Accounting of biogenic carbon in attributional LCA

- including temporary storage

Martin Erlandsson, Lars Zetterberg

Author: Martin Erlandsson, Lars Zetterberg, Swedish Environmental Research Institute
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Photographer: Martin Erlandsson
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IVL Swedish Environmental Research Institute Ltd.
P.O Box 210 60, S-100 31 Stockholm, Sweden
Phone +46-(0)10-7886500 // Fax +46-(0)10-7886590 // www.ivl.se

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Climate change poses one of the largest challenges to mankind. It's clear that significant mitigation efforts are needed in order to reach a sustainable development for our and future generations. One important strategy in climate mitigation is to convert fossil based industrial processes to those based on renewable sources. In order to make this transition possible, we will have to change to a more biobased economy. Furthermore, the energy required for the production of non-renewable materials such as steel and cement, should as much as possible be based on renewable resources in the future and will, therefore, potentially compete for the same renewable resource stock.

In each application, the best use of the renewable resources has to be evaluated. Life cycle assessment (LCA) is an analytic tool that can be used for such comparative purposes. In order to make the LCA results robust, the used methodologies and their features need to be strictly specified. If the LCA practitioner has too much freedom when applying the methodology, this may result in ambiguous results. This development is actually part of an ongoing market driven development where LCA based declarations for product are used as information modules, as defined by numerous international standards (ISO 14040, -44, -25 and e.g. ISO 21930). These resulting environmental product declarations (EPD) are supplied by the manufacturers, and then used by others in the supply chain, to for instance calculate the impact from construction projects.

The system perspective chosen for these EPD is a so called *attributional LCA*. An attributional LCA builds on a modular approach (Erlandsson et al 2015) and on the additivity principal (Tillman 2000). This approach is also described as the "100% rule", where the sum of impacts from all attributional allocated product systems equals the global impact, ideally. The same system perceptive is e.g. used for national greenhouse gas inventories (IPCC 2006). An alternative system perspective, answering another question, is a so called *consequential LCA*. A consequential LCA is used to assess a marginal and often hypothetical change as compared to a reference case. The consequential LCA provides a complimentary result to the attributional LCA, describing "what happens if" a particular change is introduced. Attributional LCA methodology is more commonly used in the EPD context since it is more unequivocal. In this paper we have therefore chosen the attributional approach in order to achieve an applicable method for EPD.

This paper describes the basis for accounting of biogenic carbon from forest products and with a focus on evaluating the impact of temporarily storing wooden based long-lived construction products in buildings.

Natural and technical ecocycles

Two types of ecocycles can be distinguished in the circular economy, namely the *natural ecocycle* and the *technical cycle*. The technical cycle account for these non-renewable resources that can be recycled or where the natural resources are so large that they can be regarded as infinite even though they cannot be replenished once extracted. The processes utilised in a technical cycle, from a life cycle perspective, have to be based on renewable resources if the technical life cycle is to be regarded as fully sustainable.

Natural ecocycles are found on renewable sources that can be replenished or reproduced easily and include water, wind, solar energy and biomass from e.g. forests. The time it takes for replenishment varies. Some are relatively quick like agricultural crop, while the regrowth in forestry takes longer time. To achieve a sustainable use of biogenic resources the harvested products shall at least be in balance with the regrowth, typically on a landscape level and over time.

To put it very simple firstly, in order to be ecologically sustainable, we have to adapt our consumption to what can be sustainably harvested from the sun, wind, water, geothermal energy and from natural systems. Secondly, products based on a technical cycle are consistent with this ecological sustainable ecocycle principle only if they are produced using renewable energy resources. Therefore, products based on a technical cycle can only be justified if the delivered function has a lower environmental impact than products based on natural resources in a life cycle perspective. Product based on downgrading cycles or linear resource use shall be limited.

Sustainable managed forests

In order to support our common needs we have to use land and natural resources in an efficient and sustainable way. To provide nutrients, we need agricultural land. In the same way, managed forests are needed to provide other services such as paper, building materials and energy. Consequently, we have to manage these systems in a sustainable way.

Concerning forestry, we have to take care of the biodiversity and balance of elements in the soil, so that the essential functionalities in natural forest remain in the managed forests. Nevertheless, the managed forest will never provide the same biological values as an unmanaged forest, why it is important that we, in addition to managed forests, protect and develop preserved forests. The biodiversity of managed forest in general can also be improved by adopting alternative harvesting methods and by creating preserved plots within the managed forest what preserve existing or potential key habitats. This would increase overall functionality of the managed forest.

In boreal forests different management regimes require a set of compensatory measures to maintain the ecological quality. From an analytic perspective, in order to study a forestry system, the chosen system should not be limited to only the part of the forest that is managed, but also include an unmanaged forest that is required in order to maintain the overall ecological quality on a landscape level.

Biogenic carbon neutral

Over one rotation cycle, a managed forest may be carbon neutral in the meaning that the carbon stock of the system is unchanged over a full rotation cycle (for instance from harvest to harvest). However, the forest is not *climate* neutral, since over time, the carbon stock will fluctuate over and under the baseline level, constituting a temporary loss or gain of stored carbon. On the landscape level can we assume that there are stands at all different ages and that harvests are equally spread over time. A carbon neutral forestry requires well managed forests, where re-planting is the starting point, and the condition that the net harvesting over time cannot be larger than the regrowth.

In a managed forest it should be noted that the forestry soil carbon pool is slowly increasing, but may reach a steady state over time (if everything else remains the same). This aspect is a subject handled in the reference scenario in the national greenhouse gas inventories. A literature review is conducted on this matter (Rosenqvist 2017) and the subject is complex and needs more systematic research before it can be included in LCA accounting. Soil carbon storage is thus considered in this evaluation and illustration of the role of temporal sinks in the forestry value chain..

In Sweden, the dominating share of forested land consists of *managed* forests and has so been for over 100 years. In this paper, we chose a baseline equal to the average carbon stock in a managed forest. Figure 1 illustrates schematically how the carbon stock in a managed forest stand varies over time. The average carbon stock is marked as the dotted (red) line. Using the average carbon stock as the baseline the managed forest is of course carbon neutral on average over a rotation period. However, the forest is not *climate* neutral, since over time, the carbon stock will fluctuate over and under the baseline level, constituting a temporary loss or gain of stored carbon as compared to the baseline.

Figure 1 illustrates how biogenic carbon stocks change over time for a managed forest stand.

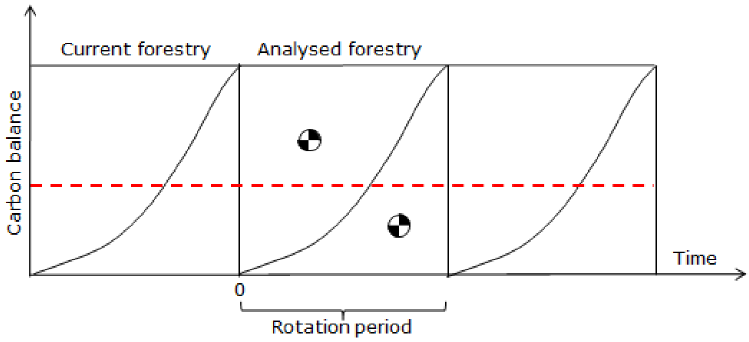

Figure 1 Carbon balance in managed forestry where the baseline is set as the current forest management on the landscape level. Solid line represent the carbon balance in a stand from harvest to harvest, red line represents the average carbon balance on a landscape scale.

If we instead have a landscape consisting of a large number of equally large stands, representing all maturity levels (ages), the carbon stock, per hectare, for this landscape will be equal to the average carbon stock (dotted line) of one stand.

An attributional LCA (ALCA) is characterised by the fact that it describes the current situation, temporally and spatially. Moreover, attributional LCA follows the additivity principle where the LCA performance for all products can be added up to the total impact for the world. If we use ALCA to model the emissions that actually take place, we will have to apply a baseline that represents the 'business as usual', i.e. the baseline illustrated in Figure 1.

Land use change

How do we consider land use change (LUC) if we apply the business as usual baseline on the managed forest? With LCA, other system analytic methods and related regulations like the European renewable energy directive (RED) it is common to include consequences from land use change (LUC) in the agricultural sector[1]. Such aspects are typically handled in the agricultural sector with a default 20-year transition period. If we would like to assess the transformation of a managed forest into a natural (or preserved) forest, we should ideally apply a time window of several hundreds of years, allowing for the carbon stocks to reach a new level. We have discovered that such transition is hard to model due to lack of knowledge and data.

A common temporal cut-off applied in LCA is 100 years, meaning that emissions may actually occur beyond this time, like in a landfill, but are not accounted for. This is regarded as an acceptable compromise assuming that the major part of impacts occurs with the first 100 years. A rotation period in managed forest in Sweden is usually shorter than 100 years. A 100 year cut-off could therefore be applied as a first assumption to account for LUC. The 100 years cut-off is also equal to the integration time of radiative forcing that result in global warming potential GWP, expressed in carbon dioxide equivalents.

[1] Indirect land use change (iLUC) is only assessable with a consequential LCA and therefore not handled here.

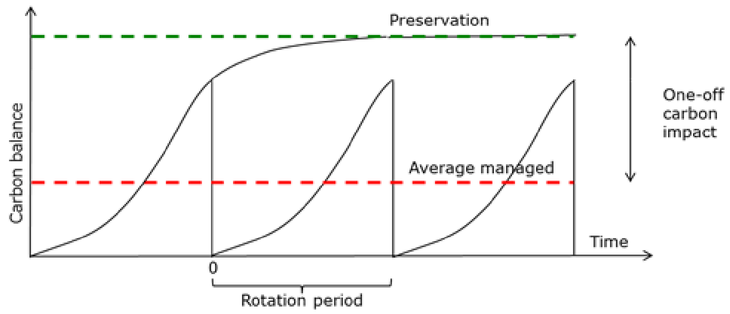

Figure 2. The impact (credit) of transforming a managed forest into a preserved forest (dashed green-line represents the steady state carbon balance on a landscape scale), assuming that the preserved forest holds more carbon. The carbon balance difference creates a one-off carbon impact. Note that the preserved forest does not deliver any wooden products.

In an attributional LCA is LUC typically handled by a one-off impact (credit or debt). The climate impact is illustrated in Figure 2 and constitutes a one-off carbon credit, equal to the difference in average carbon stock from a managed forest compared to a preserved forest. This flexible (or dynamic baseline setting) is in line with attributional LCA approach and national greenhouse gas inventories, where the goal is to evaluate what is yearly emitted in the real world[2].

The same climate impact is valid for the reverse process, when a natural forest is transformed into a managed. The difference is that such a LUC will generate a climate impact debt instead.

Temporal storage of biobased products

We have now illustrated that LUC can generate a biogenic carbon debt or a credit. Another case, in principle not so different, is when for instance wooden products are used in construction works after harvesting. The forestry is regenerated and the growth process will once more transform carbon dioxide into wood and part of the forest carbon pool. The potential differences are when such biobased products will be stored in technosphere after harvesting, instead of directly closing the loop as a biogenic emission to nature again, when wood e.g. is used as fuel in an energy recovery process. This is a common fate for most consumer product with a short duration of stay in the technosphere.

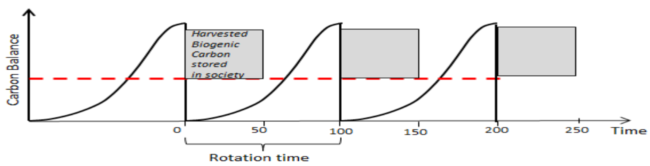

Figure 3 Temporary storage of biogenic carbon with a residence time in this case exemplified by half of the rotation period, and the baseline is set as the historical forest management.

Use of long-lived biogenic based products implies that the biogenic carbon stored in the product is not available for uptake by the forest and constitute a temporal sink (see Figure 3), since it is fixed in a product. This means that additional carbon dioxide now will be absorbed in the forest photosynthesis. This additional carbon absorbed by the forest biological cycle creates a positive temporary carbon balance change, likewise

[2] In theory, one could argue that the baseline should not follow the new use of land, but stay to the historical use. This would then illustrate a theoretical burden if the lad was not used.

to the credit in the LUC case (from managed forest to preserved forest). The difference is that the residence time is limited to the lifetime of the product and not as long as if the land use change is sustained.

Another difference with LUC is that the temporal storage in the technosphere does not affect the carbon stock in the managed forest. The temporary storage in the building is currently not accounted for in an attributional LCA, with the argument that no commonly accepted method exists. Nevertheless, a more sophisticated LCA approach is available with a so called dynamic LCA.

A dynamic LCA inventory includes the carbon uptake and emission treated per year as they appears. A number of such studies have been carried out. These studies apply dynamic LCA on forestry based products and then capture the positive aspect of temporary storage of biogenic carbon in the technosphere. It is worth to mention that the national greenhouse gas inventories account for the biogenic carbon stored in technosphere, typically combined with default residence time for different product groups.

Quantification of temporary storage

Ongoing research at IVL is focusing on how temporary storage could be quantified in an attributional LCA. Our calculations are based on dynamic LCA. The first interest is to investigate the carbon credit when forestry products are stored in the technosphere such as in the built environment. The calculations describes the difference between a managed forestry and the additional climate impact when a temporary storage for a wooden product for 50 years (see Figure 4).

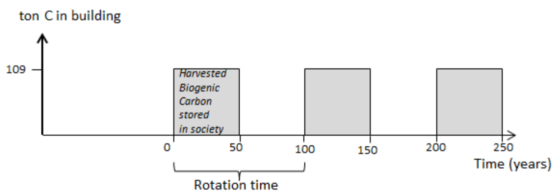

Figure 4 Terrestrial carbon stock change from 1 ha managed forest due to a 50 year temporary storage of wood in a building. Assuming the production of 109 ton C as wood per ha.

Figure 4 illustrates the net impact from storing wood as compared to not storing wood. The net impact is defined as the total carbon stock in the managed forest *plus* the technosphere *minus* the total carbon stock in a managed forest ($\Delta C_{net} = \Delta C_{Forest} + \Delta C_{wood} - \Delta C_{Forest}$). The net carbon stock is zero until the year 0, when the first forest stand is harvested, then is constant to the year 50 (when the stored wood is deconstructed and via e.g. energy recovery released as CO_2 back to the atmosphere) After 100 years, at the start of the second rotation period, the same scenario is repeated.

We have also applied a landscape level, assuming 100 stands of each 1 ha at different stages with the continuous production of 109 ton C/ha that is stored 50 years in buildings, shown in Figure 5

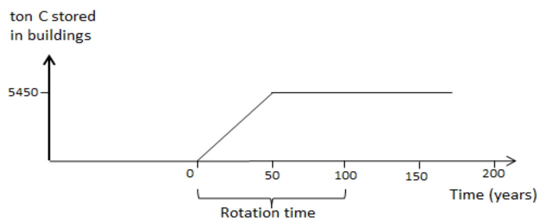

Figure 5. Landscape level. Terrestrial carbon stock change due to 50 year storage in buildings resulting from 100 1 ha stands at different maturity levels, each stand producing 109 t of C as wood. A steady state is reached 50 years after the first wood is stored, when added new wood is balanced by destroyed 50 year old wood

Based on the net carbon stock changes in Figure 5 we have calculated the climate impacts using radiative forcing as a measure, starting from reforestation. This climate impact is calculated with a dynamic LCA approach described in Zetterberg and Chen (2015), and the result is given as the yearly contribution to climate change measured in radiative forcing as shown in Figure 6.

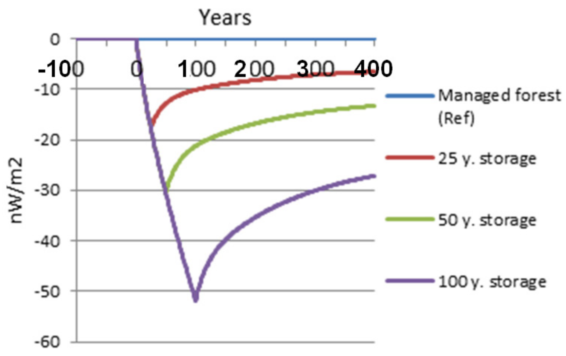

Figure 6 Radiative forcing on a landscape level. Assuming 100 stands of 1 ha each at different stages with the continuous production of 109 ton C/year that is stored 25, 50 or 100 years and then combusted and emitted to the atmosphere. Negative values correspond to a climate cooling effect.

The radiative forcing has been calculated as the radiative forcing from forestry plus wood in buildings minus the radiative forcing from forestry alone ($RF_{net} = RF_{Forest+wood} – RF_{Forest}$). Moreover, we assume three different storage times in buildings: 25 years, 50 years and 100 years. Negative radiative forcing values correspond to a cooling effect on climate. The radiative forcing is zero until the year 0, when the first forest stand is harvested, then decreases to reach a minimum level after 25, 50 or 100 years. Thereafter, net radiative forcing increases again but is always below zero. This means that storing wood temporarily has a negative radiative forcing and a cooling effect on climate.

A commonly used metric for assessing climate impacts in LCA applications is global warming potential (GWP). There is a relationship between radiative forcing and GWP. If the resulting radiative forcing, as given in Figure 6, is integrated over 100 years and divided by the integrated radiative forcing from 1 kg carbon dioxide, released at t=0, this would result in a global warming potential (GWP100) expressed in carbon dioxide equivalents (CO_2e). Using radiative forcing as a metric illustrates the temporal dependency and dynamics of the climate impacts, which GWP cannot do.

Mid-term conclusions and future research

A future sustainable society has to use the forest as a resource to feed our consumption and is an essential part of the bio-economy. A sustainable forestry demands not only that it is carbon neutral, but climate neutral and preserves biodiversity to support fundamental functionalities and ecosystem services on a landscape level.

In an attributional LCA, where the goal is to evaluate what happens in the real word, not all temporary changes in the forest biogenic carbon pool are treated equally. In the case of land use change, the negative impact and potentially positive effects are accounted for. But the temporary storage of biogenic carbon in e.g. buildings is not properly accounted for in the impact assessment. To include this aspect, a dynamic method needs to be applied e.g. dynamic LCA.

This report outlines a procedure for application of dynamic LCA that takes into account temporary storage of carbon in products in the assessment of carbon balances in the forest biomass supply chain.. By modelling the consequences on a landscape level and not for individual stands, the problems with defining boundary conditions where the forestry cycle starts and ends areavioded. Moreover, application on the landscape level allows evaluation of temporary storage and to potentially transform the result to an indicator result such as carbon dioxide equivalents (CO_2e). Carbon dioxide equivalents is well known to the LCA practitioner and the society in general, since the basic models in dynamic LCA is comparable to the current impact assessment methods to calculate the contribution to global warming potential (GWP) this should be part for further research and establishment.

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IVL Swedish Environmental Research Institute Ltd.
P.O. Box 210 60 // S-100 31 Stockholm // Sweden
Phone +46-(0)10-7886500 // Fax +46-(0)10-7886590 // www.ivl.se