The International Journal of Life Cycle Assessment (2022) 27:1038–1043
https://doi.org/10.1007/s11367-022-02086-1

COMMENTARY AND DISCUSSION ARTICLE

A general framework for including biogenic carbon emissions and removals in the life cycle assessments for forestry products

Ilkka Leinonen[1]

Received: 15 July 2022 / Accepted: 10 August 2022 / Published online: 25 August 2022

1 Introduction

At present, there are no commonly accepted methods within the life cycle assessment framework for handling the changes of biogenic carbon stocks in biomass, dead organic matter and soil (i.e. the LULUC emissions and removals) (e.g. Brandão et al. 2013). This is especially a problem when assessing the climate sustainability of forestry products. This lack of consensus had led to situation, where under the same conditions, a forestry product can be seen as a carbon source or sink, depending on the approach chosen. This is probably one of the most crucial issues in current methodological development of LCA, because such a lack of consensus is intolerable. Without consistent methodologies, effective use of the LCA framework in the biobased sector is more or less impossible, both in decision making and in communication with stakeholders. The methodological issues currently discussed in the context of biobased and especially forest-based production include the handling of different components of biogenic carbon, i.e. biomass, dead organic matter, soil carbon and products (Brandão et al. 2013), characterisation factors of biogenic carbon uptake and emissions, i.e. the 0/0 and − 1/+ 1 approaches (Pawelzik et al. 2013), inclusion of direct and indirect land use changes (Finkbeiner 2014), selection of the reference land use (Koponen et al. 2018), inclusion of the dynamics of the regrowth of the biomass (Levasseur et al. 2012) and specifying the timing of regrowth for the assessment, i.e. the chicken-and-egg dilemma (Albers et al. 2020), among others.

Despite all the methodological issues listed above and thoroughly discussed in literature, it should be important to keep in mind that the overall LCA methodological framework is already very well established, its basic principles can be scientifically justified, and there are numerous examples of the application of this framework for highly different research questions (Guinée et al. 2011). Although biobased production has its own special features, assessment of the environmental sustainability of this specific sector should, after all, be seen only as a special case of the existing general LCA framework. Following the overall principles of the life cycle inventory and the impact assessment, including the principles of mass and energy balance, it would be perfectly possible to handle the forest industry, as well as any biobased production, in a consistent way in LCA, and ensure that the results would be comparable with those from any other sector of production.

In this paper, I present a straightforward approach for accounting for the biogenic carbon emissions and removals, to be applied in LCA models for forestry products. The proposed approach (1) is applicable to all products, ranging from biofuels to constructing materials, (2) follows the mass balance principle and therefore is fully justified in physical terms, (3) is consistent with generally applied LCA standards and guidelines, (4) is consistent with calculation principles for other biobased production, such as food produced in agricultural systems, (5) is consistent with calculation methods for fossil carbon flows, and (6) avoids the problems and subjective choices of time-dependency. Furthermore, I present some examples demonstrating the applicability of the approach in practical assessments.

2 Methods

2.1 The mass balance principle

In all life cycle inventories, the mass balance principle should be followed, i.e., the elementary flows associated with the product chain should be quantified as the basis of the inventory (ISO 2006). This principle should obviously also be applied for biogenic carbon in forestry and in all other biobased production.

Communicated by Matthias Finkbeiner

✉ Ilkka Leinonen
ilkka.leinonen@luke.fi

1 Natural Resources Institute Finland (Luke), Latokartanonkaari 9, FI-00790 Helsinki, Finland

When considering the emissions and removals of biogenic carbon, in practice the scope of the assessment is limited to the *changes in the biogenic carbon stock*. Therefore, all the assessment of this stock should then strictly follow the principles of mass balance: (1) all reductions in biogenic carbon stock should be counted as carbon emissions, (2) all increases in carbons stock should be counted as removals of carbon from the atmosphere (negative emissions) and (3) all these changes should be counted only once (thus avoiding double counting). It should be also noted that these same principles are valid also for accounting for the emissions of fossil carbon; fossil emissions indicate the reduction of fossil carbon stock. However, the principle 2) will never be applied in the case of fossil carbon, as the fossil carbon stock can only be reduced, not increased.

2.2 Mass balance in LCA guidelines

The biogenic carbon stock has been usually divided to two components, namely (1) carbon stored in above- and below-ground living biomass, dead organic matter and soil organic matter, and (2) biogenic carbon stored in products. In this paper, I will mainly concentrate on the former component, although the latter component, i.e. the biogenic carbon in products, can be modelled using exactly the same principles as the carbon stored in biomass and soil, as discussed below. Following the mass balance principles outlined above, the changes in the carbon stock in biomass and soil (also known as land use and land use change [LULUC] emissions and removals) can be handled in a consistent way, as specified in carbon footprinting standards and LCA guidelines. For example, according to ISO 14067, the removals and emissions from direct land change (LUC) and change in the management of land shall be included in the assessment, and it is also stated in that standard that "the net change in carbon stock within a biogenic carbon pool corresponds with the sum of CO_2 emissions to and removals from the atmosphere" (ISO 2018). Similarly, according to the LCA standard for biobased products (EN 16760), all biogenic and non-biogenic carbon emissions and removals should be considered in the assessment (CEN 2015). The changes in the carbon stock as a result of direct LUC are also part of the PAS 2050:2011 carbon footprinting specification (BSI 2011), and it should be noted that this specification has also been adopted as part of the EU Product Environmental Footprint (PEF) guidelines (JRC 2012), and the latter in turn is referred in the EN 15804:2012 (sustainability of construction works) standard (BSI 2012). In addition to the fact that these principles follow the general idea of life cycle inventory as specified in the LCA standards, they are also consistent with the guidelines of the IPCC (2006) national greenhouse gas inventories concerning the carbon stock changes and associated emissions and removals of carbon dioxide from biomass, dead organic matter and soils.

2.3 Need for the time-dependent approach?

When modelling the changes of biomass and soil carbon stocks in LCA, often the need of so-called time-dependent approach is considered (Levasseur et al. 2012; Albers et al. 2020). This approach takes the recovery of the biomass into account, either after the harvest or before the harvest. Now the big question is as follows: how does this approach relate to the general mass balance principle that forms the basis of most LCA standards and guidelines?

The IPCC (2006) guidelines for the national greenhouse gas inventory have not adopted the time-dependent approach. Instead, according to these guidelines, all anthropogenic CO_2 emissions of the LULUCF sector should be quantified for the year of the assessment, together with all CO_2 removals (negative emissions) for the same year. As a result, the net change of the national LULUCF sector carbon stock (increase or decrease) can be quantified. In terms of quantifying the annual global GHG emissions, this approach is justified; the sum of global national level changes of the carbon stock determines the annual contribution of the LULUCF sector to the global anthropogenic CO_2 emissions.

If the time-dependent approach is not applied at the national level, is there any reason why it should be adopted to the product level assessments? After all, the fact is that in order to produce a wood-based product, a tree must be felled, and it will take time (often decades) until a new tree with an equal carbon stock will have grown *at the same spot* (but note that concerning the changes of the atmospheric CO_2 concentration, the location of the regrowth is irrelevant). So, the time-dependent approach in forestry may seem to be justified if the production unit is considered to be a single tree, or several trees growing at the same location and felled at the same time. However, the practical forestry does not work in that way. The basis of sustainable forest management is the idea that while some trees are felled and their carbon stock is lost, at the same time the growth of the remaining trees will compensate the lost stock through carbon uptake from the atmosphere. Therefore, whenever the spatial scale (production unit) of the assessment is any bigger than a single tree (or a single stand in the case of clearcut), the accounting of the carbon stock change should include both the losses of carbon in harvest and the simultaneous carbon sequestration by the growing trees. If this approach is applied consistently, the time-dependent calculation method is not needed, the contribution of the activity to the climate warming is calculated correctly through the mass balance principle, and the result is also consistent with the IPCC (2006) national level inventories. Of course, it should be noted that if the regrowth of trees does not occur, for example, as a result of deforestation, then the carbon stock changes obviously consist only of the losses of biomass and soil carbon. Similarly, if the regrowth is smaller than the losses of carbon, the partial losses of the carbon stock should be accounted for as emissions.

2.4 Mass balance principle in stand level assessments

Although the approach described above can be directly applied at the landscape, regional and national levels, there are cases where smaller scale assessments are needed. For example, if the purpose of the assessment is to quantify the effects of certain changes in management on the carbon footprint of a forestry product, smaller scale analyses might be needed. In such cases, for example in a stand level assessment, the timing of carbon losses and uptake may differ from each other, especially in clearcut-based harvest. However, also in this case, the similar mass balance-based, time-independent approach can be applied as at the landscape level. This is demonstrated in the example below.

In Fig. 1, a theoretical example is presented, where the effect of changes in land use and management on the carbon stock in commercial forestry are demonstrated. In this figure, the initial carbon stock (or the "reference land use" as specified by the ISO 14067) of the forest stand is assumed to represent that natural vegetation of that area and is indicated in the example by the stock level C_0. Assume that this forest is taken to commercial use, and as a result, the average carbon stock falls to the level C_1. Now, the CO_2 emissions associated with this change of management are simply the change in the carbon stock (C_0–C_1), multiplied by 44/12. In attributional LCA, this is the total LULUC emission that needs to be allocated to the forestry products (see "Sect. 2.5" below). Note that the average carbon stock over the rotation cycle is used here to represent the value of C_1, despite the fact the actual stock fluctuates depending on the phase of the cycle (solid blue line in Fig. 1). This is consistent with ISO 14067, which clearly states that "the cycle of forest growth, harvest and regrowth is not LUC" (ISO 2018). Furthermore, the use of the average stand level carbon stock is consistent with the time-independent assessment of landscape level carbon stock changes discussed above. If different stands can be assumed to be at different stages of development, the average of their carbon stocks at any time instant can be seen to represent the contemporary carbon stock at the landscape level, per unit of land area. This is demonstrated by the thin broken blue line in Fig. 1, indicating a separate stand, within the same area, at a different phase of the rotation cycle.

Another scenario demonstrated in Fig. 1 is the increase of the carbon stock as a result of management. Following the assessment above, the carbon stock of the forest stand has been stabilised to the level of C_1, and the emissions associated with original reduction from the reference level has been allocated to forestry products (see "Sect. 2.5" below). Now assume that the forest management changes in a way that creates an increase of the stand carbon stock to the level C_2. Following the mass balance principles, this additional change C_1–C_2 should now be accounted for as a negative emission. This would ensure that the overall change from the initial level to the final level (C_0–C_2) is correctly accounted for, and this total difference in the carbon stocks represents the actual change in the atmospheric CO_2 concentration as a result of all anthropogenic LULUC emissions and removals of this forest stand.

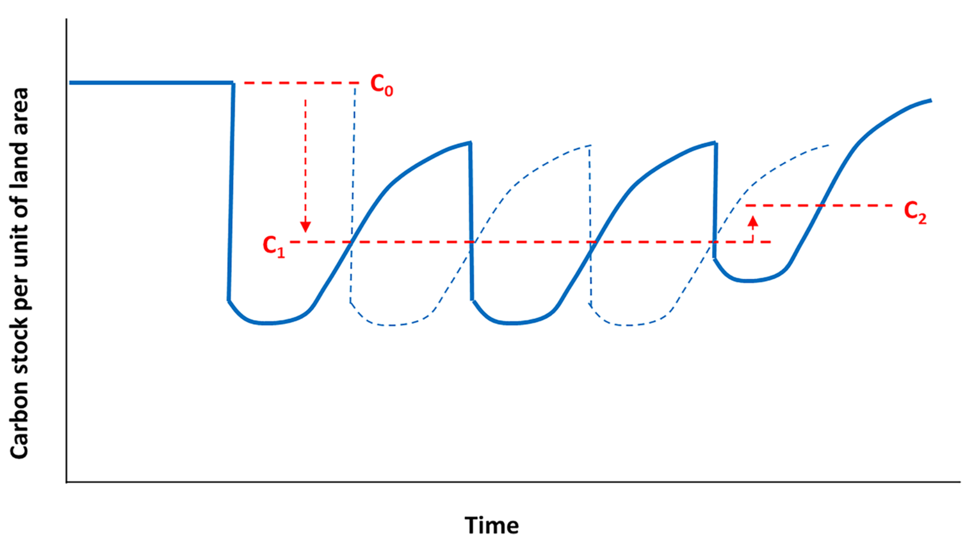

Fig. 1 A theoretical example of the changes of the carbon stock of a forest stand. C_0 indicates the initial carbon stock (natural vegetation), C_1 the average carbon stock after land use change, and C_2 the average carbon stock after a further change in management. The solid blue line indicates the temporary fluctuation of the carbon stock, and the thin broken blue line indicates the carbon stock of another forest stand at a different phase of the rotation cycle

2.5 Allocating the emissions and removals to products

The above example demonstrated the accounting for the overall LULUC emissions associated with forestry, but now the question remains how these emissions should be allocated to forestry products. Following a “traditional” LCA thinking, these LULUC emissions could be seen analogous to emissions related to capital goods. Then, in principle, the overall emissions of the above example (i.e. the change of the carbon stock from the initial level C_0 to the final level C_2) could be allocated to all forestry products obtained during the whole period when this forest stand is in commercial use. This approach, however, has some practical issues. If the commercial use of the forest (or any land area) continues for a long time, the amount of products could be extremely high, and the emissions per single product could be diluted to a minimal level, so the effect of the LUC would be invisible in the results. Furthermore, this approach could not make any difference between established commercial forestry and new land use changes where virgin forest would be converted to commercial use (agriculture or forestry). Finally, this approach would not take into account any improvements in management that could increase the carbon stock (e.g. the change from level C_1 to C_2 in the above example). Therefore, this “traditional” approach would not be very useful, if the idea is to help provide incentive for improved forest management and avoiding further land use changes.

The solution for this issue would be a more precise temporal allocation of the carbon stock changes. In practice this would mean that a fixed time period would be selected, following each occasion of a change in land use or management, and the LULUC emissions would be allocated only to products obtained during this period. This approach is already part of some LCA guidelines. In ISO 14067, for harvested wood products, this time period is suggested to be the length of the average rotation period (ISO 2018). In PAS 2050:2011, it is stated that “the assessment of the impact of land use change shall include all direct land use change occurring not more than 20 years, or a single harvest period, prior to undertaking the assessment (whichever is the longer)” (BSI 2011). Adopting the idea of a single rotation period, this approach can be easily demonstrated using the above example shown in Fig. 1. In this figure, three rotation cycles are presented (solid blue line). So, following these principles, the initial LULUC emissions (C_0–C_1) would be allocated to products obtained from the first rotation period, no emissions would be allocated to the second period as the average carbon content of the stand would remain unchanged, and finally the change C_1–C_2 would be allocated to the third rotation period as negative emissions. It is important to notice, that although in this example the average carbon stock of the commercial forest remains continuously below the refence level (natural vegetation), the reduction of the stock should be counted as emissions only once (in this case during the first rotation cycle after land transformation). Otherwise, the contribution of forest management to the atmospheric CO_2 concentration would be overestimated as a result of double counting.

Although the LULUC emissions can be allocated to the forest-based raw material (i.e. harvested wood) in a systematic way following the mass balance principle and a specified time period, allocation between co-products of the wood industry remains an open question. Usually, either mass allocation or economic allocation is applied for forestry products (Sahoo et al. 2019). A logical choice of allocation method here would be mass allocation based on the carbon content of the product (cf. Leturcq 2020). When choosing this approach, the product-level LULUC emission could be simply expressed by multiplying the carbon content of the product by a characterisation factor. This characterisation factor could be determined by dividing the total change in the forest carbon content by the carbon content of the wood harvested during selected time period of the assessment (e.g. one rotation period). Now, the value zero of this factor would indicate carbon neutrality in terms of the LULUC emissions (no change in carbon stock), while a positive value would indicate net reduction of the stock and a negative value increasing stock (net sink).

Another issue related to LCA of biogenic carbon in is handling the carbon stored in products. There is a lot of variation in LCA guidelines concerning this carbon stock. Usually, the biogenic carbon in products has been considered as negatives emissions (carbon capture from the atmosphere) only if the stock can be considered “permanent”. In practice, an arbitrary 100-year storage time is often considered as an indicator of permanency (e.g. JRC 2012). In addition, some guidelines such as PAS 2050:2011 allow separate counting and partial credits for shorter periods of storage time (BSI 2011). However, these arbitrary choices can be avoided, if a similar mass balance-based calculation method would be applied for biogenic carbon in products as for the carbon stored in biomass and soil as described above. In this case, the actual storage time would be irrelevant, and the only thing that would matter is the change of the size of the product carbon stock. In practice, this would mean that negative emissions for products would be credited if the storage increases, i.e. if the amount of carbon stored in new products would be higher than the carbon content of the products disposed of (and incinerated) at the same time, independently of their longevity. Also, in this case, this approach would result in unbiased estimates of the carbon flows between the stock and atmosphere and would be consistent for example with the IPCC (2006) guidelines for the national greenhouse gas inventory for harvested wood products. Obviously in the case of the carbon stored in products, quantification of the dynamics of the carbon stocks, determining system boundaries and solving issues related to co-product allocation would be much more complex than in the of case carbon stocks in biomass and soil.

3 Discussion

The fundamental difference between fossil and biobased raw materials is the fact that the production of biomaterials is based on capture of carbon from the atmosphere. Although fossil materials also consist of carbon that has been captured form the atmosphere for a long time ago, by definition, new fossil material is not formed in natural conditions, so for example incineration of fossil fuels or other fossil material can only reduce the fossil carbon stock and increase the atmospheric carbon concentration, never the opposite.

It is surprisingly easy to ignore this fundamental difference, when carrying out assessments of climatic sustainability at a product level, for example within the LCA framework. In contrast, the special features of biobased production are already built in the global and national greenhouse gas inventories through recognising the contemporary changes in the biogenic carbon stocks, which in turn directly indicate the contribution of biobased production to the changes of atmospheric CO_2 concentration for each year of the assessment.

Wood-based products have been seen as a special case in biobased production, as a result of the long growth cycle of trees. In reality, however, the only thing that matters in terms of the contribution to climate warming is the difference between the amount of carbon that moves form the biogenic stock to atmosphere and the carbon that moves back to the stock from the atmosphere; the length of the production cycle itself has no effect in this process. For example, at the global level, forestry is currently a net source of CO_2 because the harvests and deforestation exceed the new growth of trees (UNFCCC 2022). At the national level, forestry in some countries is a net source and in some other countries a net sink of CO_2 (UNFCCC 2022). Thus, a forest area can be a net sink of carbon despite ongoing harvests and despite the fact that the regrowth of single trees can take decades; this requires that the removal of the carbon from the stock in harvest is compensated by the simultaneous growth of the remaining trees in the same area. Therefore, it is extremely important that this process is taken into account also in smaller scale assessments. If the harvest of a single tree or a single stand is considered as a reduction of carbon stock without taking into account the simultaneous regrowth, this partial counting will unavoidably lead to biased estimates of the climate effects of wood-based products and of the overall contribution of forestry to global climate change.

Another important issue to keep in mind is that the forest industry does not occur in isolation. Therefore, any LCA methodological framework aimed for wood-based products must be consistent with methodologies applied at other production sectors. For example, alternatives for forest-based products can be obtained from agricultural production, including packaging materials (fibres, bioplastics) and biofuels (Fargione et al. 2008; Bright et al. 2012; Walker and Rothman 2020). In LCA comparison, forestry-based fuels are often assessed together with fossil fuels, and for example construction materials can be either wood-based or fossil-based (Bribián et al. 2011; Chau et al. 2015). As a result, any inter-sectorial comparisons are possible only if consistent methodologies exist. For agricultural land use changes and LULUC emissions, many LCA guidelines have adopted the PAS 2050:2011 methodology (BSI 2011), which is consistent with the framework suggested here for forestry products (see, e.g. Leinonen et al. 2013; Williams et al. 2016). In addition, systematic comparison with fossil-based production is possible when it is ensured that any changes in both fossil and biogenic carbon stocks are handled in a consistent way in the assessment.

As a conclusion, it is crucial in any assessments based on the LCA framework that all material flows, including the flows of both fossil and biogenic carbon, are quantified following strictly the principles of mass balance. Only in this way it would be possible to produce unbiased estimates of the contribution of the biobased production to the global climate change. Special care should be taken to keep the assessments consistent at different spatial scales, and especially in small-scale assessments to avoid partial counting or double counting.

Funding Open access funding provided by Natural Resources Institute Finland (LUKE).

Declarations

Conflict of interest The author declares no competing interests.

References

Albers A, Collet P, Benoist A, Hélias A (2020) Back to the future: dynamic full carbon accounting applied to prospective bioenergy scenarios. Int J Life Cycle Assess 25:1242–1258. https://doi.org/10.1007/s11367-019-01695-7

Brandão M, Levasseur A, Kirschbaum MUF et al (2013) Key issues and options in accounting for carbon sequestration and temporary storage in life cycle assessment and carbon footprinting. Int J Life Cycle Assess 18:230–240. https://doi.org/10.1007/s11367-012-0451-6

Bribián IZ, Capilla AV, Usón AA (2011) Life cycle assessment of building materials: comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. Build Environ 46:1133–1140. https://doi.org/10.1016/j.buildenv.2010.12.002

Bright RM, Cherubini F, Strømman AH (2012) Climate impacts of bioenergy: Inclusion of carbon cycle and albedo dynamics in life cycle impact assessment. Environ Impact Assess Rev 37:2–11. https://doi.org/10.1016/J.EIAR.2012.01.002

BSI (2011) PAS 2050:2011 Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. British Standards Institution (BSI)

BSI (2012) EN 15804:2012. Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products. British Standards Institution (BSI)

CEN (2015) EN 16760:2015. Bio-based products - life cycle assessment. The European Committee for Standardisation (CEN)

Chau CK, Leung TM, Ng W (2015) A review on Life cycle assessment, life cycle energy assessment and life cycle carbon emissions assessment on buildings. Appl Energy 143:395–413. https://doi.org/10.1016/j.apenergy.2015.01.023

Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P (2008) Land clearing and the biofuel carbon debt. Science 319:1235–1238. https://doi.org/10.1126/science.1152747

Finkbeiner M (2014) Indirect land use change – help beyond the hype? Biomass Bioenerg 62:218–221. https://doi.org/10.1016/j.biombioe.2014.01.024

Guinée JB, Heijungs RH, G, Zamagni A, Masoni P, Buonamici R, Ekvall T, Rydberg T, (2011) Life cycle assessment: past, present, and future. Environ Sci Technol 45:90–96. https://doi.org/10.1021/es101316v

IPCC (2006) Chapter 4. Agriculture, forestry and other land use. In: Eggleston S, Buendia L, Miwa K, et al (eds) 2006 IPCC guidelines for national greenhouse gas inventories. Intergovernmental Panel on Climate Change, Prepared by the National Greenhouse Gas Inventories Programme

ISO (2006) ISO 14040:2006 Environmental management - life cycle assessment - principles and framework. The International Standards Organisation, Geneva

ISO (2018) ISO 14067:2018 Greenhouse gases — carbon footprint of products — requirements and guidelines for quantification. The International Standards Organisation, Geneva

JRC (2012) Product environmental footprint (PEF) guide. European Commission (EC) Joint Research Centre (JRC). https://ec.europa.eu/environment/eussd/pdf/footprint/PEF%20methodology%20final%20draft.pdf

Koponen K, Soimakallio S, Kline KL et al (2018) Quantifying the climate effects of bioenergy–choice of reference system. Renew Sust Energ Rev 81:2271–2280. https://doi.org/10.1016/j.rser.2017.05.292

Leinonen I, Williams AG, Waller AH, Kyriazakis I (2013) Comparing the environmental impacts of alternative protein crops in poultry diets: the consequences of uncertainty. Agric Syst 121:33–42. https://doi.org/10.1016/j.agsy.2013.06.008

Leturcq P (2020) GHG displacement factors of harvested wood products: the myth of substitution. Sci Rep 10:20752. https://doi.org/10.1038/s41598-020-77527-8

Levasseur A, Lesage P, Margni M, Samson R (2012) Biogenic carbon and temporary storage addressed with dynamic life cycle assessment. J Ind Ecol 17:117–128. https://doi.org/10.1111/j.1530-9290.2012.00503.x

Pawelzik P, Carus M, Hotchkiss J, Narayan R, Selke S, Wellisch M, Weiss M, Wicke B, Patel MK (2013) Critical aspects in the life cycle assessment (LCA) of bio-based materials – reviewing methodologies and deriving recommendations. Resour Conserv Recycl 73:211–228. https://doi.org/10.1016/j.resconrec.2013.02.006

Sahoo K, Bergman R, Alanya-Rosenbaum S, Gu H, Liang S (2019) Life cycle assessment of forest-based products: a review. Sustainability 11(17):4722. https://doi.org/10.3390/su11174722

UNFCCC (2022) National Inventory Submissions 2021. United Nations Framework Convention on Climate Change. https://unfccc.int/ghg-inventories-annex-i-parties/2021

Walker S, Rothman R (2020) Life cycle assessment of bio-based and fossil-based plastic: a review. J Clean Prod 261:121158. https://doi.org/10.1016/j.jclepro.2020.121158

Williams AG, Leinonen I, Kyriazakis I (2016) Environmental benefits of using turkey litter as a fuel instead of a fertiliser. J Clean Prod 113:167–175. https://doi.org/10.1016/j.jclepro.2015.11.044