 1949; Falcão, 1998; Canellas et al. 2000; Metsätalouden Kehittämiskeskus Tapio 2001).

General parameters for coniferous forests were used in the soil module (Nabuurs et al. 2002; Karjalainen et al. 2002). Climate data (annual mean temperature (°C) precipitation during the growing season (mm) and potential evapotranspiration during the growing season (mm), see Paper III, Table 4), determining the decomposition rates of soil carbon in the model were derived from a global dataset (http://www.worldclimate.com). Initial soil carbon stocks were calculated and added to the soil module on the basis of preparatory simulations, which were done to determine the mean annual carbon input to forest soil with each rotation length.

Harvested wood was divided into logwood, pulpwood and harvest residues. No logwood until the mean diameter of trees in the stand exceeded 20 cm was assumed, according to the yield table used. Before this, 85% of the harvested wood was pulpwood and the rest was harvest residues. When the mean diameter exceeded 20 cm, 30% of the harvested roundwood was allocated to logwood, 60% to pulpwood, and the rest to soil as harvest residues in thinnings. In final fellings, 60% was allocated to logwood and 30% to pulpwood.

Analysis

To analyze the effect of rotation length, rotation periods at 10-year intervals were simulated and at the end of each rotation the stand was clear-felled. Branches, foliage, roots and 10–15% of stemwood from the thinnings and the final cuttings were transferred to litter, whereas the rest of stemwood was transferred to wood products. To estimate the effects of changing rotation length from the currently used, we studied differences in the average carbon stocks between the currently recommended and 20-year longer rotation lengths. The annual carbon sinks or sources were estimated by dividing the total difference by 20 years, which is theoretically the shortest time required to reach the new age-class distribution with the increased rotation length. To evaluate the efficiency of increasing rotation length with regard to Article 3.4 of the Kyoto Protocol, we accounted for tree carbon only and estimated the area where rotation length need to be changed to reach the maximum eligible sink in the countries studied (UNFCCC 2001b).

2.4 Calculating the CO_2 emissions of forest fires in the Mediterranean region and evaluating the mitigation possibilities through prescribed burning (Paper IV)

Approach

The total amount of burned biomass was calculated as per approach by Seiler and Crutzen (1980), i.e. by multiplying annually burned area by average organic matter per unit area and by efficiency of biomass burning. Burned biomass was then converted into CO_2 emissions by using emission factor, which is the weight of released CO_2 per weight of dry matter burned. By following the IPCC guidelines (IPCC 2006) three fuel components were differentiated: aboveground tree biomass (further separated into foliage and branches), deadwood, and litter. Efficiency of prescribed burning to mitigate fire emissions were calculated using four scenarios of different treatment effort and burning leverage levels based on data from Portugal.

Data

Average annual emissions were calculated using long-term (1980-2008) annual average burned area (European Commission 2009) and mean biomass stocks of each fuel compartments (aboveground biomass, deadwood and litter, FAO 2005) (Paper IV, Table 1). Biomass allocation (Vilén et al. 2005) was then used to calculate the share of foliage and branches biomass from the total aboveground biomass. The Global Forest Resources Assessment data (FAO 2005) for deadwood and litter are given as carbon stocks only, and the values were converted back to dry mass by assuming factors of 0.5 carbon units per fuel weight unit for deadwood (IPCC 2006) and 0.37 for litter (Smith and Heath 2002). The total biomass in the burned area was then calculated by multiplying burned area and the calculated mean biomass stocks of different biomass compartments (foliage, branches, deadwood and litter).

In Mediterranean conditions, the mean combustion factor (the fraction of biomass exposed to fire that is actually consumed) of aboveground tree biomass was assumed to be 1 for foliage and 0.1 for branches in a crown fire (Reinhardt 1997). These factors were adjusted by 0.75 assuming that 75% of the burned area is the resultant of a crown fire. Belowground biomass was assumed to be left unburned. A combustion factor of 0.9 was used for both litter and deadwood, which corresponds to the customary near-complete removal by fire under the Mediterranean dry summer conditions (e.g. Fernandes et al. 2004).

Emission factor is defined as the amount of a released compound per amount of dry fuel consumed, expressed in units of g/kg (Andreae and Merlet 2001). The emission factors from Carvalho et al. (2007) for Mediterranean conditions were used.

Analysis

Prescribed burning will not benefit the carbon balance unless it succeeds in decreasing the area burned by wildfire. This effect is directly quantifiable by determining the leverage (Loehle 2004) or return for effort (Price and Bradstock 2011) of prescribed burning, i.e. the area protected (saved) from wildfire per unit area treated by prescribed fire. In Europe, this analysis is precluded by the absence of long-term prescribed burning programs. However, analysis of past wildfire data can be used to uncover the general effect of fuel reduction (as opposed to weather) on future area burned. Burning leverage was determined using data from Portugal, which is characterized by wide regional variation in fire incidence and variety in land use and land cover (Nunes et al. 2005).

The estimation of the prescribed burning effect considered two levels in treatment effort, 2% and 20% of the mean annual area burned by wildfire, reflecting the current degree of prescribed fire development in Portugal [http://www.afn.min-agricultura.pt] and in France (Lázaro 2010). While the treatment effort in Spain is comparable to Portugal, prescribed fire programs are absent from Greece and Italy. The two levels in treatment effort were combined with the two burn leverage extremes, hence resulting in four emission scenarios for prescribed burning.

Combustion factors for prescribed burning were assumed to be 0.5 for litter and 0.2 for deadwood. Although prescribed burning should not damage overstory trees, a combustion factor of 0.05 was used for foliage biomass to avoid overestimating the mitigation effect of prescribed burning. These combustion factors were based on an extensive database of experimental fires (Fernandes et al. 2009). The mitigation effect of each scenario was then calculated by comparing emissions with and without prescribed burning. To evaluate the effectiveness of prescribed burning in the context of Kyoto Protocol, the emissions mitigation was compared with the year 2007 carbon stock losses of the LULUCF sector, as reported in the 2009 National Inventory submissions for UNFCCC (UNFCCC 2009). The mitigation effect in regards to the Article 3.4 of the Kyoto Protocol was considered by comparing the mitigated wildfire emissions with the Article 3.4 maximum eligible sink of the first commitment period of the Kyoto protocol in the countries studied.

3 RESULTS

3.1 Reconstruction of the forest age-structure in Europe 1950 – 2010 (Paper I)

The total forest area included in the study was 108.4 million ha in 1950 and 118.3 million ha in 2010. Based on our backcasting results, the area of forests under 80 years was larger in 2010 compared to 1950, whereas the area of forests older than 100 years was larger at the beginning of the study period compared to values in 2010 (Fig. 1). The area-weighted mean age over the study area has declined from 62 years in 1950 to 57 years in 1970, but has increased to 59 years in 2000 and has stayed on that level thereafter (Table 1). However, when looking at the change of the mean age from 1950 to 2010 at the country level, there is a large variation between the countries. Change of mean age over this 60 year period varies largely, from decrease of 21 years in Denmark to increase of 19 years in Slovenia. There have also been large changes in mean age in some countries even from 2000 to 2010 (e.g. Estonia, Latvia and Ireland) (Table 1).

The share of young forests (<20 years) in Europe was in 2010 on a similar level as it was in 1950, i.e. approximately 17% of the total forest area (Fig. 1), but peaked during the study period, reaching almost 22% in 1980. The share of old forests (>100 years) has decreased from 21% in 1950 to 17% in 1990, and remained at around that level thereafter.

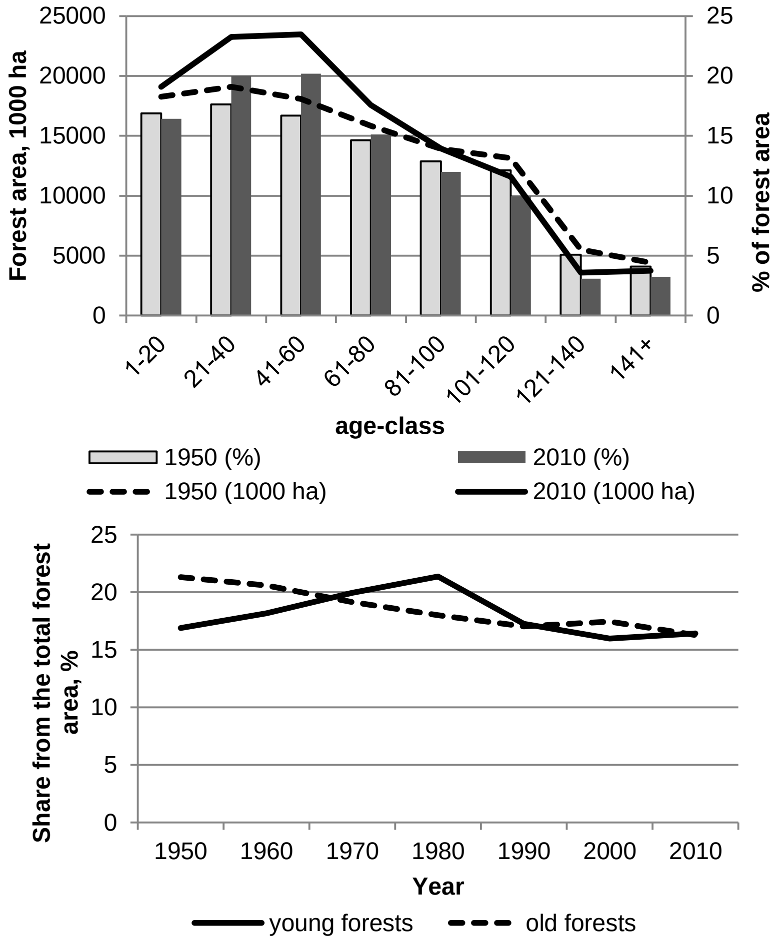


Figure 1 Age-class distribution in European forests in 1950 and 2010 and share of young (<20 years) and old (>100 years) forests on total forest area in Europe for the period 1950-2010.

Table 1 Development of area-weighted mean forest age from 1950 to 2010.

	1950	1960	1970	1980	1990	2000	2010	Change from 1950 to 2010
Austria	65	62	63	63	61	61	59	**-6**
Belgium	54	51	51	44	47	38	36	**-17**
Bulgaria	49	49	46	42	41	48	52	**3**
Czech Republic	51	54	55	59	60	62	64	**13**
Denmark	60	60	58	44	43	43	40	**-21**
Estonia	43	40	42	46	47	53	47	**4**
Finland	80	72	67	66	65	64	61	**-18**
France	73	73	60	52	66	68	72	**-1**
Germany	77	80	79	71	71	67	66	**-11**
Hungary	39	38	39	38	41	36	41	**2**
Ireland	38	36	31	27	25	25	19	**-19**
Italy	41	42	41	35	57	57	59	**17**
Latvia	56	55	54	55	57	61	50	**-6**
Lithuania	55	53	51	50	50	51	53	**-2**
Luxembourg	87	87	85	80	73	82	78	**-9**
Netherlands	43	38	43	35	48	56	56	**13**
Poland	61	54	50	51	53	56	55	**-6**
Portugal	22	22	23	27	29	31		**9***
Romania	58	56	56	51	55	57	60	**1**
Slovakia	57	56	59	60	61	63	64	**7**
Slovenia	66	66	67	70	74	81	84	**19**
Sweden	58	59	60	65	57	56	54	**-4**
United Kingdom	44	43	35	36	43	45	48	**5**
Norway	68	67	66	62	63	70	67	**-1**
Switzerland	87	90	93	88	91	86	85	**-2**
Whole area	**62**	**60**	**57**	**57**	**57**	**59**	**59**	**-3**

3.2 Effects of afforestation and increased mean growing stock volume on the development of forest biomass carbon stock (Paper II)

In both Finland and Czech Republic, the effects of afforestation to the total forest area have been quite on the same level. When excluding afforestation, the forest area in 2010 would have been 10% smaller in Finland and 15% smaller in Czech Republic. Afforestation has affected the development of mean forest age, but it has not changed the trend (Fig. 2). In Finland, the mean age of forests would have decreased also without afforestation, but less than with afforestation and in the Czech Republic, the mean forest age would have increased from the 1950´s both with and without afforestation.

The mean growing stock volume increased since the oldest data in both countries (Fig. 3). However, in Finland it first decreased 29 % from 1952 to 1962 (Fig. 3). In line with the increased mean growing stock volumes, forest biomass carbon stock has increased during the past decades in both case study countries. The increase has been larger in Finland, where carbon stock has increased by 334 Tg C from 554 to 888 Tg C. In the Czech Republic, the increase has been 89 Tg C.

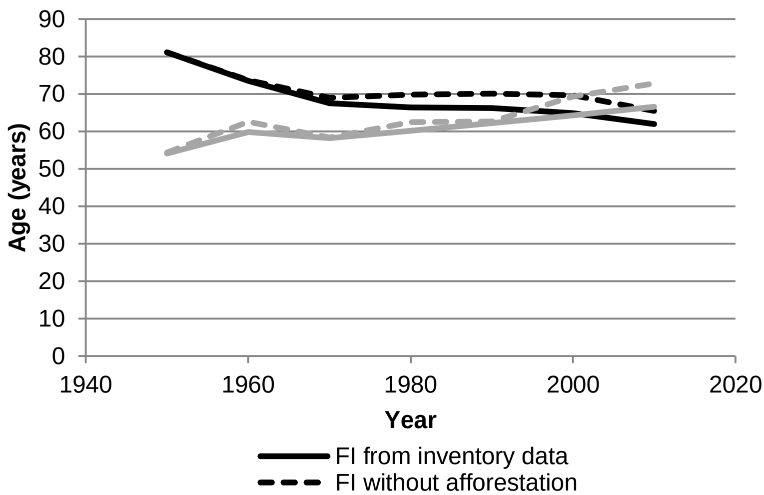


Figure 2 Development of mean forest age in Finland (FI) and Czech Republic (CZ) with and without afforestation.

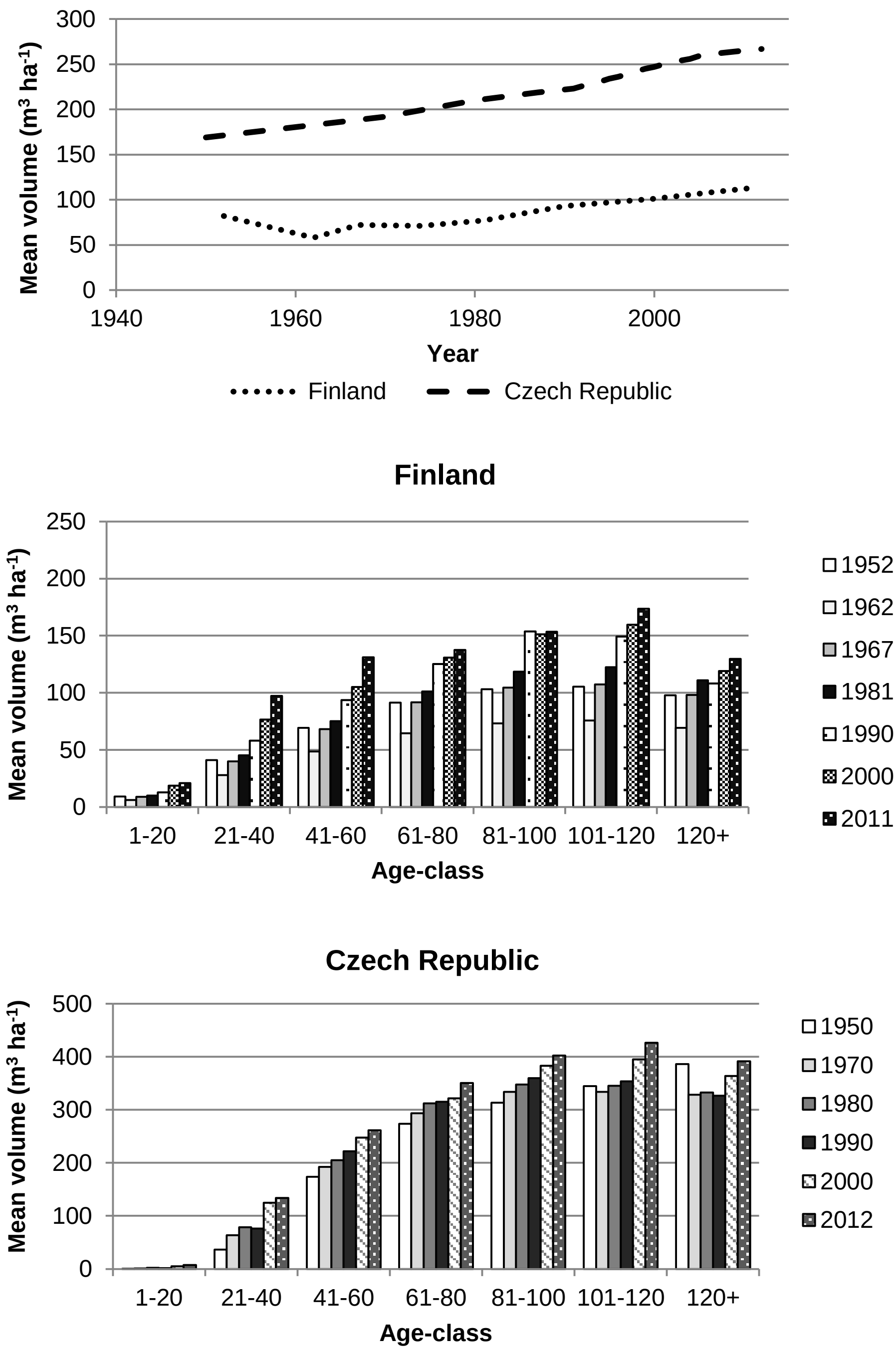
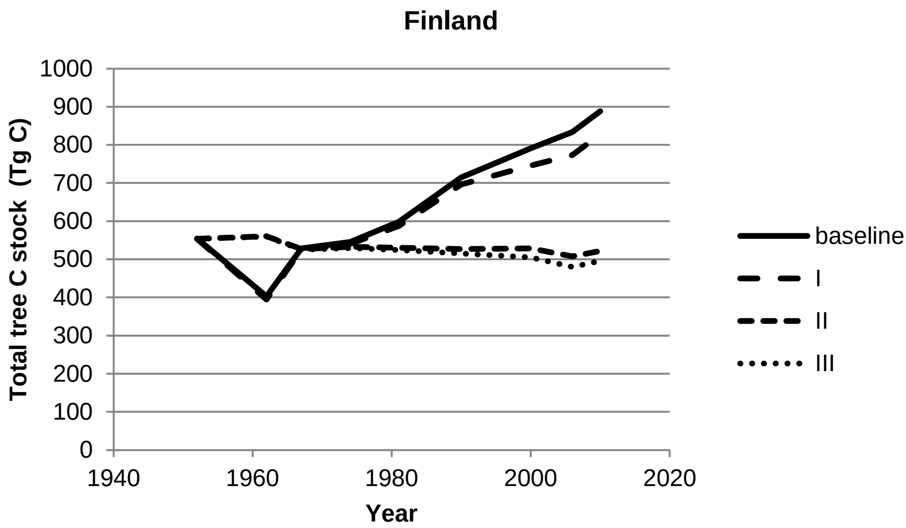


Figure 3 Development of mean volume of growing stock (m^3 ha^{-1}) in Finland and Czech Republic.



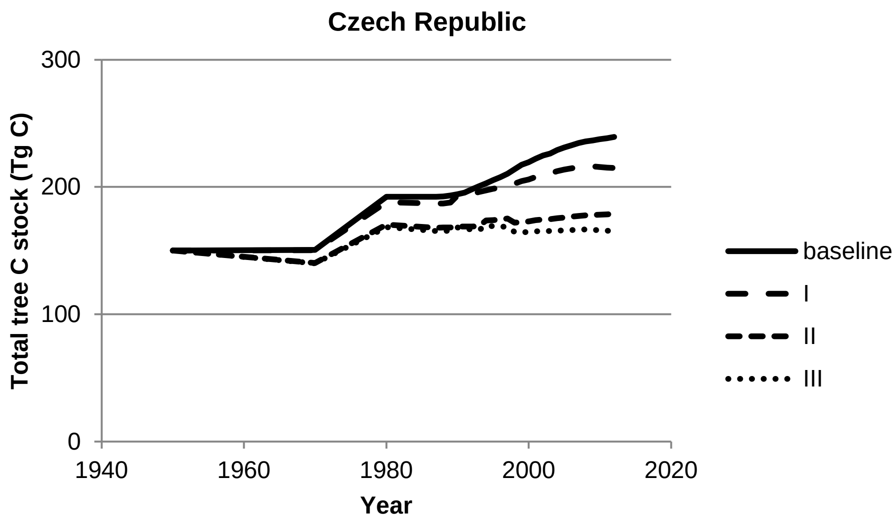


Figure 4 Development of total carbon stock in trees (Tg C) based on historical inventory data (baseline) and three scenarios (I) without afforestation, (II) without increased mean volumes and (III) without both afforestation and increased mean volumes from 1950 onwards.

To separate the effects of afforestation and change of mean volume of the growing stock on the increase of forest biomass carbon stock, the development of carbon stock using three alternative scenarios of forest area and volume development was calculated (Fig. 4). Results show that the development of forest biomass carbon stock was more strongly driven by the change of mean growing stock volumes and the effect of afforestation has been much smaller. In Finland, the carbon stock of forest biomass was in the end of the study period 828 Tg without afforestation (Scenario I), 522 Tg without increase of mean growing stock volumes (Scenario II), and 496 Tg when both afforestation and increase of mean growing stock volumes were excluded (Scenario III). The carbon stock over the study period increased by 50% with Scenario I, and decreased by 6% and 10% with Scenarios II and III, respectively. In the Czech Republic, the calculated carbon stock without afforestation in 2010 was 215 Tg in Scenario I and 179 Tg in Scenario II and 165 Tg in Scenario III and the carbon stock increased over the study period with all scenarios, 43, 19 and 10%, respectively.

3.3 Effects of rotation length on the carbon stocks of forests (Paper III)

Rotation length had a larger effect on the carbon stock of trees in spruce than in pine forests (Fig. 5). This was because the growth of trees was more age-dependent in spruce than in pine forests. The average carbon stocks of soil and wood products varied according to the carbon flux into the system (Fig. 5). The carbon stock of soil was affected least by rotation length in the Scots pine forests in Finland and Germany, where it, quite surprisingly, decreased slightly with increasing rotation length (Fig. 5). For both kinds of pine forests in Spain, the result was different because of a different biomass allocation. Older forests had still a lot of other than stem biomass, and, consequently, the calculated values of net primary production (NPP) and litter production remained high and the carbon stock of soil increased with increasing rotation length. In all spruce forests analyzed, the NPP and average carbon stock of soil increased with increasing rotation length of up to 80 or 90 years but not thereafter. The total carbon stock in forest (trees + soil) increased with increasing rotation length in each forest type following the trend in the carbon stock of trees.

In Scots pine forests in Finland and Germany, the total carbon stock in forest (trees + soil) increased slightly less than the carbon stock of trees, because of the decrease in the carbon stock of soil. The average carbon stock of wood products increased with increasing rotation length until 70–100 years, depending on the forest, and decreased slightly with any further increase in rotation length (Fig. 5). In Scots pine forests in Finland and in Norway spruce forests in both Finland and Germany, the average carbon stock of wood products increased substantially when the rotation length was extended above 60 years. At this age, part of the harvested wood was already logwood, which increased the life span of the wood products. The trends in the carbon stock of wood products did not change the trends in the total carbon stock of the systems, because the changes were an order of magnitude smaller than those of the carbon stock in the forest.

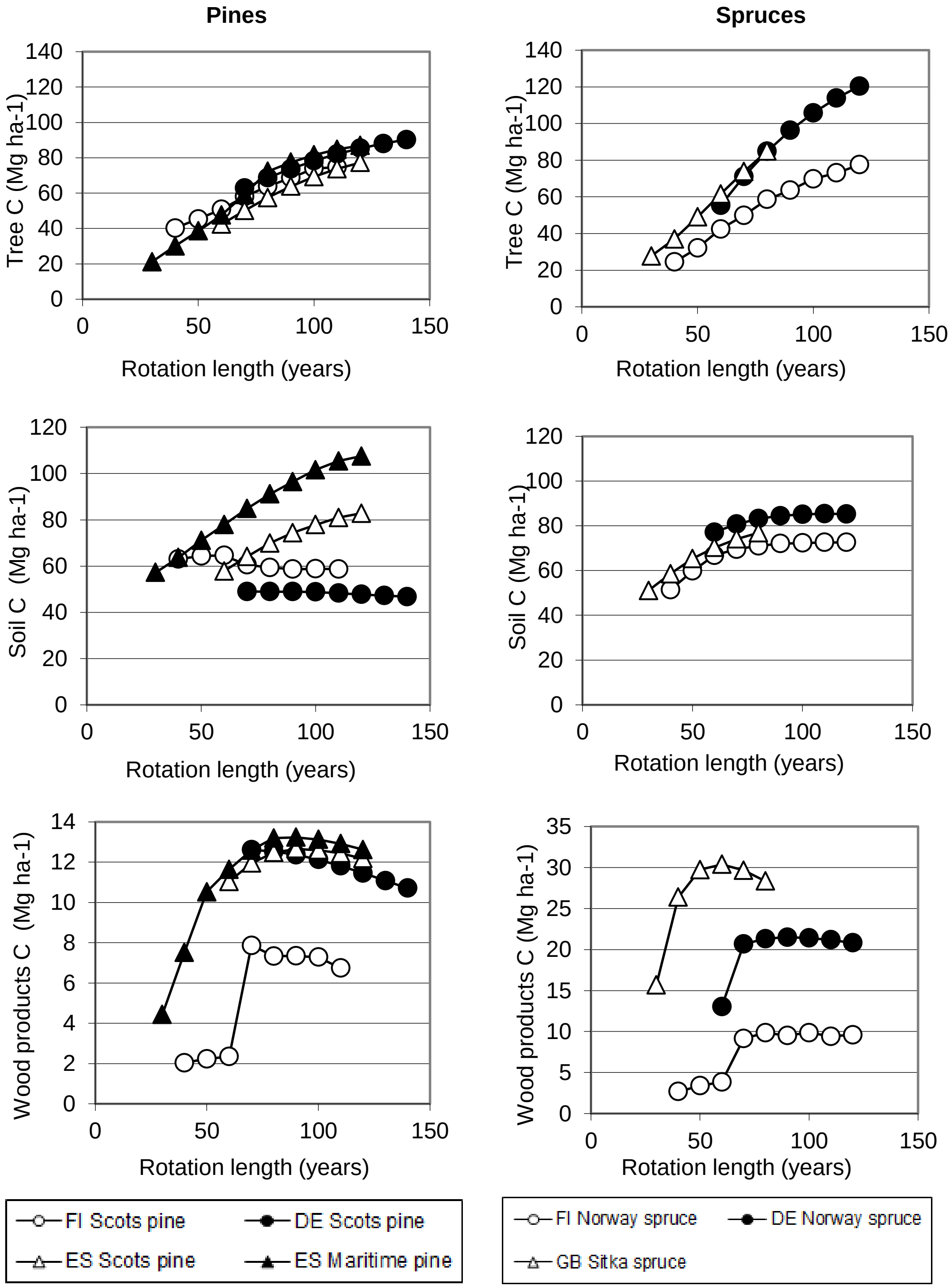


Figure 5. Carbon stock of trees, soil and wood products in forests in Finland (FI), Germany (DE), Spain (ES) and the UK (GB) when using different rotation lengths

To estimate the efficiency of increasing rotation length as an Article 3.4 activity, changes in the carbon stock of trees resulting from a 20-year increase in current rotation lengths was scrutinized. Forest areas on which the currently recommended rotation lengths would need to be increased by 20 years to reach the largest carbon sinks eligible under Article 3.4 of the Kyoto Protocol (of first commitment period) varied considerably between forests and countries, depending on the effects of the increased rotation length and the eligible carbon sinks. The required areas were largest, 1.4–5.1 Mha, in Germany and Spain, mainly because of the large eligible sinks in these countries (see Table 3 in Paper III). The required areas were smallest for Norway spruce forests in Finland (0.3 Mha) and Sitka spruce forests in the UK (0.3 Mha). The former were mainly a result of the small eligible sink in Finland, the latter from the high sink estimate per hectare. In Germany and Spain, the estimates of the required areas compared to the current areas covered by these forests, are large or even exceed them. In Finland, on the other hand, the required areas are only a few percent of the current coverage of the analyzed tree species. The 20-year increase in rotation length in areas required reaching the largest eligible sink would increase harvests by 13% in Sitka spruce forests in the UK and change the harvests by only a few percent in all the other forests.

3.4 CO_2 emissions of forest fires in the Mediterranean region and mitigation possibilities through prescribed burning (Paper IV)

Estimated annual average fire emissions in the Mediterranean countries ranged from 5816 Gg CO_2 in Italy to 359 Gg CO_2 in Greece (Table 2 in Paper IV). Litter produced most of the emissions, around 49%, and deadwood and aboveground biomass represented around 36% and 15% of emissions in all countries, respectively. Lack of data precluded consideration of the emissions coming from soil. Average fire emissions were largest in Italy although Spain registers the highest average burned area, because the mean aboveground biomass stock (average of forest and other wooded land) in Italy is 94.3 t ha^{-1} whereas in Spain it is 18.5 t ha^{-1} only, based on FRA 2005 data (FAO 2005). High fuel loads in France also lead to quite high emissions although the annually burned area is there the lowest of the studied countries.

The effect of prescribed burning on the CO_2 emissions were analyzed in this work using four alternative scenarios for treatment effort and impact on wildfire area: 2% of the annually burned area treated by prescribed fire, with 1 ha (I) or 3 ha (II) decrease in the area burned by wildfire for each treated ha, and 20% of the annually burned area treated by prescribed fire, with 1 ha (III) or 3 ha (IV) decrease in the area burned by wildfire for each treated ha, respectively. Figure 6 shows the CO_2 emissions for the four prescribed burning scenarios and the situation without prescribed burning (baseline). It also shows that a small treated area corresponds to minor decreases in emissions, even for the highest prescribed burning leverage. Prescribed burning over an area equal to 2% of the average annually burned area would lead to a reduction in emissions of only 1-5%, depending on the assumed leverage of the treatment (Scenarios I and II). Conversely, the mitigation effect of the other two prescribed burning scenarios both resulted in a substantial decrease in emissions; fire emissions are around 13% lower with Scenario III and around 52% lower with Scenario IV.

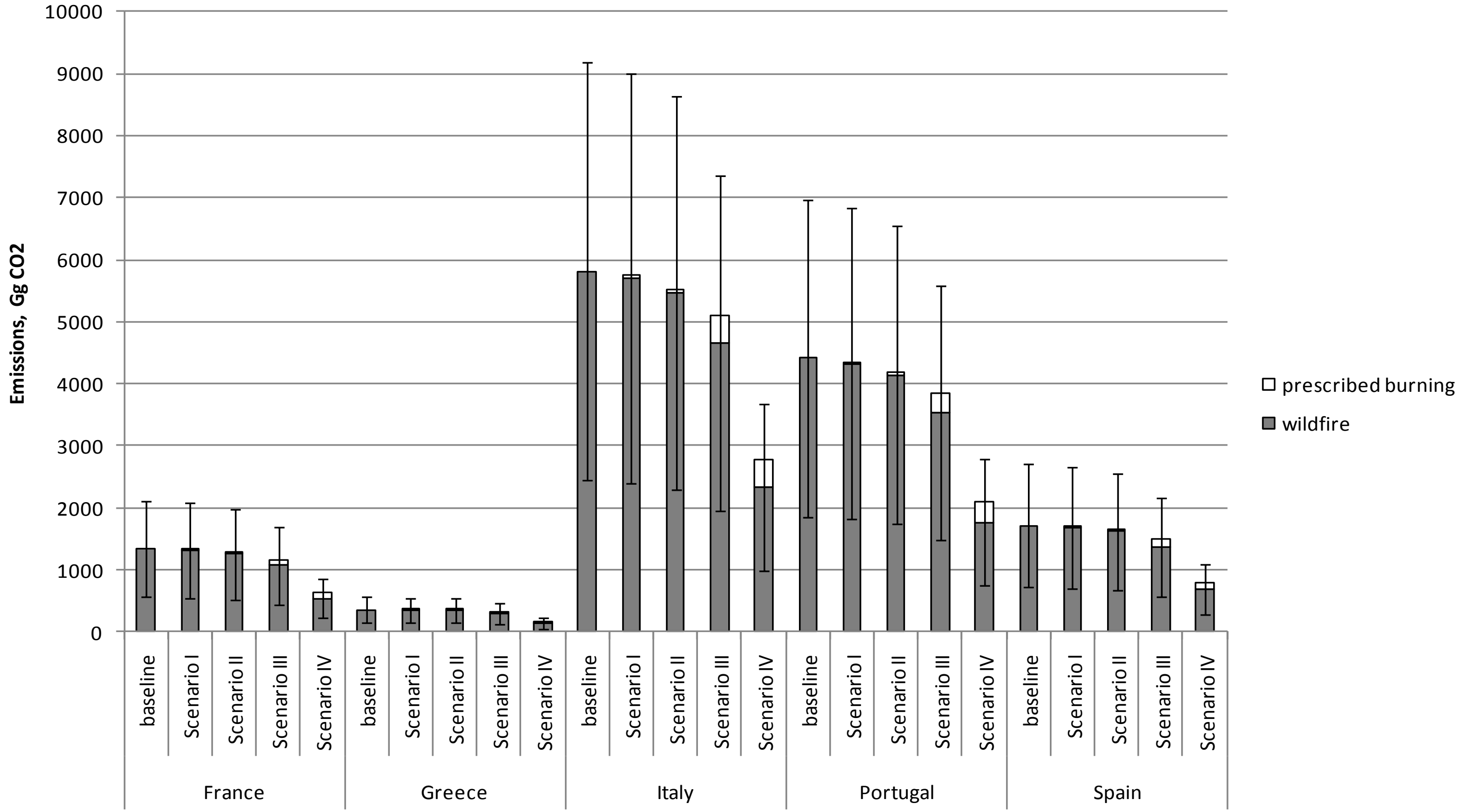


Figure 6 CO_2 emissions (Gg CO_2) in the five investigated countries under different scenario assumptions. Baseline refers to the situation without prescribed burning and Scenario I-IV to the prescribed burning scenarios. Error bars represent the standard error (±58%) of the wildfire emission estimates.

In the Kyoto Protocol, emissions from forest fires are part of the LULUCF sector balance and are calculated as losses from forest carbon stocks. Results show that the decrease in emissions resulting from prescribed burning scenario IV is also substantial in the context of the Kyoto Protocol. Compared to the LULUCF sector reported losses in 2009, the decrease in carbon stock losses were 1-11%, so that the smallest decrease was in France and largest in Portugal (see Table 4 in Paper IV). If prescribed burning would be accounted for as an Article 3.4 forest management activity, even Scenarios I and II would lead to a 0.6-31% reduction in emissions of the Article 3.4 largest eligible sink (of first commitment period), depending on country. For Scenarios III and IV, the largest eligible sink would be achieved in Italy and Portugal. Thus, prescribed burning could have a considerable effect on the carbon balance of the LULUCF sector.

4 DISCUSSION AND CONCLUSIONS

4.1 Development of forest age-structure and mean growing stock volume and the implications on forest biomass carbon stocks in European forests

Forest area and age

Paper I presented the first comprehensive European level reconstruction of the development of forest age-structure from 1950 onwards. The results show that the mean age of European forests (area weighted mean age over the studied area) has decreased from 1950´s from 62 to 59 (3 years) and the area of old forests (>100 years) has decreased from 21% in 1950 to 16% in 2010. However, there is large variation in these results between the countries, and there are also countries where the mean age is currently higher than it was in the 1950´s.

Different factors contribute the development of the forest age in Europe. In some countries (e.g. Finland), the large decrease in the mean forest age and in the share of old forests is explained by large fellings due to war reparations and by change of forest management from selective fellings of timber sized trees to a clear felling system. Changes in silvicultural regimes happened probably to different degrees in all countries. Large areas of mature and pre-mature stands were cut after World War II also in western, central and eastern Europe (Gold 2006), explaining the decrease of old forest area in different countries. Following this period, the increasing demand for wood (Kuusela 1994) had to be met through more intensive management of medium aged stands and harvesting of the remaining mature stands, resulting in a further decline in the proportion of old forests. In parallel, in the first decades after World War II, major afforestation efforts were made especially in Western Europe, but also in Central and Eastern Europe, to compensate for earlier clear cuttings and to achieve timber self-sufficiency, resulting in additional young forest areas (Gold et al. 2006). After 1980 the share of middle aged (41–80 years) forests started to increase, and the mean age on European level has kept quite stable since that.

To study more closely the role of afforestation on the development of forest area and mean age in Europe, the development of forest area and age-structure without afforestation were reconstructed in two case study countries, Finland and the Czech Republic, between 1950 and 2010 (Paper II). This reconstruction indicated that in both countries, afforestation has affected the development of forest area and mean forest age, but the effect has not been very large. The forest area without afforestation would have been 10% smaller in Finland and 15% smaller in the Czech Republic in 2010 compared to the baseline situation (based on historical forest inventory data). In both countries, afforestation did not affect the observed age trend, but only had a small influence on the magnitude. In Finland, the mean age of forests would have decreased also without consideration of afforestation which implies that the large clear fellings after the Second World War have been the driving factor for development of mean age of forests, and in Czech Republic the mean age has increased despite the afforestation. The effects of afforestation on the age class structure are probably higher in countries like Ireland, Hungary, or UK, where afforestation areas are larger compared to total forest area (Zanchi et al. 2007; HILDA dataset, Fuchs et al. 2013). At European level, the effect of afforestation on the mean forest age has been much larger than in our case study countries, and the area weighted forest mean age over the studied area in year 2010 without afforestation would have been 7 years higher than it is based on the inventory data (Vilén and Lindner 2014).

Development of mean growing stock volume

In addition to forest area, also the growth of European forests has increased substantially from the 1950´s, and the volume of growing stock has almost doubled in European forests (Spiecker et al. 1996; Gold et al. 2006), resulting in a significant increase of carbon storage in European forests (Kauppi et al. 1992; Nabuurs et al. 2003; Ciais et al. 2008; Bellassen et al. 2011). The increase of mean growing stock volume was studied in two case study countries, Finland and the Czech Republic, using historical inventory data. Based on this study, the mean growing stock volumes have increased remarkably in both countries from the 1950´s.

There are several factors behind the increase of mean volumes of growing stock, i.e. forest density (Rautiainen et al. 2011), but their effects are not easy to separate. In addition to increased growth, also the smaller annual fellings compared to forest growth has had a large effect on the increased growing stocks. In Finland, there has been considerable built-up of growing stock due to increased and clearly higher annual volume growth of forests than annual cuttings after the 1960's (Kuusela and Salminen 1991; Finnish Statistical Yearbook of Forestry 1997). The growth and growing stocks of forests have both increased due to changes in the forest management, i.e. change from selective fellings that lead to over mature and understocked stands into more sustainable silviculture with frequent thinnings and final fellings together with artificial and active natural regeneration. Also the adoption of site improvement methods like drainage of peatland forests and fertilization partly explain these increases in growth and growing stock of forests (Mielikäinen and Sennov 1996; Mielikäinen and Timonen 1996). However, also the changes in age structure of forests and environmental factors over time may have contributed to the increased forest growth in Finland during the last 60 years. According to Kauppi et al. (2014), more than half of the increased forest growth in the boreal forests of Finland since the 1960´s could be explained by climatic warming. Similar results have also been suggested for other parts of the boreal region (Frost et al. 2014; Peng et al. 2014).

Also in the Czech Republic, the development of sustainable forest management is an important factor behind the increase of growing stock. For example, the rotation period increased from 93 to 115 years and mean stand age from 53 to 64 years during the period between 1950 to 2010 (MA 2012). Another factor that contributed to enhanced growth especially in central Europe is nitrogen deposition (Magnani et al. 2007; Kahle et al. 2008; Eustach et al. 2011), which is high there, 10-20 kg N ha^{-1} yr^{-1} (Dirnböck et al. 2014) and affects the growth significantly. In Finland, the relatively low annual nitrogen deposition is unlikely to cause abnormally high growth to be distinguished from long-term growth variations (Mielikäinen & Sennov 1996).

Pretzsch et al. (2014) have reported significant increases in growing stock per age class for both Norway spruce and beech (*Fagus sylvatica*) forest stands in Central Europe based on long term observations on unmanaged or only marginally managed experimental plots. They also found notable volume growth rate increase to coincide with an increase in resource supply (CO_2, N), together with an extended growing season accompanied by changes of mean temperature and precipitation. In fact, the annual mean temperatures in Europe have increased by 1.3°C from the pre-industrial level (EEA 2014) and the growing season in Europe has extended by 2.5 days per decade since the 1970´s (Menzel et al. 2006) the growing season lengthening being largest in Continental and Boreal zones (Garonna et al. 2014). Our results demonstrate that this effect is not only limited to unmanaged or marginally managed plots as studied by Pretzsch et al. (2014): the increase of growing stock per ha occurred consistently in both Finland and the Czech Republic and this trend was consistent across age classes and throughout the study period from 1950 to 2010 (Czech Republic) or from 1962 onwards (in the case of Finland). As the increase occurred both in younger and older age classes, and in both coniferous and broadleaved species, it is likely that it is influenced by processes that operate at a large scale. Also, the ratio of annual forest growth and fellings has affected the development of growing stocks.

In addition, the growth of European forests is affected by the recovery from the past unsustainable forest uses, like litter raking, which used to be a common practice in Central Europe (Bürgi and Gimmi 2007; Gimmi et al. 2012). Litter from spruce (*Picea abies*), pine (*Pinus sylvestris*), beech (*Fagus sylvatica*) and oak (*Quercus petraea*) was removed from the forests mainly for the bedding for farm animals and e.g. in former Czechoslovakia, the practice did not stop completely until the middle of the 20th century (Hofmeister et al. 2008). Disentangling the effect of these multiple factors remains, however, challenging.

Development of forest biomass carbon stock

Our results show that in both Finland and the Czech Republic, the development of forest biomass carbon stock was strongly driven by the change of mean volumes of growing stock whereas the effect of afforestation has been much smaller. The situation is probably different in countries where the relative change in forest area due to afforestation was larger. The share of afforested area from the total forest area during the study period was 10% in Finland and 15% in Czech Republic, whereas e.g. in Western Europe, the forest area has increased by 30% from 1950 to 2000 at a relatively constant rate over the whole period (Zanchi et al. 2007). There are also countries, e.g. UK and Ireland, where most of the forests were established after the 1950's (HILDA dataset, Fuchs et al. 2013).

Several studies have investigated possible reasons for the large carbon sink in European forests since 1950. According to Magnani et al. (2007), in addition to stand-replacing disturbances, forest net carbon sequestration is overwhelmingly driven by nitrogen deposition. However, Sutton et al. (2008) claimed that the effect of nitrogen deposition would be much smaller than that suggested by Magnani et al. (2007). Erb et al. (2013) postulated that the effects of environmental changes on the forest carbon sink were overestimated in many modeling studies and that a substantial fraction of the forest carbon sink resulted from changes in management practices including species changes and cessation of grazing and litter raking. It should be noted, however, that Erb et al. (2013) did not consider nitrogen deposition among the environmental factors in their analysis, which has been found to be crucial in other studies (de Vries et al. 2009; Wamelink et al. 2009). As a part of their study, Erb et al. (2013) also calculated the effect of area change to the carbon sink of Austrian forests between 1830 and 2010 and in line with our results, they found the effect of forest area change to be only minor. In East Asia, Fang et al. (2014) found that the effect of changes in forest area and growth of growing stock on the development of carbon stock varied between the countries. The conflicting results indicate that further research is needed to better quantify the attributions of different causes to the forest carbon sink.

4.2 Sustaining the European forest carbon sink in the future

In the future, European forests will have to adapt to a changing climate. Based on the observed climate trends and future projections, the temperatures are expected to increase throughout Europe and precipitation is expected to increase in Northern Europe and decrease in Southern Europe. Occurrence of high temperature extremes, droughts and heavy precipitation events are expected to increase across Europe, whereas winter wind speed extremes are expected to increase in Central and Northern Europe (Lindner and Rummukainen 2013; Rummukainen 2013; Lindner et al. 2014). These changes will have both positive and negative effects on European forests. The forest growth will increase in northern Europe, but damages from pests and diseases will increase across Europe. Also wildfire risk in Southern Europe and storm damages in Northern and Central Europe may increase. Ecosystem resilience, and consequently also the ability of forests to continue sequestering carbon and mitigating climate change, can be enhanced by proper forest management (Janowiak et al. 2014). Thus, both adaptation to climate change and climate change mitigation actions are needed.

In this work, the efficiency of changes in the rotation length and the use of prescribed burning in mitigation of climate change were also studied. Results show that both measures could have considerable effect on the carbon balance of the LULUCF sector in Europe. In all studied cases, an increase in the rotation lengths increased the carbon stock of biomass, and the increase was higher in spruce forests than in pine forests. However, in two study cases out of seven, the amount of soil carbon decreased while rotation lengths were elongated, despite an increase in the amount of biomass. This decrease resulted from a decrease in the NPP and through that, from a decrease in litter production in old forests. In old forests, the NPP may decrease because of increased respiration burden due to the increasing woody biomass, decreased leaf area and light interception, decreased nutrient availability, decreased photosynthesis, or a shift in carbon allocation from above- to below-ground production (Smith and Resh 1999).

Although the amount of soil carbon did not decrease much, and the effect on the total forest carbon was small, it may be of importance for the reporting requirements of Article 3.4 of the Kyoto Protocol—strict interpretation of the Protocol means that if a country cannot prove that the accountable pool is not a source, it must be measured (UNFCCC 2001b). Accounting for the carbon stock of biomass only, accomplishing the maximum eligible sinks of Article 3.4 of the first commitment period of the Kyoto Protocol, would mean elongation of rotation length by 20 years in areas varying from 0.3 to 5.1 Mha depending on the type of forest and country. The differences between forests resulted from the size of the sink obtained by increasing the rotation length, but also from the maximum carbon sinks allowed to countries under Article 3.4. However, the development of tree biomass in this study (Paper III) was calculated from local growth and yield tables, published between 1949 and 1989 (Wiedemann 1949; Koivisto 1959; Hamilton and Christie 1971; Garcia Abejon and Gomez Loranca 1984, 1989), and are thus based on old data. The growth of the forests has increased a lot since that, which should be taken into account when evaluating the results.

Currently forests grow faster, which can result in earlier harvest thresholds. A specific mean tree size, standing stock and mortality rate can be reached one or more decades earlier (Pretzsch et al. 2014), which in addition to making old yield tables and traditional management guidelines outdated, also makes it difficult to define the baseline situation when defining the change in the forest management in the context of the Kyoto Protocol Article 3.4. Furthermore, under the changing climatic conditions, a shorter rotation period may reduce the risk of abiotic damages and thus be more favorable than raising standing stocks by increased rotation lengths.

In the Mediterranean area, the number of forest fires has increased dramatically during the recent decades, mostly due to changes in land use (Pausas 2004; Pausas et al. 2008). As a result of more frequent and more severe fires, Mediterranean forests can experience loss of biodiversity, soil erosion and desertification (Pausas et al. 2008). Fires also cause large economic losses and threaten human lives. In addition, forest fires are a remarkable source of greenhouse gases (GHG). In Portugal the exceptionally large burned forest area in 2003 turned the LULUCF sector from a net sink into a carbon source of 7,076 Gg CO_2 (FCCC 2006).

In the future, climate change is expected to result in more extensive and severe wildfires throughout southern Europe (Carvalho et al. 2010; Lindner et al. 2010). Consequently there is a need for landscape-level fuel treatments, like prescribed burning, which creates fuel-modified areas where the intensity of subsequent wildfires is decreased, increasing the likelihood of fire suppression and leading to a decrease in the number and size of large wildfires. Based on our results, prescribed burning could have a considerable effect on carbon balance of the LULUCF sector in Mediterranean countries by decreasing the emissions from forest fires.

Although many studies are available on the effects of prescribed burning on wildfire intensity and severity (e.g. Fernandes and Botelho 2003; Finney et al. 2005) it is difficult to assess the overall effect of prescribed burning on wildfire incidence at the country level. This is because it varies between ecosystems and is affected by the overall fire management process (Fernandes and Botelho 2003). According to Pinol et al. (2005, 2007) in the Mediterranean region the total area burned is much the same regardless of fire suppression and prescribed burning efforts. However, prescribed burning reduces fire intensity over the landscape. Also, there is strong empirical evidence that prescribed burning has significantly reduced the incidence and extent of unplanned large fires (Boer et al. 2009) and GHG emissions (Volkova et al. 2014) in Australia.

However, there are also contradictory views about how reasonable it is to use prescribed burning as a tool to maintain forest carbon stocks. Mitchell et al. (2009) found that fuel treatments can be effective in decreasing fire severity, but fuel removal almost always reduces carbon storage more than the additional carbon at a stand is able to store when made more resistant to wildfire. North et al. (2009) suggests to focus on reducing surface fuels, active thinning of most small trees and removal of only fire-sensitive species in the merchantable, intermediate size-class. That would result in the development of large, fire resistant trees and reduce emissions from potential future wildfire.

Currently the potential of prescribed burning to manage forests and wildlands in Europe remains largely unfulfilled (Fernandes et al. 2013). Future development of prescribed burning will require higher awareness of the role of fire on ecosystems, changes in fire management policies, and acceptance by stakeholders and the general public (Galiana and Lázaro 2010; Fernandes 2013).

4.3 Conclusions

Various factors affect the carbon balance of forests, but their contributions are not easy to separate. In this work, data from different sources were combined to investigate the effects of land-use change, forest age-structure, and forest management on the carbon dynamics of European forests. There are uncertainties related to the data and approaches used, but despite them, this study provides valuable, policy relevant information on the contribution of different factors on the carbon dynamics of European forests. This work showed that despite the previously reported increase of timber yield and carbon stocks in European forests, the average forest age is currently lower than in the 1950. Age structure of forest has thus affected less than previously thought on the increase of carbon stocks of European forests. Instead, the mean volume of growing stock has increased remarkably over the age classes and tree species, thus, being a strong driving factor for the increase of carbon stocks. Also afforestation has affected it in general, although its effect was not large in the two case study countries, Finland and the Czech Republic. In overall, the increase of forest carbon stocks is largely affected by the smaller harvests compared to forest growth, but the contribution of different factors varies significantly between the countries. Further country level studies are thus needed to get a more thorough understanding about the carbon dynamics of European forests. This work also showed that changes in forest management such as in the rotation length and use of prescribed burning could have a considerable effect on the carbon balance of the LULUCF sector in Europe. However, further studies taking into account the changing forest growth over time would be needed. Also the new more strict reporting and accounting rules in the second commitment period of the Kyoto Protocol create new data and research needs.

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