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LIFE CYCLE SUSTAINABILITY ASSESSMENT

Evaluating the carbon footprint of the cork sector with a dynamic approach including biogenic carbon flows

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Abstract
Purpose The aim of the present study is to assess the influence of two different attributional life cycle assessment (LCA) approaches, namely static LCA (sLCA) and dynamic LCA (dLCA), through their application to the calculation of the carbon footprint (CF) of the entire cork sector in Portugal. The effect of including biogenic carbon sequestration and emissions is considered as well.
Methods sLCA is often described as a static tool since all the emissions are accounted for as if occurring at the same time which may not be the case in reality for greenhouse gases. In contrast, dLCA aims to evaluate the impact of life cycle greenhouse gas emissions on radiative forcing considering the specific moment when these emissions occur.
Results and discussion The results show that the total CF of the cork sector differs depending on the approach and time horizon chosen. However, the greater it is the time horizon chosen, the smaller the difference between the CF results of the two approaches. Additionally, the inclusion of biogenic carbon sequestration and emissions also influences significantly the CF result. The cork sector is considered a net carbon source when biogenic carbon is excluded from the calculations and a net carbon sink when biogenic carbon is included in the calculations since more carbon is sequestered than emitted along the sector.
Conclusions dLCA allows an overview of greenhouse gas emissions along the time. This is an advantage as it allows to identify and plan different management approaches for the cork sector. Even though dLCA is a more realistic approach, it is a more time-consuming and complex approach for long life cycles. The choice of time horizon was found to be another important aspect for CF assessment.

Keywords Biogenic carbon · Carbon footprint · Cork products · Cork sector · Dynamic life cycle assessment · Static life cycle assessment

1 Introduction

Cork is a natural material deriving from the outer bark of the cork oak tree (*Quercus suber* L.). Cork oak forests are mainly located in the western Mediterranean basin, covering a total area of 2,139,942 ha (APCOR 2014). The majority of this area is distributed along Portugal (730,000 ha according the last national forest inventory (ICNF 2013)), representing 34% of the cork oak forests global area and 23% of the country's forest area (second most dominant tree species). Portugal is the leader in raw cork production with a 50% quota of the global raw cork production (APCOR 2014). Due to the unique characteristics of cork as a material, it can be used in many industrial sectors (e.g., wine industry and construction) for the manufacturing of various products (e.g., stoppers and insulation slabs) resulting in a high economic value for the country (APCOR 2014).

The environmental evaluation of cork, considering the forest management and manufacturing processes for the production of cork products, can be done through the application of life cycle

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assessment (LCA). A few LCA studies about raw cork and cork products can be found in the literature, evaluating raw cork (Rives et al. 2012a; González-García et al. 2013; Dias et al. 2014), natural cork stoppers (PwC/Ecobilan 2008; Rives et al. 2011; Demertzi et al. 2015b, 2016a), champagne cork stoppers (Rives et al. 2012b), and cork construction materials (Bribrián et al. 2010; Rives et al. 2012c, 2013; Pargana et al. 2014; Sierra-Pérez et al. 2016; Demertzi et al. 2017, 2015a).

In the life cycle of cork, biogenic carbon emissions such as carbon dioxide (CO_2) and methane (CH_4) are released. Those are defined as emissions resulting from the combustion or decomposition of biologically based materials other than fossil fuels (EPA 2011). But cork forests can act as a carbon sink as they sequester carbon from the atmosphere and store it in their perennial tissues and in the soil as organic matter for very long periods (Pereira and Bugalho 2009). Due to the periodic cork debarking of the cork oak tree, a fraction of the carbon is transferred to cork products delaying its return to the atmosphere (Dias and Arroja 2014). Additionally, the carbon contained in the cork products can be permanently stored in the landfill facilities since only a small part is released into the atmosphere in the anaerobic conditions prevailing in landfills (Demertzi et al. 2015b). Thus, both cork oak forests and cork products have the potential to mitigate climate change for long periods.

It is known that LCA often does not consider the biogenic carbon flows (e.g., González-García et al. 2013) or biogenic carbon is considered to be neutral (e.g., Dias et al. (2014)), excluding an important aspect of the cork-based systems. Only a few recent studies have considered this aspect in the carbon footprint (CF) results of cork, namely in the environmental analysis of raw cork extraction in cork oak forests in southern Europe (Rives et al. 2012a) and the integrated environmental analysis of the main cork products in southern Europe (Rives et al. 2013). It should be noted that an increasing number of studies suggest that biogenic carbon flows should be accounted for in order to have a more complete view of the system under study (Levasseur et al. 2010a, b, 2013) and in order to avoid partial conclusions (Müller-Wenk and Brandão 2010; Brandão and Levasseur 2010; Brandão et al. 2012; Garcia and Freire 2014).

Traditional attributional LCA (hereafter referred as static LCA—sLCA) is often described as a static tool, where all the emissions are accounted for as if occurring at the same time (Helin et al. 2013). In contrast, for the case of CF calculation, Levasseur et al. (2010a, b) suggested an approach that considers a dynamic life cycle inventory (considering the temporal profile of emissions) and time-dependent characterization factors (hereafter referred as dynamic LCA—dLCA), aims the evaluation of life cycle greenhouse gas (GHG) emissions impact on radiative forcing while considering the exact moment when these emissions occur. Even though dLCA is a newer approach compared to sLCA, in literature, there are a few studies where it is applied to forest-based products such as Levasseur et al. (2012) that applied dLCA to a wooden chair and Fouquet et al. (2015) to a timber house. Currently, there is no dLCA application for the case of cork as a material or for the entire cork sector. However, its application to the cork sector can be relevant since it is a more realistic approach which provides more detailed information regarding greenhouse gas (GHG) emissions per year of occurrence.

The aim of the present study is to assess the influence of using two different LCA approaches, namely sLCA and dLCA, through their application to the calculation of the CF of the entire cork sector associated with the cork produced in Portugal. The effect of including biogenic carbon sequestration and emissions is considered as well. For the application of dLCA, a software tool (dynamic carbon footprinter, $DYNCO_2$) developed for the calculation of the impact of GHG emissions over a time period is used (Levasseur et al. 2010a, b). In order to obtain quantitative results, specific data from the cork sector of Portugal are used.

2 Methods

2.1 Static and dynamic life cycle assessment

The two approaches applied for the calculation of the cork sector's CF have several differences, namely the temporal profile and the characterization factors considered. The main issue with sLCA is that it considers that all GHG emissions occur at a specific time (reference year). Thus, for the calculation of the CF of a process, the emission of GHG from the various sources considered (e.g., diesel combustion for transport and natural gas combustion for heat production) are multiplied by a characterization factor (global warming potential—GWP) for a given time horizon (20, 100, or 500 years) in order to calculate the CF of the process (in mass of CO_2 eq.). The life cycle's CF is calculated by the sum of the CF of all the processes making part of the system under study. Since sLCA does not consider time distribution of GHG emissions and uses GWPs for a fixed time horizon (usually 100 years), it has a main issue with inconsistency in temporal boundaries (Levasseur et al. 2010a, b).

The approach of dLCA takes into account the distribution of the emissions along a determined time horizon. The whole life cycle of the system under study is subdivided in yearly steps and the amount of pollutant released into the atmosphere is correspondent to each year and each GHG. Regarding the dLCA, the software tool $DYNCO_2$ is used in order to calculate the impact of GHG emissions over a time period. Through the help of an Excel spreadsheet, this dynamic approach allows taking into account the temporal distribution of the emissions by using a dynamic inventory. The respective quantities of CO_2, CH_4, and dinitrogen monoxide (N_2O), emitted when performing the various processes considered in the system under study, are introduced in $DYNCO_2$ in order to obtain the CF results for the cork oak sector.

In the case of sLCA, GWPs have been proposed by the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2013). The GWP is defined as the ratio of the time-integrated radiative forcing from the instantaneous release of a unit mass of a GHG relative to that of a unit mass of a reference GHG according to Eq. (1):

$$\mathrm{GWP_i}^{\mathrm{TH}} = \frac{\int_0^{\mathrm{TH}} a_i \times [C_i(t)]dt}{\int_0^{\mathrm{TH}} a_r \times [C_r(t)]dt} \quad (1)$$

where *TH* is the time horizon over which the calculation is considered, *a* is the instantaneous radiative forcing per unit mass increase in the atmosphere, *C(t)* is the time-dependent atmospheric load of the released GHG, *i* is the released GHG, and *r* is the reference GHG, i.e., CO_2.

In dLCA, instead of GWP, a dynamic characterization factor (DCF) for any year after the emission of the GHG is used according to Eq. (2) (Levasseur et al. 2010a):

$$\mathrm{DCF}\ i\ (\mathrm{t}) = \int_{t-1}^{t} a_i \times [C_i(t)]dt \quad (2)$$

Based on Eqs. (1) and (2), Table 1 shows the GWP and DCF values adopted in the calculation of the CF in the two LCA approaches for the three GHGs considered (CO_2, CH_4, and N_2O) and the three time horizons (20, 100, and 500). In the case of the sLCA, the GWP were used only for the time horizons of 20 and 100 years due to the high uncertainty associated with the GWP for a time horizon of 500 years (IPCC 2013). Both for sLCA and dLCA, the CF is calculated in mass of CO_2 equivalent (CO_2 eq.).

In the case of the dLCA, all the emissions of the three main GHGs (CO_2, CH_4, and N_2O) during each life cycle year must be added for all the processes considered in the system under study in order to be introduced in the $DYNCO_2$ model. This model returns three types of results:

- The instantaneous impact (GWI_{inst}) that is the radiative forcing caused by the life cycle GHG emissions at any specific time along the studied life cycle (Levasseur et al. 2013). The instantaneous impact is calculated according to Eq. (3) and shows changes over time in radiative forcing, which is not possible when using GWP.

$$\mathrm{GWI(t)}_{inst} = \sum_i \sum_{j=0}^{t} [g(i)]_j \times [\mathrm{DCF_i}]_{\mathrm{t-j}} \quad (3)$$

where, $[g(i)]_j$ is the dynamic inventory result (in this study, the three main GHGs are expressed in kg) for GHG *i* at time *j* and DCF_i is the dynamic characterization factor presented in Eq. (2) in watt square meter per kilogram ($W.m^{-2}.kg^{-1}$).

- The cumulative impact (GWI_{cum}) that is the sum of the instantaneous impacts from time zero to a specific time (Levasseur et al. 2013). Basically, it is the total amount of additional radiative forcing caused by GHGs along the studied life cycle. The cumulative impact is calculated according to Eq. (4):

$$\mathrm{GWI}(t)_{\mathrm{cum}} = \sum_{j=0}^{t} GWI(j)_{inst} \quad (4)$$

- The relative impact (GWI_{rel}) that is the ratio of the life cycle cumulative impact on global warming over the cumulative impact of a 1 kg CO_2 pulse emission at time zero. The relative impact transforms the dLCA result into the same units (kg CO_2 eq.) as the sLCA (Levasseur et al. 2010a, 2013), while taking into account the timing of the emissions which cannot be done while using GWPs. The relative impact for a given time horizon can be calculated according to Eq. (5):

$$\mathrm{GWI}(t)_{\mathrm{rel}} = \frac{\mathrm{GWI(TH)cum}}{\int_0^{\mathrm{TH}} a_{\mathrm{CO2}} \times C_{\mathrm{CO2}}(t)\mathrm{dt}} \quad (5)$$

2.2 Functional unit and system boundaries

Figure 1 presents the system boundaries considered in the present study. Both in the sLCA and dLCA, the system boundaries are the same and the functional unit (FU)

Table 1 Global warming potential (GWP) and dynamic characterization factor (DCF), respectively, in static and dynamic LCA for the main three greenhouse gases (CO_2, CH_4, and N_2O) for three time horizons (20, 100, and 500 years)

	20 years			100 years			500 years		
	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O
GWP (kg CO_2 eq.kg^{-1})[a]	1	84	264	1	28	265	N/A	N/A	N/A
DCF (W. $m^{-2}.kg^{-1}$)[b]	2.47E-14	1.78E-12	7.14E-12	8.69E-14	2.39E-12	2.59E-11	2.86E-13	2.95E-12	4.38E-11

N/A not available (IPCC 2013 does not consider 500-year GWP due to the uncertainty involved)

[a] IPCC (2013)

[b] CIRAIG (2016)

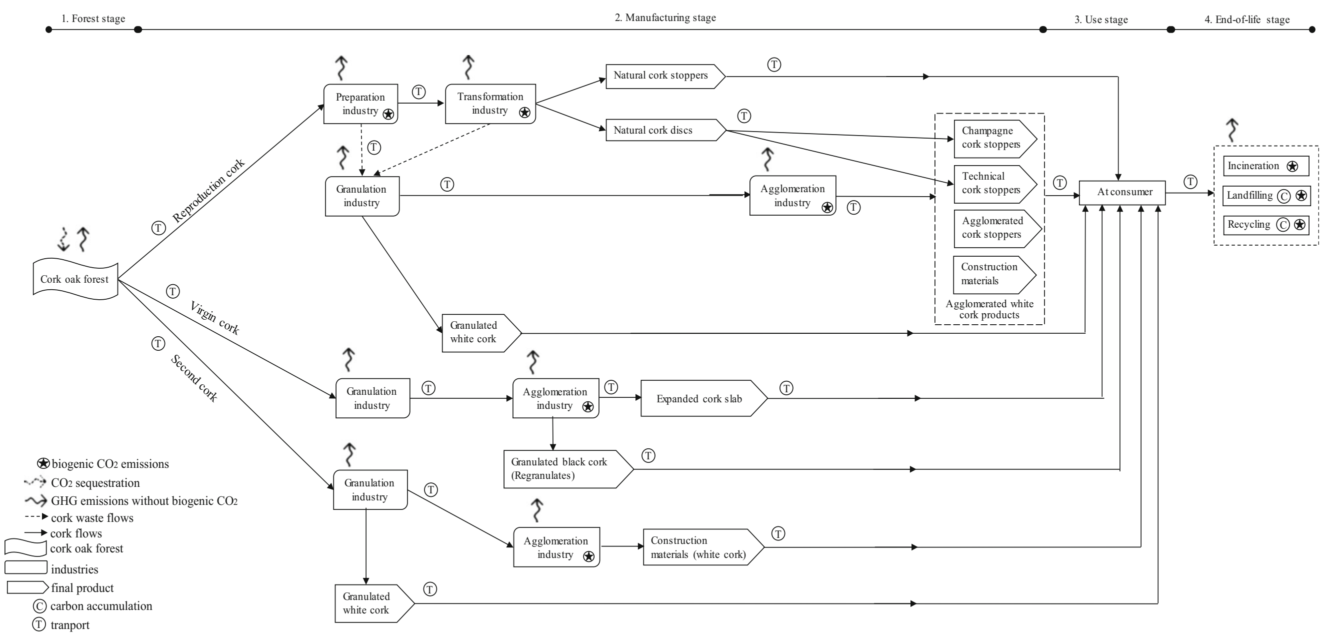

Fig. 1 Boundaries of the system

considered is cork production from 1 ha of cork oak forest assessed throughout its entire life cycle of 170 years (average life of cork oak trees in Portugal) excluding the "falca" cork type. This cork type derives from the tree branches during the pruning and thinning of the trees and is usually used for the manufacturing of products used in construction, e.g., expanded cork slab used for thermal-acoustic insulation). Consequently, the GHG emissions for the management of 1 ha of forest, the raw cork produced and the emissions from the manufacturing of the cork products using it as raw material and finally the end-of-life management of the different cork products are considered in the boundaries of the system.

The study considers an average hectare of Portuguese cork oak forest characterized by the average site index (that determines cork oak tree growth and productivity) based on Paulo et al. (2015) and on the current average tree density evolution for a typical cork oak forest in Portugal managed for silvopastoral purposes. The cork oak tree life producing cycle is, on average, 170 years and this means that after this age cork extraction is severely reduced or even totally absent, and that no more cork product is extracted from the stand. Concerning the inclusion of biogenic carbon flows in the CF of the sector, both carbon sequestration at the forest stage from the different tree components, namely cork, wood, roots, and foliage (net primary productivity) and its storage in the cork products during their use period and at the landfill facility are considered. Carbon storage in soil and dead organic matter was excluded from the calculations due to lack of data. It should be noted that the emissions from transport were also considered for all the stages where transport of cork or ancillary materials (e.g., resins) is needed.

2.2.1 Forest stage

In the forest stage, all the activities performed for the establishment of the cork oak stand and for its management throughout its entire life cycle are included in the boundaries of the system under study. Two management approaches were considered, 50% plantation and 50% natural regeneration. In the plantation approach, soil preparation (before trees plantation) was considered, which requires clearing of spontaneous vegetation and pit-opening. The plantation of the cork oak trees occurs together with a first fertilization operation. In the case of natural regeneration, the stand preparation activities do not occur since it is a natural procedure. However, the following management activities (after plantation) are the same. Furthermore, in the case of natural regeneration, the tree density is assumed to be similar to that of plantation. The number of the trees per unit area of the cork oak stand does not stay constant throughout the entire life cycle due to natural mortality that occurs in some trees and due to thinning activities occurring along the life cycle of the cork oak forest. These thinning activities are performed close to the year of the first debarking for the reduction of tree density and tree competition. Sanitary thinning occurs in order to remove dead trees from the stand. The operations of fertilization, removal of spontaneous vegetation, pruning, and thinning are included in the forest stage since they are repeated various times along the life cycle of the cork oak forest (34, 56, 5, and 2 times, respectively). When the cork oak stand trees obtain the minimum trunk diameter of 17 cm measured over bark (between 20 and 35 years of age depending on the stand conditions), the extraction of cork occurs for the first time. This is a manual operation that is repeated every 9 years along the life cycle.

The extracted cork is transported from the cork forest to the designated cork industries.

2.2.2 Manufacturing stage

In the manufacturing stage, all the production processes for the main cork products are included. As seen in Fig. 1, different cork types are used for the manufacturing of different cork products, depending on the quality of the cork used as raw material. In the same figure, the stages along the cork sector where GHG emissions occur can be seen. The first and second corks extracted, called virgin and second cork, respectively, are of low quality due to the cracks and irregularities on their exterior surface. These cork types are destined to the granulation industry (trituration of cork in granules) and then to the agglomeration industry. In the case of virgin cork, through the use of high temperatures, the natural resins of cork are used as glue for the production of expanded cork slabs and granules. In the case of the second cork, at the agglomeration industry, the cork granules are mixed with resins for the production of agglomerated cork products used in construction (e.g., for insulation and coverings).

The third and following extractions provide the reproduction cork. This cork type has the appropriate quality to be used for the production of natural cork stoppers and discs for which the manufacturing process is different than the aforementioned processes for the virgin and second cork types. In this case, cork is sent to the preparation industry where various processes occur (planks pile establishment, first stabilization, planks boiling, second stabilization, and scalding), in order to remove organic compounds embedded in the pores and enable the cork to reach the ideal moisture content for processing (around 20%). After a manual selection, the prepared planks with the appropriate thickness (27 to 55 mm) are sent to the transformation industry where they are used for the production of natural cork stoppers. Their manufacturing includes various processes, namely slicing, punching, pre-drying, rectification/correction, aspiration, selection, washing, drying, deodorization, coloring, dusting, branding, printing, surface treatment, and packaging. The prepared cork planks, that are thinner, are sent to the transformation industry for the production of natural cork discs. Their manufacturing process is different than the process of the natural cork stoppers and includes trimming, punching, drying, sanding, selection, and packaging. More details regarding the manufacturing processes of the aforementioned cork products can be found in the literature (Pereira 2007; Rives et al. 2011, 2012b; Demertzi et al. 2015a, 2016a).

2.2.3 Use stage

The use stage considers the transport of the final cork products to the distribution locations. For the dLCA approach, the use stage was considered also to account for the elapsed time between the manufacturing of the cork products and their end-of-life.

2.2.4 End-of-life stage

The final stage included in the boundaries of the system is the end-of-life stage. For all the cork products considered in this study, with the exception of the natural cork stoppers, two final destinations were considered: incineration at a municipal waste incineration plant with energy recovery for the production of electricity (avoiding the use of the country's electricity mix) and landfilling at a sanitary landfill with landfill gas recovery for flaring. In the case of the natural cork stoppers, the two aforementioned final destinations as well as the option of recycling were considered. The used natural cork stoppers are recycled in order to be used for the production of agglomerated cork products used in the construction sector (e.g., insulation slabs and coverings) avoiding the use of raw cork for their production.

2.3 Inventory analysis

Table 2 presents the GHGs emission factors for the various stages considered in the system boundaries of the study. The emission factors were based on previous studies (PwC/Ecobilan 2008; Rives et al. 2012b; Weidema et al. 2013; Dias et al. 2014; Demertzi et al. 2015a, b, 2016a) as well as the transport distances considered (Demertzi et al. 2017, 2016a,2015a, b). For the use stage, an average of 200 km was considered based on the distance between the industries and the most populated districts of Portugal. This is a simplification as the real distances are unknown. The cork distribution percentages along the cork sector derived from Demertzi et al. (2016b), and they are representative of past and current practices. Therefore, in the dLCA, they were considered constant along the time for each cork type as they were assumed to be also representative of future practices.

Table 3 presents the quantities of cork extracted per hectare during the 170 years of the forest's life cycle using the SUBER growth and yield simulation model (Paulo and Tomé 2010; Paulo 2011; Faias et al. 2012) assuming the characteristics (silviculture plan) of the average Portuguese cork oak forest, managed for silvopastoral purposes. The SUBER model includes tree growth and tree mortality functions related to site index, which is a variable known to be related with climate and soil variables (Paulo et al. 2015). The site index value considered for this study (average value for Portuguese stands) refers to current climate conditions. Thus, no inference should be made for climate change scenarios. It is important to notice that the decrease of the number of trees per hectare for the increasing stand age is assumed to be a result of the

Table 2 Emission factors of the three main greenhouse gases for the processes considered for the calculation of the carbon footprint along the cork sector and their sources

Stage/material	Fossil emissions			Biogenic emissions		Reference flow
	kg CO_2	kg CH_4	kg N_2O	kg CO_2	kg CH_4	
Virgin cork[a]	28.60	0.07	0.03			Per t of cork (extracted)
Second cork[a]	105.00	0.27	0.12			Per t of cork (extracted)
Reproduction cork[a]	105.00	0.27	0.12			per t of cork (extracted)
Preparation industry[b]	207.00	1.20	0.01			Per t of cork (prepared)
Transformation industry (natural cork stoppers)[b, c]	1200.00	4.00	0.05			Per t of natural cork stoppers
Transformation industry (natural cork discs)[d]	3102.50	0.00	0.00			Per t of natural cork discs
Granulation industry [e]	11.00	0.01	0.00			Per t of cork (to be triturated)
Agglomeration industry (stoppers)[d]	4364.80	0.00	0.00			Per t not natural cork stoppers
Agglomeration industry (construction materials)[e]	607.50	1.55	0.03	150.94		Per t of construction materials
Agglomeration industry (expanded cork slab)[f]	209.10	0.00	0.00	45.45		Per t of expanded cork slab
Agglomeration industry (expanded cork granules)[f]	210.40	0.00	0.00	45.45		Per t of expanded cork granules
Landfilling[g]	8.00	3.75	0.00	20.68	7.52	Per t of cork (for landfilling)
Incineration[g]	− 565.00	− 1.00	0.08	2068.00		Per t of cork (for incineration)
Recycling[g]	− 99.00	− 0.41	− 0.05	1327.00		Per t of cork (for recycling)
Transport[h]	0.139	0.00	0.00			Per t × km (transported)

[a] Dias et al. (2014)
[b] Demertzi et al. (2016a)
[c] PwC/Ecobilan (2008)
[d] Rives et al. (2012b)
[e] Demertzi et al. (2015a)
[f] Demertzi et al. (2017)
[g] Demertzi et al. (2015b)
[h] Weidema et al. (2013)

removal of dead trees, since thinnings are limited by national legislation in Portugal.

Table 3 also presents the year of cork extraction. On these years, the extracted cork continues to the granulation, agglomeration, and transformation industries for the manufacturing of the cork products and after the use periods they end up to the final destinations. It should be noted that the "falca" cork type is not included in the SUBER model outputs and consequently, this cork type was excluded from the system boundaries.

When biogenic carbon is included in the calculations, sequestration of CO_2 in the forest stage is treated as a negative emission since it reduces the amount of atmospheric CO_2, leading to a negative radiative forcing. The quantity of CO_2 sequestered during the cork oak forest growth was calculated using the SUBER model. The model simulates, for an annual time step, the tree diameter growth at a reference height of 1.3 m (Tomé et al. 2006). The model then uses this value for the determination of the tree biomass by the application of an allometric system of equations (Paulo et al. 2002; Paulo and Tomé 2006, 2010). The system of equations considers the stem, branches, leaves, roots, and cork components. The total biomass estimates result from the sum of the tree component biomass estimates, since the system of equations was simultaneously adjusted in order to guarantee additivity properties. The carbon content is then estimated considering a 50% fraction of the biomass dry weight. The dLCA approach considers the sequestered CO_2 per year (as calculated by SUBER), while sLCA considers the total CO_2 sequestered by the cork forest during the 170-years life cycle.

The use period for the cork products that are considered in the present study are 2 years for the agglomerated cork stoppers, 30 for the agglomerated cork construction materials (Dias and Arroja 2014), and 10 years for the natural cork stoppers (personal communication from the Portuguese Cork Association in 2015). In the end-of-life stage, the biogenic carbon emissions were considered as well. More specifically, in the case of incineration, all biogenic carbon contained in the cork products was considered to be released back into the atmosphere (after the use period of the cork products). In the case of landfilling, only a small part (2%) of the biogenic carbon contained in the products was considered to be released while the rest remained permanently stored in the landfill facility (Micales and Skog 1997; Demertzi et al. 2015b). In the case of dLCA, a 20-year delay of the emissions was considered after

Table 3 Quantities of cork extracted (based on the results from the SUBER simulation)

Number of extraction	Year of extraction	Quantity of cork extracted (t/ha)[a]
1	35	0.441
2	44	0.668
3	53	1.215
4	62	1.457
5	71	1.641
6	80	1.702
7	89	1.664
8	98	1.807
9	107	1.903
10	116	1.971
11	125	1.733
12	134	1.660
13	143	1.258
14	152	1.159
15	161	1.093
16	170	0.810
	Total	22.181

[a] Dry basis

the landfilling of the product. Finally, in the case of recycling (for natural cork stoppers), 30% of the carbon contained in the stoppers is considered to remain in the production loop while the rest is emitted during the recycling process and returns to the atmosphere. The biogenic carbon contained in the various cork products was calculated by multiplying the quantity of the cork products by the respective dry basis carbon content (Dias and Arroja 2014) in order to obtain the biogenic CO_2 emissions after the use and end-of-life stages.

Finally, based on the percentage of the various cork products ending up in the different end-of-life options, the final biogenic carbon emissions and permanent carbon storage (in the case of landfilling) was calculated. Since there are no specific data for cork products available, the percentages used for the distribution of the cork products to landfilling and incineration derived from the actual main final destinations of municipal solid waste (MSW) in Portugal. This was a simplification since there are no specific data for all the countries where cork and cork products are exported. Thus, it was assumed that the end-of-life in these countries is the same as in Portugal. A 68% of the agglomerated cork products was considered to end up in a landfill facility and the remaining 32% in an incineration facility (Eurostat 2013). For the natural cork stoppers apart from the incineration and landfill alternatives, the recycling alternative was considered as well. According to the recycling campaign in Portugal for 2013, about 3% of the used natural cork stoppers were sent to recycling (Green Cork 2013). Thus, the mentioned end-of-life percentages in the case of the natural cork stoppers were recalculated, considering that 66% is sent to landfilling, 31% to incineration, and 3% to recycling. All the end-of-life distribution percentages were kept constant through time as real data are missing and any assumed percentages would be random.

3 Results and discussion

3.1 Carbon footprint assessment excluding biogenic carbon sequestration and emissions

Figures 2, 3, and 4 (gray line) present the results obtained for GWI_{inst}, GWI_{cum}, and GWI_{rel} when excluding biogenic carbon sequestration and emissions from the calculation of the cork sector's CF (over a time horizon of 500 years). In the case of GWI_{inst} (Fig. 2), the GHG emissions start increasing around the 35th year when the manufacturing processes begin and continue up to year 170 when the last cork is extracted and sent to the transformation industry for the manufacturing of the last cork products. In the following years, the GHG emissions are decreasing since there is no more cork to be extracted and consequently there are no emissions from the manufacturing processes. During the following years, there are only GHG emissions from the end-of-life of the cork products. Furthermore, in the same graph for GWI_{inst}, there are a lot of picks and lows regarding the GHG emissions, representing the years with and without cork products manufacturing. In the years when the manufacturing stage takes place for the production of cork materials made by the extracted raw cork material, an increase of the air emissions is observed due to the emission of GHGs. During the years when there are no manufacturing processes, the total emissions are lower since there are only emissions deriving from the end-of-life stage which are lower considering the recovery of energy for the production of electricity avoiding the use of the country's electricity mix.

Figure 3 presents the GWI_{cum}, which considers the sum of the instantaneous impact of all the previous years, shows a continuously increasing impact. This is due to the GHG emissions from the various stages involved in the production of the various cork products. In Fig. 4, the CF of the cork sector, or the impact relative to a 1-kg CO_2 pulse emission at time zero as called in dLCA (GWI_{rel}), is presented. During the first years, the environmental impact is zero and it increases throughout time due to the additional GHG emissions from the manufacturing process and the end-of-life disposal. Through the dLCA approach, it is possible to obtain the specific CF of the sector along its entire life cycle.

Table 4 presents the comparison between the CF results for the two LCA approaches (sLCA and dLCA) considering three time horizons (20, 100, and 500 years). When excluding

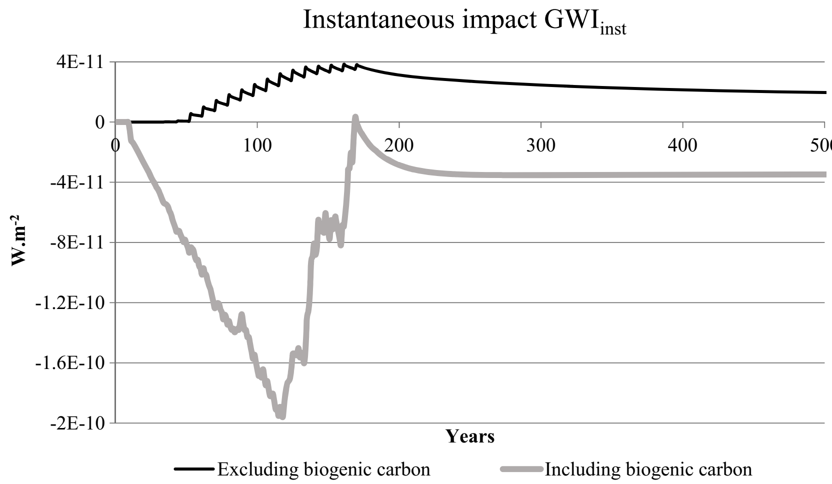

Fig. 2 Instantaneous (GWI_{inst}) impact calculated using the dynamic life cycle assessment approach when excluding (black line) and including (gray line) biogenic carbon sequestration and emissions

biogenic carbon from the calculations, the CF obtained for the sLCA approach is much higher than for the dLCA both for the 20- and 100-year time horizons. In the case of the 500-year time horizon, sLCA does not provide a CF since in the last IPCC report (IPCC 2013) there are no GWPs provided for this time horizon due to the high uncertainty involved. The total CF of the sector, in the case of sLCA, even though it decreases when a greater time horizon is considered, it does not change significantly (51,000 kg CO_2 eq. for 20 years to 49,000 kg CO_2 eq. for 100 years). In the case of dLCA, the difference noticed when distinct time horizons are considered is significant and an increasing tendency is noticed since in this case the emissions from all the previous years are summed as the time horizon increases (0 kg CO_2 eq. for 20 years, 7235 kg CO_2 eq. for 100 years, and 38,211 kg CO_2 eq. for 500 years).

The CF when applying the sLCA approach decreases with time while with the dLCA approach the CF increases with time. This occurs because according to sLCA the GWP declines as the time horizon increases (except for CO_2 that remains the same) since the GHG is gradually removed from the atmosphere through natural removal mechanisms and its influence on the GHG effect declines. On the other hand, dLCA considers different DCF for each year of the life cycle and the CF of the three specific time horizons is the sum of the CF of all the previous years, resulting to a higher CF with the increase of the time horizon. Thus, it can be considered that dLCA is more realistic, considering the possibility of providing the CF throughout the entire life cycle of the studied system, while in the case of sLCA the same information is provided for only two specific time horizons (20 and 100 years).

3.2 Carbon footprint assessment including biogenic carbon sequestration and emissions

Figures 2, 3, and 4 (gray line) present the obtained results for GWI_{inst}, GWI_{cum}, and GWI_{rel} when including carbon sequestration and emissions in the calculations. These graphs are very different from the previous case when the biogenic

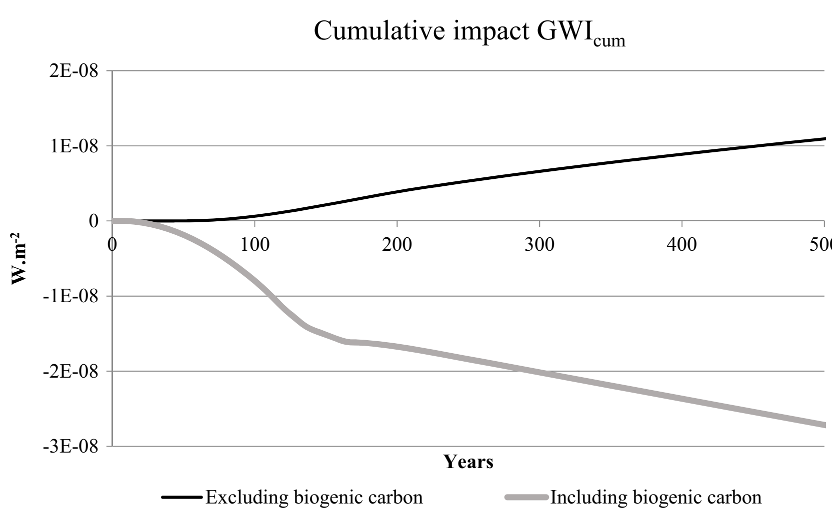

Fig. 3 Cumulative (GWI_{cum}) impact calculated using the dynamic life cycle assessment approach when excluding (black line) and including (gray line) biogenic carbon sequestration and emissions

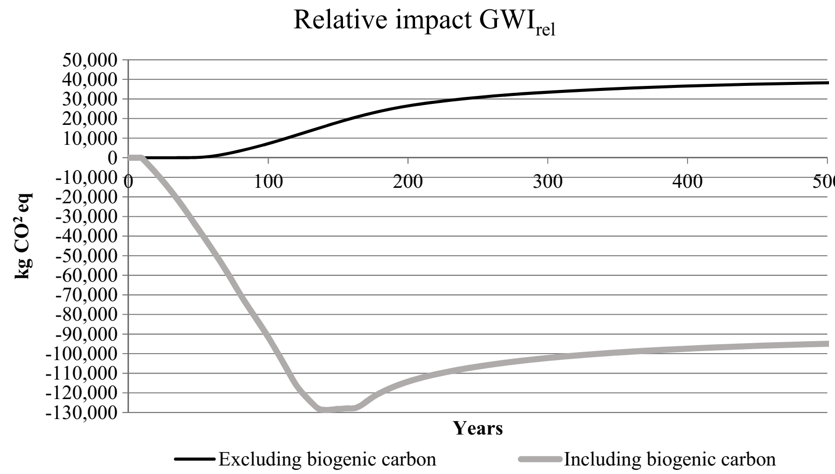

Fig. 4 Relative impact (GWI_{rel}) calculated using the dynamic life cycle assessment approach when excluding (black line) and including (gray line) biogenic carbon sequestration and emissions

carbon was excluded. In the forest stage, where sequestration occurs, the emissions were represented with a negative value since carbon is removed from the atmosphere.

In Fig. 2 (GWI_{inst}) up to around year 120 of the cork oak forest growth, there is a greater carbon sequestration per year considering that there is a higher tree density (greater number of trees per hectare) resulting to a greater carbon sequestration. After year 120 of the forest, a decrease of the cork oak tree population is noticed, resulting to a lower carbon sequestration per year during the final years of the forest. When there is growth of a greater number of cork trees at the cork oak forest, there is more carbon accumulation which then decreases due to the mortality of the trees. Then, there are only the biogenic emissions occurring after the end of the use period at the end-of-life stage when the cork products have reached their final destination (incineration, landfill, or recycling) and released the stored carbon. Consequently, during the 100-year time horizon, there are more cork oak trees resulting to a greater sequestration of biogenic carbon which then decreases since there are less trees. The main influence of CF presented in this graph derives from the sequestration of carbon in the forest stage and thus when the tree density decreases and sequesters less carbon, the emissions represented in the graph start increasing. The influence from the biogenic carbon emissions during the end-of-life stage is lower since the quantity of carbon in cork products is much less than the quantity of carbon in forest biomass.

Concerning the GWI_{cum} (Fig. 3), the trend line is decreasing (on the contrary of the case excluding biogenic carbon sequestration) due to the addition of all the previous years of the instantaneous impact. This means that the sequestration of carbon is greater that the GHG emissions from the manufacturing processes.

The same decrease of the trend line occurs in the graph for the GWI_{rel} (Fig. 4). In this graph, the lowest value of CF is reached around the 170th year of the life cycle which is when the cork oak forest accumulates the greatest amount of biogenic carbon. After that period, the cork oak forest reaches the end of its cycle and stops accumulating carbon from the atmosphere. Furthermore, there is an amount of biogenic carbon (98%) contained in the cork products which is stored permanently at the landfill facility when those cork products are considered to be landfilled at the end of their use period.

Table 4 shows that the CF results of the two approaches for the time horizons analyzed are very different when the biogenic carbon is included in the calculations. However, in both cases, the CF is negative which means that the cork sector is a net carbon sink since more carbon is sequestered than emitted along the entire life cycle. In the case of sLCA, the CF does not change significantly when changing the time horizon (− 62,570 kg CO_2 eq. for 20 years and − 65,570 kg CO_2 eq. for 100 years). In the case of dLCA, the CF changes significantly depending on the time horizon (− 8027 kg CO_2 eq. for 20 years, − 91,609 kg CO_2 eq. for 100 years, and − 94,971 CO_2 eq. for 500 years). For the 20-year time horizon, dLCA presents greater CF than sLCA, while the opposite occurs for the 100-year time horizon.

Table 4 Comparison of the CF results when applying sLCA and dLCA, with and without biogenic carbon accounting, for three time horizons (20, 100, and 500 years)

	Excluding[a]		Including[a]		
Time horizon	sLCA	dLCA	sLCA	dLCA	Units
20	51,000	0	− 62,570	− 8027	kg CO_2
100	49,000	7235	− 65,570	− 91,609	kg CO_2
500	N/A	38,211	N/A	− 94,971	kg CO_2

[a] Biogenic carbon sequestration and emissions

N/A not available, (IPCC (2013) does not consider 500-year GWP due to the uncertainty involved)

3.3 Limitations

In order to apply the two LCA approaches, since the cork material obtained nowadays is the result of the last decades, some assumptions and simplifications had to be made. More specifically, it was assumed that similar technology was used to generate cork throughout the life cycle considered. Furthermore, it was considered that the GHG emission factors, the product mix, and the end-of-life were constant throughout the time due to lack of statistical data regarding these aspects. Another assumption was the fact that the distribution was considered only for Portugal (i.e., distribution distances for Portugal and not for all countries that import cork or cork products from Portugal). The cork distribution percentages along the cork sector derived from Demertzi et al. (2016b), and they are representative of past and current practices. Therefore, in the dLCA, they were considered constant along the time for each cork type as they were assumed to be also representative of future practices.

Regarding the end-of-life stage, another assumption was made concerning the end-of-life distribution percentages (the percentages were based on the destination of MSW in Portugal) since there are no statistical data for this aspect considered in this study. Nevertheless, Demertzi et al. (2016b) shows that the contribution of the end-of-life stage for the total CF of the sector is insignificant. Thus, this assumption is not expected to influence significantly the outcome of the study and that is why the consideration of different scenarios was avoided. However, future studies could focus on this aspect of the cork sector so that more data and more details regarding the distribution percentages can be presented in dLCA.

Another limitation of the study was the exclusion of carbon storage in soil and dead organic matter due to the lack of output data from the SUBER model concerning these variables. Soil organic carbon estimates in agroforest systems, such as the montado, is a research topic under development, namely through the development of modeling approaches, but the hybridization of forest and soil models is still not very common in the literature. Palma et al. (2017) develops such an approach and simulates, for the case study of a holm oak stand with 75 trees ha^{-1} and Mediterranean climate, values between 10 and 12 Mg ha^{-1} of soil organic carbon.

Even though it is important to highlight the limitations of the present study, it is also important to point out that they are not expected to significantly prejudice the final outcome. In fact, the most influential stage of the life cycle in the cork industry is the manufacturing stage, while the assumptions made for the simplification of the study mainly influence the other stages. However, further future study of those aspects that lack of detailed data could provide even more knowledge regarding the life cycle of the cork industry. For example, a topic for further research could be the analysis of future scenarios in the dynamic approach that can be used to support decision-making aiming at reducing the environmental impacts of the sector in the future, considering changes in emission factors and end-of-life options, as well as new uses for cork that have emerged in recent years (e.g., Pullar and Novais 2017).

4 Conclusions

The present study applied a static and a dynamic LCA approach (sLCA and dLCA, respectively) for the CF evaluation of the cork sector associated with the cork produced in Portugal. The results obtained showed that the time horizon preferences have a great influence in the final values for the total CF of the cork sector. Moreover, it was concluded that the inclusion of biogenic carbon sequestration and emissions is very influential for the CF. The cork sector is considered a net carbon source when biogenic carbon is excluded from the calculations and a net carbon sink when biogenic carbon is included in the calculations since more carbon is sequestered than emitted along the sector.

However, both when including and excluding biogenic carbon from the calculation of CF, the bigger the time horizon the smaller the difference between the CF results of the two LCA approaches. When excluding biogenic carbon sequestration and emissions, sLCA presented greater CF for the cork sector, while dLCA presented smaller CF when including biogenic carbon in the calculations mainly due to the sequestration of biogenic carbon at the forest stage (in the case of the 100 years horizon and the opposite occurs for the 20 years horizon). Even though the use of dLCA for the calculation of CF is more realistic and it allows a more detailed analysis of the GHG emissions along the entire life cycle compared to the sLCA approach, it is more time-consuming and complex to apply. The complexity of this approach derives from the need to distribute along the life cycle the various processes and their emissions resulting to a great complexity when the life cycle is long and considers various products like in the case of the cork sector.

Thus, decision-makers should consider the differences between the two LCA approaches and also the importance of time horizon when assessing the CF of a product. In order to choose the most appropriate LCA approach and time horizon, the decision-makers should consider (1) the lifetime of the GHG studied (if long-living, then greater time horizon should be considered), (2) the life cycle of the system under study (e.g., as the life cycle of the cork oak tree is longer than 100 years so this time horizon could result to biased conclusions), and (3) the involved difficulties in each approach considering that dLCA is more time-consuming and more complex in its application. Consequently, the choice of approach and time horizon can be made depending on various criteria in order to obtain more realistic and correct results/conclusions.

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