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# 5 Development of climate tipping damage metric for life cycle assessment –

# 6 the influence of increased warming from the tipping

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21

# 22 Abstract

23 **Purpose** The multiple climate tipping points potential (MCTP) is a novel metric in life cycle

24 assessment (LCA). It addresses the contribution of greenhouse gas emissions to disturb those

- 25 processes in the Earth system, which could pass a tipping point and thereby trigger large, abrupt and
- 26 potentially irreversible changes. The MCTP, however, does not represent ecosystems damage. Here,
- 27 we further develop this midpoint metric by linking it to losses of terrestrial species biodiversity at
- 28 either local or global scales.

Method A mathematical framework was developed to translate midpoint impacts to temperature increase, first, and then to potential loss of species resulting from the temperature increase, using available data on the potentially disappeared fraction of species due to a unit change in global average temperature.

**Results and discussion** The resulting damage MCTP expresses the impacts on ecosystems quality in terms of potential loss of terrestrial species resulting from the contribution of GHG emissions to cross climatic tipping points. The MCTP values range from  $2.3 \cdot 10^{-17}$  to  $1.1 \cdot 10^{-15}$  PDF (potentially disappeared fraction of species) for the global scale and from  $2.7 \cdot 10^{-17}$  to  $1.1 \cdot 10^{-15}$  PDF per 1 kg of CO<sub>2</sub> emitted for the local scale. They are time-dependent, and the largest values are found for emissions occurring between 2030-2045, generally declining for emissions occurring toward the end of the century.

40 Conclusions The developed metric complements existing damage-level metrics used in LCA and its 41 application is expected to be especially relevant for products where time-differentiation of emissions 42 is possible. To enable direct comparisons between our damage MCTP and the damage caused by 43 other environmental impacts or other climate-related impact categories, further efforts are needed to 44 harmonize MCTP units with those of the compared damage metrics.

45

# 46 Keywords

Ecosystems damage modeling, climate tipping points, life cycle impact assessment, global species
losses, local species losses, potential disappeared fraction

49

# 50 **1 Introduction**

51 Life cycle assessment (LCA) aims at quantifying the potential environmental impacts of a product or

52 service over its full life cycle, from extraction of raw materials, through manufacturing and use, to

53 end-of-life (Bjørn et al., 2018). During the life cycle impact assessment (LCIA) phase of an LCA,

54 exchanges between environment and the product system (like emissions of greenhouse gases, GHG)

55 are translated into potential environmental impacts using characterization factors (CF). These

56 exchanges are first summed up and then multiplied by the corresponding substance-specific CF, 57 which represents the impact per unit of emission. CFs are calculated using a model of the underlying 58 impact pathway that connects emissions to environmental damage. These express the potency of an 59 emission in affecting an indicator of the state of the environment that is chosen to represent the 60 environmental impact in question (Hauschild and Huijbregts, 2015). The indicator may be chosen at 61 any point in the impact pathway between emissions and damage to the functioning of ecosystems or 62 human health.

63 In LCA, different types of environmental impacts are analyzed and climate change impacts from emissions of CO<sub>2</sub> and other greenhouse gases released during products' life cycles are often 64 65 quantified. Emissions of GHGs lead to a change in radiative forcing, i.e. an increase in net energy 66 trapped in the atmosphere, which in turn causes a rise in atmospheric global temperature, which 67 finally causes damage to ecosystems. In this impact pathway, the change in radiative forcing caused 68 by GHGs is typically taken as midpoint (i.e. located in the middle of the impact pathway) indicator of 69 the state of the environment, whereas the final damage to ecosystems (or human health) resulting 70 from the radiative forcing changes represents the endpoint indicator in LCA. The global warming 71 potentials (GWP) proposed by the IPCC are used as midpoint CFs to express the change in radiative 72 forcing induced by GHG emissions over a defined time horizon (typically 100 years) compared to the 73 radiative forcing of carbon dioxide (CO<sub>2</sub>) over the same period (expressed in kg CO<sub>2</sub> equivalents). To 74 assess potential damage to ecosystems from GHG emissions, characterization factors modelled at 75 damage (or endpoint) level are used. These are the damage-oriented GWP CFs (calculated as in 76 Huijbregts et al. (2017) starting from the GWP), which allow translating radiative forcing into the 77 resulting time-integrated change in global temperature and finally in damage to either terrestrial or 78 freshwater ecosystems caused by the temperature change.

Climate tipping is a relatively new impact category in LCIA (Fabbri et al., 2021; Jørgensen et al., 2014). It offers a complementary perspective to the climate change impact category represented by the GWPs, which consider the time-integrated radiative forcing change but do not link this change to potential crossing of climate tipping points. Indicators of climate tipping, the multiple climate tipping points potentials (MCTP), represent the contribution of a GHG emission to crossing climatic tipping

84 points (observed for processes of the Earth system which may pass a threshold that triggers large 85 abrupt, potentially irreversible changes like change in surface albedo resulting from loss of Artic 86 Summer see ice) (Lenton et al., 2008). In the MCTP approach, the contribution to cross tipping points 87 is expressed as contribution of an emission to deplete the remaining carrying capacity of the 88 atmosphere to absorb the GHG impact without crossing a tipping point. As explained in Fabbri et al. 89 (2021), it was modelled by first computing the time-integrated radiative forcing increase from a unit 90 emission of a greenhouse gas; secondly, by converting this radiative forcing increase to atmospheric 91 CO<sub>2</sub>-equivalent concentration increase; and finally, by relating the resulting value with the remaining 92 atmospheric capacity, i.e. the remaining increase in atmospheric CO<sub>2</sub>-equivalent concentration that 93 can still take place without crossing a tipping point. The result indicates the fraction of remaining 94 capacity occupied by the emission and is expressed as parts per trillion of remaining capacity per unit 95 of GHG emission. The MCTP, however, expresses impacts only at the midpoint level, therefore 96 further developments are necessary to link these midpoint impacts to damage to terrestrial 97 ecosystems.

98 In LCIA, damage modelling for ecosystems traditionally focuses on species biodiversity, and 99 the potentially disappeared fraction of species (PDF) is the most common metric (Curran et al., 2011; 100 Woods et al., 2018). As explained in Verones et al. (2020), exposure duration is also included in the 101 unit of ecosystem damage, so resulting ecosystem damage is expressed as PDF yr. It can be also 102 expressed as species yr, when species density and area of exposed ecosystem are known. As argued in 103 Verones et al. (2020), damage scores in LCA should be interpreted as "an increase in global 104 extinction risk over a certain exposure period of time and not so much as an instantaneous global 105 species loss". Current damage-oriented characterization factors express biodiversity loss at either 106 local, or regional or global scales, and these are frequently mixed in LCIA methods (Verones et al., 107 2020). A local (or regional) loss of species occurs within a spatially delimited area and can be 108 reverted through repopulation. Global loss means that the species become extinct across the whole 109 planet, and it is thus irreversible. This difference implies that a metric based on local species loss 110 cannot be directly compared with one based on global losses. To avoid comparability issues, it is 111 essential to clearly report at which level new metrics are developed (Jolliet et al., 2018). Local

assessments are important to ensure ecosystem functionality while global assessments are necessary to avoid irreversible extinction of species. Thus, the two measures complement each other and it has been argued that characterization factors addressing both scales should be developed for all impact categories (Jolliet et al., 2018; Purvis, 2020; Verones et al., 2020).

116 The aim of this paper is to advance the climate tipping impact category in order to 117 obtain multiple climate tipping points potential (MCTP) at endpoint (damage) level expressing 118 damage to ecosystems, enabling comparison with other damage-oriented impacts. A framework for 119 calculating endpoint MCTP characterization factors is presented for three greenhouse gases (CO<sub>2</sub>, 120 methane ( $CH_4$ ) and nitrous oxide ( $N_2O$ )), measuring biodiversity loss at either local or global scale. 121 MCTP factors were computed for three Representative Concentration Pathways, RCP4.5, RCP6 and 122 RCP8.5 representing possible future GHG emission trajectories for the world. The resulting 123 characterization factors, referred to as MCTP<sub>endpoint</sub>, quantify potential damage to terrestrial ecosystems considering the risk of crossing multiple climatic tipping points. They can be directly 124 125 applied in LCA studies to assess products and systems and here their application is illustrated with a 126 simplified case study on degradable plastic polymers.

127

### 128 **2 Methods**

### 129 **2.1 Impact pathway mechanisms**

130 The midpoint MCTP factor of a unit GHG emission represents the fraction of remaining capacity of 131 the atmosphere to absorb emissions without passing a tipping point that is taken up by the unit 132 emission and is expressed in parts per trillion of remaining capacity per unit emission of a greenhouse gas *i* (ppt<sub>rc</sub>  $\cdot$  kg<sub>i</sub><sup>-1</sup>). The midpoint MCTP is then linked to temperature increase per fraction of carrying 133 134 capacity taken up, and, further on in the impact pathway, to the potential loss of species biodiversity 135 resulting from that temperature increase (see Fig. 1). Note, that in contrast to damage-oriented GWP 136 CFs, which model impacts attributed to marginal GHG emissions (adding on top of the background 137 emissions), damage modeling in the MCTP approach applies an *average* perspective by assuming that 138 an increase in atmospheric CO<sub>2</sub>-equivalent concentration is part of the anthropogenic background.

139 Furthermore, the crossing of a given tipping point reduces the remaining carrying capacity for all 140 subsequent tipping points. This corresponds to an additional temperature increase, which further 141 contributes to loss of species diversity. Given the current lack of consistent estimates on the direct 142 effects of crossing tipping points on species loss (through e.g. forest dieback or lengthening of the dry 143 season), an impact pathway considering only effects from this additional temperature increase is 144 developed here. The resulting potential loss of species is thus a function of the global temperature levels resulting from the background emissions and effects from crossing of tipping points on 145 temperature increase. The MCTP<sub>endpoint</sub> CF represents the share that the characterized emission has in 146 the total predicted species loss. 147

148



149

150 Fig. 1 Impact pathway for climate tipping used for developing the multiple climate tipping points potential

based on ecosystem damage. Climate tipping has both direct and indirect effects on terrestrial species. Only

152 indirect effects through global temperature increase are covered in this study.

153

#### 154 **2.2 Modelling framework**

155 The endpoint MCTP ( $MCTP_{endpoint}$  in PDF·kg<sup>-1</sup>) of a given GHG *i* emitted at year  $T_{emission}$  is derived

156 from the midpoint MCTP by using a 'midpoint-to-endpoint' factor:

157



160 where  $MCTP_i$  [ppt<sub>rc</sub>·kg<sub>i</sub><sup>-1</sup>] is the multiple climate tipping points potential at midpoint of gas *i* emitted at year  $T_{\text{emission}}$ , and MEF [PDF·ppt<sub>rc</sub><sup>-1</sup>] is the midpoint-to-endpoint factor, translating the impact 161 from contribution to tipping of the emission at  $T_{\rm emission}$  to the potentially disappeared fraction of 162 163 species [PDF] at either local or global level. Note, that unlike other damage-oriented CFs of climate 164 impacts (including GWP), exposure duration is not included in the unit of our endpoint MCTP. The 165 exposure duration is considered when computing time-integrated increase in CO<sub>2</sub>-equivalent concentration, but it cancels out when the impact is related to the carrying capacity of the atmosphere. 166 Implications of this on the harmonization of metrics across impact categories will be discussed later 167 168 (section 4.2).

169

# 170 **2.3 Multiple climate tipping potential at midpoint**

As in Fabbri et al. (2021), the multiple climate tipping points potential at midpoint, MCTP<sub>*i*</sub> in [ppt<sub>re</sub>·kg<sub>*i*</sub><sup>-1</sup>] (parts per trillion of remaining capacity taken up by a unit emission) of gas *i* emitted at year  $T_{\text{emission}}$  is defined as the sum of the ratios between the *impact of the emission* and the corresponding remaining capacity for each of the *m* tipping points occurring after the emission year: 175

176 
$$MCTP_i(T_{\text{emission}}) = \sum_{j=1}^{m} \frac{I_{\text{emission},i,j}(T_{\text{emission}})}{CAP_j(T_{\text{emission}})}$$
 (2)

177

where *j* indicates the *j*th tipping point occurring after the emission year (in order of occurrence) and can take any value from 1 to *m*, which is the total number of tipping points that are predicted to be crossed under the assumed background emission pathway (RCP);  $I_{emission,i,j}$  is the *impact of the emission* of gas *i* with respect to the *j*th tipping point, *CAP<sub>j</sub>* is the remaining capacity up to the *j*th tipping point, and the emission year  $T_{emission}$  can be any year from 2021 (or the year when emissions are expected to start taking place) up to the year of the last tipping point. Details of computing impact and remaining carrying capacity are presented in Fabbri et

al. (2021). Briefly, the  $I_{\text{emission},i,j}$  is computed as the radiative forcing of gas i ( $RF_i$ ) integrated over

186 time between the emission and the tipping (referred to as the absolute climate tipping potential,

187 ACTP)  $[W \cdot m^{-2} \cdot yr \cdot kg_i^{-1}]$  divided by the radiative efficiency (RE) of 1 ppm of CO<sub>2</sub>  $[W \cdot m^{-2} \cdot ppm CO_2^{-1}]$ 

188 <sup>1</sup>]. The  $CAP_i$  [ppm CO<sub>2</sub>e·yr] represents the increase in atmospheric CO<sub>2</sub>-equivalent concentration that

189 can still take place before reaching the concentration level (in ppm CO<sub>2</sub>e) that may trigger tipping *j*.

- 190 This capacity depends on background anthropogenic emissions, and it can be reduced when preceding
- 191 tipping points are crossed.
- 192

# 193 **2.4 Midpoint to endpoint factor**

194 The midpoint-to-endpoint factor,  $MEF(T_{emission})$  as it depends on the emission year, is given by: 195

196 
$$MEF(T_{\text{emission}}) = \frac{\Delta TEMP(T_{\text{emission}})}{1 \cdot 10^{12}} \cdot \frac{\Delta PDF(T_{\text{emission}})}{\Delta TEMP(T_{\text{emission}})}$$
 (3)

197

198 where  $\frac{\Delta TEMP(T_{emission})}{1\cdot 10^{12}}$  [°C·ppt<sub>rc</sub><sup>-1</sup>] is the global atmospheric temperature change ( $\Delta TEMP$ ) resulting 199 from one part per trillion reduction of the remaining capacity [ppt<sub>re</sub>] (i.e., per unit of the midpoint 200 MCTP) and  $\frac{\Delta PDF(T_{emission})}{\Delta TEMP(T_{emission})}$  [PDF·°C<sup>-1</sup>] is the rate of potential species loss, at either global or local 201 level (PDF<sub>global</sub> and PDF<sub>local</sub> respectively), per unit change in global average atmospheric temperature. 202 The factor  $1 \cdot 10^{12}$  [ppt<sub>rc</sub><sup>-1</sup>] is needed to re-convert the midpoint *MCTP<sub>i</sub>* into unitless fraction of 203 remaining capacity. Note that both  $\Delta TEMP$  and  $\Delta PDF$  depend on the emission year.

204 The factor 
$$\frac{\Delta TEMP(T_{\text{emission}})}{1 \cdot 10^{12}}$$
 quantifies the link between the fraction of remaining

capacity eaten up by the emission occurring at  $T_{\text{emission}}$  (calculated by the midpoint MCTP) and the temperature increase associated with taking up that fraction of remaining capacity. To relate these two variables, we consider the overall remaining capacity from the emission year ( $T_{\text{emission}}$ ) up to the

- 208 year when the last possible tipping point is exceeded (under the assumed background emission
- 209 pathway) and the average temperature change expected to occur over the same period (eq. 4).
- 210

211 
$$\frac{\Delta TEMP(T_{\text{emission}})}{1 \cdot 10^{12}} = \frac{TEMP(T_{\text{tipping},j_{\text{last}}}) - TEMP(T_{\text{emission}})}{1 \cdot 10^{12}}$$
(4)

where  $TEMP(T_{tipping,j_{last}})$  is the temperature in the year when the last tipping point is exceeded and  $TEMP(T_{emission})$  is the temperature in the emission year.  $\Delta TEMP$  results from the combination of the background evolution of GHG emissions according to the assumed background emission pathway and the effect of crossing tipping points. Note, that in eq. 4 the remaining capacity  $(1 \cdot 10^{12} \text{ ppt}_{rc})$  is independent of the emission year. It represents the total capacity that is left up to the last tipping point at each considered emission year.

219 The factor 
$$\frac{\Delta PDF(T_{\text{emission}})}{\Delta TEMP(T_{\text{emission}})}$$
 represents the rate of potential species loss per unit of

220 temperature increase. The change in potentially disappeared fraction of species  $\Delta PDF(T_{\text{emission}})$  is

221 calculated as the difference between the foreseen fraction of species lost ( $F_{lost}$ ) at the highest

222 considered temperature increase, corresponding to that expected at the last tipping point,

223  $F_{\text{lost}}(T_{\text{tipping},j_{\text{last}}})$ , and the foreseen fraction of species lost at the emission year,  $F_{\text{lost}}(T_{\text{emission}})$  (eq. 224 5).

225 
$$\frac{\Delta PDF(T_{\text{emission}})}{\Delta TEMP(T_{\text{emission}})} = \frac{F_{\text{lost}}(T_{\text{tipping},j_{\text{last}}}) - F_{\text{lost}}(T_{\text{emission}})}{TEMP(T_{\text{tipping},j_{\text{last}}}) - TEMP(T_{\text{emission}})}$$
(5)

226

227 Studies estimate that this rate is not constant but accelerates as global temperature levels rise (see 228 section below). This acceleration is accounted for by calculating a different rate for each emission 229 year, so that emissions occurring at higher levels of warming are attributed a higher potential fraction 230 of species loss per unit of temperature increase caused by the emission. Note that the change in global 231 atmospheric temperature over time (resulting from both background evolution of GHG concentrations 232 and crossing of tipping points) is the only climatic parameter that influences the loss of species caused 233 by a GHG emission. Other climatic variables, such as precipitation, were not directly considered due 234 to the lack of a clear correlation between 1) changes in these climatic variables and their contribution 235 to crossing tipping points and 2) the complementary effects that crossing tipping points has on these 236 variables.

237 Following the approach developed in Fabbri et al. (2021) for calculation of midpoint 238 MCTP, we consider model uncertainties in the exact location of the temperature thresholds that may 239 trigger the identified potential tipping points. MCTP<sub>endpoint</sub> factors are thus computed as a function of 240 the emission year using Monte Carlo simulation (10000 iterations), simulating possible developments 241 with different timing and sequence of the tipping points. The considered tipping points are Arctic 242 summer sea ice loss, Greenland ice sheet melt, West Antarctic ice sheet collapse, Amazon rainforest 243 dieback, Boreal forest dieback, El Niño-Southern Oscillation change in amplitude, Permafrost loss, 244 Arctic winter sea ice loss, Atlantic thermohaline circulation shutoff, North Atlantic subpolar gyre convection collapse, Sahara/Sahel and West African monsoon shift, Alpine glaciers loss, and Coral 245 reefs deterioration (Lenton et al., 2008; Steffen et al., 2018). The uncertainties behind each of the 13 246 247 tipping points and their implementation into the model are presented in Fabbri et al. (2021) and 248 summarized in Table S1 in Supplementary Information-1. Results are given as the geometric mean of the MCTP<sub>endpoint</sub> factors calculated over 10000 iterations. 249

250

#### **251 2.5 Determination of temperature change**

252 Future temperature changes are obtained from the global mean temperature projections estimated 253 starting from the Representative Concentration Pathways (RCPs) in Meinshausen et al. (2011). The 254 choice of pathway, in particular the projected rate of GHGs concentration increase, strongly affects 255 the magnitude and the trend of the midpoint MCTPs over emission time, potentially influencing the 256 climate tipping performance of products (Fabbri et al., 2021). To reflect how this choice affects the 257 damage due to GHG emissions, we consider the three pathways RCP4.5, RCP6 and RCP8.5 (numbers referring to the resulting radiative forcing [W·m<sup>-2</sup>] in 2100) (van Vuuren et al., 2011). The lower 258 259 emission path RCP2.6 is excluded as it is deemed unrealistic (Sanford et al., 2014; van Vliet et al., 2009). 260

In addition, we account for the potential temperature change caused by crossing tipping points, starting from the estimated CO<sub>2</sub>-equivalent concentration increase following tipping that was used for computing the midpoint MCTPs. This is relevant for eight of the thirteen tipping points 264 considered, as for the remaining five tipping points there is either lack of data on the consequences of 265 tipping or lack of evidence that tipping could cause a temperature rise (Fabbri et al., 2021). The resulting global temperature rise is obtained by first adding this increment in CO<sub>2</sub>-equivalent 266 267 concentration to the concentration level projected by the RCP, obtaining a new concentration profile. 268 This new profile is then associated to the corresponding temperature profile derived from the RCP 269 pathway. This implies that while the predicted warming based on the baseline RCP projection is 270 anticipated, the maximum expected temperature increase will never exceed that projected by the RCP. 271 Implications of this modeling choice will be discussed in the method's limitations section (section 272 4.3).

273

# 274 **2.6 Determination of fraction of species lost**

275 The potentially disappeared fraction of species per unit change in global average temperature,

 $\frac{\Delta PDF(T_{emission})}{\Delta TEMP(T_{emission})}$ , is derived from studies that estimate species loss under a given emission pathway (Newbold, 2018; Urban, 2015). Here we consider both measures of local species loss, when species are lost locally but with possible reintroduction from neighboring regions, and global species loss, when species become globally extinct and there is no possibility for recolonization.

280 Local species loss due to climate change is obtained from Newbold (2018), who 281 calculated global average local losses of terrestrial vertebrate biodiversity for four RCP pathways. It 282 was chosen as one of the most recent studies focusing on climate change effects on local biodiversity 283 loss globally, from which it was possible to obtain sufficient data points to derive a curve relating 284 average local losses of species to changes in global mean temperature. Newbold (2018) developed 285 species distribution models (Elith and Leathwick, 2009) for approximately 20,000 species of 286 amphibians, reptiles, mammals and birds, to estimate local losses (across 10-km<sup>2</sup> grid cells) in 287 response to climate change. These models relate estimates of species distributions across the entire 288 terrestrial surface of the world to bioclimatic data within each 10-km<sup>2</sup> grid cell, to predict species' 289 distributions under future climates (Newbold, 2018). Estimated local losses are averaged across all terrestrial areas of the world to obtain a global average. A species is considered lost from a certain 290

area when that area becomes climatically unsuitable for that species, offset by colonization of new
species for which that area has become climatically suitable (as long as those species are estimated to
be able to reach the area by dispersal). By combining the losses predicted based on the future
evolution of four climate variables with the temperature change expected in 2070 under a given RCP,
the study shows that temperature increases of 2, 3 and 4.3°C relative to 1960 – 1990 would lead, on
average across terrestrial areas and assuming intermediate dispersal ability, to 3, 10 and 20% local
loss of species, respectively.

298 Global species loss is taken from a large synthesis of studies predicting extinction risk 299 from climate change carried out in Urban (2015). This study was chosen as it provides the most 300 comprehensive and recent estimates of global species loss from climate change and has already been 301 used to develop damage-oriented GWP factors in the ReCiPe 2016 and LC-IMPACT methods 302 (Huijbregts et al., 2017; Verones et al., 2020, 2019). Urban (2015) compiled 131 predictions covering 303 seven taxonomic groups (plants, invertebrates, amphibians, reptiles, birds, mammals and including a 304 few studies on fish), different dispersal abilities and different modeling techniques to derive the global 305 mean extinction rate per unit of future global temperature rise. Global losses of 3, 5, 8, 16 and 21% are expected for temperature increases of respectively 0.8, 2, 3, 4.3 and 5°C above pre-industrial 306 307 levels.

308 To integrate the models of Newbold (2018) and Urban (2015) with our midpoint 309 MCTP factors while enabling Monte Carlo simulations, simplified linear regressions were developed 310 based on predictions from the original models of Newbold (2018) and Urban (2015). The regressions 311 predict fraction of species lost (logit-transformed) from temperature change. Details of the regression 312 analyses (i.e., logit-transformation, parameters of the fitted curve, goodness-of-fit statistics) are presented in the Supplementary Information-1 (section S2). Fig. 2 shows predictions of the regression 313 314 models. Predictions at local and global scale show high similarity in trend and magnitude, implying 315 that the resulting MCTP<sub>endpoint</sub> factors will not be significantly different from each other in terms of 316 numerical values.





Fig. 2 Fraction of local and global species lost ( $F_{lost}$ ) as a function of global temperature change above preindustrial levels, *TEMP*. 'Data from model' refers to the pairs of values linking a change in species loss with a change in temperature retrieved from Newbold (2018) and Urban (2015) and found in Table S2 (in Supplementary Information-1). Since both reference studies for local and global species loss do not provide estimates beyond 5°C, computations of the MCTP<sub>endpoint</sub> under RCP8.5, which is the only pathway where temperature projections exceed 5°C, terminate at the year when the temperature level reaches 5°C in each iteration

326

#### 327 2.7 Case study

328 Application of the MCTP characterization factors is expected to have particular relevance when 329 studying the performance of products that have GHG emissions occurring over extended periods of 330 time, such as slowly degrading plastics (Fabbri et al., 2021). We illustrate the application of the 331 calculated MCTP<sub>endpoint</sub> factors in an illustrative case study on the end-of-life stage of four types of 332 degradable plastic polymers. Details on the considered polymers, scenarios and assumptions are found 333 in Fabbri et al. (2021), and an overview is provided in Table 1. Comparisons between the four plastics 334 were made based on emissions of CO<sub>2</sub> and/or CH<sub>4</sub> resulting from either incineration or landfilling of an amount of plastic material containing 0.5 kg of carbon. Such a functional unit based on 335 336 equivalence of the carbon content (and related emissions) between scenarios allows to highlight 337 differences in emission timing that are relevant for application of the MCTP factors. Under the

338 anaerobic conditions typical of municipal landfills, the polymers degrade at different rates, from fast 339 (90% degradation within 2 years) to very slow (1% degradation within 100 years), resulting in 340 different CO<sub>2</sub> and CH<sub>4</sub> emission profiles derived from the carbon contained in the polymer (scenarios 341 2-5 in Table 1). Degradation may also be delayed by several years in landfills (scenarios 6 and 7). In 342 contrast, during incineration only CO<sub>2</sub> emissions are released and all at the same time (scenario 1). 343 These differences in emission timing are expected to influence the performance of the polymers when 344 measured with the MCTP approach. Using the degradation rate constants of the polymers, yearly emitted quantities of GHGs are calculated, multiplied by the corresponding year-specific average 345 MCTP<sub>endpoint</sub> factor per unit emission and summed over the period from the first GHG emission 346 347 release (here assumed to be 2021) up to the last tipping point ( $T_{\text{tipping},j_{\text{last}}}$ ) and over each GHG *i*. The 348 result is the total impact score (IS) in terms of potentially disappeared fraction of species (PDF) from 349 the end-of-life degradation of plastic (eq. 6):

350

351 
$$IS = \sum_{i} \sum_{T_{\text{emission}}=2021}^{T_{\text{tipping},j_{\text{last}}}} m_i(T_{\text{emission}}) \cdot MCTP_{\text{endpoint},i}(T_{\text{emission}})$$
(6)

352

where  $m_i(T_{\text{emission}})$  is the mass of GHG *i* emitted at year  $T_{\text{emission}}$ . Impact scores are calculated with the MCTP<sub>endpoint</sub> factors for both local and global species losses, and calculations are done with CFs representing each of the three RCPs. For comparison, we also compute impact scores using the complementary and most commonly used GWP-based metric of damage to terrestrial ecosystems (damage GWP) included in the LCIA method ReCiPe 2016, where metric scores are expressed in [species·yr].

- 360
- 361
- 362

363 Table 1 Overview of the seven scenarios considered for the case study with functional limit "average treatment

	I			
Scenario	Polymer	Degradation rate constant, k (dav <sup>-1</sup> )	Note	
1. Incineration	Generic fossil-based Not relevant		All carbon contained in the polymer is released as $CO_2$ in year 1	
Plastic degradation rate			·	
2. Fast (90% degradation in 2 years)	Polycaprolactone (PCL) – fossil-based	2.97·10 <sup>-3 (a)</sup>	In total, 71% of the carbon is released as	
3. Medium (90% degradation in 31 years)	Polybutylene succinate (PBS) fossil-based	2.02·10 <sup>-4 (b)</sup>	CO <sub>2</sub> and 29% as CH <sub>4</sub> , in different years	
4. Slow (90% degradation in 105 years)	Polystyrene (PS) fossil- based	6.00·10 <sup>-5 (c)</sup>	depending on the degradation rate	
5. Very slow (1% degradation in 100 years)	Polylactic acid (PLA) – bio-based	2.77·10 <sup>-7 (d)</sup>	constant <sup>(d)</sup>	
Delayed degradation				
6. After 20 years (fast rate)	Polycaprolactone (PCL) – fossil-based	2.97·10 <sup>-3 (a)</sup>	Degradation in landfill of the fast-degrading	
7. After 50 years (fast rate)	Polycaprolactone (PCL) – fossil-based	2.97·10 <sup>-3 (a)</sup>	plastic (scenario 2) is assumed to be delayed by 20 and 50 years, respectively.	

of 0.5 kg carbon contained in the plastic material". Adapted from Fabbri et al. (2021)

365 366 <sup>(a)</sup> (Ishigaki et al., 2004); <sup>(b)</sup> (Cho et al., 2011); <sup>(c)</sup> (Tansel, 2019); <sup>(d)</sup> (Rossi et al., 2015).

# 367 **3 Results**

368 The complete set of MCTP<sub>endpoint</sub> values for CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O calculated for each RCP pathway and 369 expressed as either local or global species loss are presented in Supplementary Information-2 (Tables 370 S1-S6). Here, only selected results for CO<sub>2</sub> will be illustrated to facilitate their interpretation. Results 371 for CO<sub>2</sub> are first presented for a sample iteration (i.e. a Monte Carlo simulation representing a possible scenario in which nine different tipping elements cross their tipping point) under the RCP6 372 pathway as an example. To illustrate the influence of the adopted approach on the final MCTP<sub>endpoint</sub> 373 values, results are shown separately for all the factors underlying the calculation of MCTP<sub>endpoint</sub>. 374 375 Next, results from 10000 Monte Carlo iterations accounting for current uncertainties in tipping 376 occurrence are presented and compared between RCP pathways. Finally, main outcomes from the 377 case study are presented. The MCTP<sub>endpoint</sub> values for CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O can be found in 378 Supplementary Information-2.

#### **380 3.1 MTCPs for a sample iteration**

381 Fig. 3a shows MCTP<sub>endpoint</sub> factors for CO<sub>2</sub> for a sample iteration in terms of both local and global fraction of species loss, as depending on the time when the CO<sub>2</sub> emission occurs. The first observation 382 is that MCTP<sub>endpoint</sub> factors are proportional to their corresponding midpoint MCTP (Fig. 3b) and 383 384 follow a similar pattern. As already shown in Jørgensen et al. (2014) and Fabbri et al. (2021), 385 midpoint MCTPs peak just before the passing of a tipping point, indicating that the contribution of an 386 emission to cross the tipping point increases as the emission pathway approaches the tipping point. 387 Here, the increase in MCTP<sub>endpoint</sub> suggests that an emission occurring before an expected tipping 388 threshold has a higher potential to cause ecosystem damage due to its larger contribution to deplete 389 the remaining capacity and cross the tipping point. On the contrary, emissions after the tipping point 390 have smaller contribution to crossing subsequent tipping points. This is seen as a discontinuity in the 391 MCTP<sub>endpoint</sub> curve.

392 MCTP<sub>endpoint</sub> values generally increase until ca 2045, but they are almost 2 orders of 393 magnitude lower for emissions occurring toward the end of the century. This decreasing trend is 394 explained by the fact that the temperature change per fraction of remaining capacity taken up by the 395 emission decreases as the emission occurs later in time. Therefore, despite the fact that the potential 396 species loss per unit temperature increase, e.g. in 2070, is expected to be higher than that in 2035 (Fig. 397 3c and Table S3 in Supplementary Information-1), the resulting damage from an emission in 2070 is 398 lower than that in 2035 because the corresponding temperature change induced by that emission is 399 also lower (Fig. 3d). This observation may seem counterintuitive if one would expect larger impact to 400 be computed for emissions occurring later in time (consistently with Fig. 2) but is in line with an 401 average approach to modeling of characterization factors for use in LCA. As argued in Fabbri et al. 402 (2021), the MCTP factors represent average impact as they depend on the background level. Thus, 403 averaging temperature change between emission year and year of the last tipping point (making the 404 resulting  $\Delta TEMP$  decrease with later emission time) is necessary to calculate indicator scores for 405 emissions occurring at that specific emission year. These emissions cannot be made responsible for

the temperature increase and resulting ecosystem damage that happened before the emission year ofinterest.

Finally, MCTP<sub>endpoint</sub> factors calculated using local species loss estimates show little difference from those obtained using global species loss estimates. Results for local losses are maximum 13% larger and 5% smaller compared to results for global losses, depending on the emission time. However, we stress that their interpretation is not the same. Local losses represent potentially reversible damages through the loss of ecosystem functioning caused by local loss of species, whereas global extinctions represent irreversible losses of biodiversity (see Section 4.1 for further discussion).





417 **Fig. 3 (a)** Endpoint MCTP (MCTP<sub>endpoint</sub>) for emission of 1 kg of  $CO_2$  expressed as Potentially Disappeared 418 Fraction (PDF) of species at local (dashed line, left axis) and global (solid line, right axis) level in a sample 419 iteration under RCP6. Note that differences between the two curves are so small that they appear mostly 420 overlapping. **(b)** Midpoint MCTP for emission of 1 kg of  $CO_2$ . **(c)** Potentially Disappeared Fraction of species

421 (PDF) at local (dashed line, left axis) and global (solid line, right axis) level per degree Celsius increase in

422 global temperature. (d) Temperature change per fraction of remaining capacity. Specific results for three

423 different emission times are reported in Table S3 in Supplementary Information-1

424

#### 425 **3.2 Uncertainty and sensitivity**

426 When uncertainties about occurrence and timing of tipping points are accounted for with Monte Carlo 427 simulations, average (geometric mean) MCTP<sub>endpoint</sub> factors for both local and global species losses 428 are somewhat smoothened compared to a single iteration, indicating that uncertainties in the exact 429 location of the tipping point are so large that single tipping events are not clearly distinguishable (Fig. 430 4). Nevertheless, the fluctuations of the factors over time indicate that it is still possible to identify 431 periods with larger probability of crossing tipping points in proximity of the observed peaks. This 432 shows that, despite the uncertainties, impacts, and thus our CFs, still depend on the specific timing of 433 GHG emissions and thus on the proximity to tipping points. These findings are consistent with 434 observations noted in Fabbri et al. (2021) for the midpoint MCTP. Emissions between 2040 and 2060 435 have the largest potential to cause species loss as a consequence of crossing tipping points assuming 436 RCP6. The sharp peak around years 2050-2055 indicates that uncertainty around the tipping is lower 437 here, making the potential tipping time more identifiable. After this period, potential damage per unit 438 emission decreases, confirming the trend observed in the sample iteration. Average MCTP<sub>endpoint</sub> 439 factors calculated for local and global species losses are numerically similar. Under RCP6, average (geometric mean) MCTP<sub>endpoint</sub> factors based on local species loss range between 2.7·10<sup>-17</sup> and 1.1·10<sup>-</sup> 440 441  $^{15}$  PDF per 1 kg of CO<sub>2</sub>, depending on the year of emission, with 90% of the iterations oscillating between 2.2·10<sup>-17</sup> and 2.3·10<sup>-15</sup> PDF per unit emission (Fig. 4a). The MCTP<sub>endpoint</sub> factors for global 442 443 species losses can be up to 5% larger and 13% lower than results for local species loss, depending on 444 the emission year.

The comparison between RCP pathways shows that potential local and global species losses per kg of CO<sub>2</sub> emitted are generally larger under RCP8.5 and lower under RCP4.5. MCTP<sub>endpoint</sub> factors for local species losses can be up to 4 and 87 times larger (depending on emission time) under 448 RCP8.5 compared to RCP6 and RCP4.5, respectively, whereas for global species losses they are up to 449 3 and 35 times larger than the other two pathways. This is consistent with expectations that more 450 species will be lost at higher temperature levels. Larger impacts under RCP8.5, in terms of 451 contribution of a GHG emission to crossing tipping points, were also found in Jørgensen et al. (2014), 452 who studied the influence of RCP pathway on their developed midpoint climate tipping metric. This 453 was due to the higher GHG concentration levels projected in this pathway, which reduced the 454 remaining atmospheric capacity up to the considered tipping point (Arctic summer sea ice). 455 Conversely, the result is in contrast with what reported in Fabbri et al. (2021), where midpoint MCTPs for RCP8.5 were lower than those for RCP4.5. This reflects the inability of the midpoint 456 457 MTCPs to represent the potential larger impacts when temperature projections are higher and highlights the relevance of performing damage modelling as presented here. 458 459 The different trends observed in the three RCPs are mainly explained by the different number and timing of occurring tipping points, which in turn are determined by the level and 460 evolution of the global temperature projected in each RCP (see Table S1 in Supplementary 461 462 Information-1 for occurrence of tipping points depending on the RCPs). Under RCP8.5 impacts are 463 larger for emissions occurring within 2045, because a larger number of tipping points is expected to 464 be crossed within this period due to the rapid increase in temperatures projected in this pathway. The 465 number of potential tipping points in RCP6 and RCP4.5 is progressively lower, and their occurrence 466 is slightly postponed due to the lower rate of temperature increase (particularly for RCP6). Similar 467 trends are observed for CH<sub>4</sub> and N<sub>2</sub>O, and MCTP<sub>endpoint</sub> values for these two gases are on average 83 468 and 273 times larger, respectively, compared to those of CO<sub>2</sub> (Fig. S1)



470

471 Fig. 4 Average (geometric mean) endpoint MCTP (MCTP<sub>endpoint</sub>) of 1 kg of CO<sub>2</sub> based on local (a) and global
472 (b) species loss (solid lines) and corresponding uncertainty ranges (shaded areas enclosed between the 5<sup>th</sup> and
473 95<sup>th</sup> percentiles) calculated under RCP4.5, RCP6 and RCP8.5.

474

#### 475 **3.3 Findings from a case study**

476 Ranking between plastic end-of-life scenarios obtained with the MCTP<sub>endpoint</sub> calculated in this study 477 shows some differences when compared to ranking using the damage GWP-based metric (Table 2). 478 For the damage GWP, the lowest impacts are calculated when the plastic material degrades slowly 479 enough so that the amount of GHGs emitted in 100 years is at a minimum, explaining why the very 480 slowly and the fast-degrading plastics are the best and the worst scenarios respectively. This is also 481 the case for our MCTP<sub>endpoint</sub> (for both local and global species losses) for very slowly degrading 482 plastic, which is seen to have lowest impacts due to the very low amounts of GHGs emitted. 483 However, contrary to the GWP, where impacts are rather insensitive to biodegradation kinetics, 484 climate tipping impacts also depend on emission timing, and are largest when emissions occur at the 485 point in time where their contribution to cross tipping points is the largest (2040-2060). This 486 corresponds to fast biodegradation rate with a lag phase, followed by the scenario with medium 487 biodegradation rate without a lag. These findings however do not necessarily show that slower 488 degrading materials are always a better option (indeed the opposite is observed when comparing 489 scenarios 2 and 4 under RCP6), but rather show that the performance depends on proximity of 490 emissions to expected occurrence of tipping points. Ranking of scenarios from fast to slow

491 degradation rate differs slightly among the three RCP pathways, but the overall trends are the same,

- 492 i.e. scenarios 3 (medium rate degradation) and 6 (20-years delayed degradation) are seen as the worst.
- 493 The main difference here between RCP pathways is that MCTP<sub>endpoint</sub> scores calculated under RCP8.5

494 are always higher than scores under the other two RCP pathways, reflecting potentially larger species

loss in a high emissions pathway and, thus, the dependency of the product's performance on the

496 chosen emission path.

497

498 **Table 2** Total impact scores per functional unit (f.u.) for the considered end-of-life scenarios according to

499 endpoint MCTP (MCTP<sub>endpoint</sub>) for both local and global species losses and the complementary metric of damage

- 500 to ecosystems from ReCiPe 2016. The sequence green yellow red shading indicates ranking between
- 501 scenarios (within columns), from lowest (green) to highest (red) impact scores

Scenario	MCTP <sub>endpoint</sub> for local species losses (PDF <sub>local</sub> /f.u.)		MCTP <sub>endpoint</sub> for global species losses (PDF <sub>global</sub> /f.u.)			Damage GWP (ReCiPe 2016)	
	RCP4.5	RCP6	RCP8.5	RCP4.5	RCP6	RCP8.5	(Species · yr/f.u.)
1. Incineration	4.1E-16	1.2E-15	3.7E-15	5.0E-16	1.2E-15	3.2E-15	5.1E-09
Plastic							
degradation rate							
2. Fast	3.3E-15	7.8E-15	3.0E-14	4.0E-15	8.2E-15	2.6E-14	2.3E-08
3. Medium	4.2E-15	1.2E-14	4.3E-14	5.0E-15	1.2E-14	3.7E-14	2.3E-08
4. Slow	2.7E-15	1.0E-14	3.0E-14	3.2E-15	1.0E-14	2.5E-14	2.1E-08
5. Very slow	2.0E-17	9.0E-17	2.3E-16	2.3E-17	8.9E-17	1.9E-16	2.2E-10
Delayed							
degradation							
6. After 20	5.6E 15	$1.7E_{-}14$	5 7E-14	6 5E 15	$1.7E_{-1}$	4 8E-14	2 3E-08
years (fast rate)	5.0E-15	1.712-14	J./E-14	0.51-15	1.712-14	4.01-14	2.512-00
7. After 50	1.2E-15	9 1E-15	2 7E-14	1 5E-15	8 7E-15	2 1E-14	2 3E-08
years (fast rate)	1.21-13	J.1L-15	2.711-+	1.51-15	0.71-15	2.111-	2.51-00

502

503

# 504 4 Discussion

# 505 4.1 Metrics based on ecosystem damage

506 The MCTP<sub>endpoint</sub> factors calculated here measure the potential loss of species biodiversity from a

507 GHG emission that contributes to passing climate tipping points. We emphasize that this potential

508 species loss should be seen as the translation of the contribution of an emission to tipping (expressed

at midpoint level) into the resulting potential loss of species. The focus here is on impacts through contributions to climate tipping and not on assessing the biodiversity loss from GHG emissions through the time-integrated radiative forcing impact pathway (linking radiative forcing change to time-integrated temperature change and to final species loss) that is represented by the GWP-based metric for ecosystem damage. Similarly, it is not the aim of the present method to assess tipping points for critical loss of species.

515 In our model we have accounted for the acceleration of species loss with increasing 516 temperature levels in line with recent estimates (Newbold, 2018; Urban, 2015). Thus, we could have expected the impact on species to be larger for future emissions (i.e. occurring at higher levels of 517 518 warming) than for emissions today, returning increasing MCTP<sub>endpoint</sub> results over time. However, we 519 found that this acceleration is counteracted by the simultaneous decline in the contribution of an 520 emission to temperature rise over time. As a unit emission of CO<sub>2</sub> leads to a lower temperature 521 increase when emitted closer to the year of the last tipping point, in line with the *average* approach to 522 modelling characterization factors, it follows that the impact on species diversity can be 523 proportionally lower for emissions occurring later, toward the end of the century. Therefore, the 524 resulting decrease in MCTP<sub>endpoint</sub> factors should not be interpreted as, e.g., lower sensitivity of the 525 climate to future emissions or other climate related mechanisms.

526 In contrast to other endpoint metrics (including damage GWP) that assess effects of 527 GHG emissions on biodiversity in LCA, the MCTP<sub>endpoint</sub> introduces a temporal perspective also in the 528 midpoint to endpoint factor. As a consequence, the MCTP<sub>endpoint</sub> for a specific gas depends on the 529 emission year. The results from the case study suggest that use of the new metric gives additional 530 insights about the performance of the compared products, capturing larger potential impacts when 531 emissions from the product occur in periods when probability of tipping points is the largest (between 2040 and 2060 under RCP6), distinguishing it from the damage GWP. This finding is in line with 532 533 what was found when applying the CFs at the midpoint level (Fabbri et al., 2021).

We find little difference between the  $MCTP_{endpoint}$  factors that express local and global species losses. This is due to the similarity of the curves used to describe local and global species loss as function of temperature rise (Fig. 2). This observation seems at odds with the expectation that local

537 losses should be larger than global because a substantial local loss of species is likely to occur before 538 those species start becoming globally extinct. However, the outcome depends on the spatial 539 distribution of species and on which species are lost first. For instance, if the loss involves very 540 narrowly distributed species, then global extinctions could become high without having a large impact 541 on local diversity. Furthermore, the inclusion of some data on fish species (from 10 out of 131 542 assessed studies) slightly alters the representativeness of the study of Urban (2015) for modeling 543 terrestrial species losses and may have an influence on the similarity between local and global level 544 results. Finally, an additional reason could be that the estimates of global losses from the study of Urban (2015), which were extrapolated from local and regional studies, are, in reality, more 545 representative for local species losses, explaining the similarity with figures from Newbold (2018). 546 547

• • •

### 548 **4.2** Applicability in life cycle assessment

549 The emission year-specific MCTP<sub>endpoint</sub> factors for the three gases (CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O) provided here 550 (Supplementary Information-2, Tables S1-S6) are directly applicable in LCA studies to assess the 551 potential species loss stemming from the life cycle of products or services. The added value of the 552 MCTP<sub>endpoint</sub> compared to other damage metrics used in LCA is to consider that larger potential 553 impacts on species could occur when emissions are released in periods with higher probability of 554 crossing tipping points. As opposite, tipping points and the dependency of impacts on emission timing 555 are ignored in other PDF-based calculations. This revealed new insights about the performance of 556 different plastics when compared to the damage GWP metric, highlighting the relevance of 557 considering climate tipping as a separate impact category. This has also the advantage of showing 558 when emissions associated to product life cycles should be mostly avoided, through e.g. carbon 559 storage in products, which could potentially delay the tipping and allow implementation of climate 560 change mitigation and/or adaptation solutions. As for the midpoint MCTP, use of MCTP<sub>endpoint</sub> is 561 relevant when a time-differentiated inventory is available for the assessed products. However, since 562 temporarily disaggregated inventories are not yet easy to implement into dominant LCA software, 563 calculation of MCTP<sub>endpoint</sub> impact scores (through eq. 6) has to be conducted offline. For situations

where temporal disaggregation of the inventories is not deemed relevant, we recommend using
 MCTP<sub>endpoint</sub> factors calculated for single year (e.g. 2021) to match with aggregated emissions for the
 same year.

567 Advancing the midpoint MCTP to endpoint level should ideally allow for comparison 568 with the damage caused by other environmental impacts, such as eutrophication or ecotoxicity but 569 also other climate-related impact categories (such as those based on the GWP). For instance, 570 comparison of our MCTP<sub>endpoint</sub> for global species losses with the damage GWPs from ReCiPe 2016 could be possible as the species loss considered in both MCTP and GWP-based methods are based on 571 global extinction risks of Urban (2015). However, for direct comparisons harmonization of units is 572 573 required. This requires two steps. In the first step, conversion of the potentially disappeared fraction 574 of species (used in MCTP<sub>endpoint</sub>) to absolute number of species (used in methods such as ReCiPe 575 2016) is needed. For MCTP<sub>endpoint</sub> factors expressing global species losses, this can be done by 576 multiplying the final MCTP<sub>endpoint</sub> impact score of the assessed product (calculated through eq. 6) with 577 the total number of terrestrial species on the planet. This value is estimated to be approximately 6.5 578 million (Mora et al., 2011), of which 1.6 million are the species that have been classified (Goedkoop 579 et al., 2009). Even though the former value would be recommended as it gives a more realistic 580 measure of species diversity, the latter should be used when the purpose is to compare with ReCiPe 581 2016 (as this is the value adopted in ReCiPe). Conversion to absolute losses for the MCTP<sub>endpoint</sub> 582 factors expressing local species losses is considered less relevant for comparisons with other impact 583 categories, due to lack of existing damage metrics expressed as absolute local species losses, and thus 584 it was not carried out here. We stress however that in this case a different calculation approach would 585 be needed. It would require recalculation of the MCTP<sub>endpoint</sub> factors using estimates of absolute 586 (rather than fractional) local species losses per temperature change, obtained as an average over each 587 grid cell considered in Newbold (2018).

The second step addresses the time (exposure duration), which is not explicit in the MCTP<sub>endpoint</sub> unit. Other damage-oriented CFs include a time dimension when expressing impacts on biodiversity, e.g., species·yr (ReCiPe 2016) or PDF·yr (LC-IMPACT), which may represent the duration (in years) of the period of exposure to the pressure (e.g. the residence time of the emission in

592 the environment). To harmonize the units of the MCTP<sub>endpoint</sub> with other damage-oriented metrics, an 593 idea could be to multiply the MCTP<sub>endpoint</sub> impact scores (in either PDF or species) by the total number 594 of years from the first emission up to the last expected tipping point in each RCP pathway. This 595 number corresponds to 70, 97 and 85 years for RCP4.5, RCP6 and RCP8.5, respectively, for emissions starting in year 2021. We recall that in RCP4.5 the global temperature starts to stabilize at 596 597 around 2.5° C within 70 years, meaning that tipping points expected at higher temperature levels 598 cannot occur after this time, whereas for the other two pathways the temperature projections keep 599 increasing and later tipping points could be expected. The resulting MCTP<sub>endpoint</sub> impact scores for the 600 case study therefore become 2-3 orders magnitude higher when compared to scores obtained using 601 damage GWPs.

602

#### 603 4.3 Limitations

604 One limitation in the midpoint to endpoint factor is that the uncertainties related to estimation of 605 species loss with temperature change were not considered. Accounting for modelling uncertainties Newbold (2018) reports that temperature increases between 2.5 and 4.8°C (relative to pre-industrial) 606 607 would lead to changes in local species numbers ranging between a 2% gain and 47% loss (overall 608 figures across all used RCP scenarios and species distribution modelling algorithms). For global species losses, uncertainties across the individual studies considered by Urban (2015) for similar 609 610 temperature increases (2 - 4.3°C relative to pre-industrial) range from about 4 to 20%. 611 Second, given the dependency of the damage MCTP factors on the number of 612 considered climate tipping points, a limitation is our lack of knowledge about all potential present and 613 future tipping points. Our framework uses the current knowledge about tipping points, but it can be 614 readily updated when additional potential tipping points are discovered. 615 A third limitation is the inability of the damage MCTP factors to capture the full 616 impacts from climate tipping. The models used to estimate species loss only capture direct effects of 617 temperature increases, and do not consider other impacts of crossing the tipping points, such as major

618 biome shifts, monsoon shifts or Amazon forest dieback. The way in which species could respond to,

619 e.g. a recurring ice-free summer in the Arctic, or a gradual but irreversible dieback of the Amazon 620 forest is difficult to predict (Post et al., 2009). Several models assessing the impacts of future climate 621 change on biodiversity have been developed (see e.g. Pearson and Dawson, 2003; Thuiller et al., 622 2013), but estimates of the consequences of specific tipping events are lacking or incomplete. For this, 623 direct impacts such as those derived from loss or degradation of the natural habitat of species, e.g., biodiversity loss from forest dieback or intensified droughts, and the influence that these may have on 624 625 the fraction of species loss per unit of temperature increase were not considered. This implies that the impacts calculated through the damage MCTP factors are probably underestimated. 626

Fourth, there is a limitation in the way in which the temperature rise following a 627 628 tipping event was determined. This measure depends on several uncertain factors, such as the 629 potential consequences on the climate from tipping, the rate at which the consequences unfold and the 630 response of the climate to these changes. We used available estimates of carbon emissions and 631 relative radiative forcing change caused by tipping, but no uncertainty estimates were included as they 632 are rarely available. In addition, the approach adopted to calculate the temperature increase following 633 carbon emissions, which in practice assumes that temperature increases faster but never exceeding the 634 projection of each RCP pathway, is an oversimplification of the climate mechanisms involved. A 635 more appropriate measure would require the use of climate models simulating the climate-carbon-636 cycle system, such as Earth system models (ESMs) (Millar et al., 2017). The main implication of 637 these model limitations is to underestimate the potential temperature increase induced by passing 638 tipping points, which could actually rise above RCP projections, and, consequently, indicate an 639 underestimation of the resulting loss of species. This may affect the magnitude of MCTP<sub>endpoint</sub> factors 640 to some extent, but it is not expected to change the observed overall trends.

641

#### 642 4.3.1 Priorities for further developments

643 As every biodiversity loss metric focusing only on the loss of species diversity, our metric assigns an 644

- equal weight to all species without considering e.g. the functional role that species play in the
- 645 ecosystem, assuming that the damage to biodiversity is independent of which species are lost.

646 However, in terms of consequences for the natural ecosystems, it is not given that all species should 647 be weighted equally, and furthermore it is not given that species which remain in the future should 648 have the same weight as species living today. For example, losing species in the future, when many 649 others have already disappeared, may compromise the ecosystems' functions more severely than 650 when species diversity is still (relatively) high, as of today. Further, the loss of keystone species, 651 playing a critical role in the ecosystem, may weight more than a larger decline of species performing less crucial functions. Complex interactions exist between species in ecological communities and, for 652 653 this, the loss of certain critical species from a community could cause a cascade of secondary extinctions of many other species (Brodie et al., 2014; Dunne and Williams, 2009). Ideally these 654 dynamics could be included in our metric by introducing a *severity* factor in eq. 1, providing a 655 measure of severity of the damage. As the current ability to predict these mechanisms in the ecology 656 657 and climate fields is rather limited, however, calculation of such a severity factor is not 658 straightforward.

659

# 660 **5 Conclusions**

661 Our work is the first attempt to link midpoint multiple climate tipping points metrics of GHG 662 emissions to loss of terrestrial species biodiversity at local and global scales. The developed MCTP<sub>endpoint</sub> metric attributes a larger potential species loss to emissions occurring when their 663 664 contribution to crossing tipping points is higher, given that crossing could intensify warming and 665 further exacerbate species loss. Therefore, the main advantage of the MCTP<sub>endpoint</sub> compared to the 666 midpoint MCTP is to express impacts in terms of damage to terrestrial species. Overall, MCTPendpoint values decrease over time, meaning that emissions occurring later in the century are attributed a lower 667 668 potential species loss. This decline is found to depend on the decreasing contribution of emissions to 669 temperature rise over time, even though acceleration of species loss with increasing temperature 670 levels has been accounted for.

671 The MCTP<sub>endpoint</sub> can be used in LCA to assess the potential loss of terrestrial species
 672 stemming from the life cycle of products. Application of the metric is considered particularly valuable

673 for products where time-differentiation of emissions is relevant, such as biodegradable plastics or 674 deteriorating wooden products. The MCTP<sub>endpoint</sub> complements existing damage-level metrics used in LCIA and we therefore recommend including it as new damage category. For consistency with other 675 676 damage metrics expressing global species loss impacts, we recommend using MCTP<sub>endpoint</sub> values 677 predicting global species loss. It is also recommended to present results for all three considered RCP 678 scenarios as a sensitivity analysis. Differences in how time is treated in MCTP<sub>endpoint</sub>, however, when 679 compared to other damage metrics used in LCA warrant further harmonization efforts. In the broader 680 LCA context, our MCTP<sub>endpoint</sub> penalizes emissions occurring closer to tipping points, particularly those occurring between 2040 and 2060. Their use thus aims to discourage emissions attributed to 681 product life cycles that will occur when they matter most and result in largest damage, offering the 682 683 possibility to postpone the tipping, e.g. through carbon storage in products, thus buying time for the 684 implementation of climate change mitigation and/or adaptation solutions (Jørgensen et al., 2015).

685

686 Supplementary Information

687 Supplementary methods and results (Supplementary Information-1)

688 Emission-year specific MCTP<sub>endpoint</sub> values (Supplementary Information-2)

689

# 690 Data availability statement

All data generated during this study are included in this published article [and its supplementary

692 information files].

693

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#### **Declarations** 698

699 Conflict of interest. The authors have no competing interests to declare.

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