SCORELCA

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ACCOUNTING FOR BIOGENIC CARBON SEQUESTRATION, STORAGE AND RELEASE IN LCA: STATE-OF-THE-ART

SCIENTIFIC SYNTHESIS

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SCORE LCA is an association that has been created to financially support collaborative research on LCA and related topics. It aims to promote and organize cooperation between companies, institutional and scientists in order to support the evolution of LCA methods and its practical implementation at European and international level.

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Summary

Products and energy from biomass are increasingly seen as options to reduce the impact of human activities on global warming. In fact, growing biomass absorbs carbon from the atmosphere, stores it for a certain period and finally releases it back to the atmosphere by thermal or biochemical degradation. Conversely, fossil carbon is emitted to the atmosphere by the combustion of energy resources that were stored in a quasi-permanent form for millions of years in geological formations. Life Cycle Assessment (LCA) and Carbon Footprint (CF) methods are increasingly used to quantify the climate-change impact of biomass-based products and energy sources. However, accounting for carbon emissions and sequestration associated to biomass may be complex and implies assumptions and still unresolved issues. Results obtained from these accounting methods are often used for decision-making by consumers, industries and policy-makers. Given the importance of these decisions, it is imperative that accounting methods be as consistent and rigorous as possible.

The objective of this study is to present the state-of-the-art regarding the different issues related to accounting for carbon emissions and sequestrations in LCA, and to develop recommendations following a critical analysis of existing methods and approaches. As a first step, a review of different concepts related to the carbon cycle has been performed. This review includes a description of the natural carbon cycle and of the perturbations caused by human activities, as well as an explanation of different indicators and accounting methods used to quantify the impact of human activities on climate change. Some issues related to biomass greenhouse gas (GHG) accounting are also presented, such as the biogenic carbon neutrality principle and the consideration of temporal aspects.

A review of different methods and approaches regarding GHG-emission accounting for biomass has also been performed. These methods are included in various LCA guidelines, carbon footprint methods, environmental product declaration methods, or research papers. A critical analysis of these methods allows for their comparison based on objective criteria, as well asto draw conclusions on some methodological aspects.

Following this critical analysis, recommendations are given for best practices for accounting for biomass carbon sequestration, storage and release in LCA. Finally, some future research needs have been identified to address limits and barriers when applying these recommendations. This document presents a synthesis of the review performed for this study and of the recommendations proposed.

Review of different concepts related to the carbon cycle

It is essential to understand some key concepts related to the carbon cycle, the assessment of climate change impacts, and some biomass-specific issues. This section presents a summary of the concepts reviewed for which a more detailed explanation can be found in the final report of the project.

Carbon cycle and impacts of human activities

The Earth has four natural reservoirs of carbon: the atmosphere, oceans, biosphere and lithosphere. Various natural processes result in various forms of carbon exchanges between the different reservoirs, giving rise to the natural carbon cycle.

- Exchanges between the atmosphere and biosphere

  Carbon from the atmosphere is converted into plant biomass by photosynthesis, while the biosphere emits carbon to the atmosphere through respiration, degradation of dead organic matter, and wildfires. These processes occur on short time scales, from days to decades.

- Exchanges between the atmosphere and oceans

  The "solubility pump" and "biological pump" cause an accumulation in sediments of a part of the atmospheric carbon that is solubilized by upper ocean layers. These processes occur on very long time scales, from centuries to several thousands of years.

- Other exchanges

  Particles of carbon dissolved or suspended leaving the lithosphere to reach the ocean by run-off into different streams. A portion of the organic material decomposition in the biosphere becomes inert carbon and accumulates in the lithosphere, forming deposits of fossil fuels. This phenomenon implies time scales in the order of thousands or even millions of years. Carbon can be transferred from the atmosphere and lithosphere to the oceans by erosion and sediment accumulation. Finally, volcanic activity causes an exchange of carbon between the atmosphere and lithosphere

Human activities since the industrial era have disrupted the natural carbon cycle by modifying the interactions between the different reservoirs. The two major disturbances are 1) the combustion of fossil fuels and cement production, which release carbon stored in the lithosphere over millions of years into the atmosphere and 2) deforestation and land use, which disrupts the equilibrium exchange of carbon between the atmosphere and biosphere. The latter actually start taking place long before the use of fossil fuels in the middle of the 18^{th} century.

Impacts of greenhouse gas emissions on climate change

Carbon can be emitted to the atmosphere in various forms, such as CO, CO_2 and CH_4. These gases, as well as many others emitted by human activities, such as N_2O and halocarbons, are termed greenhouse gas emissions as they contribute to the greenhouse effect. The increase in their concentration in the atmosphere causes an increase in the average temperature of the atmosphere and oceans. This increase in temperature subsequently causes higher-level impacts affecting human health and ecosystems.

The extent of any disturbance on the radiation balance of the Earth is called radiative forcing. A positive radiative forcing tends to warm the Earth's surface while a negative radiative forcing tends to cool it. The Global Warming Potential (GWP) is the most widely-used indicator to compare the impact of different greenhouse gases on global warming. The GWP is calculated by dividing the cumulative radiative forcing caused by a gas over a period of time divided by the cumulative radiative forcing of CO_2 over the same time horizon. The Intergovernmental Panel on Climate Change (IPCC) publishes in its assessments reports every few years the updated values of GWP calculated for three time horizons, 20, 100 and 500 years,.

Following its adoption by the Kyoto Protocol, there is a strong consensus on the use of GWP as an indicator of global warming. However, some criticisms have been made in recent years regarding the use of GWP as a single indicator for global warming. Another more recent indicator to represent the evolution of the temperature increase caused by a GHG emission has been developed. The Global Temperature (change) Potential (GTP) is an indicator comparing the temperature change taking place a number of years following a GHG emission with the temperature change caused by the emission of the same amount of CO_2. It is an instantaneous indicator, unlike the GWP which is cumulative. GTP is a more appropriate indicator if the objective is not to exceed a certain threshold temperature increase at a given time. However, it does not consider the cumulative effect of warming.

Instantaneous and cumulative indicators do not measure the same type of impact. Indeed, certain types of impacts are directly connected to the increase in temperature (e.g., problems caused by heat waves), others are related to the rate of temperature increase (e.g., resilience of ecosystems), while others are connected to the cumulative effect of warming (e.g., increased sea level). Various indicators can be used depending on the type of impact to be measured. The GWP is currently the only widely-used indicator by GHG-accounting methods.

Different GHG accounting methods have been developed in order to support GHG emission reduction initiatives:

- **Guidelines for national GHG inventories** outline the methods used to estimate emissions by source type and data and provide emission factors and generic parameters for all sectors to use in case of lack of specific data.
- **Guidelines for GHG inventories for organizations** provide guidelines for corporate GHG emission inventories, proposing well-defined methods to address some methodological issues, such as the definition of system boundaries, quantification tools, etc.
- **Guidelines for products carbon footprint using a life cycle approach** provide methodological guidance to quantify GHG balances over the product life cycle.
- **LCA guidelines** provide guidelines on some given aspects of GHG accounting.
- **Methods for specific applications of LCA or carbon footprint,** such as buildings assessment or environmental labeling of products.

Issues related to the accounting of emissions of greenhouse gas emissions from biomass

The carbon emitted by human activities may be of biogenic or fossil origin. Biogenic carbon comes from the combustion or degradation of biomass-based products, whereas fossil carbon comes from fossil resources. The effect on radiative forcing is exactly the same regardless of the source of the carbon released. The major difference lies in the time period required for the carbon from the atmosphere to be captured by the source reservoir which is a few months to a few decades for the biosphere or several thousand years for fossil reservoirs. This is why the carbon sequestered by biomass is usually subtracted from carbon balances, while the carbon sequestered by fossil reservoirs is not. The principle of biogenic carbon neutrality refers to a situation where the impact of biogenic CO_2 emissions is offset by the relatively rapid sequestration of an equivalent amount of CO_2 from the atmosphere, unlike fossil carbon whose sequestration occurs on a geological time scale.

The principle of biogenic carbon neutrality has traditionally been applied in LCA where the impact assessment methods generally use a zero characterization factor for biogenic CO_2 emissions. In recent literature, a growing number of studies criticize the use of this principle of neutrality by showing its limits and consequences on the results and conclusions derived thereof. Two main aspects are the subject of these criticisms: 1) accounting errors and 2) the lack of consideration for temporal aspects.

At the scale of a project or a product, not considering biogenic CO_2 may lead to an accounting error and a bias in the results if a sector is not included in the system boundaries or if the biogenic carbon balance is not zero. An increasing number of studies have shown the importance of considering biogenic CO_2 emissions in LCA and carbon footprinting.

In addition to accounting errors, the principle of biogenic carbon neutrality is also criticized for its lack of consideration for the temporal aspects of carbon fluxes. Indeed, even if the biogenic carbon balance is zero, the time elapsed between the emission and the sequestration may causes climate impact on the short-term. Several recent studies have focused on the problem associated to the delay in carbon sequestration by biomass or, more generally, on the impact of the temporal distribution of carbon fluxes.

The concept of carbon debt associated to forest bioenergy is a good example of this problem. For a given amount of energy provided, biomass combustion emits more CO_2 than an alternative fossil fuel, this is called the carbon debt. Atmospheric carbon is then sequestered by the growing forest, bringing the balance to zero and thus paying back the carbon debt. The payback time is the time required for the carbon balance of the forest bioenergy scenario to become equal to that of the fossil-energy scenario.

The concept of carbon debt associated to forest bioenergy is a specific case of issues related to the temporal aspects of GHG emissions in LCA, but it is not the only one. Other cases have also been studied in the literature, such as temporary carbon storage in long-lived products during their use phase. Indeed, carbon storage implies the postponement of some radiative forcing caused by the otherwise presence of this carbon in the atmosphere. On a short-term perspective, temporary carbon storage allows reducing the impact on global warming and buying some time while technologies develop in the field of GHG emission reductions and climate change adaptation. The same reasoning can be applied to any GHG emission delayed, whether of fossil or biogenic origin.

The Lashof approach aims to assess the impact of temporary carbon storage by considering it equivalent to pushing back in time an emission of CO_2 at the end of the storage period. Most of the methods developed for the consideration of temporal aspects of GHG emissions are based on the same principles than the Lashof approach. The method uses the atmospheric decay function of the atmospheric mass load over time following a pulse emission of CO_2. The integration of this curve over a fixed time horizon gives the cumulative atmospheric mass loading in tonne.year. To evaluate the benefits of storing carbon for a period of time, the curve is pushed away from an amount of time corresponding to the number of years of storage. The portion of the area under the curve which is found beyond the time horizon is no longer considered and corresponds to the benefits associated with delaying the impact, or to store this amount of carbon.

The consideration of temporal aspects makes inevitable the choice of a time horizon for decision making. Indeed, for a long-term perspective, the benefits associated to temporary carbon storage become negligible. It is only a short-term perspective that delaying an emission from a few years to a few decades is advantageous or that the global warming impact of a combustion emission becomes important if not quickly offset by the sequestration of an equivalent amount of carbon. In the very long-term, if the balance of biogenic carbon is zero, the principle of neutrality is respected. Moreover, the choice of a time horizon for decision making is more political than scientific.

All the approaches developed to give a value to keeping carbon out of the atmosphere for a period of time are mainly based on the choice of a time horizon beyond which impacts are not considered. Temporary carbon storage thus allows avoiding a certain amount of impact on the time period defined by the time horizon, which is interpreted as a benefit. The most commonly used value for decision-making (e.g. for GWP calculations) is 100 years because it is the value adopted for the implementation of the Kyoto Protocol. However, it is a somewhat arbitrary value and its widespread use has been criticized.

The consideration of biogenic carbon flows and of their temporal aspects in LCA adds complexity because information is needed on the intensity and dynamics of carbon sequestration by growing biomass. Systems boundaries would need to include CO_2 sequestration from photosynthesis and CO_2 emissions associated to respiration and biomass degradation. To do so, two spatial scales can be used: stand-level and landscape-level. In a stand-level approach, carbon is considered sequestered from the atmosphere by the biomass used in the studied system or by the biomass that will grow right after harvesting the biomass used in the studied system. In a landscape-level approach, a forest is considered having several stands of different maturity levels and an equivalanet amount of the carbon contained in harvested biomass is considered sequestered by the other growing stands at the same time. Carbon flows between the atmosphere and the forest are usually modeled using a stand-level approach. A landscape-level approach is sometimes used to evaluate the impact of different forest management systems on forest carbon stocks.

Literature review of existing and developing methods

A literature review of different methods has been performed, as well as an analysis of convergent and divergent aspects. A simplified example is presented in the final report of the project to illustrate how to apply each method.

Guidelines for Life Cycle Assessment

ILCD Handbook

All biogenic carbon emissions and sequestrations should be accounted for. The general rule is not to account for temporary carbon storage and delayed emissions unless it is specified as being part of the purpose of the study. If so, any delayed emission or temporary carbon storage, from biogenic or fossil origin, must be treated the same. A 100-year time horizon is fixed by the method. The credit is calculated using a linear coefficient, i.e. one hundredth of the emission is subtracted for each year of storage or delay. Any delayed GHG emission is thus multiplied by its GWP 100, by the number of years of delay, and by the linear coefficient. This credit is then added to the GHG inventory.

Product Environmental Footprint (PEF)

The PEF requires emissions and sequestration of biogenic carbon to be recorded in a dedicated section of the inventory. It is not permitted to add a credit for temporary carbon storage or delayed emissions in the inventory. It is possible to calculate this type of credit and include it in a separate section of the report entitled "Additional environmental information". In cases where a PCR associated to the PEF methodology requests it, these credits must be presented in the "additional environmental information" section.

Carbon Footprint methods

PAS 2050

All biogenic carbon emissions and sequestrations should be included. The consideration of temporal aspects was mandatory in the first version of the method, but is now optional. The approach proposed to do so in a linear approximation. The time horizon is fixed to 100 years. For an emission that is delayed by more than 25 years, the same linear coefficient as the ILCD Handbook should be used. For an emission that is delayed from less than 25 years, another linear coefficient is proposed. All GHG emissions should be transformed in kg CO_2-eq by multiplying it by the specific GWP 100 before applying the credit.

GHG Protocol

All biogenic carbon emissions and sequestration must be considered. The GHG Protocol does not permit the addition of a credit for temporary carbon storage and delayed emissions to the carbon footprint result. However, these credits may be calculated and presented in an additional section of the report. No particular approach is proposed to do so.

Technical specification ISO/TS 14067

All GHG emissions and sequestration should be included in the carbon footprint and considered occurring at the beginning of the time horizon adopted. If GHG emissions from the use and end-of-life phases occur more than 10 years after production, they should be included in the result without considering their timing. However, the temporal distribution of these emissions must be mentioned and credits may be calculated using any approach. The amount of carbon stored in the product may be presented separately, but must not be included in the carbon footprint result.

Guidelines for Environmental Product Declarations

Climate Declaration

The concept of Climate Declaration was developed by the International EPD System for the realization of environmental product declarations based solely on GHG emissions. Evaluations should be made using product category rules (PCR), a series of guidelines for a specific group of products that meet the same function, which allows for the standardization of calculations. However, programme managers of environmental product declaration (EPD) are numerous, leading to duplication of PCRs and to a lack of harmonization. For example, the PCR used for a study on wood panels under the Climate Declaration excludes the consideration of biogenic carbon based on the principle of neutrality. Temporary carbon storage is thus not considered.

BP X30-323

The BP X30-323 requires that all biogenic carbon emissions be included. Temporal aspects may be considered, but it is not mandatory. Moreover, if credits are calculated for temporary carbon storage or delayed emissions, they must not be included in the result, but be presented in an additional section. A time horizon of 100 years is advised. The approach proposed to calculate the credits is somewhat different from other methods since it takes into account the lifetime of GHGs compared to the product's lifetime. If the time elapsed between the end-of-life of the product and the time horizon is longer than the GHG lifetime, than no credit is granted. End-of-life emissions must thus be multiplied by their GWP 100. However, if the time elapsed between the end-of-life of the product and the time horizon is shorter than the GHG lifetime, then end-of-life emissions must be multiplied by the GWP 100 and by a coefficient that depends on the product's lifetime.

Other methods

A review of other methods cited by SCORELCA has been performed in order to ascertain if and how biogenic carbon sequestration, storage and releases from biomass is treated. The results of this review can be found in the final report of the project. The methods analyzed are the following.

- ISO 14040/14044 standards
- NF P01-010 and AIMCC vademecum
- EN 15804 and EN 16485
- ISO 21930
- EN 16214-2/16214-4
- CEN/TC 411
- FSC et PEFC certifications
- 2009/28/EC directive
- BioGrace

Research work

Tonne.year approaches (Lashof and Moura-Costa)

The Lashof approach calculates the benefits associated to temporary carbon storage by calculating the avoided impact in tonne.year (because it is pushed back beyond the time horizon). The Moura-Costa approach proposes to calculate an equivalency factor of 0.021 tonne per year of storage (1/48) to determine the benefits of temporary carbon storage. This factor is calculated using the value of the cumulative mass load caused by a CO_2 pulse-emission which is 48 tonne.year for a 100-year time horizon. It is important to note that for this method, it is possible to get a credit value that is higher than the value of the delayed emission, although this is not necessary after 48 years of storage.

Dynamic LCA

A dynamic LCA approach for the assessment of global warming impacts has recently been proposed to account for the temporal distribution of GHG emissions. The method consists in calculating the radiative forcing over time caused by a temporally detailed GHG inventory. The result is a curve showing the change in radiative forcing over time. The cumulative radiative forcing can then be calculated for any chosen time horizon to compare the impact of different scenarios. The value obtained is then equivalent to a GHG inventory that would be obtained by multiplying each emission by its GWP for a time horizon corresponding to the time elapsed between the time of release and the end of the time horizon chosen for the analysis. Unlike the other approaches analyzed, dynamic LCA calculates the radiative forcing of each specific GHG in function of time instead of assimilating them to CO_2 emissions. As it is an adaptation of the LCA methodology, the method is versatile and can be applied to different cases.

Time-adjusted warming potential (TAWP)

The TAWP are factors that are similar to GWP, but that can take into account the time elapsed between the emission and the time horizon selected for the analysis. The TAWP is developed for different time horizons and emission timing. In other words, for a time horizon of 100 years, the TAWP values used will differ depending on if the emission occurs on the first year, the twentieth year or the fiftieth year of the analysis period. The different values of TAWP are obtained by changing the integration boundaries of the numerator of the equation used to calculate GWP in order to consider only the period between the emission and the time horizon, while keeping the same for the denominator so that the impact is compared to the impact of a unit mass CO_2 pulse-emission.

GWP_{bio}

This method analyzes the impact of biogenic carbon emissions by calculating the cumulative radiative forcing for a given time horizon of an emission of a unit mass of CO_2, followed by the progressive sequestration of the same amount of CO_2 over a number of years corresponding to the biomass rotation period. The value obtained is then divided by the cumulative radiative forcing of a pulse emission of a mass unit of CO_2 calculated for the same time horizon to get new GWP values (called GWP_{bio}) to characterize biogenic CO_2 emissions from different rotation periods. These GWP can be used to characterize the biogenic CO_2 emissions from biomass combustion taking into account the associated sequestration period. The GWP_{bio} are thus specific to the period of rotation of the biomass concerned and to the chosen time horizon. The concept of GWP_{bio} specifically applies to GHG emissions from the combustion of biomass occurring in the same year biomass is harvested. GWP_{bio} has also been developed to assess the impact of emissions from combustion of biomass including a storage period.

Discussion on different approaches

All the approaches presented, apart from the Climate Declaration, do not adopt the principle of biogenic carbon neutrality and consider all emissions and sequestration of GHGs, regardles of their fossil or biogenic origin. There is no clear consensus regarding the consideration of temporal aspects of GHG emissions. However, once a benefit is given for temporary carbon storage in products, it is considered important by all approaches to take into account the temporal distribution of all GHG emissions. Most accounting methods do not take into account the dynamics of sequestration.

Dynamic LCA allows for a consistent assessment of the impact of all emissions and sequestration of GHGs over time regardless of their sources (biogenic or fossil). It is probably the more complete and versatile approach, but it requires more data since the temporal distribution of all life cycle emissions must be known, as well as sequestration dynamics. The use of TAWP leads to the same type of results. However, this method does not provide time-dependent results, but a value calculated for a given time horizon that must be chosen *a priori*. Like the dynamic LCA, the TAWP method is specific to every GHG. GWP_{bio} also relies on the same scientific basis than dynamic LCA and TAWP., but is applicable only for specific cases e.g. biogenic carbon emissions from the combustion of biomass occurring the same year as the harvest or after a storage period in the anthroposphere.

The methods proposed by LCA guidelines, carbon footprint methods and guidelines for environmental product declarations are usually simplifications of methods presented in research papers, e.g. using a linear approximation. Generally, there are three main differences between these methods and those proposed in research publications:

- A fixed time horizon of 100 years is recommended in the guidelines; in constrast, this choice is left for the user in dynamic LCA, which allows testing the sensitivity of the results to this choice. The TAWP and GWP_{bio} methods propose characterization factors for the three time horizons proposed by the IPCC which are 20, 100 and 500 years.

- The dynamics of biogenic CO_2 sequestration by biomass is considered in the guidelines occurring at the same moment as the product is created. For dynamic LCA, TAWP and GWP_{bio}, the temporal distribution of sequestration flows specific to the biomass used is considered.
- All GHG emissions are converted into kg CO_2-eq before applying a credit for the methods proposed by guidelines. Dynamic LCA and TAWP use the specific value of cumulative radiative forcing for each GHG. GWP_{bio} is applicable only to CO_2 emissions resulting from biomass combustion.

Many publications have shown that the results are sensitive to the dynamics of carbon sequestration, as well as to the relative timing of this sequestration (before or after biomass is harvested). Considering that the sequestration occurs before harvesting is equivalent to assuming that the biomass has been planted with the objective of being used for this particular application and would not have been planted otherwise (afforestation). Considering that the sequestration occurs after harvesting is assuming that the forest was naturally there, has been exploited and then renewed (sustainably managed forest). Finally, for deforestation (exploitation of a forest that is not renewed), no carbon sequestration should be considered.

The use of a stand-level approach is sometimes criticized for not being representative of how forests are managed. On the other hand, a landscape-level approach assumes that the forest carbon balance is at a steady state as fluxes in a single stand are compensated by the opposite flux elsewhere in the landscape, which renders irrelevantthe consideration of the dynamics of carbon sequestration. It has been shown that the global carbon balance (without considering temporal aspects) is the same for stand-level and landscape-level approaches. Regarding the dynamics of sequestration, it would be wrong to credit the product from a stand with the carbon sequestration from another stand because the other stand would too be harvested in the future and be part of a separate non-interacting product system. For example, products issued from the very first exploited stand in a mature forest would be credited for the sequestration occurring after harvest since other stands are not growing biomass. Thus products issued from the second exploited stand cannot be credited for the carbon sequestered in the first stand, as this would be double counting, and must be credited for the sequestration occurring on this second stand following harvest. If the carbon sequestered in another stand is to be considered, then the products from that stand would too have to be considered, in which case the analyses over all single stands would equal the analysis of the whole landscape. This means that the dynamics of sequestration must be considered no matter which spatial scale is used to calculate forest carbon balances, and is occurring after harvest with the exception of forest issued from afforestation.

Synthesis table of different methods

The following table is a synthesis of the different methods presented in details in the final report comparing the different approaches used for the treatment of carbon sequestration, storage and release from biomass.

Method	**Application**	**Principe of biogenic carbon neutrality**	**Consideration of temporal aspects**	**Proposed approach**	**Consideration of the dynamics of sequestration**	**Approach specific to each GHG**	**Time horizon**	**Comment**
GUIDELINES AND STANDARDS								
ILCD Handbook	LCA Guidelines	No	If required in the goal and scope	Uniform linear credit	No	No	100 years	Replaced by the PEF
Product Environmental Footprint (PEF)	LCA Guidelines	No	Optional, in additional information	No particular approach proposed	No	N/A	100 years	
PAS 2050	Carbon Footprint	No	Optional	Linear credit, two values depending on the number of years of delay	No	No	100 years	Latest version (2011) considered
GHG Protocol	Carbon Footprint	No	Optional, in additional information	No particular approach proposed	N/A	N/A	Not specified	
ISO 14067	Carbon Footprint	No	Optional, in additional information	No particular approach proposed	N/A	N/A	Not specified	Only emissions delayed by more than 10 years
Climate Declaration	Environmental Product Declarations	Yes	No	N/A	N/A	N/A	N/A	Vary from one PCR to another
BP X30-323	Environmental Product Declarations	No	Optional, in additional information	Linear credit depending on GHG lifetime	No	Yes	100 years	Ambiguity in the description of the method
RESEARCH								

Lashof	Research	N/A	Yes	Credit based on the cumulative mass load over a selected time horizon	N/A	N/A	To be chosen	Developed to evaluate the benefits associated to temporary carbon storage
Moura-Costa	Research	N/A	Yes	Linear credit based on an equivalency factor	N/A	N/A	To be chosen	Developed to evaluate the benefits associated to temporary carbon storage
Dynamic LCA	Research	No	Yes	Time-dependent radiative forcing	Yes	Yes	All	Most complete approach
TAWP	Research	No	Yes	GWP calculated for different moments of emission	Yes	Yes	20, 100 or 500 years	Same results as dynamic LCA for a given time horizon
GWP_{bio}	Research	No	Yes	GWP calculated for biogenic emissions following by sequestration for different rotation periods	Yes	No	20, 100 or 500 years	Applicable only to emissions from biomass combustion, consistency issues

Recommendations and research needs

Following the analysis presented in chapters 2 and 3 of the final report, some recommendations regarding the treatment of carbon sequestration, storage and release from biomass in LCA are given. Two application examples, the first on environmental product declaration of a wood product and the second on scenario comparison for wood pallets at the end-of-life, are presented in the final report. In addition, some research needs that are specific to the issue of biogenic carbon have been identified.

Consideration of biogenic carbon flows

It is recommended to include all carbon flows in LCA and carbon footprinting, both biogenic and fossil, positive (emission) and negative (sequestration). However, the consideration of every carbon flow may present some difficulties. For example, it is not always clear to determine the amount of biogenic carbon released when treating biomass wastes or effluents. Indeed, this type of data is often not available and LCA practitioners will have to look for specific studies to model the fate of carbon in biomass at the end-of-life. Another problem associated to the consideration of biogenic carbon flows in LCA regards the treatment of multifunctional processes. Biogenic carbon emissions and sequestrations must be allocated to the different co-products using a carbon content basis since the intensity of each flow is directly linked to this characteristic, which complies with the causality principle when dealing with multifunctionality.

Indicators for climate change impact assessment

It is recommended the use of indicators that are based on cumulative radiative forcing until the development of other types of indicators. Indeed, the most used indicator, GWP, is based on the cumulative radiative forcing calculated for a given time horizon. The different approaches developed for the treatment of temporal aspects of GHG emissions are all based on this type of indicator too. There are different types of climate change impacts and each of them is better represented by a given indicator. However, research work is still needed in order to identify which indicators are more appropriate, what type of impacts they represent, and how they should be used.

Consideration of temporal aspects

It is recommended to consider the timing of positive and negative GHG flows when the time scale of these flows for the studied system is long enough compared to the time horizon chosen for the analysis. Furthermore, to be consistent, it is important to treat every biogenic and fossil GHG flow similarly. Some of the methods analyzed propose an approach that takes into account the timing of GHG flows, others state that it shall not be considered, while others makes it optional. These differences between methods is probably caused by the fact that there is still no consensus in the scientific community regarding some methodological aspects (e.g. the subjective choice of a time horizon) and that the consideration of the timing in methods makes data collection and calculations more complicated. However, many publications have shown that for certain types of application, not considering these temporal aspects leads to biased conclusions. Delaying emissions from a few years or decades provides benefits only if a relatively short-term perspective is considered. This is why temporal aspects become important only if the time scale of emissions is not negligible compared to the time horizon selected. Basically, product systems with long life cycles, that contain long rotation biomass-based products, or that address a particular temporal aspect such as amortizing an initial emission over several years could meet this requirement.

Approach used for the treatment of temporal aspects

It is recommended to use an approach based on the exact calculation of cumulative radiative forcing. Two main types of approaches have been proposed in the literature: the first is based on the exact calculation of cumulative radiative forcing from the moment of the emission to the time horizon, while the second is a linear approximation of this calculation. Linear approximations are easier to use, as the emission is multiplied by the number of years of delay and by a linear coefficient to determine the credit. However, an approach based on the exact calculation of cumulative radiative forcing is more accurate and may be easy to use if characterization factors have already been developed for every year of emission and every time horizon (e.g. TAWP) or if a spreadsheet containing the calculations is used (e.g. dynamic LCA). Errors induced by the use of a linear approximation are not too significant for CO_2, but may be very important for short-lived gases such as methane.

Approach specific to each GHG

It is recommended to use an approach that is specific to each GHG. Some methods transform GHG emissions in kg CO_2-eq using GWP 100 prior to applying a credit for delayed emissions. Other methods use factors that are specific to each GHG. For short-lived gases such as methane, to convert the emission into kg CO_2-eq may lead to very important errors. Indeed, since methane degrades quite fast in the atmosphere, delaying an emission from a few years does not allow for pushing back a fraction of the radiative forcing beyond the time horizon of 100 years because the total amount of radiative forcing occurs during the first decades. When using an approach based on the exact calculation, the credit for delaying a methane emission is very small for the first decades and then becomes more important for the following decades. Moreover, since it is recommended to use an approach based on the exact calculation of cumulative radiative forcing instead of using a linear approximation, a list of already computed characterization factors or a computerized tool is used and it is not more complicated to use a specific approach.

Consideration of the dynamics of sequestration

It is recommended to use an equation that is specific to the studied biomass to calculate the dynamics of carbon sequestration if it is available or to use a linear approximation if not. Many publications have shown that the sequestration delay for growing biomass has a significant impact on results, in particular for long rotation biomass. The consideration of the dynamics of sequestration makes data collection more complicated. Indeed, it may be difficult to estimate the dynamics of carbon sequestration by growing biomass and specific studies may not be available. In those cases, it may be necessary to use a linear approximation.

Selection of a time horizon

It is recommended to present results for different time horizons and to discuss the sensitivity of the conclusions to this choice. The consideration of temporal aspects necessitates the selection of a time horizon for decision making. Indeed, all the approaches are based on the choice of a time horizon beyond which impacts are considered avoided. Some authors have highlighted the fact that the choice of a time horizon is more a political than a scientific choice, but could have a significant impact on results and that the most common value of 100 years is arbitrary.

General conclusions

These recommendations focus on general methodological aspects related to the treatment of biogenic carbon in LCA and are applicable to every situation. However, the case studies and review of concepts and methods performed in this project have shown that the integration of these recommendations leads to some questions regarding other methodological aspects for which the solution depends on the objectives of the study and are not exclusive to the question of biogenic carbon. For instance, the use or not of system boundaries expansion to treat multifunctionality for end-of-life incineration with energy recovery depends on the context and on the guidelines selected. Indeed, some methods require some particular approaches to treat these issues to which users must conform.

Different references can be selected for the determination of the amount of carbon sequestered by biomass since the net carbon stock change may be calculated compared to 1) a current reference point, 2) a business-as-usual scenario, and 3) a future prospective scenario. For an attributional approach, a current reference point is usually used. For a sustainably managed forest for instance, the amount of sequestered carbon would be the same as the amount of carbon stored in harvested wood. For a consequential approach, a business-as-usual or a future prospective scenario would be used depending on the objective of the study. For instance, if a study aims at comparing the implementation of a forest bioenergy scenario to replace a current fossil energy scenario, a business-as-usual reference point would be used. In this case, it is important to take into account in the reference fossil scenario what would happen with forest biomass if the bioenergy scenario did not exist. Finally, a future prospective scenario could be used in a study aiming at guiding energy policies in order to consider the evolution of the forest without the studied policy.

Identified research needs

Development of indicators

The use of a single indicator based on cumulative radiative forcing has some disadvantages. It cannot measure the influence of each GHG for every type of climate change impact. The IPCC fifth assessment report presents and discusses different indicators alrenative to GWP. Moreover, recent papers propose indicators that take into account the notion of tipping point or that integrate impacts of changes in albedo. The current tendency is that in the following years, more developments will occur in terms of climate metrics development.

Treatment of temporal preferences

The consideration of the temporal aspects of GHG emissions and uptakes makes inevitable the choice of a time horizon for decision making. The choice of a time horizon is more political than scientific since it implies temporal preferences. Some recently published research papers studied the different physical processes of the carbon cycle that are considered depending on the time horizon selected, or proposed a method to link GHG emissions and costs in order to use discounting for decision making. Monetization of environmental impacts in general and of GHG emissions in particular could be an effective way to manage temporal preferences for decision makers.

Forest carbon balances

The consideration of biogenic carbon in LCA requires the quantification of the carbon sequestered by the studied biomass. In an attributional approach, the amount of carbon sequestered can be considered equivalent to the amount of carbon stored in the harvested biomass for a sustainably managed forest, or zero for deforestation. However, for a consequential approach, the amount of sequestered carbon by the studied biomass must be compared to the amount of carbon that would have been sequestered if the biomass has not been used, which makes accounting more complex. Several studies have been performed estimating forest carbon balances, which depend on several factors such as climate, geographical specificities, natural perturbations, and forest management techniques amongst others. Researchers are still working to better understand forest carbon balances and how forest could contribute to climate mitigation. Models have to be developed so simulate forest carbon stocks variations. These models could be used to compare different scenarios addressing the questions raised through biomass LCAs.