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COMMENTARY AND DISCUSSION ARTILCE

Carbon opportunity cost approach may result in double counting in environmental footprinting

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Abstract

Purpose Recently, carbon opportunity cost (COC) approach has been mentioned in the European Commission's draft of the updates on the Product Environmental Footprint (PEF) method, yet the COC approach has several limitations. In this commentary article, we aim to highlight the methodological and practical challenges of using COC approach in product environmental footprinting with life cycle assessment (LCA).

Methods The COC approach is typically based on the "foregone carbon sequestration" due to continued land use which postpones the natural regeneration. The foregone sequestration typically equals the difference in carbon stocks between current land use and the potential natural vegetation. In principle, the global warming potential (GWP) related to the transformation from historical land use (natural vegetation) to current land use overlaps with the GWP of the foregone sequestration. As an alternative to avoid double counting, we describe an additional COC approach.

Results The COC approach includes a risk of double counting, if it is applied simultaneously with the land transformation approach in product environmental footprinting with LCA. Double counting leads to overestimation of anthropogenic environmental impacts and harms the LCA principle of additivity. Furthermore, the suitability of the COC approach in attributional LCA is limited, since it does not represent the anthropogenic environmental impacts compared with the non-anthropogenic natural baseline. Regardless of the benefits of the additional COC approach in terms of avoided double counting, any COC approach includes high uncertainties related to the estimation of historical carbon stock and potential natural vegetation carbon stocks. Furthermore, the additional COC approach only provides benefits if potential natural vegetation exceeds the historical carbon stock.

Conclusions Overall, the COC approach based on foregone sequestration has a risk of double counting. Furthermore, any COC approach has high uncertainties and limited practical benefits, and therefore, we highly recommend keeping COC approaches apart from the European Commission's PEF method.

Keywords Carbon opportunity cost approach · Double counting · Footprinting

1 Introduction

Lately, the possible inclusion of the COC approach in environmental footprinting has been mentioned, for example, in the draft (JRC 2024) of the new methodology to be applied in the European Commission's Product Environmental Footprint (PEF) method. COC approach is also included in the Greenhouse Gas Protocol's Land Sector and Removals Guidance draft (Greenhouse Gas Protocol 2022). The COC approach is based on the estimation of "foregone carbon sequestration" due to the continuation of the current land use (e.g., agricultural land use) instead of the natural regeneration of vegetation (Greenhouse Gas Protocol 2022; JRC 2024). In principle, foregone sequestration refers to the quantity of carbon that remains in the atmosphere because of the current land use, and that could be stored if the land area were returned to its natural vegetation. In that case, foregone sequestration estimated with the COC approach equals the difference between potential natural vegetation (PNV) and

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the current land carbon stock in soil and vegetation. Regardless of the interest in the COC approach, we want to point out several concerns related to its use as part of product environmental footprinting with attributional LCA. Here, we focus on the impact category "climate change."

2 Double counting

The basic idea of attributional LCA is to estimate the environmentally relevant physical flows—more precisely anthropogenic environmental impacts associated with a product (Finnveden et al. 2009; Brander 2015, 2016). Avoidance of double counting is a crucial principle in LCA (Leinonen 2022) since double counting leads to overestimation of the total anthropogenic environmental impacts and incorrect estimation of carbon budgets. Also, additivity is an important LCA principle, and it enables the environmental impacts to be added to each other to estimate the accumulated environmental impact during the life cycle of a studied product (Tillman 2000). This requires that the environmental impacts of the studied product system are not overlapping and not counted twice. Considering these principles, both uptake and losses of carbon into the system and out of the system shall be calculated without double counting. Next, we describe how the application of the COC approach in environmental footprinting with attributional LCA may result in double counting.

In the first approach, here called the land transformation approach, the land use change (LUC) emissions are calculated in LCA by estimating the total carbon stock change related to a transformation of the land from one land use to another. The typical baseline in the land transformation approach is the historical carbon stock (i.e., natural vegetation). The resulting carbon emissions—or in some cases, carbon removals—caused by the LUC are allocated to products produced on the land area during an amortization period (Maciel et al. 2022; Lehtilä et al. 2025). The amortization period defines the period during which the GWP caused by the carbon released to the atmosphere is fully allocated to products produced on the land (Maciel et al. 2022), and its typical length is 20 years or the length of a single harvest rotation following LUC (BSI 2011). After the consideration of emissions caused by the LUC from historical carbon stock to the new land use, all the subsequent LUCs on the same land are accounted for, and the resulting impacts are allocated to products (Lehtilä et al. 2025). The land transformation approach is applied, for example, in the current PEF methodology (European Commission 2021) and in Greenhouse Gas Protocol's Land Sector and Removals Guidance draft (2022).

The COC approach estimates the foregone sequestration due to the current land use, and its baseline is usually PNV (i.e., natural regeneration; Koponen and Soimakallio 2015). The carbon stock under PNV can be equal, higher or lower compared to the historical carbon stock, and the difference can be caused by natural succession of vegetation, natural disturbances, or fertilization effect of the increasing atmospheric CO_2 concentration. Regardless of the quantity of carbon stock in the PNV, if the COC approach is used in addition to the land transformation approach, the same carbon stock change is counted twice. This leads to double counting, which overestimates the quantity of carbon in the atmosphere, and thus the GWP related to LUC as well as the anthropogenic environmental impacts. The concern of double counting has been previously raised by Brander (2015, 2016).

The issue of double counting is illustrated in Fig. 1. Here, the historical carbon stock represents the natural vegetation of the land area, and in this example, it is lower than the PNV. With the land transformation approach, the carbon stock change (ΔC_land_transformation) is equal to the amount of carbon released to the atmosphere from the land area because of the land transformation. With the COC approach, the foregone sequestration (ΔC_COC) overlaps with the ΔC_land_transformation. In principle, following the framework of attributional LCA—similarly to the case of ΔC_land_transformation—the ΔC_COC should only be accounted for once and then allocated to products produced on the specific land area. The allocation is conducted by using a specific amortization period. If *both* land transformation and COC approaches are used in the same LCA study, a partly or fully overlapping share of ΔC and the consequent GWP is allocated to products, leading to double counting and an overestimation of product GWP. The double counting remains an issue regardless of whether the amortization period after the land transformation to the current land use is ongoing or has already passed. Therefore, the ΔC_COC (= foregone sequestration) is inclusive of, not additive to, the ΔC_land_transformation; thus, these two approaches should not be applied in attributional LCA simultaneously.

However, there is also an alternative to the COC approach presented above. Therefore, we refer to the COC approach with a PNV baseline as the standard COC approach from now on. Another option would be to quantify only the *additional* foregone sequestration, that is, estimate the difference between the historical carbon stock and PNV. We refer to this as the additional COC approach from now on. An example of the standard COC approach would be a case where the current agricultural land was abandoned and left to regenerate naturally. Then, the foregone sequestration represents the carbon that could be stored in the natural vegetation if the current human actions on the land area were ceased. Within the additional COC approach, the foregone sequestration would occur only if the PNV carbon stock after the regeneration was higher than the historical carbon stock in

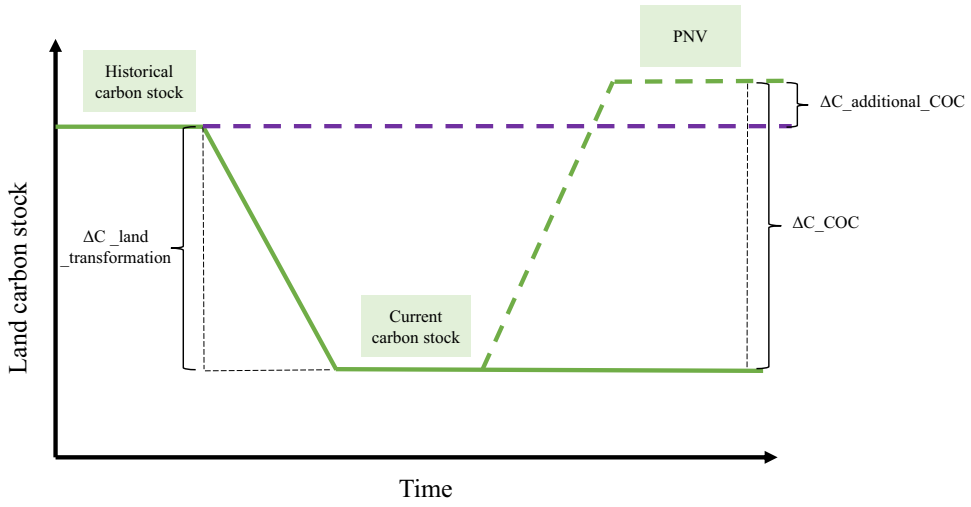

Fig. 1 Land carbon stock change estimated with the land transformation approach (ΔC_land_transformation; carbon emission) and with the COC approach (ΔC_COC; foregone sequestration). In the land transformation approach, the baseline is the historical carbon stock, and in the COC approach, it is the PNV. In this example, PNV is higher than the historical carbon stock, but it may also be equal to or lower than the historical carbon stock. The suggested method to estimate the *additional* foregone sequestration equals ΔC_additional_COC = PNV–historical carbon stock

the natural forest. This means that the additional foregone sequestration represents the additional carbon that could have been naturally sequestered if human actions had not taken place on the land area. That could be a result of, for example, climate warming or CO_2 fertilization.

When estimated with the additional COC approach, the foregone sequestration (ΔC_additional_COC) does not—in principle—overlap with ΔC_land_transformation estimated with the land transformation approach but is additive to ΔC_land_transformation (Fig. 1). Therefore, the additional COC approach could be seen as suitable to be used simultaneously with the land transformation approach. However, both standard and additional COC approaches have uncertainties and limitations which are further discussed in Section 4.

3 Suitability in attributional LCA

In attributional LCA, the total anthropogenic environmental impacts are estimated relative to a non-anthropogenic, natural baseline (Brander 2015, 2016). Therefore, the attributional LCA inventory may be considered to consist of anthropogenic emissions and removals, as well as foregone non-anthropogenic emissions and sequestration (i.e., removals). The foregone non-anthropogenic emissions and sequestration can be classified as attributional LCA, since they represent the emissions or sequestration that would occur in the absence of human actions, meaning that the anthropogenic impacts are compared with the natural baseline.

The land transformation approach represents anthropogenic emissions, as it considers the human-made land use and land management changes compared with the natural baseline. The standard COC approach represents the foregone *anthropogenic* sequestration, indicating that the anthropogenic impacts are not compared with the natural baseline, but rather with the natural regeneration baseline (Brander 2015). This means that the foregone sequestration only occurs if the land has gone through anthropogenic LUC and the sequestration is not non-anthropogenic (Brander 2015). Therefore, the standard COC approach does not represent impacts that are included in the attributional LCA inventory. Although not considered suitable for attributional LCA, the standard COC approach can be suitable for consequential LCA studies that evaluate the potential changes in environmental impacts following specific decisions (Finnveden et al. 2009; Brander 2015 2016). Still, the standard COC approach should not be incorporated in the environmental footprinting of products, which follows principles of attributional LCA.

The additional COC approach represents the natural sequestration that would have occurred without any human actions on the land area (Brander 2016). This means that the baseline is natural and the estimated impacts are non-anthropogenic. Therefore, the additional COC approach represents the foregone non-anthropogenic sequestration and is—in principle—compatible with attributional LCA. On the other hand, part of the foregone sequestration estimated with the additional COC approach may be indirectly related to partly anthropogenic impacts such as climate warming and CO_2 fertilization. The separation of non-anthropogenic foregone sequestration from anthropogenic foregone sequestration may be challenging or impossible, which poses a risk of double counting the environmental impact if the additional

COC approach is used simultaneously with the land transformation approach.

4 Uncertainties and practical points of view

Both standard and additional COC approaches include major uncertainties. Firstly, there is high uncertainty related to the quantity of carbon stock in PNV (Koponen and Soimakallio 2015), since it can be lower, equal to, or higher than the historical carbon stock due to natural disturbances, climate warming, and CO_2 fertilization, among other factors (IPCC 2023). If the historical and PNV carbon stocks were equal, the foregone sequestration would equal the anthropogenic emissions related to LUC. Therefore, applying the standard COC approach alongside the land transformation approach would not provide any benefits. Also, simply abandoning the land area does not necessarily lead to the restoration of natural vegetation (Greenhouse Gas Protocol 2022).

Then again, the estimate of historical carbon stock may also be uncertain. If the land transformation approach is applied, it does not affect the results. This is because, in the land transformation approach, the current land use is always compared to the preceding land use within an amortization period. Therefore, the uncertainty related to baseline carbon stock estimation is reduced in the land transformation approach compared to the standard COC approach. However, if the additional COC approach is applied, the uncertainty of the historical carbon stock becomes a more crucial source of error compared with the land transformation approach, since the additional foregone sequestration requires that the PNV carbon stock exceeds the historical carbon stock. Information on the quantities of historical and PNV carbon stocks is potentially limited, or their estimates may be very uncertain. Therefore, the application of the additional COC approach would only provide benefits if the historical and PNV carbon stocks could be reliably determined, and their difference could be validated. This limits the practical benefits of the additional COC approach in product environmental footprinting.

Secondly, the time needed to reach the PNV—also known as regeneration time (or relaxation time)—is highly uncertain. Additionally, the method of allocating the foregone sequestration has varied in past studies (Müller-Wenk and Brandão 2010; Koponen and Soimakallio 2015; Searchinger et al. 2018). Consequently, the standard COC approach results are very dependent on the projected regeneration time and allocation based on the definition of the amortization period, which may make it difficult to interpret and communicate the results. Furthermore, the starting point of the regeneration time is purely subjective. If the land regeneration is not ongoing and, therefore, the amortization period is not ongoing, the foregone sequestration should be zero to avoid double counting. The same applies to both standard and additional COC approaches, since they both may lead to double counting if the amortization period is not clearly defined and followed.

Thirdly, we see that the COC approach makes no difference between recent and historical land use changes. Therefore, there are no incentives for preventing deforestation, if the COC approach is applied as a part of product environmental footprinting with attributional LCA instead of the land transformation approach. For example, cropland transformed from forest land 100 years or 1 year ago would receive the same quantity of foregone sequestration, which creates no pressure to avoid deforestation. It is true that the standard COC approach provides incentives to make land use more efficient and has benefits in scenario-level assessments such as Röös et al. (2016) and Hayek et al. (2021) have noted. Nevertheless, the scenario assessments are outside the scope of product environmental footprinting, which aims to quantify the environmental impacts related to the supply chain of a specific product.

5 Future suggestions

We argue that the land transformation approach has several benefits already demonstrated in the existing applications of product environmental footprinting. Considering the conflict of the standard COC approach with attributional LCA principles, we recommend not adopting the standard COC approach in the PEF method. This is because the PEF method is based on attributional LCA; thus, any consequential element within PEF assessments should be avoided. Also, the methodological uncertainties of foregone sequestration estimated with either the standard or additional COC approach and the potentially limited practical benefits of using the additional COC approach are reasons why we recommend not adopting any COC approach in PEF. Generally, we suggest keeping COC approaches separate from the product environmental footprinting conducted with attributional LCA.

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Declarations

Conflict of interest The authors declare no competing interests.

References

Brander M (2015) Response to "Attributional life cycle assessment: is a land-use baseline necessary?" – appreciation, renouncement, and further discussion. Int J Life Cycle Assess 20:1607–1611. https://doi.org/10.1007/s11367-015-0974-8

Brander M (2016) Conceptualising attributional LCA is necessary for resolving methodological issues such as the appropriate form of land use baseline. Int J Life Cycle Assess 21:1816–1821. https://doi.org/10.1007/s11367-016-1147-0

BSI (2011) PAS 2050:2011. https://knowledge.bsigroup.com/products/specification-for-the-assessment-of-the-life-cycle-greenhouse-gas-emissions-of-goods-and-services?version=standard. Accessed 23 Jul 2024

European Commission (2021) Commission recommendation on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations (EU) C/2021/9332. Annex I. Product Environmental Footprint Method. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=PI_COM%3AC%282021%299332. Accessed 24 Jul 2024

Finnveden G, Hauschild MZ, Ekvall T, Guinée J, Heijungs R, Hellweg S, Koehler A, Pennington D, Suh S (2009) Recent developments in Life Cycle Assessment. J Environ Manage 91:1–21. https://doi.org/10.1016/j.jenvman.2009.06.018

Greenhouse Gas Protocol (2022) Land sector and removals guidance. Part 1: Accounting and reporting requirements and guidance. https://ghgprotocol.org/land-sector-and-removals-guidance. Accessed 5 Aug 2024

Hayek MN, Harwatt H, Ripple WJ, Mueller ND (2021) The carbon opportunity cost of animal-sourced food production on land. Nat Sustain 4:21–24. https://doi.org/10.1038/s41893-020-00603-4

IPCC (2023) Sections. In: Climate change 2023: synthesis report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland

JRC (2024) Quantifying the climate change impacts of the biogenic carbon flows under the EC's Product Environmental Footprint method. https://ec.europa.eu/transparency/expert-groups-register/screen/meetings/consult?lang=en&meetingId=54161&fromExpertGroups=3710. Accessed 24 Jul 2024

Koponen K, Soimakallio S (2015) Foregone carbon sequestration due to land occupation—the case of agro-bioenergy in Finland. Int J Life Cycle Assess 20:1544–1556. https://doi.org/10.1007/s11367-015-0956-x

Lehtilä A, Ghani HU, Liu X et al (2025) Framework for including national-level LULUC emissions and removals in the GWP of agricultural and forestry products in LCA. J Clean Prod 494:144999. https://doi.org/10.1016/j.jclepro.2025.144999

Leinonen I (2022) A general framework for including biogenic carbon emissions and removals in the life cycle assessments for forestry products. Int J Life Cycle Assess 27:1038–1043. https://doi.org/10.1007/s11367-022-02086-1

Maciel VG, Novaes RML, Brandão M et al (2022) Towards a non-ambiguous view of the amortization period for quantifying direct land-use change in LCA. Int J Life Cycle Assess 27:1299–1315. https://doi.org/10.1007/s11367-022-02103-3

Müller-Wenk R, Brandão M (2010) Climatic impact of land use in LCA—carbon transfers between vegetation/soil and air. Int J Life Cycle Assess 15:172–182. https://doi.org/10.1007/s11367-009-0144-y

Röös E, Patel M, Spångberg J (2016) Producing oat drink or cow's milk on a Swedish farm — environmental impacts considering the service of grazing, the opportunity cost of land and the demand for beef and protein. Agric Syst 142:23–32. https://doi.org/10.1016/j.agsy.2015.11.002

Searchinger TD, Wirsenius S, Beringer T, Dumas P (2018) Assessing the efficiency of changes in land use for mitigating climate change. Nature 564:249–253. https://doi.org/10.1038/s41586-018-0757-z

Tillman A-M (2000) Significance of decision-making for LCA methodology. Environ Impact Assess Rev 20:113–123. https://doi.org/10.1016/S0195-9255(99)00035-9