

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

Jørgensen, Susanne Vedel; Hauschild, Michael Zwicky; Nielsen, Per H.

Published in: International Journal of Life Cycle Assessment

Link to article, DOI: 10.1007/s11367-015-0845-3

Publication date: 2015

Document Version Peer reviewed version

Link back to DTU Orbit

Citation (APA):

Jørgensen, S. V., Hauschild, M. Z., & Nielsen, P. H. (2015). The potential contribution to climate change mitigation from temporary carbon storage in biomaterials. *International Journal of Life Cycle Assessment, 20*(4), 451-462. https://doi.org/10.1007/s11367-015-0845-3

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.

- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.



23 climatic target level is reached increases the CTP value of the product compared to a situation with no storage of the product,

^{*} Corresponding author e-mail: suvjo@dtu.dk

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.

27 Conclusions Temporary carbon storage in biomaterials has a potential for contributing to avoid or postpone the crossing
28 of a climatic target level of 450 ppm CO₂e, depending on GHG concentration development scenario. The potential
29 mitigation value depends on the timing of sequestration and re-emission of CO₂. The suggested CTP approach enables
30 inclusion of the potential benefit from temporary carbon storage in the environmental profile of biomaterials. This should be
31 seen as supplement to the long-term climate change impacts given by the global warming potential which does not account
32 for temporary aspects like benefits from non-permanent storage in terms of avoiding a critical climatic target level.

33

KEYWORDS: Climate change mitigation, Temporary carbon storage, Biomaterials, Climate Tipping Potential (CTP), Life
 cycle assessment (LCA)

36

37 **1 Introduction**

38 Climate change is a major environmental concern of today and mitigation options are high on the global political agenda. 39 Besides the general importance of limiting long-term climate change impacts, there are climatic 'target levels' which are 40 important to stay below (see e.g. Jørgensen et al. 2013a). This is due to the predicted existence of so-called tipping points for 41 our climate system, the crossing of which will lead to dramatic/structural changes in the climate system that may be 42 irreversible (Meehl et al. 2007; Hansen et al. 2008). Mitigating climate change is thus both highly important and very urgent, 43 and different options for climate change mitigation are currently being explored, including different ways to decrease CO₂ 44 emissions. There is currently no consensus on how to assess the potential climate change mitigation value of this temporary 45 carbon storage in life cycle assessment (LCA) (Brandão et al. 2012, Jørgensen and Hauschild 2013, Guest et al. 2013). 46 Temporary storage of carbon in products makes little difference in terms of long-term climate change, so the value in terms 47 of climate change mitigation is if the temporary carbon storage can help avoiding the passing of climate tipping points 48 (Jørgensen and Hauschild 2013). Either through offering a bridging potential to a future with lower atmospheric greenhouse 49 gas (GHG) concentration, thereby avoiding crossing the target level, or at least postponing it, thus buying time to allow 50 lasting climate change mitigation and/or adaption solutions to be implemented. As a supplement to assessing long-term 51 climate change impacts using the GWP, Jørgensen et al. (2013a) propose a method to assess the Climate Tipping Potential, 52 CTP, based on the contributions of GHG emissions to the crossing of climate tipping points. The CTP method can also be 53 used for estimating the climate change mitigation value of carbon storage in terms of its potential for helping avoiding 54 passing of such tipping points. However, being developed for estimating the short term climate change impacts of GHG 55 emissions, the current approach needs to be adapted to distinguish between the value of permanent carbon storage and that 56 of temporary carbon storage.

57 The paper provides recommendations on how to model carbon storage in products in LCA in order to include the potential 58 mitigation value relative to crossing critical climatic target levels, based on adaption of the newly developed CTP method 59 (Jørgensen et al. 2013a) and illustrates its use through case examples.

- 60
- 61 2 Method
- 62 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 two 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.

69

70 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 CO₂e has been chosen as target level here, as discussed by Jørgensen et al. (2013a). In the RCP3PD Scenario, the target level of 450 ppm CO₂e is only exceeded for a 24 years period (year 2034-2057; see Figure 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 Figure 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.

85 Fig. 1

86

87 2.3 The CTP approach

The CTP method proposed by Jørgensen et al. (2013a) 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 Equation (1):

91
$$CTP_{x,T}(t_e) = \frac{Impact_{x,T}(t_e)}{Capacity_T(t_e)} = \frac{\left(\frac{AGWP_{x,T}(t_e)}{A_{CO_2,ppm}}\right)}{\int\limits_{t=t_e}^{t=T} (C_T - C_t)dt}$$
(1)

Where $CTP_{x,T}(t_e)$ is the climate tipping potential measured in parts per trillion (ppt) of the remaining atmospheric capacity for receiving 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 CO₂ *per ppm* [Wm⁻²ppm CO₂ -¹], C_T is the target level concentration of atmospheric GHG, occurring at the target time [ppm CO₂e], and C_t is the concentration of atmospheric GHG at time t [ppm CO₂e] of the assumed GHG concentration scenario.

For CO₂, which requires a special expression to account for its complex atmospheric removal processes when calculating
the AGWP, Equation (1) takes the form of Equation (2):

99
$$CTP_{CO2,T}(t_e) = \frac{\left(\frac{A_{CO2}[a_0t + \sum_{i} a_i \alpha_i (1 - \exp(-t/\alpha_i))]}{A_{CO2,ppm}}\right)}{\int_{t=t_e}^{t=T} (C_T - C_t) dt}$$
(2)

Where A_{CO2} is the specific radiative forcing of $CO_2 per kg$ in the atmosphere [Wm⁻²kg⁻¹] and α and α are 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): $\alpha_0 = 0.217$, $\alpha_1 = 0.259$, $\alpha_2 = 0.338$, $\alpha_3 = 0.186$, $\alpha_1 = 172.9$ years, $\alpha_2 = 18.51$ years, $\alpha_3 = 1.186$ year.

104

105 2.4 Adapting the CTP approach to address temporary carbon storage

106 The CTP of a GHG emission reflects its impact in terms of contributing to the crossing of a climatic target level. 107 Therefore, impacts occurring after the time when the target level is exceeded are not included in the calculation of the 108 emission's CTP, but only assessed in terms of long-term climate change impacts using the GWP. This approach is 109 immediately compatible with permanent carbon storage, where uptakes are counted as negative emissions, with t_e in this case 110 being exchanged with the year of uptake and permanent storage, t_{st} of atmospheric CO₂. The logic derivation for this is to 111 subtract the CTP of the amount of CO₂ sequestered from the atmosphere by the biomass, at the time it occurs, from the CTP 112 at the time it is released. For storage of one kg of carbon at time t_{st} followed by its full release at time t_e , this is described by 113 Equation (3):

114 If $t_{st} < T$, then:

$$115 \quad CTP_{CO2Storage,T}(t_{st}, t_{e}) = \frac{\left(\int_{t=t_{e}}^{t=T} A_{CO2}[a_{0} + \sum_{i} a_{i} \exp(-t'/\alpha_{i})]dt'\right)}{\int_{t=t_{e}}^{t=T} (C_{T} - C_{t})dt} - \frac{\left(\int_{t=t_{st}}^{t=T} A_{CO2}[a_{0} + \sum_{i} a_{i} \exp(-t'/\alpha_{i})]dt'\right)}{A_{CO2,ppm}}$$
(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.

119 Using the CTP approach as given in Equation (3) means that all carbon storage will be given equal value to permanent 120 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.
- 129

130 In order to address those issues, the following steps have been performed for adjusting the CTP approach to the special 131 case of addressing temporary carbon storage:

• First, the duration of storage defined as having full benefit, τ , needs to be defined.

- 133 o In the case of the RCP3PD scenario, starting from year 2014, the storage needs to be at least 44 years to
 134 last beyond the period where the GHG level is above the target level, and preferably a few years more to
 135 have an increased capacity
- o 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
- 139 \circ For those reasons, we have chosen a duration of τ =50 years of storage as having full benefit using both 140 scenarios
- 141o In order to ensure consistency in the assessment using the two different scenarios, the value of buying time142is also reflected in the RCP3PD Scenario, which means the same method is used in both cases
- The increasing value of storage as the year of CO₂ uptake and storage approach T, is then represented automatically
 by the CTP approach, with uptake of CO₂ 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 years storage after T the CTP
 value of the storage is 1/5 the value of 50 years storage)
- 148 This is summarised in Equation (4), assuming that the temporarily stored carbon is sequestered from the atmosphere, and 149 later emitted again, in the form of CO₂:
- 150 If $t_{st} < T$:
- 151 If $t_e < T$: Equation (3) applies
- 152
- 153 If $t_e e T$:

$$154 \qquad CTP_{CO2,Storage,T}(t_{st},t_{e}) = \frac{n}{\tau} \left[\frac{\left(\int_{t=t_{e}}^{t=T} A_{CO2}[a_{0} + \sum_{i} a_{i} \exp(-t'/\alpha_{i})]dt' \right)}{A_{CO2,ppm}} - \frac{\left(\int_{t=t_{st}}^{t=T} A_{CO2}[a_{0} + \sum_{i} a_{i} \exp(-t'/\alpha_{i})]dt' \right)}{A_{CO2,ppm}} \right] - \frac{\int_{t=t_{st}}^{t=T} A_{CO2}[a_{0} + \sum_{i} a_{i} \exp(-t'/\alpha_{i})]dt'}{A_{CO2,ppm}} \right]$$

155 (4)

156 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

 $157 \quad \text{ period of } \tau \ .$

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

162

163 **3 Temporary carbon storage case scenarios**

164 All product level cases are based on products from biobased PE, with different lifetimes, to assess the impact of varying

165 storage durations. The GHG emissions from conversion of biobased PE to final products are not included, as that would

166 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 two years including the time from carbon sequestration in the biomass until disposal, assuming 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.

172 An example of long-term storage is building and construction materials from biomass-based PE with a lifetime in the 173 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).

179

180 3.1 Production of biobased PE

181 Biobased PE can be produced from different feedstocks. In the cases addressed here, results are calculated for three 182 different biomass feedstocks; miscanthus, sugar cane and maize. The modelling of GHG emissions from the conversion over 183 fermentable sugar yield to PE from the three types of biomass is based on current agricultural practice represented in data 184 from Bos et al. (2012), which includes GHG savings from energy production from co-products to the extent that it is part of 185 current agricultural practice, as outlined in Table 1. This assumption in Bos et al. (2012) affects GHG results for the 186 biobased PE from the different biomass feedstocks. The purpose of presenting the hypothetic cases is to illustrate the use of 187 the newly developed CTP approach adjusted to assess temporary carbon storage in LCA, including life cycle GHG 188 emissions, and not to discuss the environmental performance of biobased PE produced from different biomass feedstocks.

189 Therefore, these assumptions are not important for the outcome of this article. Nevertheless, where the CTP results are 190 presented, a comment is included on how they would be affected if GHG savings due to the energy production from co-191 products were not included.

- 192
- **193 Table 1**
- 194
- **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.

200

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 Section 4.1.1 and 4.1.2, for the RCP3PD and the RCP6 Scenario, respectively.

204

205 4.1.1 The RCP3PD Scenario

206 For the case of the RCP3PD Scenario, which predicts crossing of the 450 ppm CO₂e target level in year 2034, and getting 207 back below in year 2058 as seen from Figure 1a), exceeding the target level could be avoided if GHG emissions contributing 208 to the presence of GHGs in the atmosphere during that period are reduced. The amount of carbon emission that needs to be 209 avoided can be estimated as the amount of C present in the atmosphere that corresponds to the atmospheric CO_2 210 concentration that is above the target level. The revised Bern carbon cycle model (see Forster et al. 2007) allows estimating 211 how much of the carbon, if emitted as CO₂, would be removed from the atmosphere again over time by the global carbon 212 cycle processes. Due to those atmospheric CO_2 removal processes, the sequestration in biomass of x kg atmospheric CO_2 in 213 one year, will mean that the hereby induced reduction in atmospheric GHG concentration, compared to leaving the x kg CO₂ 214 in the atmosphere, will in the following years decrease and thus be less than x kg CO₂. Thus the revised Bern carbon cycle 215 removals need to be accounted for when estimating the amount of carbon in the atmosphere over time which should be 216 avoided, as done in Online Resource 1.

The value of temporary carbon storage in biomaterials in terms of avoiding exceeding the climatic target level of 450 ppm CO₂e 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. E.g. 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 reemission 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 CO₂) from 2034 until 2057. In many years, it could even account for more than the total amount, as shown in Figure 2 (details on calculations can be seen in Online Resource 1).

- 242
- 243 Fig. 2

244

The estimates given in Figure 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.

4.1.2 The RCP6 Scenario

251 Contrary to the RCP3PD Scenario, the GHG concentrations in the RCP6 Scenario keep increasing towards year 2100 as 252 shown in Figure 1b), and so does the amount of carbon emission that must be avoided to stay below 450 ppm CO2e as seen 253 in Figure 3. In this case the potential benefit of temporary carbon storage lies in buying time up to a maximum of 50 years 254 (as described in Section 2.4). Similar as for the RCP3PD Scenario, amounts of GHG to be avoided to avoid crossing 450 255 ppm are calculated as shown in the Online Resource 1, Table O2 and the resulting values are given in Figure 3. The 256 mitigation potential of long-term storage in biopolymers is 10-28% each year, except for the first year, where it is 90%, as 257 the target level is only slightly exceeded that year according to the RCP6 Scenario.

258

- 259 Fig. 3
- 260

261 4.2 Adjusted CTP approach for addressing temporary carbon storage

While Section 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 CO₂e 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 Equation (4). Using this gives the temporary carbon storage CTP characterisation factors shown in Figure 4a) and 4b), for the RCP3PD mitigation GHG concentration scenario and the RCP6 medium target level GHG concentration scenario, respectively.

268



270

Figure 4a) and 4b) illustrate 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 years and 50 years for all CO₂ uptake times from present until the target time T are shown for both presented scenarios in the Online Resource 2.

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 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 281 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

283 year.

284

285 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 Section 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.

291 CTP impacts of lifecycle GHG emissions other than the temporarily stored carbon are calculated using CTP 292 characterisation factors for GHG emissions from Jørgensen et al. (2013a). Results are shown as function of time of carbon 293 sequestration in Figure 5.

294

```
295 Fig. 5
```

296

297 At a first glance, results may seem a bit complex, as impacts do not follow a simple pattern as function of storage 298 duration, timing of sequestration or feedstock type. This is due to the merging of two aspects, the temporary carbon storage 299 part and the life cycle GHG impacts, which vary differently with those parameters. Disregarding the life cycle impacts, 300 results could be extracted directly from Figure 4, which shows a more homogenous picture in terms of trends. As shown in 301 Figure 4, temporary carbon storage gives a CTP saving if the carbon is stored beyond the target time, but increases CTP 302 impacts if carbon is released again before the target time. This is why biobased PE products with short- and medium-term 303 lifetimes in some cases have high CTP impacts, while in other cases show CTP savings, depending on the timing of the 304 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 Figure 5 are thus negative if there is a net mitigation of climate tipping potential, e.g. when the CTP saving 311 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.

313 In the long-term storage case, CTP values are all negative, and increasingly so, the closer to the target time the storage 314 starts, as the capacity left is then smaller and the urgency of action for avoiding the target level therefore more critical. 315 If, on the other hand, no energy was produced from by-products, that would give net GHG emissions from producing bio-316 PE from all three feedstocks considered here, leading to CTP impacts for bio-PE in all the cases addressed in Figure 5. 317 CTP values are similar for the two GHG concentration scenarios in most cases, with a higher numeric trend for the 318 peaking scenario (RCP3PD). For the biobased PE products with short-term storage however, there are some obvious 319 differences for the case of carbon sequestration in year 2030, which is due to the different target times of the two scenarios. 320 The impact of a GHG depends on the time it resides in the atmosphere before the target time, meaning that in Scenario 321 RCP3PD where the target time occurs two years later than in the RCP6 Scenario, the impact of a GHG emissions in a given 322 year will be a little higher for the RCP3PD Scenario. The same is true in the case of a mitigation value from carbon 323 sequestration in a given year. Further, due to the differences in the pathways of the two scenarios, the remaining capacity in 324 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 325 emission/sequestration in the RCP3PD Scenario than in the RCP6 Scenario in a given year (except in year 2031, which is the 326 last year before T in the RCP6 Scenario).

327 Using the CTP approach without the adaption for temporary storage would give the same results as here for emissions 328 before the target level and for emissions with at least 50 years storage, as inherent in the derivation using 50 years as τ (i.e. 329 Equation (4)).

330

5 Discussion

332 5.1 The adapted CTP approach for temporary carbon storage

333 The developed approach reflects that emission before the target level is always worse than after, and thus that temporary 334 carbon storage pushing impacts beyond the target time, T, should always be of value in terms of mitigating climate change. 335 However, this means that a gradual decrease of impacts after the target time is not possible, as later emission might then be 336 worse than earlier. Consequently, emissions in year T-1 will have large impact whereas emissions one year later will have no 337 impact. Likewise, using the method directly, all uptakes of carbon just before T will yield large benefits, regardless of when 338 it is reemitted. For including the aspect that short-term storage (e.g. just a few years) does not have the same value as 339 permanent storage, the gradual valuation in terms of length of storage has been introduced as described in Section 2. This is 340 necessary in order to give fair weighting to storage of different lengths, as storage for just a few years has accordingly less 341 potential for 'buying' time than long-term storage. This is in line with the fact that pushing emissions a few years ahead will 342 not have much real value in terms of avoiding tipping points, but at the most just push the target year. 343 While further elaboration is possible, the presented method fulfils the task of showing the value of temporary carbon 344 and the presented method fulfils the task of showing the value of temporary carbon

- 344 storage in terms of only yielding a value if pushing impacts beyond the target level, thus buying time, and giving value 345 gradually in terms of length of the time bought.
- 346

347 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 Section 2.4.

353

354 5.3 Difference between CTP and GWP

355 The CTP results from Section 4.3 can be seen to differ a lot for the different cases. In contrast, GWP₁₀₀ for the same

356 biobased PE production is constant and independent on sequestration year, production year and storage duration, as GWP₁₀₀

357 is a static measure aimed at long-term assessment and not taking into account storage and emissions timing. GWP₁₀₀ per ton

358 miscanthus, sugar cane and maize based PE in the three cases is thus $-1789 \text{ kg } \text{CO}_{2}e_{100}^{\dagger}$, $-1042 \text{ kg } \text{CO}_{2}e_{100}$ and 3031 kg

359 CO₂e₁₀₀, respectively, irrespective of the duration of the temporary carbon storage.

360

361 5.4 The potential contribution of carbon storage in biomaterials for mitigating climate change

As shown in Section 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 Section 4.1.2.

[†] Note the notation of the unit, for clearly illustrating over which period the CO₂e is determined. Such notation is here suggested to always be used when giving CO₂e for a certain integrated period, rather than instant equivalence in terms of specific radiative forcing, to avoid misunderstanding.

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 CO₂e 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 CO₂e, 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).

383 Another aspect connected to land use and land use change of biomass production is the potential change in biogenic 384 carbon stocks, including soil organic carbon, as well as surface albedo on the land (see e.g. Bright et al. 2012; Cherubini et 385 al. 2012: Jørgensen et al. 2013b). It is of course important to include all relevant GHG emissions and changes in biogenic 386 carbon stocks in the CTP assessment, just as it is for the GWP. The inclusion of climate change impacts from surface albedo 387 change is likewise important; however the application of the CTP approach for this aspect requires further elaboration, 388 which is beyond the scope of this paper. On a qualitative note, it may be mentioned that such impacts may be influential for 389 the results, and that the influence can go in both directions leading to both increasing and decreasing atmospheric GHG 390 concentrations depending on the conditions. It is thus important that the increased biobased production is done in a 391 sustainable way, not decreasing existing carbon stocks or changing the surface albedo in a way that counteracts the potential 392 climate change mitigation value from the temporary carbon storage in biomaterials.

393

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 reemission before the target time even increases the CTP impact rather than mitigating it.

400 By including the CTP approach in the environmental impact assessment, the potential benefit from temporary carbon 401 storage in biomaterials can be included in their environmental profile, and the different potentials from different biomaterials 402 and different feedstock use etc. can be distinguished. As CTP characterisation factors for all storage durations at different 403 sequestration times are given for the two GHG concentration development scenarios, this can be directly included in LCA. 404 This should be seen as supplement to the long-term climate change impact assessment given by the GWP, which clearly has 405 a different role than the CTP, as it gives the same value for all storage durations and thus does not account for the potential 406 value of the temporary carbon storage in terms of avoiding a critical climatic target level. This emphasizes the value of 407 including the CTP, for inclusion of that important aspect.

408

409 Acknowledgments

This paper has been written as part of an industrial PhD project which is co-funded by the Danish Agency for Science,Technology and Innovation.

412

413 References

Bos HL, Meesters KPH, Conijn SG, Corré WJ, Patel MK (2012) Accounting for the constrained availability of land: a comparison of bio-based ethanol, polyethylene, and PLA with regard to non-renewable energy use and land use. Biofuels,

416 Bioprod. Bioref. 6: 146–158

- 417 Brandão M, Levasseur A, Kirschbaum MUF, Weidema BP, Cowie AL, Jørgensen SV, Hauschild MZ, Pennington DW,
- 418 Chomkhamsri K (2012) Key issues and options in accounting for carbon sequestration and temporary storage in life cycle

419 assessment and carbon footprinting. Int J Life Cycle Assess 18:230-240

420 Bright RM, Cherubini F, Strømman AH (2012) Climate impacts of bioenergy: Inclusion of carbon cycle and albedo

- 421 dynamics in life cycle impact assessment. Environ Impact Asses Rev 37: 2-11
- 422 Cherubini F, Bright RM, Strømman AH (2012) Site-specific global warming potentials of biogenic CO₂ for bioenergy:
- 423 contributions from carbon fluxes and albedo dynamics. Environ Res Lett 7: 045902 (11pp)
- 424 EPA (2013a) Clean Energy, Calculations and References. Accessible at: <u>http://www.epa.gov/cleanenergy/energy-</u>
- 425 <u>resources/refs.html</u> (accessed December 21 2013)

- 426 EPA (2013b) National Greenhouse Gas Emissions Data. Energy. Inventory of U.S. Greenhouse Gas Emissions and Sinks
- 427 1990-2011. Accessible at: <u>http://www.epa.gov/climatechange/ghgemissions/usinventoryreport.html</u> (accessed December 21
- 428 2013)
- 429 Forster P, Ramaswamy V, Artaxo P, Berntsen T, Betts R, Fahey DW, Haywood J, Lean J, Lowe DC, Myhre G, Nganga J,
- 430 Prinn R, Raga G, Schulz M, Van Dorland R (2007) Changes in Atmospheric Constituents and in Radiative Forcing. In:
- 431 Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate Change 2007 The
- 432 Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel
- 433 on Climate Change. Cambridge University Press: Cambridge, U.K. and New York, NY, USA
- 434 Fujino J, Nair R, Kainuma M, Masui T, Matsuoka Y (2006) Multi-gas mitigation analysis on stabilization scenarios using
- 435 AIM global model. Multigas Mitigation and Climate Policy. The Energy Journal Special Issue
- 436 Guest G, Cherubini F, Strømman, AH (2013) Global warming potential of carbon dioxide emissions from biomass stored
- 437 in the anthroposphere and used for bioenergy at end of life. J Indust Ecol 17:20-30
- 438 Hansen J, Sato M, Kharecha P, Beerling D, Berner R, Masson-Delmotte V, Pagani M, Raymo M, Royer DL, Zachos JC
- 439 (2008). Target atmospheric CO₂: Where should humanity aim? Open Atmospheric Science Journal 2:217-231
- Harmsen P, Hackmann M (2013) Green building blocks for biobased plastics. Wageningen UR. Accessible at:
 http://www.groenegrondstoffen.nl/Serie GG.html (accessed December 21 2013)
- Jørgensen SV, Cherubini F, Michelsen O (2013b; submitted) Biogenic CO2 fluxes, changes in surface albedo and biodiversity impacts from establishment of a miscanthus plantation. Submitted to: J Environ Manag
- 444 Jørgensen SV, Hauschild MZ (2013) Need for Relevant Timescales when Crediting Temporary Carbon Storage. Int J Life
- 445 Cycle Assess 18:747-754
- Jørgensen SV, Hauschild MZ, Nielsen PH (2013a) Assessment of urgent impacts of greenhouse gas emissions
 the climate tipping potential (CTP). Int J Life Cycle Assess. doi: 10.1007/s11367-013-0693-y
- 448 Meehl GA, Stocker TF, Collins WD, Friedlingstein p, Gaye AT, Gregory JM, Kitoh A, Knutti R, Murphy JM, Noda A,
- 449 Raper SCB, Watterson IG, Weaver AJ, Zhao ZC (2007) Global Climate Projections. In: Solomon S, Qin D, Manning M,
- 450 Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate Change 2007 The Physical Science Basis.
- 451 Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.
- 452 Cambridge University Press: Cambridge, UK and New York, NY, USA, pp 747-845
- 453 Meinshausen M, Smith SJ, Calvin K, Daniel JS, Kainuma MLT, Lamarque J-F, Matsumoto K, Montzka SA, Raper SCB,
- 454 Riahi K, Thomson A, Velders GJM, van Vuuren DPP (2011) The RCP greenhouse gas concentrations and their extensions
- 455 from 1765 to 2500. Climatic Change 109:213-241

456 PlasticsEurope (2011) Plastics - the Facts 2011, An analysis of European plastics production, demand and recovery for

457 2010. Accessible http://www.plasticseurope.org/documents/document/20111107101127at: 458

final pe factsfigures uk2011 lr 041111.pdf (accessed April 9, 2013)

459 van Vuuren, D, den Elzen M, Lucas P, Eickhout B, Strengers B, van Ruijven B, Wonink S, van Houdt R (2007)

460 Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs. Climatic Change

461 81:119-159

462

463 Table 1 Uptake and release of GHGs over time from sequestration to release R years later for 1 t biobased PE produced from various 464 feedstocks according to current agricultural practice. Data for GHG emissions from biobased PE production (cradle to gate) from different 465 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	-3138	-3138	-3138
	biobased PE product			
	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
^d CO ₂ emi	issions are estimated from original data given as GJ non-renewable end oil as the NREU source, with conversion factors of 0.43 tCO ₂ /barrel a	ergy use (NREU)/to	on biobased PE, co	nverted to CO_2e
assuming	oil as the NREU source, with conversion factors of 0.43 tCO ₂ /barrel a	nd 5.8 mmBtu/barr	el (EPA 2013a), as	s well as 0.9478
e The stor	age in the biomass starts from the time of sequestration, that is year 1	and continues throu	19h the life time of	f the product
^f As the p	roducts are assumed incinerated at their end-of-life, all carbon stored in	n the biomass will b	be released as CO ₂	The product
F	,,, _			
Fig. 1 Ex	Excess atmospheric GHG concentrations (grey hatched area) above the level of 450 ppm CO ₂ e (grey punctured line) in the fut			
following	ving a) the peak and decline scenario (RCP3PD) (Meinshausen et al. (2011) and van Vuuren et al. (2007)) and b) the continu-			
increase s	crease scenario (RCP6) (Meinshausen et al. (2011) and Fujino et al. (2006))			

Fig. 2 Additional CO₂ 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 CO₂e, 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 CO₂ in the period

485

Fig. 3 Additional CO₂ 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 CO₂e, 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 CO₂ in the period

490

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

494

495 Fig. 5 CTP of temporary carbon storage in one t biobased PE products of varying durations (short: 2 years, medium: 10 years, long: above 496 50 years), and different years of carbon sequestration in biomass, including life cycle GHG impacts for current agricultural practice as 497 outlined in Section 3, for three different feedstock crops, using a) the RCP3PD Scenario and b) the RCP6 Scenario













