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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 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,

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24 whereas storage extending beyond the time where the climatic target level is predicted to be crossed according to the GHG
25 concentration scenarios contributes with negative CTP values, which means mitigation. The longer the duration of the
26 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

34 **KEYWORDS:** Climate change mitigation, Temporary carbon storage, Biomaterials, Climate Tipping Potential (CTP), Life
35 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

63 The geographical scope of the assessment is global, and while the focus is on temporary storage of carbon, the life cycle
64 emissions of both CO₂ and other GHGs are considered where relevant. Temporary carbon storage is here defined as carbon
65 sequestered from atmospheric CO₂, which is temporarily stored and later emitted again as CO₂.

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

69

70 2.2 Atmospheric GHG concentration scenarios

71 Two development scenarios of future atmospheric GHG concentrations are assumed in the assessment; one predicting a
72 peak and decline and one predicting a continuous increase. The two scenarios are the RCP3PD and the RCP6 scenarios of
73 the so-called Representative Concentration Pathway (RCP) scenarios (Meinshausen et al. 2011). The RCP3PD is a
74 mitigation scenario with a peak radiative forcing level of 3 Wm⁻², followed by a decline, so the radiative forcing level in year
75 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.
76 Both scenarios are made available by Meinshausen et al. (2011), based on background data from van Vuuren et al. (2007)
77 and Fujino et al. (2006), respectively.

78 An atmospheric GHG concentration of 450 ppm CO₂e has been chosen as target level here, as discussed by Jørgensen et
79 al. (2013a). In the RCP3PD Scenario, the target level of 450 ppm CO₂e is only exceeded for a 24 years period (year 2034-
80 2057; see Figure 1a) and can thus be bridged if avoiding that temporary overrun, meaning that storage of enough carbon for
81 a sufficiently long period of time has bridging potential in this case. In the RCP6 scenario, with continuously increasing
82 GHG concentrations until year 2100 (see Figure 1b), the potential benefit of temporary carbon storage lies in buying time,
83 by postponing the crossing of the target level, as bridging is not possible.

84

85 **Fig. 1**

86

87 2.3 The CTP approach

88 The CTP method proposed by Jørgensen et al. (2013a) describes the marginal contribution of GHG emissions to the
89 passing of critical climate tipping points. It expresses the impact of each GHG emission relative to the available capacity of
90 the atmosphere to take up additional GHGs before crossing a certain climate level through Equation (1):

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

92 Where $CTP_{x,T}(t_e)$ is the climate tipping potential measured in parts per trillion (ppt) of the remaining atmospheric capacity
93 for receiving GHGs without crossing the target level (ppt_{rc}) $AGWP_{x,T}(t_e)$ is the absolute global warming potential of GHG x
94 between emission time t_e [year], and target time T [year], $A_{CO_2,ppm}$ is the specific radiative forcing of CO_2 per ppm [$Wm^{-2}ppm$
95 CO_2^{-1}], C_T is the target level concentration of atmospheric GHG, occurring at the target time [ppm CO_2e], and C_t is the
96 concentration of atmospheric GHG at time t [ppm CO_2e] of the assumed GHG concentration scenario.

97 For CO_2 , which requires a special expression to account for its complex atmospheric removal processes when calculating
98 the AGWP, Equation (1) takes the form of Equation (2):

$$99 \quad CTP_{CO_2,T}(t_e) = \frac{\left(\frac{A_{CO_2} [a_0 t + \sum_i a_i \alpha_i (1 - \exp(-t / \alpha_i))] }{A_{CO_2,ppm}} \right)}{\int_{t=t_e}^{t=T} (C_T - C_t) dt} \quad (2)$$

100 Where A_{CO_2} is the specific radiative forcing of CO_2 per kg in the atmosphere [$Wm^{-2}kg^{-1}$] and \mathbf{a} and α are coefficients and
101 time constants for the removal processes that are active in the IPCC decay function for CO_2 in the atmosphere according to
102 the revised Bern carbon cycle model (Forster et al. 2007): $\mathbf{a}_0 = 0.217$, $\mathbf{a}_1 = 0.259$, $\mathbf{a}_2 = 0.338$, $\mathbf{a}_3 = 0.186$, $\alpha_1 = 172.9$ years,
103 $\alpha_2 = 18.51$ 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:

$$115 \quad CTP_{CO_2 Storage, T}(t_{st}, t_e) = \frac{\left(\frac{\int_{t=t_e}^{t=T} A_{CO_2} [a_0 + \sum_i a_i \exp(-t'/\alpha_i)] dt'}{A_{CO_2, ppm}} \right)}{\int_{t=t_e}^{t=T} (C_T - C_t) dt} - \frac{\left(\frac{\int_{t=t_{st}}^{t=T} A_{CO_2} [a_0 + \sum_i a_i \exp(-t'/\alpha_i)] dt'}{A_{CO_2, ppm}} \right)}{\int_{t=t_{st}}^{t=T} (C_T - C_t) dt} \quad (3)$$

116 Equation (3) can be applied to different amounts of carbon stored and later emitted, also in the case where not all stored
 117 carbon is emitted at the same time, by splitting the stored carbon into fractions and applying the respective emission time for
 118 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.

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

- 124 • The value assigned to the temporary carbon storage beyond the target time T should increase with storage duration
 125 up to a period that is defined as comparable in value to permanent storage, regarding the avoidance of crossing
 126 the climatic target level (but not in terms of the long-term climate change impacts).
- 127 • The adjusted CTP approach to assess temporary carbon storage beyond the target time should be compatible with
 128 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:

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

- 133 ○ 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
- 136 ○ In the case of the RCP6 Scenario, the value lies in buying time, which means that the storage time needs to
 137 be sufficient for implementing lasting solutions for mitigating climate change and/or adapting to the
 138 changes to mitigate the most dramatic impacts
- 139 ○ For those reasons, we have chosen a duration of $\tau=50$ years of storage as having full benefit using both
 140 scenarios
- 141 ○ In order to ensure consistency in the assessment using the two different scenarios, the value of buying time
 142 is also reflected in the RCP3PD Scenario, which means the same method is used in both cases
- 143 • The increasing value of storage as the year of CO₂ uptake and storage approach T, is then represented automatically
 144 by the CTP approach, with uptake of CO₂ being treated as negative emissions
 - 145 • The value of the storage, for all temporary carbon storages which end after T, is calculated from the full storage
 146 CTP value multiplied by the ratio between the storage period and τ (e.g. for 10 years storage after T the CTP
 147 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 $t_e \in T$:

$$154 \quad CTP_{CO_2, Storage, T}(t_{st}, t_e) = \frac{n}{\tau} \left[\frac{\int_{t=t_e}^{t=T} A_{CO_2} [a_0 + \sum_i a_i \exp(-t'/\alpha_i)] dt'}{A_{CO_2, ppm}} - \frac{\int_{t=t_{st}}^{t=T} A_{CO_2} [a_0 + \sum_i a_i \exp(-t'/\alpha_i)] dt'}{A_{CO_2, ppm}} \right] \frac{\int_{t=t_e}^{t=T} (C_T - C_t) dt}{\int_{t=t_{st}}^{t=T} (C_T - C_t) dt}$$

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 period of τ .

158 This approach satisfies the requirements presented above and supports application together with the regular CTP for
159 assessing climate tipping potential of GHG emissions. The adapted CTP characterisation factors for temporary carbon
160 storage are shown in Figure 4 in Section 4, and applied to three case scenarios with different storage durations and different
161 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.

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

170 A medium-term case example is biomass-based PE materials used in the automotive industry, with a carbon storage period
171 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.

174 The cases are hypothetical and created to provide simple illustrations of the use of the CTP approach for temporary carbon
175 storage. PE is the polymer produced in the largest amounts globally, and currently 39% of the European production is used
176 for packaging, while 21% is used in building and constructing and 8% is used in the automotive industry (PlasticsEurope
177 2011). While the main part of the polymer production is still petrochemically based, biobased PE as produced today can be
178 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 hypothetical 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

195 **4 Results**

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

200

201 4.1 Climate change mitigation potential of temporary carbon storage in biopolymers

202 The aspect of potential mitigation value of biomaterials in terms of avoiding the climatic target level of 450 ppm is
203 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 CO_{2e} 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 CO₂
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 CO₂ removal processes, the sequestration in biomass of x kg atmospheric CO₂ 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.

217 The value of temporary carbon storage in biomaterials in terms of avoiding exceeding the climatic target level of 450 ppm
218 CO_{2e} can be estimated as its fraction of the estimated amount of carbon emission that must be avoided as described above.

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

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

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

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

238 Assuming an average carbon mass content of the polymers of 77% the carbon storage in construction biopolymers could
239 account for at least 26% of the total mass of carbon that must be avoided emitted each year (as CO₂) from 2034 until 2057.
240 In many years, it could even account for more than the total amount, as shown in Figure 2 (details on calculations can be
241 seen in Online Resource 1).

242

243 **Fig. 2**

244

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

249

250 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

262 While Section 4.1.1 and 4.1.2 illustrated that there is a noteworthy potential of temporary carbon storage in biomaterials to
263 contribute to avoiding/postponing the crossing of the 450 ppm CO₂e target level, this potential is currently not included in
264 LCIA. A possibility of expressing this value is introduced by the adapted CTP approach to incorporate temporary carbon
265 storage as described by Equation (4). Using this gives the temporary carbon storage CTP characterisation factors shown in
266 Figure 4a) and 4b), for the RCP3PD mitigation GHG concentration scenario and the RCP6 medium target level GHG
267 concentration scenario, respectively.

268

269 **Fig. 4**

270

271 Figure 4a) and 4b) illustrate the development in CTP of temporary carbon storage as function of time of sequestration for
272 selected storage periods. CTP characterisation factors for storage periods between 2 years and 50 years for all CO₂ uptake
273 times from present until the target time T are shown for both presented scenarios in the Online Resource 2.

274 While the trends of the CTP values for the two scenarios are similar, the timing and the size of CTP values differ. It is
275 obvious from the figures that the timing of the CO₂ uptake and storage, and later emission, is decisive for the potential value
276 of temporary carbon storage. Temporary carbon storage for relatively short periods ending before the target time T will have
277 a positive net climatic tipping potential, rather than a mitigation value, as the atmospheric capacity is critically declining
278 close to the target level, and avoiding GHG emissions thus becomes more urgent. This means that for storage that begins the
279 same year and ends before the target year, longer storage durations will result in higher CTP values for a given sequestration
280 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
282 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

286 Using the adjusted CTP approach the mitigation value of temporary carbon storage in biomaterials in terms of avoiding
287 crossing the climatic target level of 450 ppm CO₂e can be estimated. Here this is done for the three case examples with
288 different storage durations and different biomass feedstocks, as defined in Section 3. The purpose of these hypothetical case
289 examples is to illustrate the potential and consequences of using the newly developed CTP approach to assess temporary
290 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.

305 What further differentiates the results is that for miscanthus and sugar cane there is a net GHG saving in the production
306 year due to energy surplus production from by-products, whereas for maize there is a net GHG emission from the production
307 as more energy is used for producing bio-PE from maize, than the energy produced from by-products, according to current
308 agricultural practice (Bos et al. 2012). GHG emission savings always lead to negative CTP values (savings), while GHG
309 emissions lead to positive values, but the magnitude depends again on the timing of the emissions relative to the target time.

310 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
312 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

331 **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 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

348 The sensitivity of the approach to the choice of the parameter τ is straightforward, as the temporary storage value varies
349 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
350 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
351 rather important for the outcome and should be chosen carefully. The proposed choice of a τ value of 50 years is based on
352 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, GWP_{100} for the same
356 biobased PE production is constant and independent on sequestration year, production year and storage duration, as GWP_{100}
357 is a static measure aimed at long-term assessment and not taking into account storage and emissions timing. GWP_{100} per ton
358 miscanthus, sugar cane and maize based PE in the three cases is thus $-1789 \text{ kg CO}_2\text{e}_{100}^\dagger$, $-1042 \text{ kg CO}_2\text{e}_{100}$ and 3031 kg
359 $\text{CO}_2\text{e}_{100}$, 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

362 As shown in Section 4.1.1, biomaterials can play a quite substantial role in terms of avoiding the crossing of a climatic
363 target level in the RCP3PD Scenario. In the case that the RCP6 Scenario applies, biomaterials can also have a noteworthy
364 contribution to postponing the crossing of the 450 ppm CO_2e target level for 50 years, thus buying time, as shown in Section
365 4.1.2.

[†] 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.

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

371 While the storage potential in long-lived biopolymers alone does not provide sufficient mitigation potential to avoid or
372 postpone the crossing of the target level of 450 ppm CO_{2e} in the respective scenarios, temporary carbon storage in other
373 biomaterials, substituting current petrochemical based materials, can further add to the mitigation potential. Thus
374 biomaterials could be part of the solution for avoiding the crossing of a climatic target level of 450 ppm CO_{2e}, giving the
375 temporary storage of carbon in biomaterials a clear mitigating value in terms of the impacts of man-made climate change.

376 One important aspect of biobased production is the need for land. According to results from Bos et al. (2012), the land use
377 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
378 using miscanthus or maize, respectively. Comparing these numbers to the current global polymer demand, the substitution
379 of all polymers with biobased ones does not seem unrealistic in terms of land requirements (while PE is the most abundant
380 polymer today, a large part of global polymer production of course comes from other polymer types; however as the land
381 requirement of PE is rather high, e.g. nearly three times higher than that of polylactic acid (Bos et al. 2012), it seems
382 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

394 **6 Conclusions**

395 Temporary carbon storage in biomaterials has the potential for playing a noteworthy role in mitigating climate change, in
396 terms of avoiding or postponing (depending on the GHG concentration development scenario) the crossing of a climatic

397 target level of e.g. 450 ppm CO₂e and thus the related predicted tipping point damages. However, the potential mitigation
398 value is highly dependent on the timing of sequestration and re-emission of carbon relative to the target time, and re-
399 emission 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

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411 Technology and Innovation.

412

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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 biobased PE product	-3138	-3138	-3138
	N ₂ O 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

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

469 ^b Miscanthus is not yet produced in a large scale quantities as the other two feedstocks (Bos et al. 2012)

470 ^c Reported as CO₂-eq. in Bos et al. (2012), here converted back to N₂O emission using GWP₁₀₀ of N₂O: 298 CO₂-eq. (Forster et al. 2007)

471 ^d CO₂ emissions are estimated from original data given as GJ non-renewable energy use (NREU)/ton biobased PE, converted to CO₂e
 472 assuming oil as the NREU source, with conversion factors of 0.43 tCO₂/barrel and 5.8 mmBtu/barrel (EPA 2013a), as well as 0.9478
 473 mmBtu/GJ (EPA 2013b)

474 ^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

475 ^f As the products are assumed incinerated at their end-of-life, all carbon stored in the biomass will be released as CO₂

476

477 **Fig. 1** Excess atmospheric GHG concentrations (grey hatched area) above the level of 450 ppm CO₂e (grey punctured line) in the future,
 478 following a) the peak and decline scenario (RCP3PD) (Meinshausen et al. (2011) and van Vuuren et al. (2007)) and b) the continuous
 479 increase scenario (RCP6) (Meinshausen et al. (2011) and Fujino et al. (2006))

480

481 **Fig. 2** Additional CO₂ emissions that must be avoided each year in the period, provided that the avoided emissions needed for previous
482 years have been accomplished, in order to avoid exceeding the climatic target level of 450 ppm CO₂e, following the RCP3PD Scenario
483 (black bars). Grey negative bars show the potential role of temporary carbon storage in long-lived biopolymer products for removing
484 atmospheric CO₂ in the period

485

486 **Fig. 3** Additional CO₂ emissions that must be avoided each year in the period, provided that the avoided emissions needed for previous
487 years have been accomplished, in order to buy 50 years of extra time before exceeding the climatic target level of 450 ppm CO₂e,
488 following the RCP6 Scenario (black bars). Grey negative bars show the potential role of temporary carbon storage in long-lived
489 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_{trc}), with negative values meaning mitigation potential

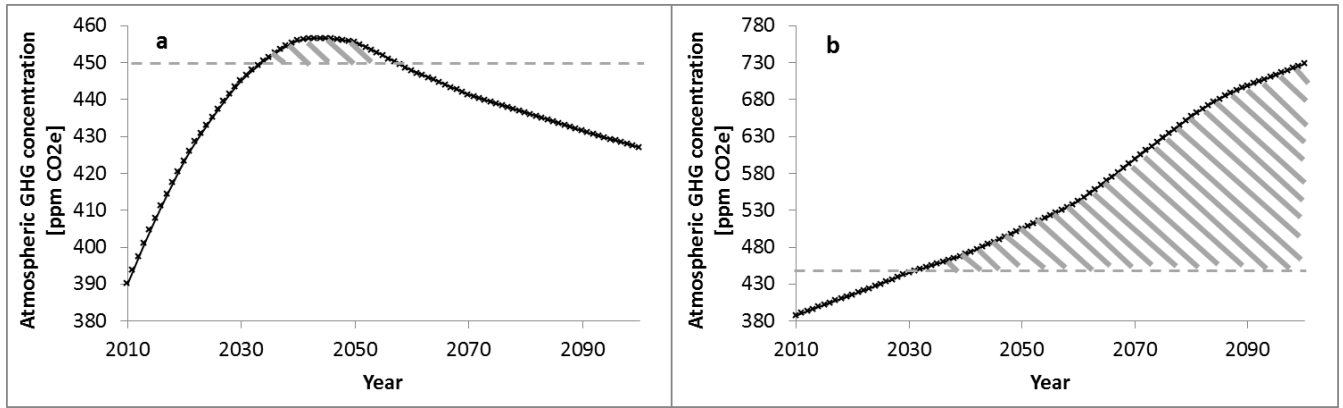
494

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

498

499

Fig. 1

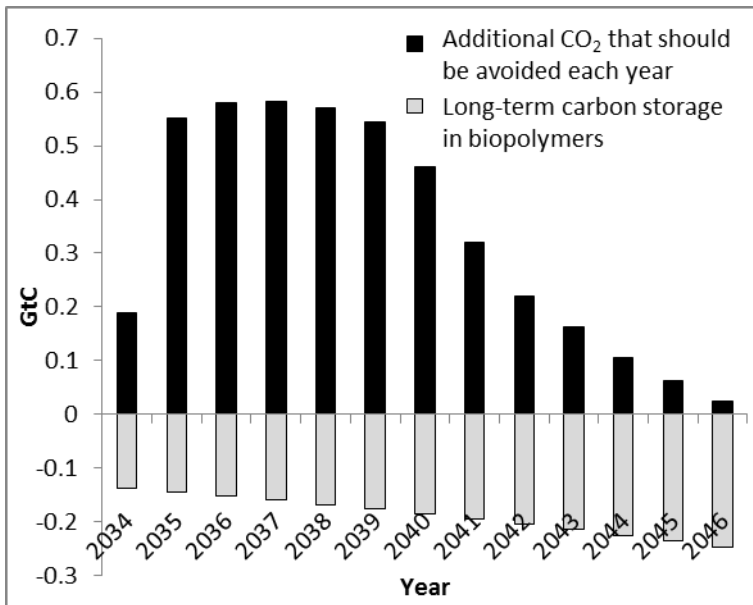


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Fig. 2

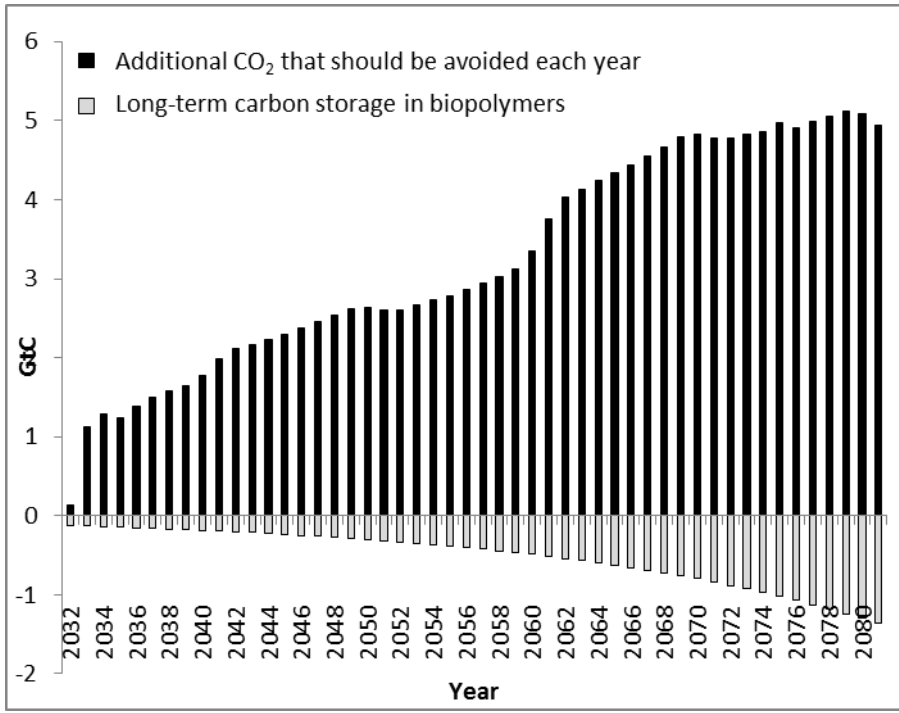


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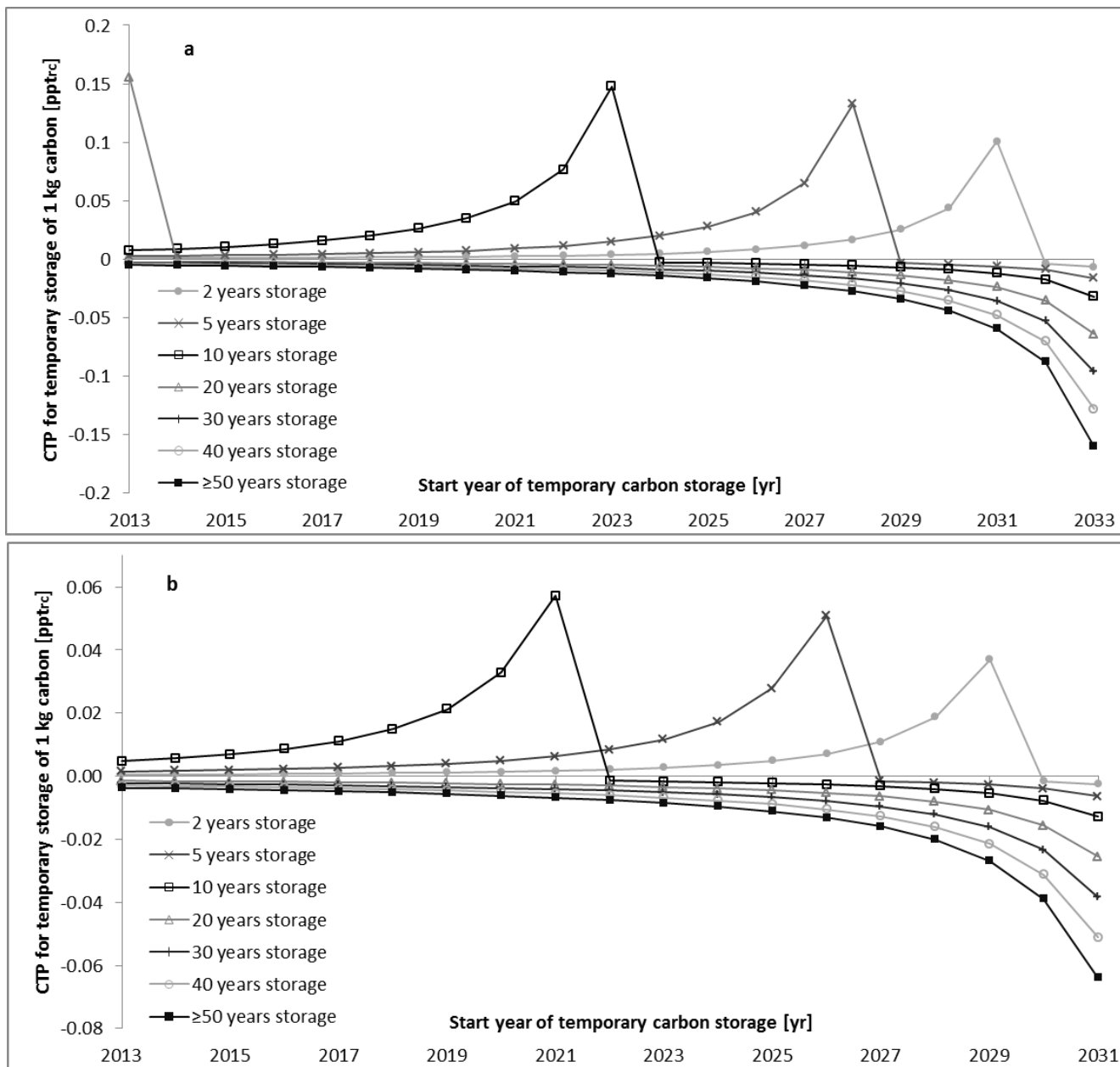
505 Fig. 3

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508 Fig. 4

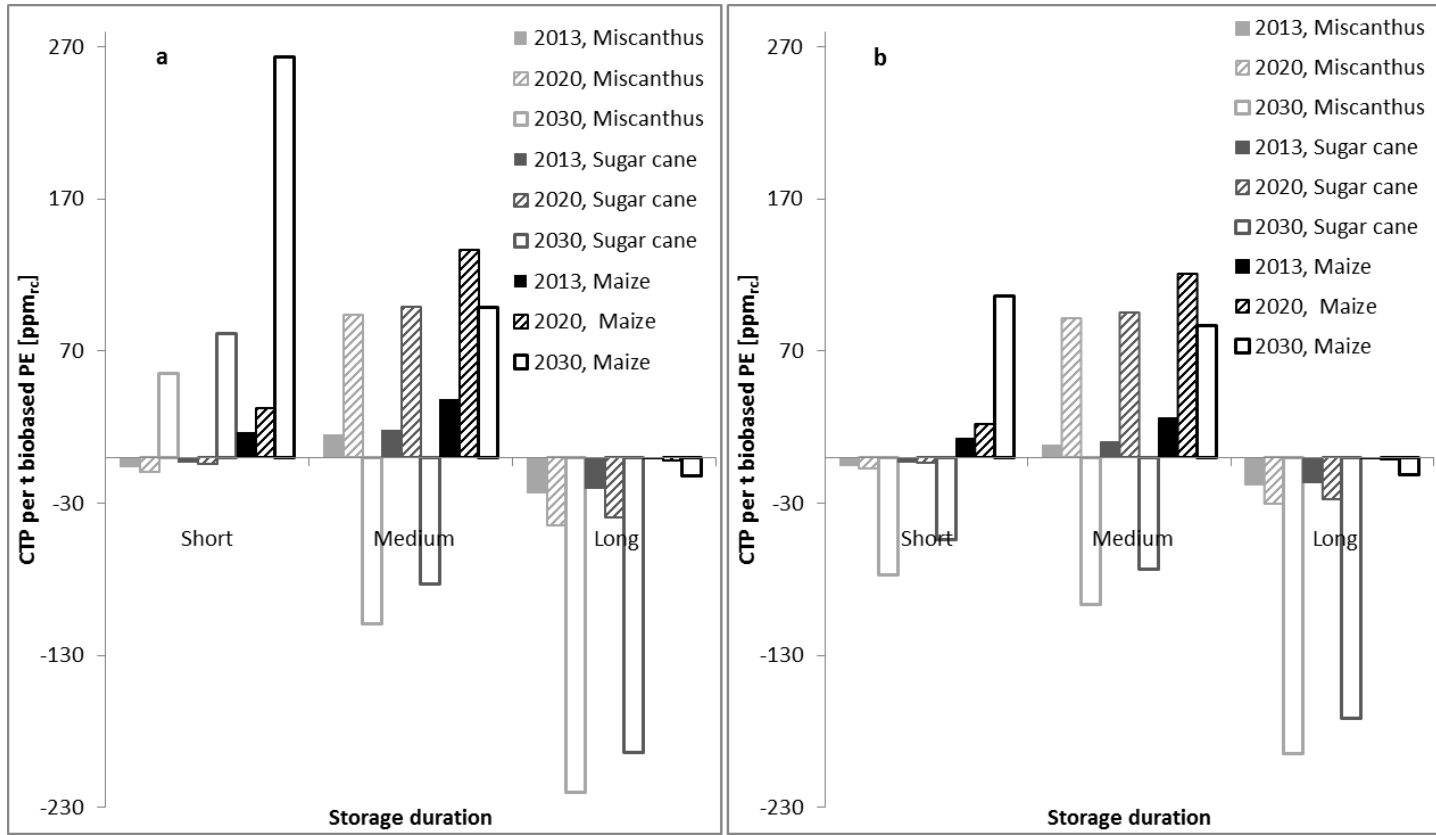


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511 Fig. 5

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