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A model for estimating carbon accumulation in cork products

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Abstract

Aim of study: This study aims to develop a calculation model for estimating carbon accumulation in cork products, both whilst in use and when in landfills, and to apply the model to Portugal as an example.

Area of study: The model is applicable worldwide and the case-study is Portugal.

Material and methods: The model adopts a flux-data method based on a lifetime analysis and quantifies carbon accumulation in cork products according to three approaches that differ on how carbon stocks (or emissions) are allocated to cork product consuming and producing countries. These approaches are: stock-change, production and atmospheric-flow. The effect on carbon balance of methane emissions from the decay of cork products in landfills is also evaluated.

Main results: The model was applied to Portugal and the results show that carbon accumulation in cork products in the period between 1990 and 2010 varied between 24 and 92 Gg C year^{-1}. The atmospheric-flow approach provided the highest carbon accumulation over the whole period due to the net export of carbon in cork products. The production approach ranked second because exported cork products were mainly manufactured from domestically produced cork. The net carbon balance in cork products was also a net carbon accumulation with all the approaches, ranging from 5 to 81 Gg C_{eq} year^{-1}.

Research highlights: The developed model can be applied to other countries and may be a step forward to consider carbon accumulation in cork products in national greenhouse gas inventories, as well as in future climate agreements.

Key words: atmospheric-flow approach; greenhouse gas balance; modelling; production approach; stock-change approach.

Introduction

Cork is a unique natural material extracted from the outer bark that covers the stems and branches of the cork oak tree (*Quercus suber* L.). It consists in a thick and continuous layer of suberized cells produced by the cambium. Cork oak forests are located in the Western Mediterranean Basin and they can be found in Portugal, Spain, Morocco, Algeria, Tunisia, France and Italy. About 200 thousand tonnes of cork are harvested annually worldwide, of which approximately 50% are harvested in Portugal (APCOR, 2013). Portugal has also a leading role in cork processing, being responsible for about 68% of the global production of cork products (Pestana and Tinoco, 2009). Cork is processed into a variety of products such as natural cork stoppers, agglomerated cork stoppers, insulation panels, wall and floor coverings, gaskets, shoe insoles, household utensils, decorative products and many other products used in building construction, industry, aerospace and sports, among other sectors.

Cork oaks, like other trees, absorb carbon dioxide (CO_2) from the atmosphere. Since they are long-living trees (up to 200-250 years), they store carbon for long periods. For example, cork oak stands in Portugal store almost 17,500 thousand tonnes of carbon in above and below ground biomass, accounting for 23% of the total carbon stocks of the Portuguese forest (AFN, 2010). When managed sustainably, cork oaks may also be carbon sinks. In fact, eddy covariance measurements in a Portuguese cork oak woodland (*Quercus suber* mixed with *Quercus ilex* ssp. *rotundifolia*) with an average tree cover of 30% showed that CO_2 sequestration varied between 1.0 and 5.1 t CO_2 ha^{-1} year^{-1}, with an average of 3.2 t CO_2 ha^{-1} year^{-1} (Pereira *et al*., 2007).

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Part of the carbon sequestered by cork oak trees is transferred to cork products. Some of these products may stay in use for long periods and therefore delay the return of the carbon to the atmosphere. Even cork products with a relatively short lifetime may store carbon for long periods if they are disposed of in landfills at the end of their life, because under anaerobic conditions their decay is slow and incomplete mainly due to the presence of suberin and lignin, the cork major components (Pereira, 2007). Despite the potential of cork products to accumulate carbon and thus contribute to climate change mitigation, the amount of carbon stored in these products is currently unknown.

Different methods for estimating carbon accumulation in wood products have been proposed but, so far, none of them has been applied to cork products. Depending on the data required, these methods fall into three major categories: flux-data methods, stock-data methods and direct estimation of emissions. Flux-data methods estimate the changes in carbon stocks as the difference between the inflow of carbon into the pool of wood products and the outflow of carbon from that pool. There are two alternative types of flux-data methods: lifetime analysis, where the outflow of carbon is estimated using assumed lifetimes for the wood products (*e.g.* Skog *et al.*, 2004; Winjum *et al.*, 1998), and direct observation, where the outflow of carbon is estimated directly based on statistical data (*e.g.* Flugsrud *et al.*, 2001). Stock-data methods estimate the changes in carbon stocks as the difference between the stocks of carbon in wood products at two or more points in time (*e.g.* Hashimoto and Moriguchi, 2004; Pingoud *et al.*, 2003). These stocks are obtained directly based on statistics and sampling techniques. The method based on direct estimation of emissions calculates directly all forms of emissions from the decay and combustion of wood products (*e.g.* Flugsrud *et al.*, 2001). According to this method, the changes in carbon stocks of wood products are estimated from the difference between carbon contained in the harvested wood and the total carbon emissions generated over the life cycle of that harvested wood.

Moreover, the amount of carbon accumulated in wood products may be included on a voluntary basis in the national greenhouse gas (GHG) inventories performed under the United Nations Framework Convention on Climate Change (UNFCCC), which may create incentives for the consumption of wood products, but cork products have been disregarded in these inventories. For GHG inventorying purposes, the Intergovernmental Panel on Climate Change (IPCC) has been proposing default methods to quantify carbon accumulation in wood products, first in the Good Practice Guidance for Land Use, Land-use Change and Forestry (IPCC, 2003) and then in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). These methods are flux-data methods based on a lifetime analysis and have been applied by several countries (*e.g.* Dias *et al*., 2007, 2009, 2012; Donlan *et al.*, 2012).

This study aims to develop a calculation model for estimating carbon accumulation in cork products, both whilst in use and when in landfills, and to apply the model to Portugal as an example. The model adopts a flux-data method based on a lifetime analysis and allows the quantification of carbon accumulation in cork products according to three main approaches that have been originally proposed for wood products: the stock-change approach (SCA), the production approach (PA), and the atmospheric-flow approach (AFA) (Brown *et al.*, 1999; IPCC, 2006). These approaches differ on how they define system boundaries and have been the subject of a long and intense debate on what approach should be selected for using in national GHG inventories and in future climate agreements.

Methane (CH_4) generated from the decay of cork products in landfills has a global warming potential of 25 kg CO_{2eq} (IPCC, 2007) and may potentially counteract carbon accumulation in landfills. Therefore, the effect of CH_4 emissions is also evaluated in this study by performing a net carbon balance.

Material and methods

Approaches

The SCA, AFA and PA differ in the way carbon stocks (or emissions) are allocated to countries that consume and produce cork products. The SCA considers that carbon accumulation is equal to the change in carbon stocks of cork products within national boundaries. Thus, carbon stock changes in cork products are accounted for in the country where the cork products are consumed. According to the PA, carbon accumulation is equivalent to the change in carbon stocks of cork products manufactured from domestically produced cork. In this case, carbon stock changes in cork products are allocated to the country where the cork that serves as raw material was produced.

Rather than estimating carbon stocks, the AFA estimates the flow of carbon between the forest sector and the atmosphere within national boundaries. Under this approach, emissions from the oxidation of cork products are allocated to the consuming country. In practice, carbon accumulation in cork products in the AFA is equal to that estimated by the SCA, plus the net export of carbon in cork products.

Cork product categories

The model estimates the change in carbon stocks separately for three categories of products that were established based on their longevity in use: cork stoppers, panels of agglomerated cork for construction and other cork products. Since the products within each category have different carbon content, further disaggregation was needed to estimate carbon flows. Cork stoppers include stoppers from natural and agglomerated cork used mainly to seal wine bottles. Panels of agglomerated cork for construction are mostly used for insulation and wall/floor coverings and were disaggregated into pure agglomerates and composite agglomerates. Pure agglomerates are manufactured from virgin cork (obtained in the first cork stripping) without any external agglutinant. Composite agglomerates require an agglutinating agent and are made from low quality raw cork (second cork obtained in the second cork stripping, refuse, pieces and very thin planks) and from by-products/wastes produced in the manufacturing of natural cork products. Other cork products comprise all the remaining products, divided in products of natural cork and products of agglomerated cork. For these products, other kind of disaggregation that takes into account their utilization was not possible due to limitations in the available data.

The net export term considered in the AFA considers not only the product categories above mentioned but also all other cork materials traded: raw cork, cork slabs and other cork semi-manufactured, and cork by-products/wastes (*e.g.,* in pieces, grinded, granulated or pulverized).

Carbon accumulation in cork products in use

The carbon stocks and the change in carbon stocks in cork products in use were calculated using the calculation algorithm recommended by the 2006 IPCC Guidelines (IPCC, 2006) for wood products (Equations [1] and [2]).

$$S_{t+1} = e^{-k} \times S_t + \left(\frac{1 - e^{-k}}{k}\right) \times I_t \quad [1]$$

$$\Delta S_t = S_{t+1} - S_t \quad [2]$$

where S_t and S_{t+1} are the carbon stocks in two consecutive years, t and (t+1), respectively; k is the decay rate (fraction lost per year); I_t is the input of carbon to the pool of cork products in year t; ΔS_t is the change in carbon stocks for year t.

Calculations of the carbon stocks start in the year 1900 and continue until the current year t.

In the SCA and AFA, the input to the pool of cork products in use is equal to the consumption of cork products in the country, estimated from the fluxes of production, import and export. In the PA, the input to the pool of cork products in use refers to the consumption of cork products manufactured from domestically produced cork. As, in practice, the collection of the data required by this approach in all the countries that import domestically produced cork or cork products produced from domestically produced cork is unfeasible, it was assumed that domestically produced cork and cork products produced from that cork have the same fate as cork and cork products consumed inside national boundaries. This simplification is also suggested by the 2006 IPCC Guidelines (IPCC, 2006) for wood products. Thus, the input of carbon to the pool of cork products for a certain year under the PA was calculated using Equations [3] and [4] respectively for pure cork agglomerates and other cork products. Pure cork agglomerates are produced from virgin cork, whereas other cork products are produced from both second cork and reproduction cork (obtained from the third stripping onwards).

$$I_{PA,\ pure\ ag} = P_{pure\ ag} \times \left(\frac{P_{virgin\ cork}}{P_{virgin\ cork} + I_{virgin\ cork} + E_{virgin\ cork}}\right) \quad [3]$$

$$I_{PA,\ other} = P_{other} \times \times \left(\frac{P_{other\ raw\ cork}}{P_{other\ raw\ cork} + I_{other\ raw\ cork} + E_{other\ raw\ cork} + I_{slabs} + E_{slabs}}\right) \quad [4]$$

where $I_{PA,\ pure\ ag}$ is the input of carbon to the pool of pure cork agglomerates for a certain year under the PA; $P_{pure\ ag}$ is the production of pure cork agglomerates in a certain year (expressed as carbon mass); $P_{virgin\ cork}$ is the production of virgin cork in a certain year (expressed as carbon mass); $I_{virgin\ cork}$ is the import of virgin cork in a certain year (expressed as carbon mass);

$E_{virgin\ cork}$ is the export of virgin cork in a certain year (expressed as carbon mass); $I_{PA,\ other}$ is the input of carbon to the pool of each cork product other than pure cork agglomerates for a certain year under the PA; P_{other} is the production of each cork product other than pure cork agglomerates in a certain year (expressed as carbon mass); $P_{other\ raw\ cork}$ is the production of second and reproduction cork in a certain year (expressed as carbon mass); $I_{other\ raw\ cork}$ is the import of second and reproduction cork in a certain year (expressed as carbon mass); $E_{other\ raw\ cork}$ is the export of second and reproduction cork in a certain year (expressed as carbon mass); I_{slabs} is the import of cork slabs and other cork semi-manufactures in a certain year (expressed as carbon mass); E_{slabs} is the export of cork slabs and other cork semi-manufactures in a certain year (expressed as carbon mass).

Table 1 shows the decay rates and corresponding average lifetimes adopted for cork products in use. The values considered for panels used in construction are the same adopted by Dias *et al*. (2007) for wood products used in construction, as they are also applicable to cork panels (Gil, 2011). For the remaining products the decay rates were assumed.

Statistical data on production, import and export of cork materials and products were collected from several available sources (Suppl. Table S1), such as the National Statistics Institute (INE, 1944-2012a,b), Portuguese forest authorities (DGF, 1991; Sampaio, 1986), the Portuguese Cork Association (APCOR, 2011), Mendes (2002), Eurostat (EC, 2014b) and the United Nations Commodity Trade Statistics Database (UN Comtrade) (UN, 2014). When data from several sources were available, they were compared and the more reliable data were selected based on a consistency check. This was accomplished by performing mass balances and by comparing, for each product category, production data with exportation data. Some inconsistencies were found mainly because production data were incomplete due to the existence of confidential data. In these cases, the production amounts needed to be estimated by considering the same ratio between exportation and production as in adjacent years.

Table 1. Decay rates for cork products in use and their corresponding average lifetimes

Cork products	Decay rate (year^{-1})	Average lifetime (year)
Stoppers	0.67	1.5
Panels of agglomerated cork for construction	0.03	30
Other products	0.50	2

Statistical data for raw cork are available from 1900 onwards, while for natural cork stoppers they are available from 1943 onwards. For the period from 1900 to 1942, the input to the pool of natural cork stoppers in use was estimated considering an exponential growth rate established based on the trend presented by the input to the pool of natural cork stoppers in use for the period covered by statistical data. The remaining cork products started to be produced in Portugal during the XX century and statistical data are available since the first year of their production.

Statistical data are reported as cork mass (wet basis). They were converted to mass of carbon using the carbon and moisture contents shown in Table 2.

Carbon accumulation in cork products in landfills

The input of carbon to the pool of cork products in landfills was obtained from the amount of carbon estimated by the model to be going out of use and the fraction of discarded cork products going to landfills, following IPCC (2003) guidance. Both sanitary landfills and open dumps were included. As for Portugal there are no data regarding the flows of discarded cork products at the end of their useful life, they were assumed to be disposed of in the same way as municipal solid waste. Thus, the fraction of discarded cork products going to landfills was taken from national waste statistics available from 1960 onwards (Maciel *et al*., 2012). Prior to 1960 it was estimated by assuming linear extrapolation from the past and in the year 1900 it was considered to be zero. According to these data, the fraction of discarded cork products going to landfills increased almost linearly from zero in 1990 to 0.89 in the late nineties. Then, it decreased to 0.72 in 2000 (due to an increase in the flow going to incineration) and this value was kept almost constant up to the present time.

In landfills, there are three types of carbon stocks that were treated differently:

1) Stock undergoing aerobic decay. This stock, that was assumed to decay completely and immediately, was only considered for open dumps, where 40% the products decayed in aerobic conditions (IPCC, 2006).

Table 2. Carbon and moisture content in cork materials and products

Cork material/product	Carbon fraction (dry basis)	Moisture fraction
Raw cork		
Virgin cork	0.60[a]	0.06[b]
Second and reproduction cork	0.55[a]	0.06[b]
Cork slabs and other cork semi-manufactured	0.57[a]	0.06[c]
Stoppers		
Natural cork stoppers	0.55[d]	0.06[e]
Agglomerated cork stoppers	0.47[f]	0.06[e]
Panels of agglomerated cork for construction		
Pure agglomerates	0.65[g]	0.02[h]
Composite agglomerates	0.48[i]	0.06[e]
Other cork products		
Other of natural cork	0.55[d]	0.06[e]
Other of agglomerated cork	0.47[j]	0.06[e]
Cork by-products/wastes	0.57[a]	0.06[e]

[a] Gil and Pereira (2007). [b] Pintor et al. (2012) and Rives (2011). [c] Rosa and Fortes (1989). [d] Assumed to be similar to the carbon content in reproduction cork. [e] Pereira (2007) and Pintor *et al.* (2012). [f] Estimated by considering an adhesive content of 9% (Rives *et al.,* 2012; Six and Feigenbaum, 2003) and a cork carbon content similar to the one in reproduction cork. [g] Gil *et al.* (2011). [h] Rosa and Fortes (1989). [i] Estimated by considering an adhesive content of 7% (Gil *et al.,* 2000) and a cork carbon content similar to the one in reproduction cork. [j] Estimated by considering an adhesive content similar to the one in agglomerated cork stoppers and a cork carbon content similar to the one in reproduction cork.

2) Stock undergoing anaerobic decay. The carbon stocks and the change in carbon stocks in cork products undergoing anaerobic decay were calculated using Equations [1] and [2] respectively. A decay rate of 0.025 year^{-1} (corresponding to an average lifetime of 40 years) was adopted (IPCC, 2006).

3) Permanent stock. This stock is formed by the carbon contained in the cork products that does not decay under anaerobic conditions, which was considered to be 50% (IPCC, 2006).

Methane emissions and net carbon balance

Methane emissions from the anaerobic decay of cork products disposed of in landfills were calculated based on the amounts of biogas produced (equal to the output from the pool of products undergoing anaerobic decay estimated by the model), the fraction of CH_4 in biogas (0.50 according to IPCC (2006)) and the global warming potential of CH_4 (25 kg CO_{2eq} (IPCC, 2007), meaning that 1 kg of carbon emitted as CH_4 is equivalent to 9.1 kg of carbon emitted as CO_2). The amount of CH_4 in the biogas recovered and burnt was subtracted, because it is converted into CO_2. The biogas recovery rates in Portugal were considered (Maciel *et al*., 2012). They were zero until 2003 and have been increasing almost linearly up to 16% in 2010.

The net carbon balance in cork products was determined by subtracting the additional emissions of CH_4 to the carbon accumulation. The additional emissions of CH_4 are the difference between total carbon emissions from landfills expressed as mass of carbon equivalent and total carbon emissions from landfills expressed as mass of carbon.

Sensitivity analysis

The decay rates for cork products in use are highly uncertain as they are not based on empirical data but were rather assumed based on cork product-using practices. The decay rates of cork products in landfills are also affected by great uncertainty (IPCC, 2006). For these reasons, a sensitivity analysis was undertaken to assess the effects of changing the decay rates in the carbon accumulation. In this analysis, the decay rates were allowed to vary between half and double of the reference values.

Results

Although the model estimates carbon accumulation in cork products from 1900 onwards, the analysis of the results obtained for Portugal is undertaken for the period of 1990 to 2010. Cork products have been accumulating carbon throughout the analysed period, but the estimates of carbon accumulation greatly depend on the accounting approach used (Fig. 1).

The SCA generated the lowest carbon accumulation over the whole period, varying between 24 and 42 Gg C year^{-1}. In opposition, the AFA produced the largest estimates of carbon accumulation, ranging from 62 to 92 Gg C year^{-1}. The difference between the results obtained with these two approaches is due to the net carbon export that occurred during the period studied (Suppl. Fig. S1). In fact, Portugal was a net carbon exporter in cork products, mainly in panels of agglomerated cork for construction and stoppers. The net import of raw cork over the whole period, as well as the net import in some years of cork by-products/wastes, cork slabs and other cork semi-manufactured, negatively affected carbon accumulation estimated by the AFA.

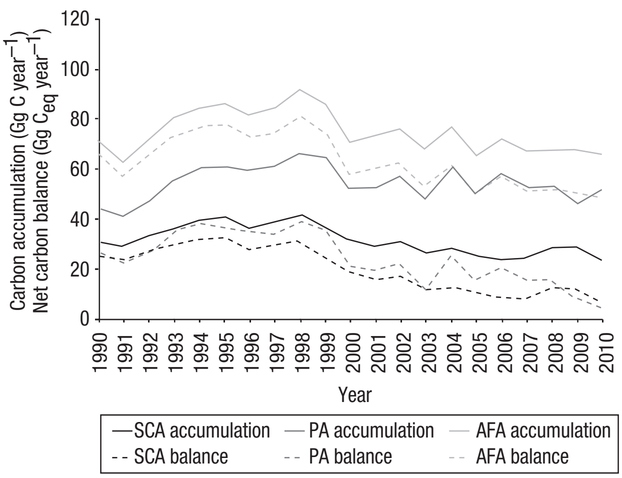

Figure 1. Carbon accumulation and net carbon balance in cork products for Portugal under the three approaches from 1990 to 2010.

The carbon accumulation obtained with the PA ranged from 41 to 66 Gg C year^{-1}, which is higher than the estimates obtained with the SCA, because Portugal was a net exporter of cork products (46 to 62% of the carbon contained in the cork products produced in Portugal was exported between 1990 and 2010) that were mainly (ca. 80-90%) produced from domestically produced cork.

The largest contribution to carbon accumulation estimated with the SCA, over the whole period, was from panels of agglomerated cork for construction (Suppl. Fig. S2), mainly composite agglomerates, accounting for 67-87% of the total carbon accumulation, because they contain the majority (65-80%) of the carbon contained in cork products consumed in Portugal in the period 1990-2010. Besides, they are the product whose consumption increased more since 1900 and their lifetimes in use and in landfills are long. Stoppers in use and other cork products in use were small net sources of carbon in some years with the SCA (Suppl. Fig. S2), because they are short-living products and the consumption of these products in previous years was higher than their consumption in these years.

Panels of agglomerated cork for construction are also the major contributors to carbon accumulation estimated with the PA, accounting for 60-77% of the total carbon accumulation over the whole period (Suppl. Fig. S3). Stoppers in use and other cork products in use were small net sources of carbon in some years with the PA (Suppl. Fig. S3), due to the same reasons mentioned for the SCA. However, it should be noted that the contribution of stoppers, more specifically, stoppers in landfills, in the PA is higher than in the SCA, because the flows of carbon in the stoppers produced from domestically produced cork are larger than the flows of carbon in the stoppers consumed in Portugal. Besides, the flows of carbon in the stoppers produced from domestically produced cork showed a more significant growth than the flows of carbon in the stoppers consumed in Portugal.

The results of the sensitivity analysis are shown in Table 3. The impact of changing the decay rates (in use and/or in landfill) is similar in the SCA and the PA. It consists in a decrease (when the decay rates double) or increase (when the decay rates become half) of carbon accumulation that ranges from 9 to 26% when both the decay rate in use and in landfill are changed. For these approaches, the effect of changing the decay ra-

Table 3. Sensitivity analysis results. The variation in relation to the reference scenario shown in Fig. 1 is expressed by the percentage of decrease (D) and increase (I)

Scenario	SCA		PA		AFA	
	Double	Half	Double	Half	Double	Half
Decay rate in use	D = 7-13%	I = 7-15%	D = 6-13%	I = 7-14%	D = 3-6%	I = 3-5%
Decay rate in landfill	D = 3-12%	I = 2-9%	D = 5-12%	I = 4-10%	D = 1-4%	I = 1-3%
Decay rate in use and in landfill	D = 12-26%	I = 9-21%	D = 13-22%	I = 11-20%	D = 6-10%	I = 4-8%

te in use did not differ significantly from the effect of changing the decay rate in landfill. For the AFA, the impact of changing the decay rates is smaller than for the other two approaches (ranging from a decrease or increase around 4-10% when both the decay rate in use and in landfill are changed), because the net export term considered in this approach is not affected.

Fig. 1 shows the results of the net carbon balance obtained by subtracting the additional emissions of CH_4 to carbon accumulation in products in use and in landfills. The net carbon balance is positive for all the approaches, meaning that CH_4 emissions are smaller than carbon accumulation. However, the net carbon balance is considerably lower than carbon accumulation for the PA and in some years for the SCA. In the PA, the net balance ranged from 5 to 39 Gg C_{eq} year^{-1}, representing a significant decrease of 37-91% in relation to carbon accumulation. In the SCA, the net carbon balance varied between 6 and 33 Gg C_{eq} year^{-1} and the decrease in relation to carbon accumulation was of 18-73%. The net carbon balance with the AFA was less affected than the other approaches, ranging from 49 to 81 Gg C_{eq} year^{-1}, which represents a decrease of 8-26% in relation to carbon accumulation.

The net carbon balance in landfills obtained by subtracting the additional emissions of CH_4 to carbon accumulation in products in landfills is positive for the SCA (2-10 Gg C_{eq} year^{-1}) and for the PA (1-14 Gg C_{eq} year^{-1}), except in 2010 (–9 Gg C_{eq} year^{-1}) for this last approach.

Discussion

In this study, a model to quantify carbon accumulation in cork products was developed for the first time. This model may be an important contribution for the inclusion of carbon accumulation in national GHG inventories performed under the UNFCCC, which may create incentives for using cork products instead of alternative materials that require more fossil fuels in their manufacture (*e.g.* plastic bottle stoppers, petrochemical-based insulation products).

The approaches applied in this study have been the focus of analysis and discussion by the UNFCCC and the international scientific community since the late 90s in order to select one approach to be used in the national GHG inventories and in future climate agreements. This selection has been particularly difficult because each approach may generate different socio-economic and environmental impacts. The technical aspects (*e.g.,* feasibility, accuracy, and consistency with other GHG inventories) and effects resulting from the application of the approaches (*e.g.,* on the wood product market, national policies, forest management and bioenergy use) have been analysed for wood products (Hashimoto, 2008; Nabuurs and Sikkema, 2001; UNFCCC, 2003). In principle, the results of these analyses are also valid for cork products, but a deeper analysis that is beyond the scope of this study should be performed.

The complexity of the model was kept at a low level, as high complexity does not necessarily make calculation methods more reliable and may make gathering input data more difficult (Pingoud *et al*., 2003). Therefore, some simplifications in the calculation procedures were undertaken. One of the most relevant simplifications pertains to the PA and consists in the assumption that domestically produced cork and cork products produced from that cork have the same fate as cork and cork products consumed inside national boundaries. This assumption could lead to misleading results particularly for carbon accumulation in cork products in landfills, because the waste management options may significantly differ from country to country. However, it would be unfeasible to follow the fate of domestically produced cork and cork products produced from that cork in all the countries where they are consumed. Besides, it should be noted that a similar assumption is also adopted in the default method suggested for carbon storage calculation in wood products by the 2006 IPCC Guidelines (IPCC, 2006).

Based on that assumption, the calculation of the input of carbon to the pool of cork products in use was performed differently for pure cork agglomerates and other cork products (Equations [3] and [4], respectively) because they are produced from different raw materials. Pure cork agglomerates are produced from virgin cork. However, there are other products also produced from virgin cork (*e.g.* decorative objects), but the amounts of virgin cork going to the production of these products are normally unknown as they are not considered separately by the statistical nomenclatures [*e.g.* combined nomenclature and prodcom (EC, 2014a)]. Therefore, these products were not taken into consideration, but the uncertainty introduced by this simplification is likely small as the amount of these products is normally small compared with pure cork agglomerates. The input of carbon to the pool of other cork products in use was estimated by considering that the raw materials for these products are second cork, reproduction cork, cork slabs and other semi-manufactures. However, there are other raw materials for these products, such as virgin cork as explained before, and cork by-products (*e.g.,* pieces and granulates). As statistical data on cork by-products are reported together with cork wastes for the majority of the statistical nomenclatures, it was not possible to consider the import and export of cork by-products in Equation [4].

The input of carbon to the pool of cork products in landfills was also calculated in a simplified way by multiplying the amount of carbon in cork products estimated to be going out of use by the fraction of discarded cork products going to landfills. An alternative, which is recommended by the 2006 IPCC Guidelines (IPCC, 2006) for wood products, would be to estimate that input directly from waste statistics based on the total production of municipal solid waste (MSW), the fraction of cork products in MSW and the fraction of discarded cork products going to landfills. This alternative calculation procedure was not adopted in the model as data for the fraction of cork products in MSW are normally not available, because cork is a minor component in MSW.

The model was applied to Portugal as a case study but it could also be applicable to other countries, even those that are only cork product consumers. In fact, for those countries, the SCA could generate positive values of carbon accumulation in cork products provided that the consumption of cork products has been increasing. According to the PA, carbon accumulation in cork products would be zero (as these countries are not raw cork producers), while according to the AFA, carbon accumulation in cork products would be negative (i.e. cork products would be a source of GHGs to the atmosphere). For countries like Portugal that are simultaneously producers of raw cork and net exporters of cork products, the AFA would generate the highest carbon accumulation followed by the PA and then the SCA, provided that both the consumption of cork products and the production of cork products from domestically produced cork have been increasing. If these fluxes show a decreasing trend, instead of accumulating carbon, cork products may behave as carbon sources.

A condition required to allow the application of the model to other countries is the existence of statistical data on production and international trade of cork materials and products for a sufficiently long time series (at least equal to the total lifetime of the cork products). Contrastingly to what happens for wood products, for which there is the international database FAOSTAT-Forestry (FAO, 2014) compiled by the Food and Agriculture Organization (FAO) covering statistical data from 1961 onwards for all countries, for cork products there is not such a broad database. The United Nations Comtrade database (UN, 2014) contains data on cork materials and products from 1962 onwards for all countries, but they refer to international trade only. For European countries, the Easy Comext database (EC, 2014b) provides data on both production and international trade of cork materials and products but they are only available from 1995 onwards. Therefore, countries must use nationally compiled statistics as alternative or as complement of these international databases. In the case of Portugal, these data are available from several sources and inconsistencies between them were found. Moreover, some data needed to be estimated, as explained in Section 2.3, which introduced uncertainty to the estimates. Therefore, this study highlights the need of creation of international databases on production and international trade of cork materials and products with good quality data, checked through mass balances or other methods, in order to obtain reliable estimates of carbon accumulation in cork products for all countries. Another condition necessary for applying the model to other countries is the existence of statistical data on the fraction of cork products (or municipal solid waste as assumed in this study) going to landfills at the end of their life. These data are normally available as they are also required for the national GHG inventories performed under the UNFCCC.

The remaining data required by the model such as decay rates in use and in landfills, carbon and moisture content in cork materials and products, and other landfill related data (fraction of aerobic decay, fraction of degradable carbon that effectively decomposes and fraction of CH_4 in biogas) should preferentially be country-specific. The results of the sensitivity analysis showed that the decay rates of cork products both in use and in landfills may affect significantly the results. However, it should be noted that empirical data for decay rates are not available and they are often assumed. Concerning carbon and moisture content in cork materials and products, in the absence of country-specific data, the data provided in Table 2 could be adopted as they are typical data based on measurements taken from the literature. Obtaining landfill related data specific of each country, particularly the fraction of degradable carbon in cork products that effectively decomposes, could be a difficult task due to the absence of data. In fact, some studies have been determining the decomposition of biogenic carbon in landfills using excavated waste samples (*e.g.* De la Cruz *et al*., 2013; Ximenes *et al*., 2008) but cork products have not been addressed by these studies. Thus, the default data adopted in this study, which were taken from IPCC (2006) could be also adopted by other countries in the absence of more reliable data.

The results of the application of the model to Portugal suggest that both cork products consumed in Portugal and cork products produced from Portuguese cork have been accumulating carbon during the period between 1990 and 2010. The range of carbon accumulation in cork products estimated in this study is about 10% of the range estimated for carbon accumulation in wood products in Portugal with the same approaches (Dias *et al*., 2007, 2012) and about 1-4% of the total change in carbon stocks in the Portuguese forest (biomass, litter and soil) estimated in the last National GHG Inventory (Maciel *et al*., 2012). An estimate of the total annual carbon stock changes for the Portuguese cork oak woodlands was not found in the literature. However if we extrapolate the average carbon sequestration of 0.88 t C ha^{-1} year^{-1} (3.2 t CO_2 ha^{-1} year^{-1}) measured by Pereira *et al*. (2007) to the total cork oak occupation area given in the last National Forest Inventory (AFN, 2010) and assuming that cork harvest has negligible effects on carbon storage (Bugalho *et al*., 2011), a carbon stock change of about 600 Gg C year^{-1} is obtained. Using this estimate, the share of the cork products for the total carbon accumulation of the cork oak sector varies between 4 and 13% depending on the approach and year.

When CH_4 emissions from landfills are taken into account, the net carbon balance obtained for cork products is still a net carbon accumulation with all the approaches, although CH_4 emissions have significantly decreased the benefit of carbon accumulation in landfills, mainly for the PA and in some years for the SCA. However, for the PA it is assumed that the fraction of cork products going to landfills and the biogas recovery rate are the same as in Portugal, which could introduce some bias in the results. In a scenario where the fraction of cork products sent to landfill are half of the fraction set for Portugal and the biogas recovery rate is the same as in Portugal, the net carbon balance with the PA would differ only slightly (accumulation of 8-35 Gg C_{eq} year^{-1}) as the landfill net carbon balance would not be very different (accumulation of 1-7 Gg C_{eq} year^{-1} from 1990 to 2009 and emission of 4 Gg C_{eq} year^{-1} in 2010). In a worst case scenario, where 100% of the discarded cork products are disposed of in landfills without biogas recovery, the net carbon balance in cork products with the PA would be positive from 1990 to 2000 (accumulation of 2-22 Gg C_{eq} year^{-1}) and negative from 2001 to 2010 (emission of 2-21 Gg C_{eq} year^{-1}), but the net carbon balance in landfills would be always negative (emission of 9-32 Gg C_{eq} year^{-1}). Therefore, this study points out that the role of landfills in carbon accumulation is greatly dependent on the amounts of products disposed of in these facilities and also on the CH_4 recovery rates.

Conclusions

This study provides a model for estimating carbon accumulation in cork products that could be used by any country. The consideration of carbon accumulation in cork products in the national GHG inventories and eventually in any future climate agreement could create incentives for using cork products that could contribute to climate change mitigation and could also be of strategic importance for the cork sector from an economic point of view.

From the application of the model to Portugal it was concluded that both cork products consumed in Portugal and cork products produced from Portuguese cork have been accumulating carbon during the period of 1990 to 2010. Carbon accumulation varied from 24 to 92 Gg C year^{-1}, depending on the approach considered. For the same year, the AFA provided the highest carbon accumulation, followed by the PA and the SCA. This ranking is expected for countries like Portugal that are net exporters of cork products originated mostly from domestically produced cork. The net carbon balance in cork products was also a net carbon accumulation for all the approaches, ranging from 5 to 81 Gg C_{eq} year^{-1}. This balance highly depends on the fraction of cork products disposed of in landfills and the biogas recovery rates.

Finally, this study highlights that more complete statistical data on production and trade of cork materials and products should be provided by the competent entities in order to obtain more reliable estimates of carbon accumulation in cork products. Moreover, these data should be checked for consistency through mass balances or other methods.

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