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CARBON FOOTPRINTING

Key issues and options in accounting for carbon sequestration and temporary storage in life cycle assessment and carbon footprinting

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Abstract
Purpose Biological sequestration can increase the carbon stocks of non-atmospheric reservoirs (e.g. land and land-based products). Since this contained carbon is sequestered from, and retained outside, the atmosphere for a period of time, the concentration of CO_2 in the atmosphere is temporarily reduced and some radiative forcing is avoided. Carbon removal from the atmosphere and storage in the biosphere or anthroposphere, therefore, has the potential to mitigate climate change, even if the carbon storage and associated benefits might be temporary. Life cycle assessment (LCA) and carbon footprinting (CF) are increasingly popular tools for the environmental assessment of products, that take into account their entire life cycle. There have been significant efforts to develop robust methods to account for the benefits, if any, of sequestration and temporary storage and release of biogenic carbon. However, there is still no overall consensus on the most appropriate ways of considering and quantifying it.
Method This paper reviews and discusses six available methods for accounting for the potential climate impacts of carbon sequestration and temporary storage or release of biogenic carbon in LCA and CF. Several viewpoints and approaches are presented in a structured manner to help decision-makers in their selection of an option from competing approaches for dealing with timing issues, including delayed emissions of fossil carbon.
Results Key issues identified are that the benefits of temporary carbon removals depend on the time horizon adopted when assessing climate change impacts and are therefore not purely science-based but include value judgments. We therefore did not recommend a preferred option out of the six alternatives presented here.

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Conclusions Further work is needed to combine aspects of scientific and socio-economic understanding with value judgements and ethical considerations.

Keywords Climate change · Carbon footprint · Carbon cycle · Carbon stocks · Carbon sinks · Global warming potential (GWP) · Time preferences

1 Introduction

Climate change is increasingly seen as a major problem for the future of nature and humanity, and significant reductions in net greenhouse gas (GHG) emissions will be needed to mitigate potential problems and set the world on a sustainable path to the future (e.g., IPCC 2007). Reductions of the required magnitude are difficult to accomplish without major changes in the energy supply system that modern society has come to rely on.

There has therefore been growing interest in increasing use of renewable sources of energy, including bioenergy. For example, the EU's *Europe 2020—a strategy for smart, sustainable and inclusive growth* (European Commission 2010a), supports this with its climate change and energy targets for the year 2020:

- Reducing GHG emissions by 20 % (or even 30 %, if the conditions are right) relative to those in 1990,
- Increasing the share of energy from renewables to 20 %, and
- Increasing energy efficiency by 20 %

However, questions have been raised about the timing of the benefits of bioenergy (Searchinger et al. 2009; Manomet Center for Conservation Sciences 2010; Zanchi et al. 2010): bioenergy based on harvest of existing forests may deplete forest carbon stocks causing a temporary release of carbon until the forest regrows.

On the other hand, bioenergy may utilise biomass from land newly converted to forest. In this case, the carbon is first sequestered before it is released. Carbon sequestration refers to the removal of carbon dioxide from the atmosphere, while temporary storage refers to the subsequent maintenance of sequestered carbon for a limited period of time in non-atmospheric pools. Removal of carbon from the atmosphere and temporary storage—for example in vegetation, soil, minerals, or biomass products—is often discussed as a means to mitigate climate change by temporarily avoiding some radiative forcing. Similarly, products or processes that delay the emissions of fossil carbon are considered to offer a benefit through delaying the warming impact. However, there is no standard or universally agreed procedure for accounting for temporary carbon storage or release, or delayed emissions in the climate change impact category of life cycle assessment (LCA) and in the carbon footprinting (CF) of products.

Biospheric carbon management differs from fossil-fuel carbon management in that carbon can be both sequestered to and emitted from the biosphere. An initial carbon release can be balanced by subsequent biomass regrowth, or conversely an initial carbon sequestration balanced by subsequent release. Although the net exchange in these examples may be the same, their different timing with respect to the order of uptake and release of carbon will lead to different trajectories of atmospheric CO_2 concentrations and thus different cumulative radiative forcing, because the atmospheric concentration is determined by the interactions between anthropogenic CO_2 flows (both emissions and sequestration), on one hand, and the CO_2 exchange between the atmosphere and the world's natural carbon reservoirs (terrestrial biosphere and oceans), on the other hand.

Despite significant efforts to develop robust methods, there is currently no consensus on how to account for temporary removals of carbon from, or additions to, the atmosphere in LCA and CF accounting. To further the scientific debate on this issue, and to inform those considering alternative approaches, this paper describes and evaluates six available methods for accounting for the potential climate impacts of carbon sequestration and temporary storage or release of biogenic carbon in LCA and CF. It does not recommend a particular approach, but points to further research needs. The paper results from a workshop organised by the European Commission's Joint Research Centre in Ispra, Italy, in October 2010 which brought together experts on climate change, greenhouse gas (GHG) accounting, LCA and CF to review available options and to discuss methods for accounting for the potential benefits of temporary carbon storage (see Brandão and Levasseur 2011).

2 General climate impact metrics

2.1 Global warming potential and global temperature potential

Global warming potentials (GWPs) are widely applied for assessing the contribution of GHGs to climate change: they are used in LCA, and have also been adopted for national inventory reporting to the United Nations Framework Convention on Climate Change (UNFCCC) and accounting under the Kyoto Protocol.

GWPs indicate the climatic impact of a GHG emission as a function of the GHG's radiative efficiency and its lifetime in the atmosphere (see, for example, Forster et al. 2007). The GWP index for a given GHG is calculated as the cumulative radiative forcing caused by a unit mass emission of that GHG integrated over a given time horizon, as

compared with the cumulative radiative forcing due to emission of a unit mass of carbon dioxide (CO_2) over that same time horizon. As each GHG has a different atmospheric lifetime, the choice of a time horizon is critical, with shorter time horizons shifting the relative importance toward the shorter-lived GHGs (i.e. methane) whereas longer time horizons increase the relative importance of the long-lived GHGs (i.e. CO_2, N_2O, CFCs). The most common time horizon used for GWP in LCA and CF, and in reporting to the UNFCCC, is currently 100 years.

An alternative metric for comparison of different GHGs, the Global Temperature Potential (GTP), was proposed by Shine et al. (2005). In contrast to GWPs, that integrate the warming potential of different gases, the GTP assesses the difference in temperature reached after a specific time period as a consequence of the emission of a unit emission of the GHG, in comparison with the temperature reached as a consequence of a unit mass of CO_2. For a given time period this would result in different characterisation factors between GWPs and GTPs.

2.2 Need for complementary metrics for a more inclusive assessment

Kirschbaum (2003a, b, 2006) has argued that the adoption of any kind of metric to quantify the effect of different GHG emissions should be explicitly based on the identification and quantification of climate change impacts.

Kirschbaum argued that there are at least three different kinds of impacts to consider in relation to the man-made global warming: impacts related to instantaneous future temperatures (like direct heat-wave impacts), impacts related to the rate of temperature increase (such as those of importance for ecological or societal mal-adaptation) and impacts related to cumulative temperature increases (such as those influencing sea level rise). All three types of impacts are important, and he argued that all three should be recognised in the development of impact metrics.

GWPs essentially account for the impacts caused by cumulative temperature increases, whereas the proposed GTPs quantify the impact of instantaneous temperature increases (e.g. extreme weather conditions and diseases). Other aspects of climate change, such as the rate of temperature increase, are not well represented by either the GWP or GTP indicators. This calls for different metrics to be applied for the assessment of each of the three types of impacts on climate change (Tanaka et al. 2010). None of these metrics is universally preferable. The key issue is not that one kind of metric is better than another, but that several are important in order to express different impacts that need to be considered, and that the commonly used GWP is not a fully adequate measure of the impact of changes in atmospheric GHG concentrations on the global climate system. A differentiation of GHG impacts according to the types of consequences that they cause will also prepare a better ground for assessment of the damages associated with climate change—one of the major challenges to current endpoint approaches in life cycle impact assessment (European Commission 2011). Multiple or more complex metrics will supply additional information and, if an aggregated climate change impact metric is to be devised, e.g. via damage modelling, it would need to recognise and reflect explicitly the three types of impacts described above.

The incorporation of these additional considerations in methods for LCA and CF will not necessarily limit their use as pragmatic tools of analysis; the metrics developed by impact assessment experts will be utilised within LCA methods in a similar manner to currently used GWP. Hence, increased complexity and robustness in impact assessment should not limit the value of LCA/CF as a decision-support tool.

2.3 Application in LCA and CF

LCA and CF commonly adopt the 100-year GWP as the climate change metric to determine the relative contribution of different GHG emissions. Carbon sequestration during biomass growth can be accounted for as a negative emission in LCA, but the duration of carbon storage is usually not taken into account.[1] In fact, carbon stock changes in biomass and soils are often completely ignored in biofuel LCAs (see, e.g. Cherubini et al. 2009; Brandão and Levasseur 2011), despite ISO (2003) providing the rationale for accounting for carbon sinks related to forestry activities.

Impacts of carbon stock changes could be expressed in a variety of ways: (1) cumulative radiative forcing (quantified via GWPs), which is the traditional treatment of GHG emissions in LCA and CF, (2) as direct temperature impacts (via GTP) or (3) as a compound index that includes different climatic impacts. For completeness, it would be warranted to include any climate change impacts of temporary carbon storage and removals. These impacts are usually neglected in current environmental assessment of products, where only the impact of fossil-fuel based GHG emissions is included.

3 Key issues

3.1 Carbon stock change in biosphere and fossil-fuel pools: the issue of additionality

Some land uses and land-management practices result in carbon sequestration, while others result in carbon emissions (e.g. afforestation and deforestation, respectively).

[1] An exception is the PAS 2050 (BSI 2008), see Section 4.4.

The use of existing forests for bioenergy essentially amounts to a temporary emission: forest carbon stocks are decreased at the time of harvest, and CO_2 is released to the atmosphere when the biomass is combusted. It is sequestered again as the forest regrows. Under the rules of the Kyoto Protocol, bioenergy is deemed "carbon neutral".[2] Emissions from bioenergy are not accounted at the point of combustion because it was intended that the carbon stock changes that accompany the production of biomass would be accounted in the "Land Use, Land Use Change and Forestry" sector. However, these forest carbon stock changes are not necessarily included in Kyoto Protocol accounting: if bioenergy is produced from land without leading to any change in land use, then carbon-stock changes are not counted unless the country has elected to include Forest Management in their Kyoto Protocol account. Therefore, credit is effectively given for biomass used for energy without acknowledging that it may be many decades before the benefit from avoided fossil-fuel emissions cancels the "carbon debt" created by a decline in average forest carbon stock when additional biomass is extracted for bioenergy (Manomet Center for Conservation Sciences 2010; Zanchi et al. 2010; Pingoud et al. 2010). The impact of this temporary emission is not counted. On the other hand, if biomass comes from land use change in a country that has a commitment under the Protocol, then the carbon stock changes must be accounted. If biomass is imported from a country that has no commitment under the Protocol, carbon stock changes due to biomass production are not counted, whether or not there is land use change. This leaves the potential for incomplete accounting for bioenergy, under the Kyoto Protocol (Pingoud et al. 2010). Adoption of the "carbon neutral" status for bioenergy for offset project accounting, LCA and CF also leads to incomplete assessment of climate change impacts of activities with temporal imbalance in sequestration and emission of carbon.

Some workshop participants argued that, for project level accounting, LCA or CF, climate benefits only arise when taking *additional* carbon out of the atmosphere and into a sink.[3] Following this rationale, the only products that could gain credits are those coming from a new afforestation project, thus distinguishing forests newly established with the intention of sequestering carbon from existing managed forests. However, this logic could lead to unbalanced accounting: if products are taken from an existing managed forest where harvest equals regrowth, and credit is not given for initial sequestration but emissions are counted at the time C is released from the products, then net emissions are overestimated.

Rather, it would be more consistent if wood products were credited with initial sequestration and any change in carbon stock in the forest, whether positive or negative, were also included in the inventory. To determine the mitigation value, such as for project level emissions trading, the total life cycle net emissions of the product should be compared with that of a reference product system.

Other workshop participants argued that delaying a fossil emission (despite the lack of additionality) is equivalent to storing carbon in biomass. They argued that, since the atmospheric reactions do not distinguish between fossil and biogenic carbon, delayed fossil or biogenic emissions should be treated equally. However, in the case of the biomass, there is a negative emission due to the carbon uptake from the atmosphere. For consistency, all flows of carbon between a product and the atmosphere must be considered and if the decision is made to account for the timing of these flows, it has to be done for every carbon uptake and emission, regardless of the fossil or non-fossil origin of the carbon.

3.2 The time value of carbon sequestration and temporary storage

There is an extensive literature on the time value of carbon emissions that deals with how to consider and value temporary storage and whether it is appropriate to discount emissions over time, and there are precedents even within climate mitigation policy for giving value to time-dependent phenomena (see, for example, Richards 1997; Herzog et al. 2003; Moura-Costa and Wilson 2000; Fearnside et al. 2000).

Shirley et al. (2011) have shown that when carbon emissions are assigned monetary value, as with a carbon tax or in a cap-and-trade system, the timing of carbon emissions can have very large economic implications. A delayed payment has less net present value than a current payment so long as the cost does not increase faster than the discount rate. As stated succinctly by Richards (1997): "Wherever there is a positive time value to carbon there is a positive value to temporary capture and storage".

On the other hand, any assessment of the value of temporary storage should recognise the feedbacks that may act to negate the benefit: if CO_2 is temporarily removed from the atmosphere, it lowers the effective concentration gradient between the atmosphere and the oceans, and the oceans therefore may absorb less CO_2 than they would without the atmospheric concentration temporarily lowered (Meinshausen and Hare 2002; Korhonen et al. 2002; Kirschbaum 2003a, b). If the same quantity of CO_2 is then returned to the atmosphere at a later stage, such as when a biofuel is utilised, the atmospheric CO_2 concentration may temporarily be higher than it would

[2] Carbon neutrality is assumed only when carbon is emitted as CO_2. If any carbon is emitted as CH_4, this quantity is recognised as an emission.

[3] If carbon would have been sequestered anyway, there would be no additional mitigation from undertaking this activity. Most offset schemes require an activity to be "additional to business as usual", known as an "additionality test".

have been without temporary storage in vegetation. The benefit of delayed warming must then be balanced against the possibly higher future warming, taking into account induced changes in all three global warming impacts presented in Section 2.2. Conversely, when re-releasing carbon and increasing radiative forcing, the carbon-concentration gradient becomes higher between the atmosphere and the oceans, and the uptake by the oceans will be similarly higher. This further emphasizes the importance of the timing of emissions relative to tipping points in the global climate system that we want to avoid exceeding.

3.3 Time horizon

Several time aspects are discussed in this debate: (1) characterisation time horizon (e.g. that for calculating GWPs); (2) time period of assessment (the period over which GHG emissions and removals from a product system are considered, see PAS 2050); and (3) life cycle (i.e. the period covering the whole life cycle of a product). This section is concerned with the first aspect.

One of the key points in determining the benefits of temporary carbon storage is the possible choice of a time horizon beyond which radiative forcing is neglected. From a time perspective of infinity, there is no benefit in taking carbon out of the atmosphere and releasing it back later, as the burden is just shifted further in time. Applying a finite time horizon beyond which impacts are disregarded violates the principle of inter-generational equity, which is embedded in the concept of sustainable development (unless it can be reasonably expected that society will be better able to cope with climate change in the future). A too-short time horizon would give too much weight to early GHG emissions (as well as to the first years of carbon storage or the first years by which an emission is delayed), and would encourage fossil-fuel emissions as long as some temporary carbon storage compensates for it. On the other hand, a too-long time horizon would not take into account the urgency of the issue, which should be tackled before any tipping points are reached.

There are several arguments in the discussions for and against using the 100-year time horizon. If GHG concentrations in 100 years have returned to pre-industrial levels, either because of effective global lifestyle choices, technological innovation or widespread war and economic disruption, then one might not have to worry about the level of radiative forcing beyond that point. If, on the other hand, radiative forcing has continued to increase for the next 100 years, even more dangerous levels may have been reached by then and controlling it would be critical. However, as predictions over more than 100 years would be highly uncertain, it might not be warranted to assign much importance to them in an assessment. Nevertheless, ignoring what happens beyond 100 years would imply either that problems will have been solved by then or that we do not care about the generations that live then.

A time horizon of 100 years is now frequently chosen as a reference time scale for calculation of GWPs because of the widespread use of 100-year GWPs in policies and accounting related to the Kyoto Protocol (see e.g. Fearnside 2002). The 100-year GWPs compare radiative forcing integrated over 100 years for non-CO_2 GHGs with that of CO_2—i.e. they ignore radiative forcing beyond 100 years in determining their relative warming impact.

According to Shine (2009), one of the lead authors who proposed the GWP concept in the IPCC First Assessment Report, however, the choice of the 100-year time horizon cannot be made on scientific grounds, but is a subjective, policy-driven, choice. In Life Cycle Impact Assessment (LCIA), most methods are currently using the 100-year GWP for defining characterization factors, although an infinite time horizon is applied in the modelling of most other environmental impacts in accordance with an ambition to avoid any discounting or cut-offs. By contrast, some analyses (e.g. Müller-Wenk and Brandão 2010; IMPACT2002+) used 500 years because it is closer to infinity. Using an infinite time frame for global warming results in CO_2 dominating the climate impact, with other GHGs becoming negligible, as the CO_2 concentration following a pulse-emission never returns to pre-emission levels in the commonly used Bern carbon cycle model which assumes that a fraction of emitted CO_2 is permanently retained in the atmosphere.

4 Existing and developing approaches for assessing carbon sequestration and temporary storage and release, and delayed emissions, in LCA and CF

It may be necessary to consider other indicators in addition, or in alternative, to GWP for climate change impact assessments. However, as it will require time and resources for research to develop new indicators, and as there is an important international consensus on the use of the 100-year GWP, we considered methods for assessing temporary carbon storage and delayed emissions using the GWP concept and a given time horizon. Six options were discussed to determine how timing could be accounted for using the cumulative radiative forcing concept (Fig. 1). In all cases, a time horizon must be chosen beyond which the impact of emissions is considered to be no longer relevant. This time horizon is related to the characterisation of interventions that affect the climate (e.g. GHG emissions, carbon sequestration and temporary storage) and not to the time period of assessment. The characterisation time horizon and the time period of assessment do not necessarily have to be harmonised, despite attempts for doing so (e.g. Levasseur et al. 2010).

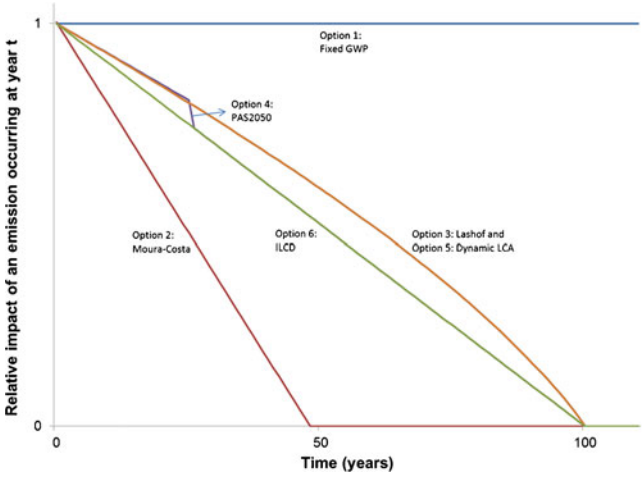

Fig. 1 Illustration of the six options discussed for the assessment of temporary carbon storage and delayed emissions in LCA and CF for a 100-year time horizon. Here, options 3 and 5 are the same. NB: Options 2, 3 and 4 presume carbon sequestration before rerelease, whereas options 1, 5 and 6 do not. In contrast to options 1, 4, 5 and 6, options 2 and 3 were not devised for application to delayed fossil emissions. The 'step' in option 4 at year 25 is due to the dual nature of the PAS 2050 approach: for short delay/storage times (2–25 years) it applies one approach, and another for longer periods (25–100 years; see Section 4.3)

4.1 Current LCA practice (option 1: fixed GWP)

Conventional LCA methodology does not assign any benefits to temporarily removing carbon from the atmosphere because it does not consider the timing of emissions relative to removals. Thus, conventional LCA methodology uses a constant characterization factor throughout the life cycle of a product.

To calculate net GHG emissions for biologically based products, the amount of CO_2 taken up during biomass growth, in the first stage of the product life cycle, is typically subtracted from the amount of CO_2 (including biogenic CO_2) released to the atmosphere during all life cycle stages of the product. Carbon neutrality is often claimed on the basis that expected CO_2 sequestration from biomass growth is equal to or greater than the expected CO_2 release over the full life cycle, regardless of the difference in timing of uptake and release. Biogenic carbon fluxes are consequently omitted from many LCA studies (Cherubini et al. 2009).

Another variant of current LCA practice is not to adopt GWPs varying with time, but rather to limit the time period of assessment. As a result, emissions occurring within the time period of assessment would all have the same impact and emissions occurring beyond (e.g. those from landfills) would have no impact. A disadvantage of this option is that a high value is given for an emission occurring 1 year before the chosen time horizon ends, and then no value for an emission occurring the following year. Consequently, a substantial benefit would be given for delaying an emission past that final year of assessment. For long time horizons, the consequences of this would not be significant, but for shorter time horizons, this would be avoided by using a decreasing characterization factor, as in the following options.

4.2 The Moura-Costa method (option 2)

The Moura-Costa method for dealing with sequestration and temporary storage of carbon (Moura-Costa and Wilson 2000) was discussed in the IPCC Special Report on Land Use, Land Use Change and Forestry (LULUCF; Watson et al. 2000), but has not been applied or further developed for GHG inventory calculation. Instead, the annual stock change method, proposed in the IPCC *Good Practice Guidance for Land Use, Land Use Change and Forestry* (Penman et al. 2003) was adopted for national GHG emissions inventory reporting and Kyoto Protocol accounting. Nevertheless, the Moura-Costa method has been proposed for LCA-related applications (see Müller-Wenk and Brandão 2010). This method calculates an equivalence factor between kg CO_2-eq and kg CO_2-year, which serves as the basis for crediting sequestration and storage of CO_2 for the number of years it is removed and kept out of the atmosphere. This credit can then be subtracted from a GHG inventory, as it is assumed to compensate for the impact of an equivalent GHG emission. The Moura-Costa method is described in further detail in the workshop report (see Brandão and Levasseur 2011).

One issue with this option is that it adopts a fixed length but not a fixed start and end point of the time horizon. In this way, the impact of an emission is considered for a period with a fixed length, regardless of when the emission occurs. For example, if a 100-year time period is adopted, the impact of an emission occurring in year 2000 is considered up to year 2100 and that of an emission occurring in 2010 is considered over the following 100 years, i.e. up to 2110. This method is consistent in the way it treats all emissions/removals, i.e. considering their impact always for the defined length of the period following an emission/removal. As the atmospheric CO_2 concentration following an emission decreases over the time horizon, this means that the benefit of sequestering a unit mass of carbon for a number of years equal to the time horizon and then releasing it is higher than the total impact of the emission of a similar amount integrated over this time horizon. For example, using a 100-year time horizon 1 t CO_2 sequestered and stored for 96 years would result in −2 t CO_2-eq, i.e. the credit reflects the avoidance of the radiative forcing from 200 % of the carbon that is actually being stored. It may be misleading to credit the sequestration and temporary storage of 1 tonne of CO_2 with more than −1 t CO_2-eq. Doing so could be seen as inconsistent because the radiative forcing incurred were this

carbon released into the atmosphere instead would never be more than 1 t CO_2-eq.

4.3 The Lashof method (option 3)

Like the Moura-Costa method, the Lashof method (Fearnside et al. 2000) was discussed in the IPCC Special Report on LULUCF (Watson et al. 2000) and is described in further detail in the workshop report (see Brandão and Levasseur 2011). It has been proposed for LCA-related applications (Courchesne et al. 2010), but has not been applied or further developed for national reporting under the Kyoto Protocol. It aims to calculate a credit in kg-eq CO_2 for removing and keeping carbon out of the atmosphere for a given number of years, although it can also been interpreted as a credit for a delayed fossil emission.

Contrary to the Moura-Costa approach, the application of this method never results in more than 100 % credit when delaying an emission. An emission would have to be delayed by 100 years in order to be considered neutral.

4.4 The PAS 2050 method (option 4)

In 2008, timing issues regained attention due to the development of the British specification PAS 2050 for carbon footprinting (BSI 2008), where credits were given to temporary carbon storage and delayed emissions. The PAS 2050 (BSI 2008) approach accounts for temporary carbon storage in products by looking at the effect of delaying an emission on radiative forcing from the time of product manufacture and up to 100 years. It applies a dual approach: for short storage times, it uses a linear approximation of the Lashof method (see Clift and Brandão 2008), whereas for longer storage times where this approximation is not valid, it simply considers the average amount of carbon stored over 100 years.[4] All emissions taking place after 100 years are not accounted for, which is a marked departure from conventional LCA approaches. In LCA, the use of a 100-year time horizon for assessing global warming impacts implies a cut-off of the 'tails' of GHG's atmospheric residences at 100 years following their emission. However, this is consistently applied to all emissions regardless of when they occur. Under PAS 2050, emissions delayed by more than 100 years are entirely ignored.

The revised PAS 2050 (BSI 2011) maintains the 100-year assessment period, but requires that carbon footprints be calculated with no credit for temporary storage of less than 100 years. Despite being no longer a requirement, organisations intending to undertake the assessment of delayed emissions may still do so, according to the method above (PAS 2050, 2011).

[4] Emission delayed by x years gets a credit of $0.0076x$ (from 2 years to 25 years) and $0.01x$ (from 25 years to 100 years)

4.5 The dynamic LCA method (option 5)

The dynamic LCA approach (Levasseur et al. 2010), developed recently to account for the timing of the emissions in LCA, considers the temporal distribution of GHG emissions over the life cycle and calculates their impact on radiative forcing at any time using dynamic characterization factors, which consist of the absolute GWP integrated continuously through a fixed time horizon.

Despite the same characterisation factors being derived from both this and the Lashof methods (see Fig. 1), one important difference between the two is that the dynamic LCA approach fixes the beginning of the accounting period and the Lashof approach does not. This implies that removing a certain amount of atmospheric carbon always has the same climate impact in the latter method, but not in the former. The dynamic LCA approach aims at consistency between the time period of the assessment and the overall time horizon within which radiative forcing is considered For example, if a 100-year time period for the assessment is adopted, a 100-year time horizon is chosen for impact assessment (i.e. for integrating radiative forcing). As a result, the impact of an emission occurring in year 2000 is considered up to year 2100 and that of an emission occurring in 2090 is also considered up to 2100, i.e. its radiative forcing is only modelled for the following 10 years. This means that the radiative forcing in the full 100-year period following the emission is only considered for the former but not for the latter emission.

4.6 The ILCD handbook method (option 6)

The European Commission's ILCD Handbook (European Commission 2010b), also proposes a way to account for the timing of GHG emissions in LCA. According to the ILCD Handbook, temporary carbon storage and delayed emissions shall not be considered in LCA, unless the goal of the study clearly warrants it (e.g. the study aims to assess the effect that delayed emissions have on the overall results of an LCA study). In this case, any delayed GHG emission is to be treated on the same basis as temporary carbon storage. In this approach, to account for a delayed emission, a credit is given by multiplying kg CO_2-eq. of the emission by the number of years the emission is delayed by, up to 100 years, and by a factor of −0.01. Emissions occurring beyond 100 years from the time of the study are inventoried separately as "long-term emissions", and are not included into the general LCIA results calculation and aggregation, but are to be calculated, presented and discussed as separate LCIA results. Emissions are ignored if they occur after 100,000 years.

Like the Moura-Costa method, the linearity of this method makes it very simple to use in LCA, as the yearly benefit

for delaying an emission is constant. However, as opposed to some interpretations of the Moura-Costa method, application of the ILCD method to carbon storage results in a maximum of 100 % compensation of a corresponding CO_2 emission.

4.7 New and developing approaches

Two other documents provide guidelines on whether temporary carbon storage should be accounted for, and how. The International Organization for Standardization (ISO) is developing a new standard for carbon footprinting of products, ISO 14067. Also, a partnership between the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD) recently released the Product Life Cycle Greenhouse Gas Accounting Standard (WRI and WBCSD 2011), also known as the GHG Protocol. Both of these standards concern the quantification and communication of carbon footprints of products over their life cycle. Like the revised PAS 2050 (BSI 2011), these standards require that no credit be given to temporary storage in the base calculation although, like the original PAS 2050 (BSI 2008), they may allow a supplementary figure to be calculated that does include temporal aspects to be reported separately.

Some alternative approaches to account for biogenic carbon uptake and emissions were presented during the JRC workshop. The first was the indicator $GWP_{bio,}$ developed to assess the climate change impact of biogenic CO_2 emissions while considering the dynamics of vegetation regrowth (Cherubini et al. 2011). The GWP_{bio} approach combines the CO_2 impulse response function described by the Bern cycle model, as used in the calculation of GWP, with a forest growth curve to assess the radiative forcing resulting from temporary carbon release due to bioenergy produced from existing forests. These factors are thus specific to a given type of vegetation with a specific growth cycle.

Zanchi et al. (2010) described the concept of the carbon neutrality factor (CN; modified from Schlamadinger et al. 1995) to quantify the GHG emission reduction caused by the use of biomass as an energy source. As stated above, GHG emissions from the combustion of biomass are currently often assumed to be carbon-neutral. When the time needed to sequester back this carbon in re-growing biomass is long, the capability of bioenergy to reduce the GHG emissions on a short- to medium-term is reduced. The CN factor is defined as the ratio between the net reduction/increase of carbon emissions in the bioenergy system and the carbon emissions from the substituted reference energy system, over a specified time period. Zanchi et al. (2010) suggest that, rather than assuming carbon neutrality in GHG accounting for bioenergy, a CN factor could be applied to effectively discount emissions, reflecting the extent to which various bioenergy systems are carbon neutral over a chosen policy-relevant time period.

Cowie presented the concept of net present value of emissions reduction developed under the IEA Bioenergy Task 38 (Bird et al. 2011) to account for the differences in timing of emissions and removals in different bioenergy systems. While discounting of physical units is often contentious (e.g. O'Hare et al. 2009), Bird et al. (2011) suggest that financial indicators can be adapted to convey the concept of time preference for current versus future emissions.

5 General discussion and summary of key points

There are different environmental and techno-economic arguments in favour of temporary carbon storage: it buys time for technological progress and adaptation, postpones or temporarily avoids radiative forcing, and some temporary carbon storage may become permanent or contribute to a permanent sink by successive temporary activities. Sequestering carbon also keeps us on a lower carbon path and reduces the risk of exceeding possible tipping points, etc. (Marland et al. 2001; Dornburg and Marland 2008; Fearnside 2008). However, the effectiveness of using temporary carbon sequestration and storage to mitigate climate change has been questioned (Meinshausen and Hare 2002; Korhonen et al. 2002; Kirschbaum 2003a, 2006). This is a critically important issue that requires further study and analysis so that optimal GHG management options can be devised based on the best overall understanding of the combined effect of these competing factors and considerations.

Carbon captured into elements of product systems (e.g. biomass, soils or products made from these) can increase the carbon stocks of these non-atmospheric reservoirs and thereby can constitute temporary carbon sinks. Since the embodied carbon is sequestered from, and retained outside the atmosphere for a period of time, some radiative forcing is avoided. Carbon removal from the atmosphere and temporary storage in the biosphere or anthroposphere, therefore, has the potential to help mitigate climate change, even though the benefits might be temporary. Carbon sequestration and temporary storage may, however, also lead to reduced carbon uptake by the oceans so that the atmospheric CO_2 concentration, and therefore radiative forcing, may be higher after release of carbon than it would have been without temporary carbon sequestration and storage. From the same reasoning, when re-releasing stored carbon and increasing radiative forcing, the carbon uptake by the oceans will similarly increase. This further outlines the importance of timing of emissions in relation to tipping points.

Relative GWPs are a metric developed by the IPCC to allow GHGs of different radiative efficiencies and atmospheric lifetimes to be compared, so that CO_2 as well as

non-CO_2 GHGs can be included in GHG inventories for reporting and accounting under UNFCCC and the Kyoto Protocol. Use of GWPs enables net emissions/removals for a product or project, in t CO_2-eq., to be calculated. The application of GWPs constitutes an interesting and unusual way of dealing with time preference in that it applies no discount for the radiative forcing within the chosen time horizon. Hence, all radiative forcing across the time horizon is assigned the same importance. Subsequent radiative forcing is abruptly assigned a value of 0 beyond the end of the chosen time horizon. For example, in using 100-year GWP, the radiative forcing in both year 1 and year 100 after emission (e.g. that in year 99) is accounted fully, but any radiative forcing after year 100 (e.g. that in year 101) is excluded.

The adoption of GWPs implicitly assigns greatest importance to those types of climatic impacts that are related to cumulative radiative forcing. Adoption of GTPs, on the other hand, implies equating climatic impacts with future temperatures in specific years rather than the cumulative radiative forcing leading up to those years. The adoption of different metrics for the climate change impact category in LCA was proposed by Kirschbaum to account for the different types of impact and may lead to different evaluations of the value of temporary carbon storage. A single indicator could also be developed by going further in the impact chain (that is, by modelling ultimate damage), while considering different pathways (midpoints) before aggregating, as is done with other impact categories in LCIA. If midpoint modelling is preferred to damage modelling,[5] several different indicators could be used and this would also support a more qualified assessment of the damages associated with the different types of midpoint impacts. However, this would depart from the trend of combining different indicators to facilitate decision-making. Extensive work is still needed to model the full impact pathways of all GHG-related interventions (Fig. 2).

Six options are presented that could be used for assessing time in LCA and CF. None is recommended over the others. One important point is that all these options (with the exception of option 1) imply that there is a value to delaying emissions. Implicitly, the use of any of these options prejudges the outcome of discussions about the relative merit of temporary storage that have not yet been concluded.

As the difference between the PAS2050 (option 4) and the dynamic LCA (option 5) is small, either could be used in LCA and CF without significant differences in the results between them.

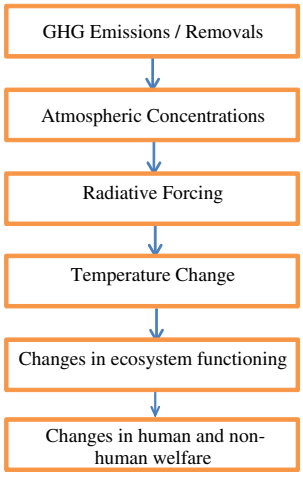

Fig. 2 The cause–effect chain or environmental mechanism of GHG flows to and from the atmosphere on climate change and associated impacts and damages further along the chain (adapted from IPCC 2009). Policy relevance increases further down the chain, but so do uncertainties. The figure shows GHG emissions/removals acting on climate change only via radiative forcing. It is acknowledged that climate impacts happens via other routes

No clear consensus was reached from the workshop discussions regarding whether or not to account for temporary carbon storage in LCA or CF and, if so, what method to employ. Nonetheless, some key points were raised but ways to address these were not uniformly endorsed. Since the benefits given to temporary carbon storage rely on policy-based accounting choices, it is important to make these choices explicit and transparent when using any accounting method. A sensitivity analysis should be provided, including a baseline scenario of zero benefits for temporary storage. Studies of generic product categories would be beneficial to identify for which product types the issue of timing of emissions and removals could significantly affect the life cycle carbon footprint.

It is important to do more research in order to improve climate change modelling in LCA to include other climate change impact types and their associated indicators (e.g. instantaneous temperature increase and rate of temperature increase) since they can lead to different conclusions than from the single focus on cumulative radiative forcing. It was agreed that further research is needed on how to consider the dynamics of the carbon cycle in assessing sequestration and temporary storage of carbon and delayed GHG emissions.

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[5] While midpoint modelling refers to the modelling of impacts (e.g. climate change) at a middle point in the cause–effect chain or environmental mechanism, endpoint modelling refers to that at the end of the cause–effect chain (i.e. damage to Human Health, Ecosystems or Natural Resources).

Disclaimer Some of the views and opinions raised in this workshop and presented in this summary paper are not necessarily shared by all of the authors nor by their associated organisations.

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