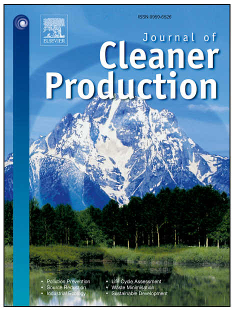

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Carbon sequestration for different management alternatives in sweet chestnut coppice in northern Spain

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Abstract

This paper provides an innovative approach to assessing carbon sequestration in sweet chestnut coppice taking into account the importance of carbon fluxes in the whole forest-industry value chain in the mitigation of climate change. The goals of this study were: to evaluate the baseline carbon capture of sweet chestnut forest in the north of Spain; to assess the effect of thinning and extending the rotation period on carbon storage; and to evaluate the substitution effect of using sweet chestnut products as an alternative to other materials. The CO2FIX model was used to estimate carbon content in different forest components: aboveground and belowground biomass, soil and wood products, under five different thinning and rotation scenarios. Model parameterization as a function of stand age was carried out using growth data, climate data, litterfall rates, sawmill processing data, and data on the lifespan of products and their final end. Sawmill efficiency was measured *in situ* using the Lumber Recovery Factor.

The scenarios in which only one thinning was made resulted in more total carbon accumulating than the baseline, especially when the 40 years rotation was increased by 20 years. In contrast, scenarios involving two thinning did not even reach the baseline value of total carbon. Additionally, a positive impact on GHG emissions was found for using wood to substitute other materials, i.e. cement and fossil fuel. Taken together, these results highlight the sustainability of thinning and rotation treatments in terms of carbon storage in sweet chestnut coppice, and quantifiably supports the environmental benefits of the substitution effect of sweet chestnut wood products. As such, it provides valuable information for forest managers and policy makers who wish to address climate change mitigation in forest management planning.

Keywords: CO2FIX, *Castanea sativa* Mill., Thinnings, Forest management, Carbon, Wood products.

Introduction

Tackling climate change has become a major concern at an international level because despite efforts to create mitigation policies, greenhouse gas (GHG) emissions have continued to rise (IPCC, 2014). As a consequence, forest management has become a political priority, due to its potential influence in this respect (Lippke et al., 2011). Currently, about 90% of forests in industrialized countries are managed. In Europe more than 80% of forests are sustainably managed (FAO, 2010), meaning that forest management can make a significant contribution to reducing the effect of carbon emissions (Groen et al., 2006).

While the principal forest management technique for storing carbon and thus mitigating atmospheric CO_2 involves afforestation or reforestation (Machado et al., 2015), it is also important to take into account the management of existing forests. Forests are highly complex systems and are influenced by numerous external and internal factors which need to be considered when developing different sustainable management strategies in different forest types and regions. Knowledge of the carbon cycle in forest dynamics facilitates an understanding of forest carbon pools (living and dead biomass, soil and wood products) and enables the estimation of the carbon stocks and stock changes in and between carbon pools (Pérez- Cruzado et al., 2012; Ruiz-Peinado et al., 2013). At the same time, there exists a variety of possible silvicultural management alternatives, and the suitability of each in a given situation depends on many variables, such as type of harvesting, length of rotation period or tree species composition (Alvarez et al., 2014). Thus it is essential to evaluate the effect of each alternative, in various situations, on carbon storage and so achieve a practical and realistic assessment of each alternative's (potential) role in mitigating climate change.

As regards the forest carbon pools mentioned above, the storage of carbon in wood products is the least studied aspect of this field. Despite this, some authors have highlighted the fact that the carbon stored in wood and wood products offers a valuable strategy for mitigating climate change (Bravo et al., 2008a), particularly when it is not only the forest system but rather the whole forest-industry value chain which is considered. Carbon stored in wood products is held until the end of the item's useful life, but at the same time, sustainably managed forests regenerate and thus, through the increase in forest biomass, they go on to sequester more carbon (Karjalainen et al., 1994). The length of time the carbon is stored depends on the type of wood product (short-, medium- or long-term), its disposal (landfill, recycling or energy production) and the efficiency of the sawmill processes. The production of more long-term products can help increase the global amount of carbon stored (Hennigar et al., 2008), and hence in recent years, some researchers have begun to focus on wood products in this respect (Martel, 2010; Fortin et al., 2012; Proft et al., 2009). Furthermore, if the "substitution effect" of wood as a material is taken into consideration (i.e., using wood products in place of other materials which are more energy intensive to produce, like concrete or fossil fuel), the amount of GHGs emitted into the atmosphere could be considerably reduced (Gustavsson and Sathre 2011). However, neither approach is included within the Kyoto Protocol, despite the fact that almost 80% of wood removals correspond to roundwood, according to the Food and Agriculture Organization of the United Nations (FAO) report on the evaluation of the Global Forest Resources (2010).

To explore how the different forest management alternatives influence carbon stores in a forest, researchers have relied on model projections of the biomass-soil-product chain in managed forests for different broadleaf and conifer species (Alvarez et al., 2014; Bravo et al. 2008b; Lizarralde et al., 2008; Masera et al., 2003; Nabuurs and Schelhaas, 2002; Pérez-Cruzado et al., 2012), and thus provide appropriate tools to assist managers in decision making and policy development. However, most of these studies focus principally on conifers and not on hardwood species. Furthermore, despite the latter having wide distribution ranges in the area, they have been little studied in Europe. A good example is the sweet chestnut (*Castanea sativa* Mill.) (EUFORGEN, 2009), which has long played an important economic role in many European countries (Conedera et al., 2004). In fact, in France, improved forest management practices were recently evaluated to estimate the carbon balance and the carbon storage (both in the forest and wood products) of this species (Martel, 2010). In Northern Spain, sweet chestnut is particularly important in construction due to its good characteristics as a structural material and there is currently considerable interest in improving its management as a forestry resource. Hence, the study and evaluation of new forest management strategies is essential, not only to improve the management and economic potential of sweet chestnut, but also to quantify its role in mitigating climate change through its storage of carbon in long- and medium-term products.

The present study, therefore, evaluates the effect of different silvicultural management alternatives on *C. sativa* Mill. in Northern Spain. The current chestnut coppice stands in the area are the result of cultural and economic changes in the late XVIII century (Miguelez Menendez et al., 2013). Traditionally, chestnut has been widely used for construction (houses, traditional grain stores), carpentry and furniture, as well as for fruit and firewood. However, the abandoning of these stands in recent decades (Martínez-Alonso and Berdasco, 2015), along with the absence of sprout selection in many of the remaining stands, has resulted in degraded, extremely dense, over-mature and thus unstable stands. To address this problem, the regional government of Asturias (Northern Spain) has launched management initiatives for this species (Álvarez-Vergel et al., 2011) based primarily on performing thinnings at different ages. It is therefore of great interest to investigate how different regimes and rotations affect both growth and timber production, and hence carbon storage.

Using the CO2FIX v 3.1 model (Masera et al., 2003; Schelhaas et al., 2004), the main aims of this study are (1) to quantify the baseline for carbon stored in biomass, soil and wood products (short-, medium- and long-term) for an important forestry species in Northern Spain i.e. sweet chestnut coppice, (2) to evaluate the effect of different forest management alternatives (thinning intensities and rotation lengths) on the carbon stored, compared to the baseline, and (3) estimate the substitution effect of sweet chestnut products against alternative materials.

Materials and Methods

Study Area

The study was conducted in sweet chestnut coppice stands (*Castanea sativa* Mill.) in the north of the Iberian Peninsula, in Asturias, Spain (Fig. 1). These stands are located between 176 and 880 m.a.s.l., with different orientations and with a slope of between 19 and 75%. The average annual temperature is 10-11° C, and the annual rainfall ranges from 818 to 1380 mm, with 525-821 mm falling throughout the growing season (March to October). The soil humidity regime is Udic with sufficient soil moisture in the growing season, except for one month in summer when there is drought. The soil has a sandy loam and/or sandy clay loam texture. In the study area, this species occupies 123,549 ha, mainly as coppice (DGCONA, 2003), with an annual total harvested volume of 24,664 m^3 (SADEI, 2011). Although a single large local company transforms the great majority of the sweet chestnut wood produced in Asturias, about 26% of the harvested volume is processed by a considerable number of small sawmills, the destination and use of the wood depending on the size reached by the tree. Only a few of the stands studied had been subjected to management, which was of low intensity and consisted solely of a final cutting at the end of the rotation (R=40 years).

To carry out this study, 15 circular plots (15 m radius) were used (Table 1). These plots are part of the long-term *C. sativa* permanent network established and maintained by CETEMAS (Forest and Wood Technology Research Centre) in Asturias (Miguélez Menendez et al., 2013).

CO2FIX Model

The CO2FIX v 3.1 model (Masera et al., 2003; Schelhaas et al., 2004) quantifies the carbon stored in a forest stand, providing information about carbon fluxes and balances over time. The model also allows simulations for multiple rotations. Its applicability has been previously demonstrated for a wide range of typologies of European forests (Nabuurs and Schelhass, 2002), tropical forests (Groen et al., 2006), plantations and/or monocultures (Schelhaas et al., 2004) and coppice (Schelhaas et al., 2004). CO2FIX v 3.1 (http://www.efi.fi/projects/casfor/) converts volumetric net annual increment data, allocation data, turnover rates and forest management and wood products data to annual carbon stocks and fluxes. It consists of six modules: biomass, soil, products, bioenergy, carbon finance and carbon accounting. In this study, only the first three modules were used for the evaluations.

Biomass module

The biomass module estimates the carbon stored in biomass using the annual volume increment of stems, branches, leaves and roots, natural mortality, competition, forest management mortality (thinning) and silvicultural characteristics to simulate treatments. The biomass module was parameterized as a function of stand age. Stem production (current annual increment, CAI, $m^3ha^{-1}year^{-1}$) was obtained from the yield models developed for sweet chestnut coppice in the study area (Cabrera, 1998). The calculation of the carbon stored in stems was carried out using specific sweet chestnut data and considering a wood density of 0.584 Mg m^{-3} at 12% moisture (Vega, 2013) and a carbon content of 48.4% (Montero et al., 2005). These values were used for all biomass fractions (stem, branches, leaves and roots) because no specific data exists for values of carbon in each individual biomass fraction. The biomass growth of foliage, of branches and of roots were expressed as fractions relative to the growth rate of the stem biomass (Schelhaas et al., 2004). In the case of leaves and branches, the proportion of each was calculated with the biomass equations developed by Menéndez-Miguélez et al. (2013) for this species in Northern Spain. However, due to the absence of root biomass equations for sweet chestnut coppice, the model developed for sweet chestnut high forest by Ruiz-Peinado et al. (2012) in Spain was used to estimate belowground biomass. Natural mortality was assessed in all plots two years after carrying out the initial inventory by counting the number of trees which had died since the inventory was conducted, and a value of 0.03% obtained (this value was established as a constant for the entire rotation length). Management mortality (thinning) and competition, considered in the CO2FIX as factors that modify current annual increment competition, were not included in this study due to lack of data.

Soil module

This module describes the decomposition and carbon dynamics in well-drained soils following the Yasso model which is used in the CO2FIX model (Liski et al. 2005). Briefly, decomposition of litter and harvesting residues is simulated using basic climate and litter quality information, and which has been shown to adequately describe the effects of climate on decomposition rates of several litter types in a wide range of ecosystems from arctic tundra to temperate forests and tropical. The model depends on the climatic data of the site studied (sum of the daily temperatures during the year that are above 0ºC, precipitation and potential evapotranspiration in the growing season), litterfall rates and turnover (annual rate of mortality of the biomass component) of the biomass fractions (stems, branches, leaves and roots) (Schelhaas et al 2004). The fractionation rates of woody litter and decomposition rate are determined by temperature and water availability. The average climate data used here were obtained from the digital climate Atlas of the Iberian Peninsula (Ninyerola et al., 2005).

Leaf turnover was estimated considering that all leaves fall in 1 year because sweet chestnut is a deciduous species (value equal to 1). Branch turnover was calculated considering that a value of 0.40 Mg $ha^{-1}$of carbon was provided to the soil (Patricio et al., 2012). Stem fraction was evaluated directly and the trees which had fallen between the taking of the inventory and the census of dead trees were also included. The contribution of roots to soil was calculated with the equation proposed by Dahlman and Kucera (1965) and tested by Gill and Jackson (2000) for different climatic gradients and functional plant groups, due to the lack of specific data for sweet chestnut in the literature (Equation 1):

$$Root\ turnover = \frac{Annual\ belowground\ production\ (kgha^{-1}year^{-1})}{Maximum\ belowground\ biomass(kgha^{-1}\ )} \quad (1)$$

The annual belowground production of root biomass was estimated using the annual difference in root production from 0-40 years (rotation age). This required fitting a model (Equation 2) that related plot age (t, years) with root biomass (W_{root}, kgha^{-1}), estimated with the equation of Ruiz-Peinado et al. (2012). Equation 2 was fitted by non-linear regression with the NLIN procedure of SAS/STAT® (SAS Institute Inc., 2004). The initial parameters for running the non-linear regression had been previously obtained by linearizing the non-linear regression. In addition, the coefficient of determination (R^2) was calculated. The maximum belowground root biomass value used was that corresponding to the maximum found across all plots. All data were taken from the permanent plots used to carry out this study.

$$W_{root} = b_0 * exp^{(t*b_1)} \quad (2)$$

In the soil module, decomposition of litter and harvest residues was simulated using basic climate and litter quality information.

Product module

This module tracks the carbon in wood from harvesting to processing into various products to their disposal (Karjalainen et al., 2002; Masera et al., 2003) and it is based on a model developed and used before by Karjalainen et al. (1994). Data were obtained from the largest local sawmill in the area, mentioned previously, which processes 74% of the total chestnut sawn timber production in Asturias (SADEI, 2011). The products manufactured from chestnut logs at the sawmill were beams, planks, poles and firewood, depending on log size. To evaluate the percentage of each product produced, the methodology proposed by Martínez-Alonso and Berdasco (2015) was used. The logs were painted and numbered to ensure traceability during the sawmill processing (sawing, drying, debarking, planing, optimizing, grading and sorting). At each stage products and co-products were weighed and the volume of each log was calculated. In the drying process the contraction of the wood after drying was taken into account (4% in thickness and 7% in width) (Fernández-Golfín and Álvarez 1998).

The product module distinguishes three categories for the different usage of wood products and their possible later re-use, each with a different lifespan (options: long-, medium- and short-term). The lifespan considered for long-term products (beams) was 40 years (Eggers, 2002; Fortin et al., 2012), 15 years for medium-term products (poles and planks) and 1 year for short-term products (firewood) (Schelhaas et al., 2004).

Total carbon

The CO2FIX model calculates the total carbon as the sum of the carbon stored in the soil and that stored in wood products, making the assumption that the carbon stored in biomass is subsumed within the category of wood products.

Simulated management alternatives

After model parameterization, five different silvicultural alternatives (scenarios) were simulated for sweet chestnut coppice (Table 2). The first scenario (baseline scenario) was the current management of this species in the study area (baseline carbon sequestration), which consisted of one single harvesting, set at 40 years, with no previous silvicultural interventions. The other scenarios simulated were: A) selection of sprouts at 10 years, one thinning at 15 years and harvest at 40 years (A-Th_1R_{40}), or at 60 years (A-Th_1R_{60}); and B) selection of sprouts at 10 years, one thinning at 15 years, another thinning at 26 years and harvest at 40 years (B-Th_2R_{40}) or at 60 years (B-Th_2R_{60}). Scenarios A-Th_1R_{60} and B-Th_2R_{60} were based on those proposed by Martel (2010). The relative percentages of harvested wood and slash were measured in the field following thinnings (72% and 28%, respectively) and following the final harvest (70% and 30%, respectively) when rotation was 40 years. When rotation was 60 years, these data were obtained through consultation with experienced forestry experts. For all scenarios it was assumed that the harvest fraction was 0 when selection of sprouts was made because the tree remained in the forest and the slash fraction was left on the ground.

In each scenario, five rotations were simulated, in order to compare how the carbon content in the stands evolves over time, considering each of the different proposed management alternatives in turn. Hence, when rotation was 40 years the simulation period was 200 years and when the rotation was 60 years the simulation period was 300 years.

Substitution effect: wood as alternative material

One important carbon impact is that resulting from the use of wood products in place of other materials. Hence in this work, material substitution was calculated by comparing the lifecycle inventory of the sweet chestnut wood products evaluated in the simulated scenarios with those of the most usual alternative materials (Fortin et al. 2012). In this study, 1 kg CO_{2e} m^{-3} of wood product was evaluated and compared with 1 kg CO_{2e} m^{-3} of the alternative material.

For building products it was assumed that wood would substitute concrete, and for heating purposes that wood biomass would replace fossil fuel. The fossil fuel emissions related to the processing of products were estimated using available lifecycle inventories. The lifecycle inventories for wood products of sweet chestnut used in this study were obtained by Martinez-Alonso & Berdasco (2015), focusing on forestry (harvesting practices), haulage and sawmill processing. Those related to the substitute material were taken from European LCIs.

Results

Carbon stored in biomass, soil and products

For the baseline scenario, the carbon stored in the aboveground biomass was 119.75 Mg C ha^{-1}, of which 79% was stored in stems (95.08 MgC ha^{-1}), 20.5% in branches (24.61 MgC ha^{-1}), and less than 1% in leaves (0.06 MgC ha^{-1}). The carbon stored in belowground biomass was 48.42 MgC ha^{-1} and that in soil was 131 MgC ha^{-1}. The turnover considered to establish the soil carbon content was 0.06 for stems, 0.021 for branches and 0.024 for roots. In the latter case, the model obtained for the calculation of root biomass as a function of age had an R^2 of 0.82, and both b_0=29369.63 and b_1=0.038 were significant with a confidence interval of 95%.

The carbon stored in the aboveground and belowground biomass remained constant over time in all scenarios. However, with one exception, compared to the baseline, in the alternative scenarios the carbon stored in all fractions of biomass decreased as the number of silvicultural interventions increased, the trend being much more pronounced in stems than in other components. The exception was scenario A-Th_1R_{60}, where carbon stored in stems increased significantly compared to both the baseline and scenario A-Th_1R_{40} (Fig. 2).

The proportion of wood destined for each product type entering the sawmill depended on the timing and type of selvicultural intervention performed. The largest products were beams and small beams, which were only obtained after final harvesting. Poles were obtained as a result of thinnings, while firewood was obtained from both harvesting and thinning operations. Planks were obtained after final harvesting and in some cases also as a result of thinnings. For the products evaluated, the lumber recovery factor (LRF) decreased in the following order: firewood>pole>small beam>plank>beam>small plank (Table 3). Note that sometimes the co-products produced in one stage are the actual products produced in another stage, for example, a co-product of beam production is planks, which is in itself a medium-term product.

In all the alternative scenarios considered, the percentage of wood designated for better quality and larger-sized products increased in the final harvesting compared to the baseline. As a result, the amount of firewood decreased in the following way; baseline > A scenarios (one thinning) > B scenarios (two thinnings). More specifically, in scenarios A-Th_1R_{40} and B-Th_2R_{40} the percentage of wood suitable for the manufacture of long- and medium-term products increased by 7% and 9.5 %, respectively, compared to the baseline. In the extended rotation scenarios (60 years), the increase was 8.25% and 10.5%, for one thinning and two thinning scenarios, respectively.

In terms of long-term products, the carbon stored was highest in scenario A-Th_2R_{60} (29 MgC ha^{-1}), values for the rest of the scenarios evaluated being 25.27 for the baseline, and 27.59, 23.49 and 25.34 MgC ha^{-1} for scenarios A-Th_1R_{40}, B-Th_1R_{40} and B-Th_2R_{60}, respectively. The same tendency was observed for medium-term products, with A-Th_2R_{60} being the highest with 37.39 MgC ha^{-1} compared to the baseline with 28.37 MgC ha^{-1} and scenarios A-Th_1R_{40}, B-Th_1R_{40} and B-Th_2R_{60} having 31.76 MgC ha^{-1}, 29.70 MgC ha^{-1} and 32.96 MgC ha^{-1}, respectively. However, carbon storage in short-term products was higher in the baseline than in any of the alternative scenarios evaluated (Table 4).

At the end of the simulated period, it can clearly be seen that in three of the four scenarios the application of thinnings provoked a decrease in the amount of carbon stored in total biomass with respect to the baseline of 168 (i.e. amounts of 155, 115 and 145 MgC ha^{-1} for scenarios A-Th_1R_{40}, B-Th_2R_{40} and B-Th_2R_{60}, respectively). The exception was scenario A-Th_1R_{60}, where 178 MgCha^{-1} was stored. This trend was not however observed in the soil carbon, where the baseline accumulated more carbon than in any of the scenarios (131 MgC ha^{-1} compared to 125, 119, 108 and 107 for scenarios A-Th_1R_{40}, A-Th_1R_{60}, B-Th_2R_{40} and B-Th_2R_{60}, respectively). The amount of carbon stored in wood products was higher in the A-Th_1R_{40}, A-Th_1R_{60} and B-Th_2R_{60} scenarios (208, 241 and 225 MgC ha^{-1}, respectively) than in the baseline (197 MgC ha^{-1}) but this was not the case for scenario B-Th_2R_{40} (195 MgC ha^{-1}).

Total Carbon

The total carbon stored (above and belowground biomass, soil and products) (Table 5) was 328 MgC ha^{-1} in the baseline scenario and 334 and 303 MgC ha^{-1} in scenarios A-Th_1R_{40} and B-Th_2R_{40}, respectively (at 200 years) and 361 and 333 MgC ha^{-1} in scenarios A-Th_1R_{60} and B-Th_2R_{60} (at 300 years). Regardless of the management involved, total carbon stock increased over time in each of the five scenarios evaluated, scenario A-Th_1R_{60} at 300 years being that which stored most carbon. There were however considerable differences between scenarios. With respect to the 40 year rotation scenarios: in A-Th_1R_{40}, the carbon stored in the baseline was higher during the two first rotations but in the third rotation (120 years) the amounts were similar, while in the fourth and fifth rotation (160 and 200 years) the carbon stored in scenario A-Th_1R_{40} exceeded the baseline; Meanwhile in the extended rotation scenarios, less carbon was stored in scenario B-Th_2R_{40} at the end of each rotation than in either the baseline or scenario A-Th_1R_{40}, while, in contrast, the single thinning scenario, A-Th_1R_{60}, was that which stored the most carbon at the end of every rotation (60, 120 and 180 years), due to the fact that the carbon stored in products was always higher when only one thinning was made.

Substitution effect

Emissions avoided corresponded to 879.83 kg CO_{2e} m^{-3} in the case of wood replacing concrete as a building material, and 2711.92 kg CO_{2e} m^{-3} when it replaced gas or oil as a heating material (Fig 3). The sweet chestnut products considered with respect to building materials were: pole, small beam, plank, beam and small plank, and with respect to heating material, firewood was the only product considered.

Discussion

The comparison of the different simulated scenarios for sweet chestnut coppice showed that thinnings modified carbon distribution in the different elements evaluated: biomass, soil and products. When one thinning was applied, there was a slight increment in carbon stock in biomass compared to the baseline. However, in the scenarios with two thinnings there was a decrease in biomass carbon stock decreased. This has also been observed in other species, both softwood and hardwood (Mund and Schulze, 2006; Ruiz-Peinado et al., 2014). One factor that could account for this decrease in biomass carbon relates to the site index, whereby better quality sites imply greater growth, which in turn means more carbon storage and hence an increased mitigation potential of the stand (Profft et al., 2009). The effect of thinning on the carbon accumulated in the biomass therefore has less impact in stands with better site indexes due to their higher productivity (Perez-Cruzado et al., 2012), making the relatively costly silvicultural intervention of thinnings in such sites more economically viable. In stands with lower site indexes, meanwhile, one way to incentivize silvicultural intervention, and thus increase carbon storage capacity, could be through the carbon being considered as an ecosystem service (Bravo et al., 2008a). Future research is needed to study how the influence of the site index affects the carbon stored in sweet chestnut coppice in the region.

This study carries out a full characterization of wood products in the forest-industry value chain for sweet chestnut coppice. Thinnings showed a positive influence on carbon storage in products, with the exception of scenario B-Th_2R_{60}. The results of the present study demonstrate that long- and medium-term products store more carbon than short-term ones. This may be due to thinning interventions providing better quality roundwood at final harvesting which can be used for long-term products (Proft et al., 2009) to meet potential market demand, and is thus an important issue to consider in future research. Another factor which influences and is key to the results of the products module is the lifespan assigned to each of the products. The globalization of markets makes the traceability of wood products difficult, meaning that in many cases there is an absence of data on their longevity (Larson et al., 2012). There is great variation in the lifespan periods which can be attributed, e.g., the definition of long-term products may range from 20 to 50 years, medium-term products from 10 to 20, and short-term products from 1 to 2 (Karjalainen et al., 1994; Profft et al., 2009; Perez-Cruzado et al., 2012). Moreover, since silviculture also affects the lifespan of harvested products, the further development of this type of study is essential for the correct characterization of products (Miner, 2006). The results presented here indicate that for the long-term products considered (beams) the most favourable scenario in terms of carbon stored was A-Th_2R_{60} followed by A-Th_1R_{40}. The same tendency was observed for medium term products (poles and planks) with A-Th_2R_{60} being the most favourable scenario. However, for short-term products (firewood) the baseline was found to be the scenario.

Wood products can in fact have a double mitigating effect: on the one hand, through carbon sequestration in the raw material and on the other, by substituting alternative products (e.g. steel, concrete, fossil fuels etc.) (Gustavsson and Sathre, 2011; Lippke et al., 2011) which brings about a sustainable reduction in atmospheric carbon. This first consideration of the substitution effect of sweet chestnut wood products shows their potential use, particularly the use of firewood to substitute gas or oil in heating. There are other studies that have also found a positive impact on carbon fluxes, albeit with other species (Fortin et al., 2012; Lippke, 2011; Murphy et al. 2015; Perez-García, 2005; Petersen and Solberg, 2005; Røyne et al. 2016). A full assessment of the impact of forests on climate change mitigation should consider the carbon stored in wood products harvested from stands which are sustainably managed, as well as the substitution effect so as not to underestimate the potential of the forest sector in the fight against climate change (Karjalainen et al., 1994; Ståhls et al.2011).

The goal of a silvicultural treatment might be for timber exploitation, conservation, recreational use or storage of carbon, as in this work. Our results indicate that as far as total carbon accumulation is concerned scenario B-Th_2R_{60} is the least viable. Moreover, the two A- scenarios considered (i.e. a single thinning) were clearly the best management option, particularly when the rotation was extended to 60 years (ATh_1R_{60}). Silviculture actions which encourage the increment of biomass have also been proposed by entities such as the Verified Carbon Standard (VCS, 2013) as a way to extend the mitigation potential of forestry exploitations. Different European forests have been analysed to see how the application of long rotations affect carbon accumulation, results indicating that an increment of 20 years in the rotation age increases total carbon stored in pine forests by between 6 and 13% and in spruce forests by 14-67% (Kaipainen et al., 2004). Our finding that increasing the rotation period in sweet chestnut coppice in Northern Spain is an effective silvicultural management strategy supports observations for the same species in France (Martel, 2010), and for softwood species (*Pinus sylvestris*, *Picea abies*) in other European regions like Finland (Liski et al., 2001).

This work therefore demonstrates the validity of the CO2FIX model as a tool to allow the identification of the mean differences in forest carbon stock according to the different selvicultural managements (thinnings and rotation length) implemented for sweet chestnut coppice, in line with its proven success in other ecosystems (Alvarez et al., 2014). This study contributes to assessing and detecting differences in carbon stocks under different forest management operations and therefore it will help to incorporate the carbon sequestration issue in the forest management agenda. Forest managers and policy makers interested in mitigating climate change should be considering: (1) lengthening the rotation period by 20 years; (2) reducing the number of thinnings implemented; and (3) promoting the use of sweet chestnut wood products, especially as woodfuel. These actions will also bring about co-benefits in terms of rural development, especially in those areas where sweet chestnut coppices have been abandoned because of their low forestry profitability.

Conclusions

The estimations of carbon sequestration by sweet chestnut coppice under five alternative management scenarios (including baseline) in this work shed new light on the effect of different silvicultural management alternatives on carbon storage in biomass, soil and wood products. The results reveal that the application of thinnings altered the total carbon of the system. When the forest management was intense (more than one thinning), a loss of carbon was observed with respect to the baseline. However, in scenarios where only one thinning was considered, a small increase in the total carbon compared to the baseline was observed, principally in terms of the carbon stored in wood products. Also, extending the rotation from 40 to 60 years under this silvicultural regime would provide a 9.14% increase in total carbon by allowing greater growth in biomass and therefore increasing the carbon stock of sweet chestnut coppice. Moreover, a positive effect on carbon storage was noted when more wood was available for the manufacture of long-term products. The positive effect on GHG emissions of substituting materials such as concrete and fossil fuel with sweet chestnut is an addition plus in terms of the mitigation effect of this species. Taken as a whole, the information in this work with respect to growth and the carbon storage capabilities of this species (in soil, biomass and products) under different silvicultural interventions, and the evaluation of the substitution effect, provides valuable information about sweet chestnut management and carbon sequestration which will help forest managers in their planning and decision making, taking into account the important mitigation option.

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Table 1. Stand characteristics of the 15 plots of *Castanea sativa* Mill. studied.

	Site index (SI=19 m)[1]			
	Av.	**Max.**	**Min.**	**SD**
Age (years)	35	55	14	12.4
N (stems ha^{-1})	1903	4315	608	1193
G (m^2 ha^{-1})	38.9	52.7	16.3	11.2
dg (cm)	18.5	30.9	8.4	6.6
Total biomass (Mg ha^{-1})	168.2	279.0	58.3	65.8

[1]Reference age=30 years. *N=density; G=Basal area; dg=quadratic mean diameter*.

Table 2. Simulated management scenarios (baseline and A-Th_1R_{40}, A-Th_1R_{60}, B-Th_1R_{40} and B-Th_2R_{40}) in sweet chestnut coppice.

	Age (years)	Management operations	N_b (stems/ha)	N_a (stems/ha)	Harvested Wood (% in volume)	Slash (% in volume)
Baseline scenario	40	Final harvesting	1903	-	70	30
Scenario A-Th_1R_{40}	10	Selection of sprouts	1903	700	-	100
	15	Thinning	700	325	72	28
	40	Final harvesting	325	-	70	30
Scenario A-Th_1R_{60}	10	Selection of sprouts	1903	700	-	100
	15	Thinning	700	325	72	28
	60	Final harvesting	325	-	70	30
Scenario B-Th_2R_{40}	10	Selection of sprouts	1903	700	-	100
	15	Thinning	700	325	72	28
	26	Thinning	325	180	72	28
	40	Final harvesting	180	-	70	30
Scenario B-Th_2R_{60}	10	Selection of sprouts	1903	700	-	100
	15	Thinning	700	325	72	28
	26	Thinning	325	180	72	28
	60	Final harvesting	180	-	70	30

N_b=density before harvesting, N_a=density after harvesting.

Table 3. The Lumber Recovery Factor (LRF) of the products studied.

	LRF (%)	Co-product (Plank) (%)	Co-product (Firewood) (%)	Residues (%)
Long-term products				
Beam	37.29	34.19	4.5	24.02
Small beam	40.02	4.32	5.3	50.36
Medium-term products				
Plank	38.38	-	12.89	43.46
Board	20.89	26.85	6.91	37.55
Pole	57.76	-	42.24	-
Short-term products				
Firewood	96.43	-	-	3.57

Table 4. Percentage (%) of wood designated to each type of product at each stage (beams, planks, pole and firewood) depending on the management scenario.

	Beam (%)	**Small beam (%)**	**Plank (%)**	**Small plank (%)**	**Pole (%)**	**Firewood (%)**
Baseline scenario						
Final harvesting	32	6	32	6	-	24
Scenario A-Th$_1$R$_{40}$						
Thinning	-	11	10	-	52	27
Final harvesting	39	6	39	6	-	10
Scenario A-Th$_1$R$_{60}$						
Thinning	-	11	10	-	52	27
Final harvesting	40.25	6	40.25	6	-	7.5
Scenario B-Th$_2$R$_{60}$						
1ª Thinning	-	11	10	-	52	27
2ª Thinning	-	17	20	-	48	15
Final harvesting	41.5	6	41.5	6	-	5
Scenario B-Th$_2$R$_{40}$						
1ª Thinning	-	11	10	-	52	27
2ª Thinning	-	17	20	-	48	15
Final harvesting	42.5	6	42.5	6	-	3

1 Table 5. Evolution of the carbon content in each scenario by rotations and components.

		MgC/ha			
	Years	**Biomass**	**Soil**	**Products**	**Total**
Baseline scenario	40	168	131	88	220
	80	168	132	122	255
	120	168	131	152	284
	160	168	131	176	308
	200	168	131	197	328
Scenario *A-Th1R40*	40	155	126	83	209
	80	155	126	122	248
	120	155	125	156	282
	160	155	125	185	310
	200	155	125	208	334
Scenario *A-Th1R60*	60	178	123	106	230
	120	178	122	154	277
	180	178	121	191	313
	240	178	120	220	340
	300	178	119	241	361
Scenario *B-Th2R40*	40	115	109	70	180
	80	115	109	110	219
	120	115	108	143	252
	160	115	108	171	280
	200	115	108	195	303
Scenario *B-Th2R60*	60	145	111	93	205
	120	145	110	140	251
	180	145	109	177	286
	240	145	108	205	313
	300	145	107	225	333

2

3

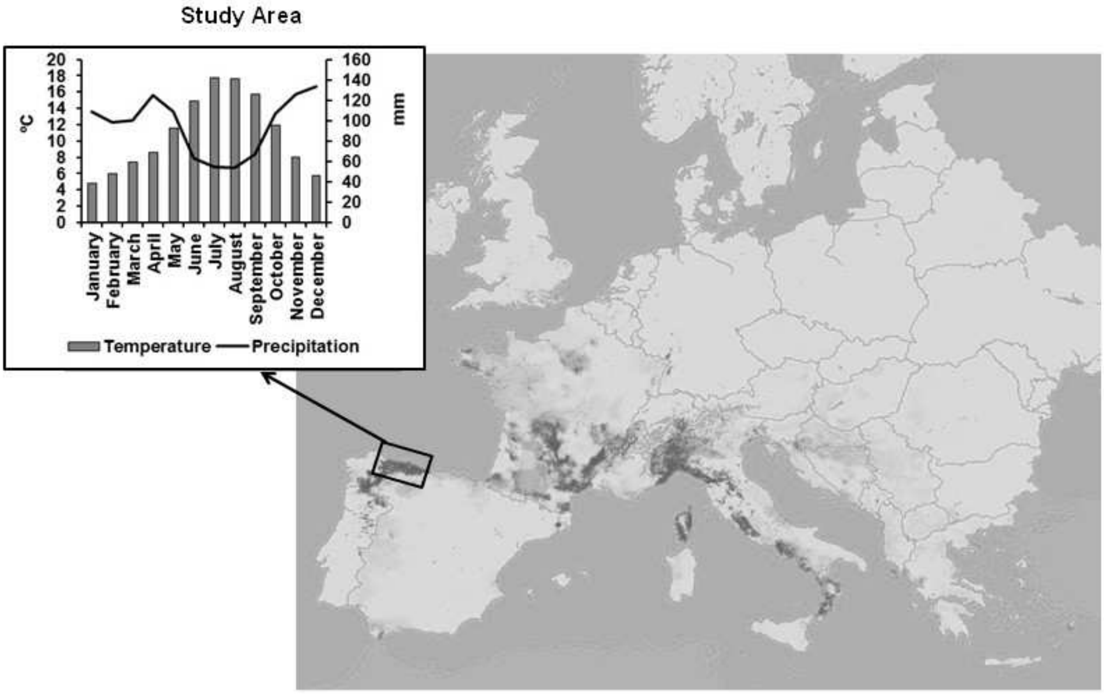

Fig 1. Distribution of sweet chestnut in Europe and location of the study area.

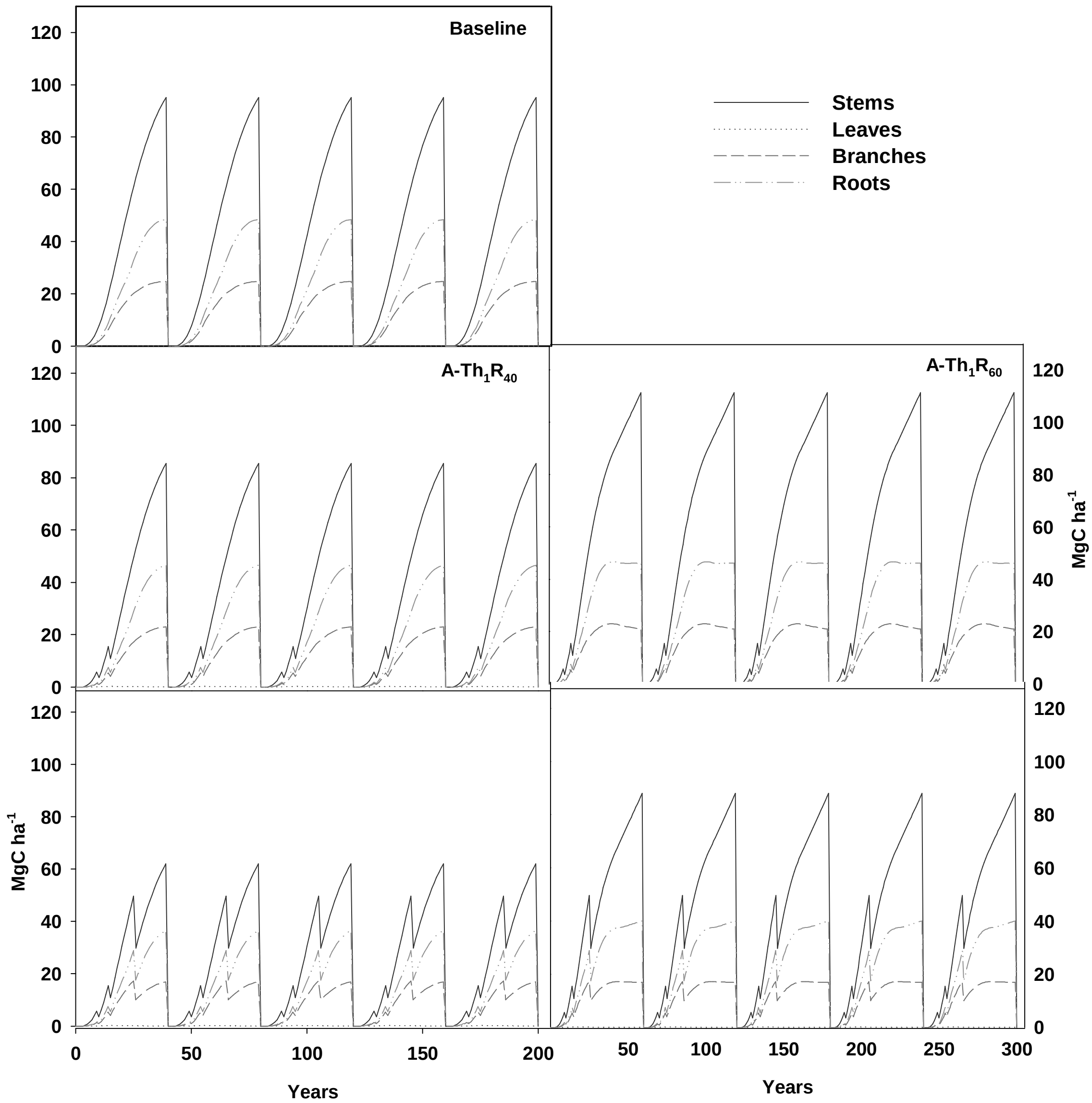

Fig 2. Carbon stored in each biomass fraction in each scenario simulated. Homogenous comparisons of the results considering mean values for each alternative evaluated; when rotation was 40 years, the simulation period was 200 years and when the rotation was 60 years, the simulation period was 300 years.

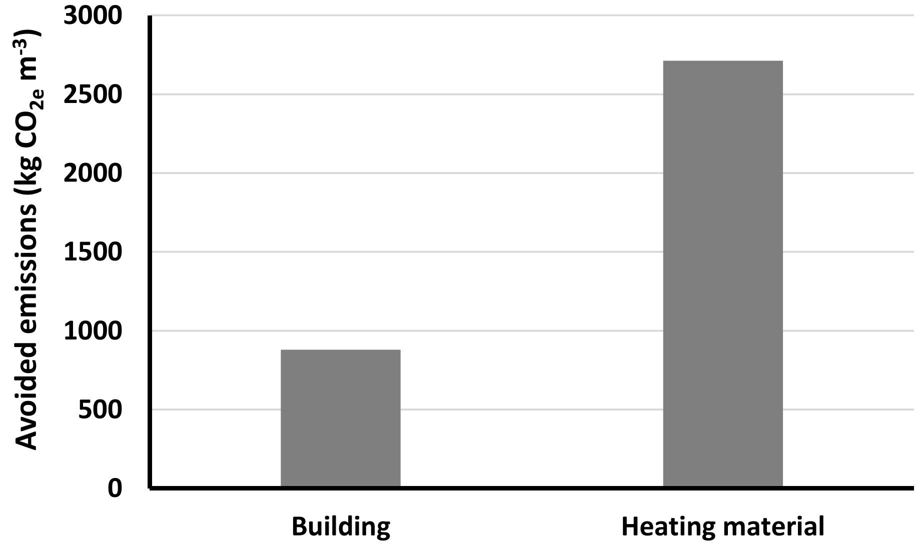

Fig 3. Substitution effect on GHG emissions when replacing traditional materials (concrete for building and fossil fuel for heating) by sweet chestnut wood products.

Highlights

- Establishment of the baseline of carbon capture in sweet chestnut coppice.
- Assessment of the effect of thinnings intensities and rotation lengths on carbon storage.
- Simulation of different silvicultural management alternatives (scenarios).
- Evaluation of the substitution effect of sweet chestnut products against alternative materials.