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LCA FOR AGRICULTURAL PRACTICES AND BIOBASED INDUSTRIAL PRODUCTS

The potential contribution to climate change mitigation from temporary carbon storage in biomaterials

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Abstract

Purpose While lasting mitigation solutions are needed to avoid climate change in the long term, temporary solutions may play a positive role in terms of avoiding certain climatic target levels, for preventing the crossing of critical and perhaps irreversible climatic tipping points. While the potential value of temporary carbon storage in terms of climate change mitigation has been widely discussed, this has not yet been directly coupled to avoiding climatic target levels representing predicted climatic tipping points. This paper provides recommendations on how to model temporary carbon storage in products in life cycle assessment (LCA), in order to include the potential mitigation value relative to crossing critical climatic target levels. Further, estimates are made on potential magnitude of this value, highlighting the importance of including this aspect in climate change impact assessment of biomaterials.

Methods The recently developed approach for quantifying the climate tipping potential (CTP) of emissions is used, with some adaption, to account for the value of temporary carbon storage. CTP values for short-, medium- and long-term carbon storage in chosen biomaterials are calculated for two possible future atmospheric greenhouse gas (GHG) concentration development scenarios. The potential magnitude of the temporary carbon storage in biomaterials is estimated by considering the global polymer production being biobased in the future.

Results and discussion Both sets of CTP values show the same trend; storage which releases the carbon again before the climatic target level is reached increases the CTP value of the product compared to a situation with no storage of the product, whereas storage extending beyond the time where the climatic target level is predicted to be crossed according to the GHG concentration scenarios contributes with negative CTP values, which means mitigation. The longer the duration of the storage, the larger the mitigation potential.

Conclusions Temporary carbon storage in biomaterials has a potential for contributing to avoid or postpone the crossing of a climatic target level of 450 ppm CO_2e, depending on GHG concentration development scenario. The potential mitigation value depends on the timing of sequestration and re-emission of CO_2. The suggested CTP approach enables inclusion of the potential benefit from temporary carbon storage in the environmental profile of biomaterials. This should be seen as supplement to the long-term climate change impacts given by the global warming potential which does not account for temporary aspects like benefits from non-permanent storage in terms of avoiding a critical climatic target level.

Keywords Biomaterials · Climate change mitigation · Climate tipping potential (CTP) · Life cycle assessment (LCA) · Temporary carbon storage

1 Introduction

Climate change is a major environmental concern of today, and mitigation options are high on the global political agenda. Besides the general importance of limiting long-term climate

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change impacts, there are climatic ‘target levels’ which are important to stay below (see, e.g. Jørgensen et al. 2014b). This is due to the predicted existence of so-called tipping points for our climate system, the crossing of which will lead to dramatic/structural changes in the climate system that may be irreversible (Meehl et al. 2007; Hansen et al. 2008). Mitigating climate change is thus both highly important and very urgent, and different options for climate change mitigation are currently being explored, including different ways to decrease CO_2 emissions. There is currently no consensus on how to assess the potential climate change mitigation value of this temporary carbon storage in life cycle assessment (LCA) (Brandão et al. 2012; Jørgensen and Hauschild 2013; Guest et al. 2013). Temporary storage of carbon in products makes little difference in terms of long-term climate change, so the value in terms of climate change mitigation is if the temporary carbon storage can help avoiding the passing of climate tipping points (Jørgensen and Hauschild 2013). Either through offering a bridging potential to a future with lower atmospheric greenhouse gas (GHG) concentration, thereby avoiding crossing the target level, or at least postponing it, thus buying time to allow lasting climate change mitigation and/or adaption solutions to be implemented. As a supplement to assessing long-term climate change impacts using the GWP, Jørgensen et al. (2014b) propose a method to assess the climate tipping potential, CTP, based on the contributions of GHG emissions to the crossing of climate tipping points. The CTP method can also be used for estimating the climate change mitigation value of carbon storage in terms of its potential for helping avoiding passing of such tipping points. However, being developed for estimating the short-term climate change impacts of GHG emissions, the current approach needs to be adapted to distinguish between the value of permanent carbon storage and that of temporary carbon storage.

The paper provides recommendations on how to model carbon storage in products in LCA in order to include the potential mitigation value relative to crossing critical climatic target levels, based on adaption of the newly developed CTP method (Jørgensen et al. 2014b) and illustrates its use through case examples.

2 Methods

2.1 Scope

The geographical scope of the assessment is global, and while the focus is on temporary storage of carbon, the life cycle emissions of both CO_2 and other GHGs are considered where relevant. Temporary carbon storage is here defined as carbon sequestered from atmospheric CO_2, which is temporarily stored and later emitted again as CO_2.

Three case scenarios illustrate the adjusted CTP approach. One scenario addresses short-term storage of 2 years, one addresses medium-term storage of 10 years, and finally one addresses long-term storage of above 50 years. The scenarios are hypothetic case scenarios of biobased polyethylene (PE) products, produced from miscanthus, sugar cane and maize.

2.2 Atmospheric GHG concentration scenarios

Two development scenarios of future atmospheric GHG concentrations are assumed in the assessment: one predicting a peak and decline and one predicting a continuous increase. The two scenarios are the RCP3PD and the RCP6 scenarios of the so-called Representative Concentration Pathway (RCP) scenarios (Meinshausen et al. 2011). The RCP3PD is a mitigation scenario with a peak radiative forcing level of 3 Wm^{-2}, followed by a decline; so, the radiative forcing level in year 2100 is 2.6 Wm^{-2}. The RCP6 is a medium stabilization level scenario with a radiative forcing level of 6 Wm^{-2} in year 2100. Both scenarios are made available by Meinshausen et al. (2011), based on background data from van Vuuren et al. (2007) and Fujino et al. (2006), respectively.

An atmospheric GHG concentration of 450 ppm CO_2e has been chosen as target level here, as discussed by Jørgensen et al. (2014b). In the RCP3PD scenario, the target level of 450 ppm CO_2e is only exceeded for a 24-year period (years 2034–2057; see Fig. 1a) and can thus be bridged if avoiding that temporary overrun, meaning that storage of enough carbon for a sufficiently long period of time has bridging potential in this case. In the RCP6 scenario, with continuously increasing GHG concentrations until year 2100 (see Fig. 1b), the potential benefit of temporary carbon storage lies in buying time, by postponing the crossing of the target level, as bridging is not possible.

2.3 The CTP approach

The CTP method proposed by Jørgensen et al. (2014b) describes the marginal contribution of GHG emissions to the passing of critical climate tipping points. It expresses the impact of each GHG emission relative to the available capacity of the atmosphere to take up additional GHGs before crossing a certain climate level through Eq. (1):

$$CTP_{x,T}(t_e) = \frac{Impact_{x,T}(t_e)}{Capacity_T(t_e)} = \frac{\left(\frac{AGWP_{x,T}(t_e)}{A_{CO2,ppm}}\right)}{\int\limits_{t=t_e}^{t=T} (C_T - C_t)dt} \qquad (1)$$

where $CTP_{x,T}(t_e)$ is the CTP measured in parts per trillion (ppt) of the remaining atmospheric capacity for receiving

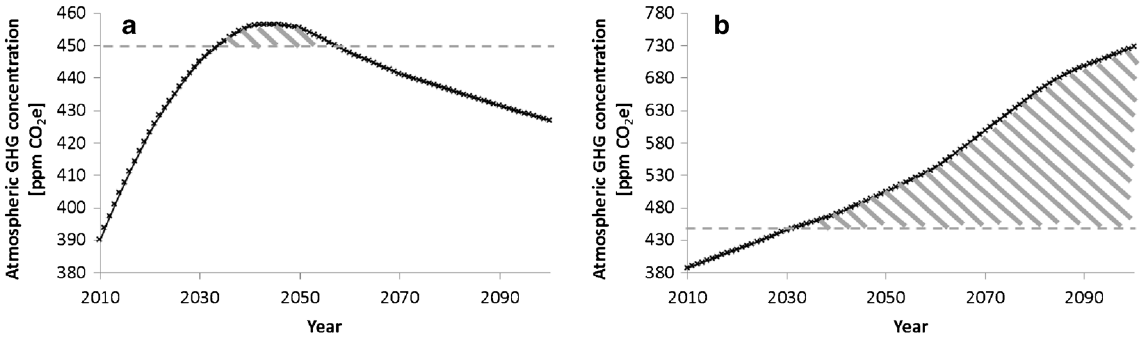

Fig. 1 Excess atmospheric GHG concentrations (*grey hatched area*) above the level of 450 ppm CO$_2$e (*grey punctured line*) in the future, following **a** the peak and decline scenario (RCP3PD) (Meinshausen et al. 2011; van Vuuren et al. 2007) and **b** the continuous increase scenario (RCP6) (Meinshausen et al. 2011; Fujino et al. 2006)

GHGs without crossing the target level (ppt$_{rc}$), AGWP$_{x,T}$(t$_e$) is the absolute global warming potential of GHG *x* between emission time t$_e$ [year], and target time T [year], A$_{CO2,ppm}$ is the specific radiative forcing of CO$_2$ *per ppm* [Wm^{-2} ppm CO$_2$$^{-1}$], C$_T$ is the target level concentration of atmospheric GHG, occurring at the target time [ppm CO$_2$e], and C$_t$ is the concentration of atmospheric GHG at time t [ppm CO$_2$e] of the assumed GHG concentration scenario.

For CO$_2$, which requires a special expression to account for its complex atmospheric removal processes when calculating the AGWP, Eq. (1) takes the form of Eq. (2):

$$CTP_{CO2,T}(t_e) = \frac{\left(\dfrac{A_{CO2}[a_0 t + \sum_i a_i \alpha_i (1 - \exp(-t/\alpha_i))]}{A_{CO2,\,ppm}}\right)}{\int\limits_{t=t_e}^{t=T} (C_T - C_t)dt} \tag{2}$$

where A$_{CO2}$ is the specific radiative forcing of CO$_2$*per kg* in the atmosphere [Wm^{-2} kg^{-1}] and α are the coefficients and time constants for the removal processes that are active in the IPCC decay function for CO$_2$ in the atmosphere according to the revised Bern carbon cycle model (Forster et al. 2007): α_0= 0.217, α_1=0.259, α_2=0.338, α_3=0.186, α_1=172.9 years, α_2=18.51 years, α_3=1.186 year.

2.4 Adapting the CTP approach to address temporary carbon storage

The CTP of a GHG emission reflects its impact in terms of contributing to the crossing of a climatic target level. Therefore, impacts occurring after the time when the target level is exceeded are not included in the calculation of the emission's CTP, but only assessed in terms of long-term climate change impacts using the GWP. This approach is immediately compatible with permanent carbon storage, where uptakes are counted as negative emissions, with t$_e$ in this case being exchanged with the year of uptake and permanent storage, t$_{st}$ of atmospheric CO$_2$. The logic derivation for this is to subtract the CTP of the amount of CO$_2$ sequestered from the atmosphere by the biomass, at the time it occurs, from the CTP at the time it is released. For storage of 1 kg of carbon at time t$_{st}$ followed by its full release at time t$_e$, this is described by Eq. (3):

If t$_{st}$ < T, then:

$$CTP_{CO2\ \mathrm{Storage},T}(t_{st}, t_e) = \frac{\left(\dfrac{\int\limits_{t=t_e}^{t=T} A_{CO2}[a_0 + \sum_i a_i \exp\left(-t'/\alpha_i\right)]dt'}{A_{CO2,\,ppm}}\right)}{\int\limits_{t=t_e}^{t=T} (C_T - C_t)dt} - \frac{\left(\dfrac{\int\limits_{t=t_{st}}^{t=T} A_{CO2}[a_0 + \sum_i a_i \exp\left(-t'/\alpha_i\right)]dt'}{A_{CO2,\,ppm}}\right)}{\int\limits_{t=t_{st}}^{t=T} (C_T - C_t)dt} \tag{3}$$

Equation (3) can be applied to different amounts of carbon stored and later emitted, also in the case where not all stored carbon is emitted at the same time, by splitting the stored carbon into fractions and applying the respective emission time for each fraction.

Using the CTP approach as given in Eq. (3) means that all carbon storage will be given equal value to permanent storage independent of the length of the storage period, as long as it ends after the target time T.

However, carbon storage in biobased materials can normally not be considered ‘permanent’ as the product lifetimes are finite and often relatively short. For assessing the value of *temporarily* storing carbon, the method needs to give a fair valuation in terms of the temporary aspect by addressing the following issues:

- The value assigned to the temporary carbon storage beyond the target time T should increase with storage duration up to a period that is defined as comparable in value to permanent storage, regarding the avoidance of crossing the climatic target level (but not in terms of the long-term climate change impacts).
- The adjusted CTP approach to assess temporary carbon storage beyond the target time should be compatible with the CTP approach to assess GHG emissions.

In order to address those issues, the following steps have been performed for adjusting the CTP approach to the special case of addressing temporary carbon storage:

- First, the duration of storage defined as having full benefit, τ, needs to be defined.
  - In the case of the RCP3PD scenario, starting from year 2014, the storage needs to be at least 44 years to last beyond the period where the GHG level is above the target level, and preferably a few years more to have an increased capacity.
  - In the case of the RCP6 scenario, the value lies in buying time, which means that the storage time needs to be sufficient for implementing lasting solutions for mitigating climate change and/or adapting to the changes to mitigate the most dramatic impacts.
  - For those reasons, we have chosen a duration of τ= 50 years of storage as having full benefit using both scenarios.
  - In order to ensure consistency in the assessment using the two different scenarios, the value of buying time is also reflected in the RCP3PD scenario, which means that the same method is used in both cases.
- The increasing value of storage as the year of CO_2 uptake and storage approach T is then represented automatically by the CTP approach, with uptake of CO_2 being treated as negative emissions.
- The value of the storage, for all temporary carbon storages which end after T, is calculated from the full storage CTP value multiplied by the ratio between the storage period and τ (e.g. for 10-year storage after T the CTP value of the storage is 1/5 the value of 50-year storage).

This is summarised in Eq. (4), assuming that the temporarily stored carbon is sequestered from the atmosphere, and later emitted again, in the form of CO_2:

If $t_{st}<T$:
If $t_e<T$: Eq. (3) applies
If $t_e \geq T$:

$$CTP_{CO2,\,\mathrm{Storage},T}(t_{st},t_e)=\frac{n}{\tau}\left[\frac{\left(\frac{\int_{t=t_e}^{t=T} A_{CO2}[a_0+\sum_i a_i \exp\left(-t'/\alpha_i\right)]dt'}{A_{CO2,\,ppm}}\right)}{\int_{t=t_e}^{t=T}(C_T-C_t)dt}-\frac{\left(\frac{\int_{t=t_{st}}^{t=T} A_{CO2}[a_0+\sum_i a_i \exp\left(-t'/\alpha_i\right)]dt'}{A_{CO2,\,ppm}}\right)}{\int_{t=t_{st}}^{t=T}(C_T-C_t)dt}\right] \quad (4)$$

where *n* is the length of the storage period from 1 to τ [years], with all periods above τ having a value equal to that of a period of τ .

This approach satisfies the requirements presented above and supports application together with the regular CTP for assessing CTP of GHG emissions. The adapted CTP characterisation factors for temporary carbon storage are shown in Fig. 4 in Sect. 4 and applied to three case scenarios with different storage durations and different biomass feedstocks. The case scenarios are described in Sect. 3.

3 Temporary carbon storage case scenarios

All product level cases are based on products from biobased PE, with different lifetimes, to assess the impact of varying storage durations. The GHG emissions from conversion of biobased PE to final products are not included, as that would interfere with the illustration of CTP impacts from different carbon storage times.

Packaging materials made from biobased PE offer a short-term storage case, with an assumed carbon storage period of 2 years including the time from carbon sequestration in the biomass until disposal, assuming that the product is incinerated after disposal.

A medium-term case example is biomass-based PE materials used in the automotive industry, with a carbon storage period of 10 years from the carbon sequestration into the biomass and through the lifetime of an average car.

An example of long-term storage is building and construction materials from biomass-based PE with a lifetime in the building above 50 years from the sequestration of the carbon.

The cases are hypothetic and created to provide simple illustrations of the use of the CTP approach for temporary carbon storage. PE is the polymer produced in the largest amounts globally, and currently 39 % of the European production is used for packaging, while 21 % is used in building and constructing and 8 % is used in the automotive industry (PlasticsEurope 2011). While the main part of the polymer production is still petrochemically based, biobased PE as produced today can be used in the same way as the petrochemical PE as the technical properties are identical (e.g. Harmsen and Hackmann 2013).

3.1 Production of biobased PE

Biobased PE can be produced from different feedstocks. In the cases addressed here, results are calculated for three different biomass feedstocks: miscanthus, sugar cane and maize. The modelling of GHG emissions from the conversion over fermentable sugar yield to PE from the three types of biomass is based on current agricultural practice represented in data from Bos et al. (2012), which includes GHG savings from energy production from co-products to the extent that it is part of current agricultural practice, as outlined in Table 1. This assumption in Bos et al. (2012) affects GHG results for the biobased PE from the different biomass feedstocks. The purpose of presenting the hypothetic cases is to illustrate the use of the newly developed CTP approach adjusted to assess temporary carbon storage in LCA, including life cycle GHG emissions, and not to discuss the environmental performance of biobased PE produced from different biomass feedstocks. Therefore, these assumptions are not important for the outcome of this article. Nevertheless, where the CTP results are presented, a comment is included on how they would be affected if GHG savings due to the energy production from co-products were not included.

4 Results

Section 4.1 addresses the potential of temporary carbon storage in biomaterials to reach a magnitude at the societal level that makes it interesting for assisting in avoiding exceeding a climatic target level of 450 ppm. Sections 4.2 and 4.3, on the other hand, address temporary carbon storage at product level, presenting the newly developed CTP approach adjusted for temporary carbon storage assessment and showing results of its use in a product case.

4.1 Climate change mitigation potential of temporary carbon storage in biopolymers

The aspect of potential mitigation value of biomaterials in terms of avoiding the climatic target level of 450 ppm is addressed in Sects. 4.1.1 and 4.1.2, for the RCP3PD and the RCP6 scenarios, respectively.

4.1.1 The RCP3PD scenario

For the case of the RCP3PD scenario, which predicts crossing of the 450-ppm CO_2e target level in year 2034, and getting back below in year 2058 as seen from Fig. 1a, exceeding the target level could be avoided if GHG emissions contributing to the presence of GHGs in the atmosphere during that period are reduced. The amount of carbon emission that needs to be avoided can be estimated as the amount of C present in the atmosphere that corresponds to the atmospheric CO_2 concentration that is above the target level. The revised Bern carbon cycle model (see Forster et al. 2007) allows estimating how much of the carbon, if emitted as CO_2, would be removed from the atmosphere again over time by the global carbon cycle processes. Due to those atmospheric CO_2 removal processes, the sequestration in biomass of x kg atmospheric CO_2 in one year will mean that the hereby induced reduction in atmospheric GHG concentration, compared to leaving the x kg CO_2 in the atmosphere, will in the following years decrease and thus be less than x kg CO_2. Thus, the revised Bern carbon cycle removals need to be accounted for when estimating the amount of carbon in the atmosphere over time which should

Table 1 Uptake and release of GHGs over time from sequestration to release R years later for 1 t biobased PE produced from various feedstocks according to current agricultural practice. Data for GHG emissions from biobased PE production (cradle to gate) from different feedstocks estimated based on Bos et al. (2012)

Time, year	Process	GHG emission [kg]/t biobased PE[a]		
		Miscanthus[b]	Sugar cane	Maize
1	CO_2 avoided through carbon sequestration and storage in biobased PE product	−3138	−3138	−3138
	N_2O emissions from agricultural production of biomass [c]	0.8	0.7	3.7
	CO_2 emissions from production of biobased PE [d]	−2038	−1405	2038
2 to R	Storage in biobased PE products [e]			
R	Incineration - CO_2 emission [f]	3138	3138	3138

[a] In current agricultural practice, there are GHG saving in the production year for miscanthus and sugar cane due to energy surplus production from by-products, whereas for maize, this is not the case for current agricultural practice, where more energy is consumed than produced in the process (Bos et al. 2012)

[b] Miscanthus is not yet produced in as large-scale quantities as the other two feedstocks (Bos et al. 2012)

[c] Reported as CO_2e in Bos et al. (2012), here converted back to N_2O emission using GWP_{100} of N_2O: 298 CO_2e (Forster et al. 2007)

[d] CO_2 emissions are estimated from original data given as GJ non-renewable energy use (NREU)/t biobased PE, converted to CO_2e assuming oil as the NREU source, with conversion factors of 0.43 tCO_2/barrel and 5.8 mmBtu/barrel (EPA 2013a), as well as 0.9478 mmBtu/GJ (EPA 2013b)

[e] The storage in the biomass starts from the time of sequestration, that is year 1, and continues through the life time of the product

[f] As the products are assumed incinerated at their end-of-life, all carbon stored in the biomass will be released as CO_2

be avoided, as done in Online Resource 1 (Electronic Supplementary Material).

The value of temporary carbon storage in biomaterials in terms of avoiding exceeding the climatic target level of 450 ppm CO_2e can be estimated as its fraction of the estimated amount of carbon emission that must be avoided as described above.

The potential future market for biopolymers is estimated by assuming full substitution of the global, mainly petrochemically based, polymer production with biopolymers. While a lower consumption might often be preferred to a shift in materials from an environmental perspective, changing consumption patterns is not an issue addressed in this article.

The future polymer demand is estimated by extrapolating from the global production of 0.265 GtC in 2010 (PlasticsEurope 2011), assuming a 5 % annual increase, which is in line with the long-term trend in global plastic production growth during the last 20 years (PlasticsEurope 2011).

While many petrochemical polymers today cannot be directly substituted with biobased ones, substitution by new biopolymer types with similar properties is often an option, and further biopolymer development is ongoing. For example, biobased polypropylene (PP) is expected very soon to be produced at commercial scale, and together, PP and PE account for approximately half of the mass of the current plastic consumption in Europe (PlasticsEurope 2011). Considering that the year that the target level is predicted to be crossed according to RCP3PD is 20 years from now, we see it as quite possible that the majority of current petrochemical polymers can be replaced by biopolymers at that time.

In order to have a bridging potential, bridging beyond the time of the 'peak level' above the climatic target level, the storage duration must at least span the length of the period where the GHG concentration is above the peak, which is 24 years. Starting from the year of predicted crossing of the target level, 2034, that means storage for at least 25 years and preferably more, to get well below the target level before re-emission of the carbon. With this storage duration, only the fraction of polymers used in building and construction is relevant to consider here. This fraction is approximately 21 % of global polymer production (PlasticsEurope 2011). Considering the five main polymer types, accounting for 74 % of polymer consumption today in Europe, the weighted average carbon mass content is 77 % (PlasticsEurope 2011).

Assuming an average carbon mass content of the polymers of 77 %, the carbon storage in construction biopolymers could account for at least 26 % of the total mass of carbon that must be avoided emitted each year (as CO_2) from 2034 until 2057. In many years, it could even account for more than the total amount, as shown in Fig. 2 (details on calculations can be seen in Online Resource 1, Electronic Supplementary Material).

The estimates given in Fig. 2 only consider the potential of the temporarily stored amount of carbon in long-lived biopolymer products and do not take into account life cycle GHG impacts from production nor the potential GHG savings from substituting conventional petrochemical products. Finally, no land use or land use change impacts are included in these estimates.

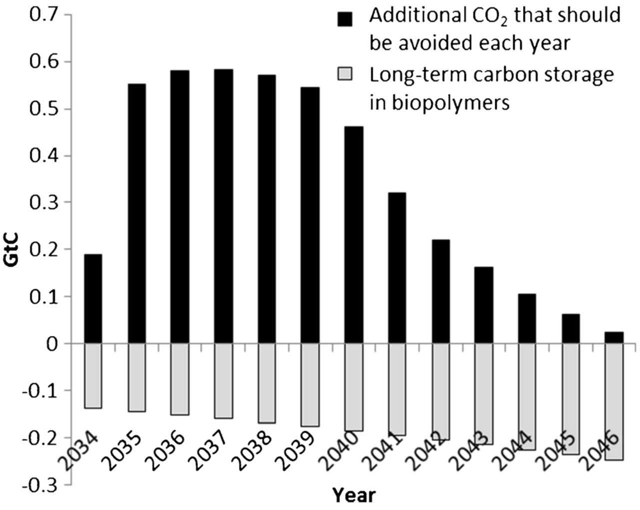

Fig. 2 Additional CO_2 emissions that must be avoided each year in the period, provided that the avoided emissions needed for previous years have been accomplished, in order to avoid exceeding the climatic target level of 450 ppm CO_2e, following the RCP3PD scenario (*black bars*). *Grey negative bars* show the potential role of temporary carbon storage in long-lived biopolymer products for removing atmospheric CO_2 in the period

4.1.2 The RCP6 scenario

Contrary to the RCP3PD scenario, the GHG concentrations in the RCP6 scenario keep increasing toward year 2100 as shown in Fig. 1b, and so does the amount of carbon emission that must be avoided to stay below 450 ppm CO_2e as seen in Fig. 3. In this case, the potential benefit of temporary carbon storage lies in buying time up to a maximum of 50 years (as described in Sect. 2.4). Similar to the approach for the RCP3PD scenario, amounts of GHG to be avoided to stay below 450 ppm CO_2e are calculated as shown in the Online Resource 1 (Electronic Supplementary Material); Table O2 and the resulting values are given in Fig. 3. The mitigation potential of long-term storage in biopolymers is 10–28 % each year, except for the first year, where it is 90 %, as the target level is only slightly exceeded that year according to the RCP6 scenario.

4.2 Adjusted CTP approach for addressing temporary carbon storage

While Sects. 4.1.1 and 4.1.2 illustrated that there is a noteworthy potential of temporary carbon storage in biomaterials to contribute to avoiding/postponing the crossing of the 450-ppm CO_2e target level, this potential is currently not included in LCIA. A possibility of expressing this value is introduced by the adapted CTP approach to incorporate temporary carbon storage as described by Eq. (4). Using this gives the temporary carbon storage CTP characterisation factors shown in Fig. 4a, b, for the RCP3PD mitigation GHG concentration scenario and the RCP6 medium target level GHG concentration scenario, respectively.

Figure 4a, b illustrates the development in CTP of temporary carbon storage as function of time of sequestration for selected storage periods. CTP characterisation factors for storage periods between 2 and 50 years for all CO_2 uptake times from present until the target time T are shown for both presented scenarios in the Online Resource 2 (Electronic Supplementary Material).

While the trends of the CTP values for the two scenarios are similar, the timing and the size of CTP values differ. It is obvious from the figures that the timing of the CO_2 uptake and storage, and later emission, is decisive for the potential value

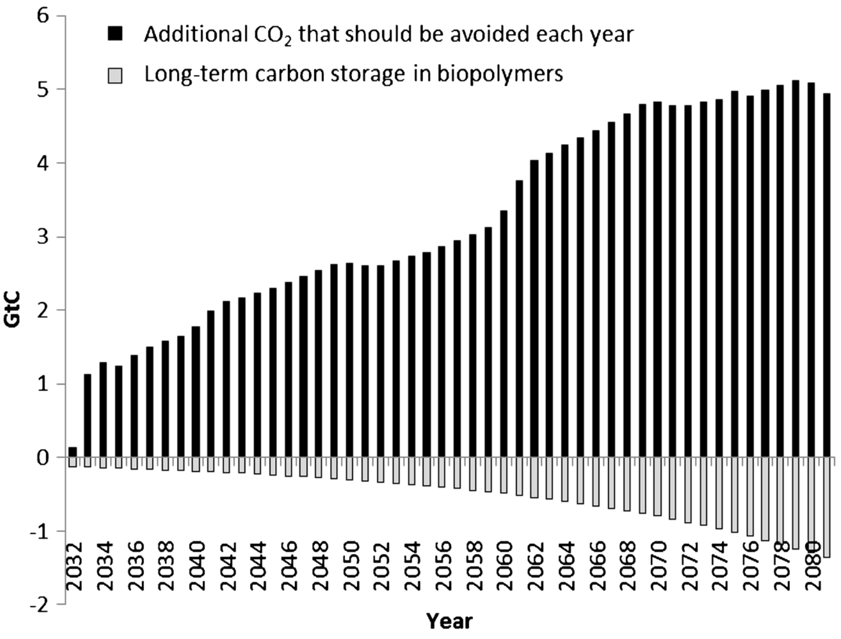

Fig. 3 Additional CO_2 emissions that must be avoided each year in the period, provided that the avoided emissions needed for previous years have been accomplished, in order to buy 50 years of extra time before exceeding the climatic target level of 450 ppm CO_2e, following the RCP6 scenario (*black bars*). *Grey negative bars* show the potential role of temporary carbon storage in long-lived biopolymer products for removing atmospheric CO_2 in the period

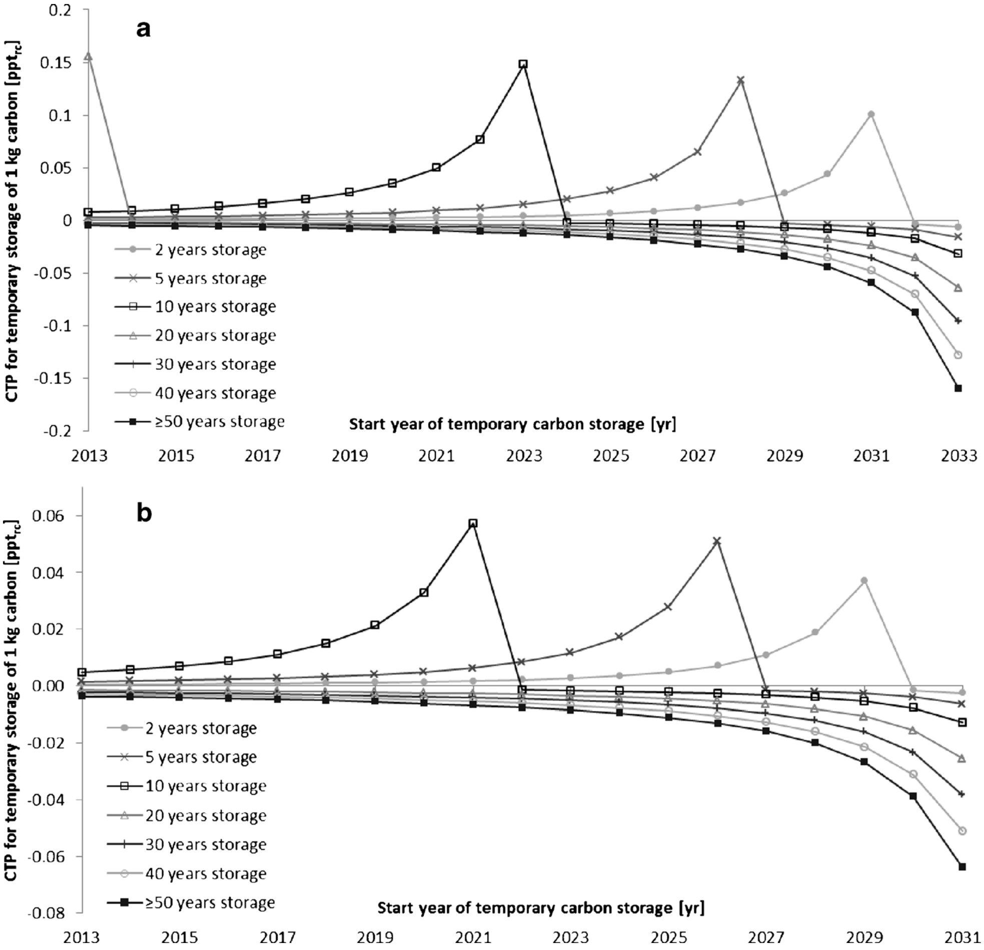

Fig. 4 CTP for temporary carbon storage, with uptake before T for different storage durations and start years of storage, assuming **a** scenario RCP3PD and **b** scenario RCP6. CTP is measured in ppt of the remaining atmospheric capacity for taking up GHGs without exceeding the target level (ppt$_{rc}$), with negative values meaning mitigation potential

of temporary carbon storage. Temporary carbon storage for relatively short periods ending before the target time T will have a positive net climatic tipping potential, rather than a mitigation value, as the atmospheric capacity is critically declining close to the target level, and avoiding GHG emissions thus becomes more urgent. This means that for storage that begins the same year and ends before the target year, longer storage durations will result in higher CTP values for a given sequestration year, as the longer storage duration results in emission closer to the target year. For storage durations above 20 years for the RCP6 scenario, and 30 years for the RCP3PD scenario, all temporary storage with sequestration year from present until the target time will have a mitigation value, which increases with storage duration and proximity of the storage year to the target year.

4.3 Product level results based on the adjusted CTP approach

Using the adjusted CTP approach, the mitigation value of temporary carbon storage in biomaterials in terms of avoiding crossing the climatic target level of 450 ppm CO_2e can be estimated. Here, this is done for the three case examples with different storage durations and different biomass feedstocks, as defined in Sect. 3. The purpose of these hypothetic case examples is to illustrate the potential and consequences of using the newly developed CTP approach to assess temporary carbon storage in LCA, under different conditions.

CTP impacts of lifecycle GHG emissions other than the temporarily stored carbon are calculated using CTP characterisation factors for GHG emissions from Jørgensen et al. (2014b). Results are shown as function of time of carbon sequestration in Fig. 5.

At a first glance, results may seem a bit complex, as impacts do not follow a simple pattern as function of storage duration, timing of sequestration, or feedstock type. This is due to the merging of two aspects, the temporary carbon storage part and the life cycle GHG impacts, which vary differently with those parameters. Disregarding the life cycle impacts, results could be extracted directly from Fig. 4, which shows a more homogenous picture in terms of trends. As shown in Fig. 4, temporary carbon storage gives a CTP saving if the carbon is stored beyond the target time, but increases CTP impacts if carbon is released again before the target time. This is why biobased PE products with short- and medium-term lifetimes in some cases have high CTP impacts, while in other cases show CTP savings, depending on the timing of the sequestration, and thus of the emission.

What further differentiates the results is that for miscanthus and sugar cane, there is a net GHG saving in the production year due to energy surplus production from by-products, whereas for maize, there is a net GHG emission from the production as more energy is used for producing bio-PE from maize, than the energy produced from by-products, according to current agricultural practice (Bos et al. 2012). GHG emission savings always lead to negative CTP values (savings), while GHG emissions lead to positive values, but the magnitude depends again on the timing of the emissions relative to the target time. CTP values in Fig. 5 are thus negative if there is a net mitigation of CTP, e.g. when the CTP saving value of buying time by storing the carbon beyond the target time is larger than the CTP impacts of the product over the rest of its life cycle.

In the long-term storage case, CTP values are all negative, and increasingly so, the closer to the target time the storage starts, as the capacity left is then smaller and the urgency of action for avoiding the target level therefore more critical.

If, on the other hand, no energy was produced from by-products, that would give net GHG emissions from producing bio-PE from all three feedstocks considered here, leading to CTP impacts for bio-PE in all the cases addressed in Fig. 5.

CTP values are similar for the two GHG concentration scenarios in most cases, with a higher numeric trend for the peaking scenario (RCP3PD). For the biobased PE products with short-term storage, however, there are some obvious differences for the case of carbon sequestration in year 2030, which is due to the different target times of the two scenarios.

The impact of a GHG depends on the time it resides in the atmosphere before the target time, meaning that in scenario RCP3PD where the target time occurs 2 years later than in the RCP6 scenario, the impact of GHG emissions in a given year will be a little higher for the RCP3PD scenario. The same is true in the case of a mitigation value from carbon sequestration in a given year. Further, due to the differences in the pathways of the two scenarios, the remaining capacity in each year is higher in the RCP6 scenario, until a few years before T. Both aspects lead to a higher numeric CTP value of an emission/sequestration in the RCP3PD scenario than in the RCP6 scenario in a given year (except in year 2031, which is the last year before T in the RCP6 scenario).

Using the CTP approach without the adaption for temporary storage would give the same results as here for emissions before the target level and for emissions with at least 50-year storage, as inherent in the derivation using 50 years as τ (i.e. Eq. (4)).

5 Discussion

5.1 The adapted CTP approach for temporary carbon storage

The developed approach reflects that emission before the target level is always worse than after, and thus that temporary

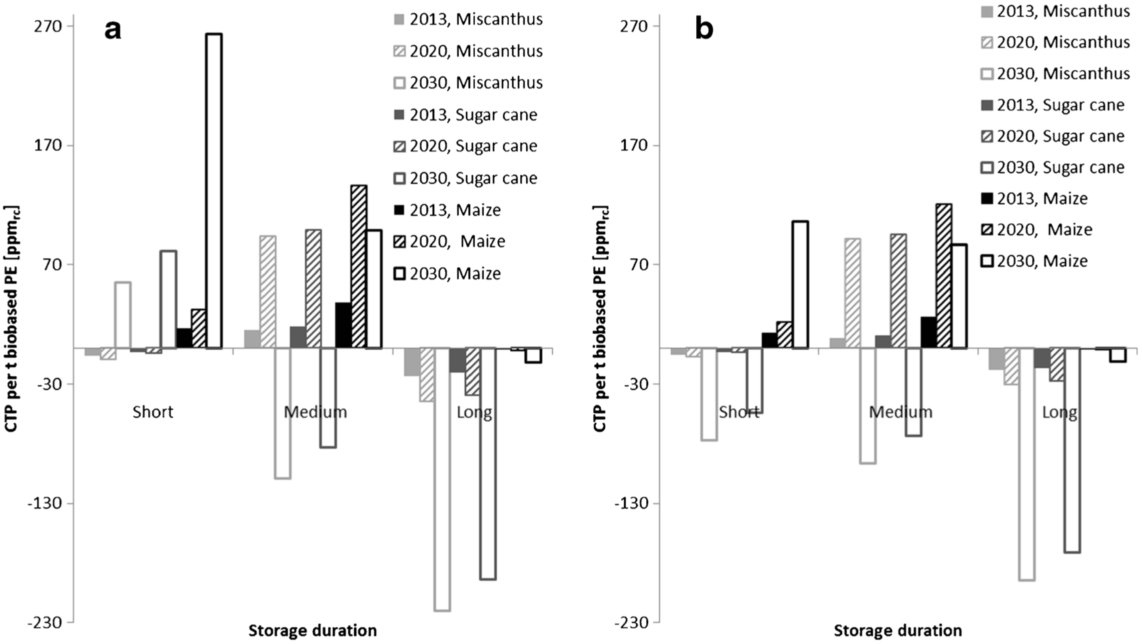

Fig. 5 CTP of temporary carbon storage in 1 t biobased PE products of varying durations (short 2 years, medium 10 years, long above 50 years), and different years of carbon sequestration in biomass, including life cycle GHG impacts for current agricultural practice as outlined in Sect. 3, for three different feedstock crops, using **a** the RCP3PD scenario and **b** the RCP6 scenario

carbon storage pushing impacts beyond the target time, T, should always be of value in terms of mitigating climate change. However, this means that a gradual decrease of impacts after the target time is not possible, as later emission might then be worse than earlier. Consequently, emissions in year T-1 will have large impact whereas emissions 1 year later will have no impact. Likewise, using the method directly, all uptakes of carbon just before T will yield large benefits, regardless of when it is reemitted. For including the aspect that short-term storage (e.g. just a few years) does not have the same value as permanent storage, the gradual valuation in terms of length of storage has been introduced as described in Sect. 2. This is necessary in order to give fair weighting to storage of different lengths, as storage for just a few years has accordingly less potential for 'buying' time than long-term storage. This is in line with the fact that pushing emissions a few years ahead will not have much real value in terms of avoiding tipping points, but at the most just push the target year.

While further elaboration is possible, the presented method fulfils the task of showing the value of temporary carbon storage in terms of only yielding a value if pushing impacts beyond the target level, thus buying time, and giving value gradually in terms of length of the time bought.

5.2 Impact of choice of τ

The sensitivity of the approach to the choice of the parameter τ is straightforward, as the temporary storage value varies with the inverse of τ for all storage durations up to the new value of τ, so a doubling of τ leads to half the value for a given temporary storage duration (when $t_e>T$, that is there is a mitigation value of the storage). This means that the choice of τ is rather important for the outcome and should be chosen carefully. The proposed choice of a τ value of 50 years is based on the reasoning in Sect. 2.4.

5.3 Difference between CTP and GWP

The CTP results from Sect. 4.3 can be seen to differ a lot for the different cases. In contrast, GWP_{100} for the same biobased PE production is constant and independent on sequestration year, production year and storage duration, as GWP_{100} is a static measure aimed at long-term assessment and not taking into account storage and emissions timing. GWP_{100} per t miscanthus, sugar cane and maize based PE in the three cases is thus −1789 kg CO_2e_{100},[1] −1042 kg CO_2e_{100} and 3031 kg CO_2e_{100}, respectively, irrespective of the duration of the temporary carbon storage.

5.4 The potential contribution of carbon storage in biomaterials for mitigating climate change

As shown in Sect. 4.1.1, biomaterials can play a quite substantial role in terms of avoiding the crossing of a climatic target level in the RCP3PD scenario. In the case that the RCP6 scenario applies, biomaterials can also have a noteworthy contribution to postponing the crossing of the 450-ppm CO_2e target level for 50 years, thus buying time, as shown in Sect. 4.1.2.

For the potential to buy time, this should not be considered a way to push impacts to later, which would be contradicting to sustainability agendas on intergenerational equality/rights to meet their needs. Rather, it should be seen as a limited extension of time to react to the threat of crossing critical climatic target levels, by developing and implementing additional measures for climate change mitigation, or at least adaptation, to avoid the most critical impacts. This would be in the interest of both current and future generations.

While the storage potential in long-lived biopolymers alone does not provide sufficient mitigation potential to avoid or postpone the crossing of the target level of 450 ppm CO_2e in the respective scenarios, temporary carbon storage in other biomaterials, substituting current petrochemical based materials, can further add to the mitigation potential. Thus, biomaterials could be part of the solution for avoiding the crossing of a climatic target level of 450 ppm CO_2e, giving the temporary storage of carbon in biomaterials a clear mitigating value in terms of the impacts of man-made climate change.

One important aspect of biobased production is the need for land. According to results from Bos et al. (2012), the land use for producing 1 t biobased PE varies between ~0.34 ha, if sugar cane is used as feedstock, and just below or above 0.6 ha if using miscanthus or maize, respectively. Comparing these numbers to the current global polymer demand, the substitution of all polymers with biobased ones does not seem unrealistic in terms of land requirements (while PE is the most abundant polymer today, a large part of global polymer production of course comes from other polymer types; however, as the land requirement of PE is rather high, e.g. nearly three times higher than that of polylactic acid (Bos et al. 2012), it seems reasonable to assume that the required land for biopolymers on average will likely not be much higher).

Another aspect connected to land use and land use change of biomass production is the potential change in biogenic carbon stocks, including soil organic carbon, as well as surface albedo on the land (see, e.g. Bright et al. 2012; Cherubini et al. 2012; Jørgensen et al. 2014a). It is of course important to include all relevant GHG emissions and changes in biogenic carbon stocks in the CTP assessment, just as it is for the GWP. The inclusion of climate change impacts from surface albedo change is likewise important; however, the application of the CTP approach for this aspect requires further elaboration,

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[1] Note the notation of the unit, for clearly illustrating over which period the CO_2e is determined. Such notation is here suggested to always be used when giving CO_2e for a certain integrated period, rather than instant equivalence in terms of specific radiative forcing, to avoid misunderstanding.

which is beyond the scope of this paper. On a qualitative note, it may be mentioned that such impacts may be influential for the results, and that the influence can go in both directions leading to both increasing and decreasing atmospheric GHG concentrations depending on the conditions. It is thus important that the increased biobased production is done in a sustainable way, not decreasing existing carbon stocks or changing the surface albedo in a way that counteracts the potential climate change mitigation value from the temporary carbon storage in biomaterials.

6 Conclusions

Temporary carbon storage in biomaterials has the potential for playing a noteworthy role in mitigating climate change, in terms of avoiding or postponing (depending on the GHG concentration development scenario) the crossing of a climatic target level of, e.g. 450 ppm CO_2e and thus the related predicted tipping point damages. However, the potential mitigation value is highly dependent on the timing of sequestration and re-emission of carbon relative to the target time, and re-emission before the target time even increases the CTP impact rather than mitigating it.

By including the CTP approach with the adjustment for temporary carbon storage in environmental impact assessment, the potential benefit from temporary carbon storage in biomaterials can be included in their environmental profile, and the different potentials from different biomaterials and different feedstock use etc. can be distinguished. As CTP characterisation factors for temporary carbon storage for all storage durations at different sequestration times are given for the two GHG concentration development scenarios, this can be directly included in LCA. This should be seen as supplement to the long-term climate change impact assessment given by the GWP, which clearly has a different role than the CTP, as it gives the same value for all storage durations and thus does not account for the potential value of the temporary carbon storage in terms of avoiding a critical climatic target level. This emphasizes the value of including the CTP, for inclusion of that important aspect.

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