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A deception or real contribution to circularity?

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Short Communication: Biogenic carbon in fast-moving products: A deception or real contribution to circularity?

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ABSTRACT

Packaging is lately identified as one of the biggest environmental problems and is at a focus of the scientific community and the industry aiming at minimizing environmental impacts. One of the most applied eco-design measures is to substitute traditional packaging materials with bio-based materials. One of the driving incentives for the packaging industry is the calculation of biogenic carbon (BC), even though there is no unified method for the calculation of credits from carbon sequestration.

We developed a case study of paper-based packaging and tested the two variables important in the circular economy: (i) material, by modeling three different end-of-life scenarios; (ii) and time, by assessing the importance of this variable using bottom-up and top-down calculations.

The results of the case study showed that credits from carbon sequestration could lead to undesirable linear pathways of the EoL, by giving the biggest credits for landfilling and, thus, contradicting the circularity principles. Moreover, the time variable is critical for the calculation of biogenic carbon. Credits for carbon sequestration for short-lived products can lead to an overestimation of the storing impact because the top-down calculus of national inventories, developed based on the UNFCCC method, cannot register carbon savings.

This short communication indicates that we need to invest in additional research to identify the correct way to calculate the carbon credits when using bio-based materials and to improve the practice for calculations of the overall carbon footprint of the short-lived materials in the technosphere.

1. Introduction and methods

Using bio-materials is the preferable eco-design method for decreasing the environmental impacts when energy-intensive materials are replaced. Bio-materials can contribute to climate change mitigation by storing carbon from the atmosphere (Garcia et al., 2020).

Based on the information from the European Union (EU), GHG Protocol is the most used standard for greenhouse emission accounting and management (European Climate Pact, n.d.). The GHG Protocol requires that the total inventory results include emissions and removals from biogenic, non-biogenic and land-use emissions, which should be reported separately (GHG Protocol, 2011). To guide the calculation of the carbon footprint (CF), the European Commission developed the Product Environmental Footprint (PEF) Method (European Commission, 2021) that follows similar practices as the GHG Protocol.

This approach resulted stimulated different industries in Europe with the main goal of incentivizing the usage of bio-materials by combining biogenic and fossil-based carbon (BioChem Europe, 2022; CEPF, 2022; EUROGAS, 2022; European Chemical Industry Council, 2022). At the same time, independent organizations and expert groups (Carbon Market Watch, 2023; Climate Social Science Network, 2022) reported on the methodological inconsistencies and approximations in the calculation of carbon sinks that can lead to unjustified crediting of bio-based products.

Calculations of BC are an extensive topic of research in the scientific literature. Tellnes et al. (2017) provided a review of the methodological aspects in calculations of BC embedded in bio-materials by different standards. They concluded that there was a need for a more sophisticated modeling approach related to BC in Life Cycle Assessments (LCA) related to the source of the bio-material and time of usage of the products.

Pawelzik et al. (2013) provided a review of different methodological approaches for the calculation of BC concluding that there is a need for

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methodological harmonization to improve their practical implementation. They suspect the accuracy of consequential LCA studies, due to the secondary impacts of bio-materials which are often difficult to anticipate and quantify.

Performing a literature review of the guidelines, standards and scientific papers Arzoumanidis et al. (2014) report on unresolved issues in accounting for exchanges of BC. Additional clarifications are necessary for forest management, agricultural practices and land use, soil erosion, the inclusion of all parts of a tree, and the inclusion of the end-of-life phase of bio-material production.

Brandão et al. (2013) compared six methodological approaches for dealing with timing issues, including delayed emissions of fossil carbon without recommending a preferred option from the methods assessed.

Scientists use dynamic LCA of building materials (Shen et al., 2022b), hemp cement and car panels (Shen et al., 2022a) for assessing the global mean temperature change, concluding that mitigation potential is relative to time scale (Shen et al., 2023) and the selection of the applicable product for bio-material.

Besides all methodological inconsistencies, the practitioners calculate the credits from BC stored in the bio-materials, for example, construction materials (Breton et al., 2018; Garcia et al., 2020; Garcia and Freire, 2014; Head et al., 2021; Pittau et al., 2018; Tellnes et al., 2017), recycling paper (James, 2012), cork oak (Demertzi et al., 2016), sack kraft paper and paper sacks (Swedish research institute RISE, 2021) and beverage cartons (Eriksson et al., 2010; O'Sullivan et al., 2016; Wohner and Tacker, 2020).

Countries report their national GHG inventories to the Secretariat of the United Nations Framework Convention for Climate Change (UNFCCC), based on their status as either Annex 1 or non-Annex 1 of the UNFCCC reporting guidelines. The National Inventories present a top-down monitoring of the emitted GHG on a national level, and they serve as a base for climate negotiation as well as the design of climate change mitigation strategies (United Nations, 1992). Using bio-materials instead of energy-intensive materials can be considered as one of the mitigation strategies for the industrial sector.

Sazdovski et al. (2022) concluded that the three main variables for value creation in a circular economy (CE) are energy, material, and time and presented the influence of variable "time" on the overall LCA, especially the case studies of products with short usage time in the technosphere, such as packaging.

The main aim of this research is to assess the influence of two variables of CE (material and time) on the calculation of BC for short-lived products. Therefore, the specific objectives of this short communication are the following: (i) to calculate the BC of short-lived products and compare it to the overall CF; (ii) to compare results from the three EoL scenarios (incineration, landfill and recycling) using three different allocation methods (mass-based, cut-off and zero burden); and (iii) to compare the BC calculus using bottom-up calculated CF with the official UNFCCC GHG inventory reporting timeline using top-down indicators. The functional unit of the study is defined as the production, use and end-of-life of tetra-brick packaging from $1000m^3$ of biomass for the EU market.

For the calculation of the stored BC, we are using the Excel-based calculator developed by WWF, publicly available at https://www.worldwildlife.org/projects/biogenic-carbon-footprint-calculator-for-harvested-wood-products. The calculator develops a dynamic accounting approach that considers BC in wood-based products and is based on dynamic accounting and applies time-dependent characterization factors to BC emissions and removals. The calculator is developed by compiling a specific methodological approach, background data and calculation process developed by Gmünder et al. (2020) and the data used are from the scientific literature, IPCC, and other relevant sources of data and statistics.

The time horizon is preset to calculate 100-year of the Global Warming Potential (GWP), using a dynamic life cycle assessment approach for GWP_{bio} calculation. It includes the forest carbon stock model and the dynamics of the forests' carbon pools: above- and below-ground biomass, natural dead wood, and the effect of harvesting on the soil carbon pool. The calculation includes all parts of the three, which was a main suggestion in the paper of Arzoumanidis et al., (2014). The calculus differentiates the time dynamics based on different wood species, the main science gap indicated by Brandão et al. (2013) and Tellnes et al. (2017). Three CO_2 sources and sinks are considered when calculating net CO_2 emissions to the atmosphere: CO_2 decay in the atmosphere, assimilation of CO_2 from onsite biomass growth and decomposition and net CO_2 emissions in the reference system.

The calculation takes into account the following assumptions related to EoL treatment scenarios. For incineration and combustion no storage is assumed, due to immediate release of the sequestrated carbon. For recycling, no benefits beyond the product lifespan are assumed either, the benefits are assigned to the product using the recycled material. Related to landfilling, the decay of wood biomass over time is calculated (extended storage time), differentiating non-degradable and degradable pools. The non-degradable pool is permanently sequestered and the fraction of the degradable pool remaining in subsequent years is determined by first-order decay.

Three different allocation methods are possible for the calculation of the sequestrated carbon:

- Mass balance: considering that the amount of carbon contained in material is equal to the amount of carbon extracted from the forest;
- Recycled or cut-off: considering that no burden from wood extraction is assigned if recycled material is used; and
- Waste biomass or zero burden: considering that no burden from wood extraction is assigned if "waste" material is used.

As an example of a short-lived product, we took the tetra-brick packaging made of carton. A baseline scenario is developed using the European statistics for the tetra-brick with specific data for the European market. Also, we developed three comparison scenarios with different EoL pathways (100 % landfilled, 100 % incineration and 100 % recycling) and we repeated the exercise using all three allocation methods offered by the calculator.

Finally, we compared the official methodology regarding the frequency of national inventory reporting (UNFCCC, n.d.), and linked the timeline with the time of the short-lived products in the technosphere to assess the effects of sequestrated carbon from the atmosphere.

2. Results and discussion

The paper-based packaging industry claims that the paper used by the industry derives from the boreal forests in Finland and Sweden and it is certified and sustainably managed (Eriksson et al., 2010; ProCarton, 2009; Swedish research institute RISE, 2021; Wohner and Tacker, 2020). Based on the information presented in the study by O'Sullivan et al. (2016), 92 % of the area of the boreal forest in Finland and Sweden consists of managed forests, with protected forests making up the remaining 8 %. Therefore, as input of prime material, we selected $1000m^3$ of soft sawlog and vaneer log, from pinus trees, as a representative of the boreal forest (IBFRA, 2022) with a rotational period preset at 39 years. We disregarded the emission of fossil carbon from the production and usage stage of the life cycle, considering them as similar, and solely focused on the amount of BC.

To present a real case that can serve as a base for comparison among the scenarios, we used the data of the EoL of the tetra-brick in EU from the PEF Category Rules, Guidance document (European Commission, 2018). Based on the circular footprint formula default parameters, the postconsumer recycling rate of the tetra-brick in the EU is 43 %. The share between landfill and incineration of municipal waste is calculated based on the PEF rules as an average of municipal waste in the EU, incineration rate of 25.5 % and a landfill rate of 31.5 %.

To simulate different EoL scenarios for comparison, we calculated three pathways of the tetra-brick packaging, i.e., 100 % incineration, 100 % recycling rate and 100 % landfill, with the same inflow of material, and the same species of wood using different allocation methods. The results of the calculation are presented in Fig. 1 and Table 1.

For fulfilling the functional unit, 225,253 kg of carbon are extracted from the forest and contained in the material by emitting 61, 605$kgCO_2eq$ of fossil carbon to produce the input material.

From the results, we can observe that mass-balance allocation model is the least favorable for the calculation of GWP_{bio}. When we apply the cut-off and zero-burden allocation the GWP_{bio} in the base case increases from $-22,013kgCO_2eq$ using the mass-balance allocation model to $-153,304kgCO_2eq$ using the other allocation models. By changing the EoL scenario we are following similar patterns of increasing the GWP_{bio}. By changing the allocation method the calculated GWP_{bio} increases from $125,035kgCO_2eq$ to $-6,256kgCO_2eq$ in 100 % incineration and 100 % recycling scenarios. Undeniably, the biggest GWP_{bio} is calculated in 100 % landfill scenario and increases from $-341,784kgCO_2eq$ to $-473,075kgCO_2eq$ by changing the allocation method due to the long presence of the material in the technosphere, compared to all other EoL scenarios. However, the calculations of GWP_{bio} don't differentiate if the material has an active role in the technosphere. It calculates the GWP_{bio}, by storing the bio-material permanently in the landfill.

The calculated results presented one limitation related to the creation of methane through the decomposition of organic material in the landfill. The calculator is focused solely on carbon dioxide (CO_2) molecules emitted to the atmosphere from "biogenic" or "fossil" sources. This can lead to an overestimation of the credits given through the landfilling keeping in mind that produced methane from the decomposition phase is 25–28 times more potent GHG than CO_2 (Greenhouse Gas Protocol, 2016). However, the difference in the results between 100 % landfill and 100 % recycling scenario is so big that even if this methodological issue is taken into consideration the most preferred EoL scenario for the calculation GWP_{100} will be landfilling of the bio-material after usage.

Consequently, the most preferred scenario for the paper-based packaging industry would be the landfill of the products due to the higher amount of credits from stored carbon that can be given to the CF of their products. These results are in contradiction with all of the principles of CE because the linear scenario will be most beneficial in the calculation of the overall CF of the products.

2.1. Discussion on the time horizon of the GWP and time variable of CE

An additional issue for discussion is the selection of the time horizon of the GWP for the calculation of the BC. GWP_{100} is selected for easy calculation of credits (Breton et al., 2018). However, GWP varies based on the time horizon (Garcia and Freire, 2014; Guest et al., 2013; Yue et al., 2017). Based on the calculus of the BC for the building materials in the paper of Head et al. (2021), the impacts of emissions occurring beyond the time horizon are not accounted for in the environmental impacts. The study developed by Pawelzik et al. (2013) discusses that the concentration of atmospheric CO_2 in the next 50–100 years is likely to be higher than today, and the benefit of contemporary carbon storage may be illusive. Delayed carbon emissions may disproportionately enhance global warming if atmospheric CO_2 concentrations are higher in the future than they are today.

Similarly, Brandão et al. (2013) warn that even more dangerous future levels of GHG in the atmosphere may be reached, hence controlling the levels is critical. Ignoring what happens beyond 100 years would imply either that climate problems will be solved by then or that we do not care about the future.

Our exercise shows the same. During the time horizon of 100 years, 50 % of the carbon is emitted in the best scenario; however, the remaining 50 % is still embedded in the product and will be emitted afterwards. Keeping in mind that the carbon won't mineralize, the same will be emitted in the form of a GHG. This impact is not being calculated just because the general LCA practice is using 100 years time horizon of the GWP.

Following the top-down method of calculating GHG emissions, the time variable has a crucial role. Based on the requirements from the UNFCCC guidelines, Annex I countries must report their annual GHG inventories in National Communications on Climate Change (NCCC), Annual inventories or Biannual Reports while Annex II Countries report biannually through NCCCs and Biannual Update Reports (Ellis and Moarif, 2015).

This simple example shows the contradiction of the calculation of credits by using BC as an eco-design measure. If the company decides to use paper-based packaging instead of energy-intensive packaging materials like glass or aluminium, it should receive credits in the calculation of the GHG emissions from BC using the bottom-up method according to the industry. However, current paper-based packaging is used mainly for beverage packaging and stays in the market only for some months. The usual beverages packed in paper-based packaging are milk, juices, and yogurts with a 3–6-month shelf-life. This packaging will end its life after several months of storing the carbon and the same quantity of carbon will be again released in the form of carbon emissions before the next reporting cycle using the top-down calculation methods. Therefore, these emissions will be non-visible in the official national

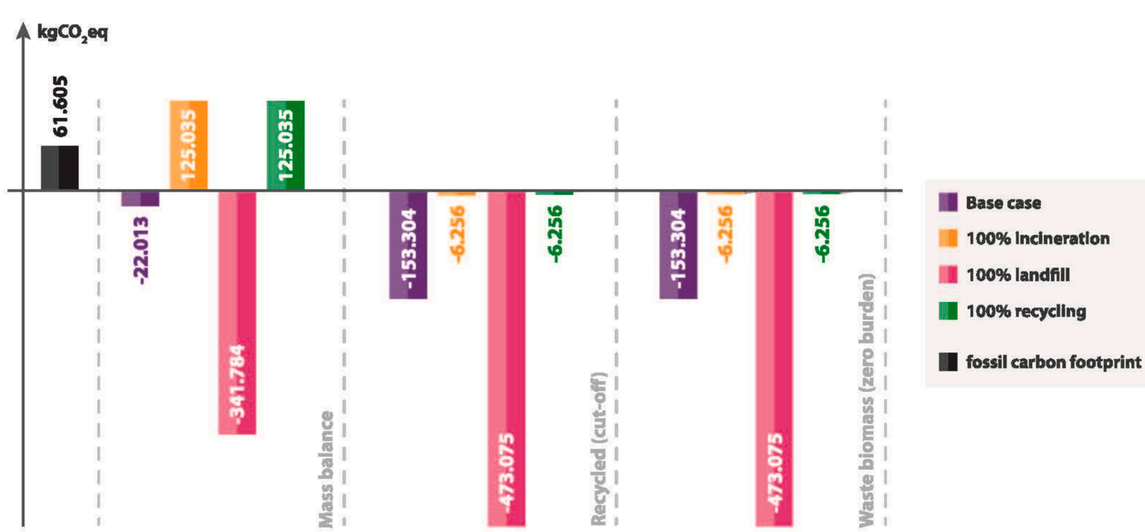

Fig. 1. Comparative analysis of the obtained results from the baseline case and three EoL scenarios based on different allocation methods.

Table 1
Results of carbon balance.

	Base case	EoL Scenario			Allocation method
		100 % incineration	100 % landfill	100 % recycling	
Global warning bio *[kgCO2eq]*	-22,013	125,035	-341,784	125,035	Mass balance
Carbon emitted after 100 years *[%]*	84	100	50	100	
Global warning bio *[kgCO2eq]*	-153,304	-6,256	-473,075	-6,256	Recycled (cut-off)
Carbon emitted after 100 years *[%]*	84	100	50	100	
Global warning bio *[kgCO2eq]*	-153,304	-6,256	-473,075	-6,256	Waste biomass (zero burden)
Carbon emitted after 100 years *[%]*	84	100	50	100	

reporting obligations. Consequently, short-lived paper-based products cannot receive credits for storing BC if their lifetime in the technosphere is less than one year if the product is used in an Annex I country, or lifetime is shorter than two years if the product is aimed for the non-Annex I countries.

3. Conclusions

In this study, we are estimating how two of the three main variables for value creation of the CE (material and time) influence the calculation of GWP_{bio}.

The calculation exercise provides an example of benefits from carbon sequestration based on the three scenarios of waste management. The results are clear that landfilling of wood-based material is the most preferable option resulting in the highest GWP_{bio} due to longer storage of the material in the landfills. This proves that non-efficient waste management treatment leads to more credits from BC, and this is in direct contradiction with the principles of CE. CE aims at the usage of as little material as possible to serve the same function and keep them effective in the technosphere. Landfilling simply contradicts this principle because the material is ineffective for the function, and more material needs to be inserted in the technosphere. Moreover, the preferable EoL treatment is in contradiction with the waste management hierarchy where landfill is the least favorable option for any material.

The simple case of top-down reporting obligations towards UNFCCC proves that BC stored in products with a short lifetime (less than one year) in the technosphere is not presented in the inventory. Moreover, the WWF calculation tool that we used cannot provide the opportunity for the calculation of BC for products that stay in the technosphere for less than one year. The default value of one year in the calculator is an assumption that paper-based packaging has one year of lifetime. The tetra-brick, for example, is used for packaging milk, juices, water, and yogurts and has a shelf-life of only several months. Based on the used calculator, and the national GHG reporting, the calculation of credits from BC can lead to over-crediting of the CF for unjustified storage of carbon because it won't be reflected in the overall National Inventories. Carbon stored in bio-materials for products staying longer in the technosphere, such as furniture or construction materials, is understandable but for products with a usage time of less than one year it is simply unjustifiable.

This short communication gives an additional view to the announced policy development by the European Commission for the Certification Framework for Carbon Removals (European Parliament, 2023) and the amending of the Packaging and Packaging Waste Directive (Ragonnaud, 2023).

CRediT authorship contribution statement

Ilija Sazdovski: Conceptualization, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Michael Zwicky Hauschild:** Validation, Writing – review & editing. **Sergi Arfelis:** Writing – review & editing. **Alba Bala:** Writing – review & editing. **Pere Fullana-i-Palmer:** Supervision, Writing – review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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