

1 **Title Page**

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3 **Title:** Simulating growth-based harvest adaptive to future climate change

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15

16 **Abstract**

17

18 Forests are the main source of biomass production from solar energy and take up globally  
19 around  $2.4 \pm 0.4$  PgC per year. Future changes in climate may affect forest growth and  
20 productivity. Currently, state-of-the-art Earth system models use prescribed wood harvest rates  
21 in future climate projections. These rates are defined by integrated assessment models (IAMs)  
22 only accounting for regional wood demand and largely ignoring the supply side from forests.  
23 Therefore, we assess how global growth and harvest potentials of forests change when they are  
24 allowed to respond to changes in environmental conditions. For this, we simulate wood harvest  
25 rates oriented towards the actual rate of forest growth. Applying this growth-based harvest rule  
26 (GB) in "JSBACH", the land component of the Max-Planck-Institute's Earth System Model,  
27 forced by several future climate scenarios, we realized a growth potential twice to four times  
28 ( $3-9 \text{ PgCy}^{-1}$ ) the harvest rates prescribed by IAMs ( $1-3 \text{ PgCy}^{-1}$ ). Limiting GB to managed forest  
29 area (MF), we simulated a harvest potential of  $3-7 \text{ PgCy}^{-1}$ , two to three times higher than IAMs.  
30 This highlights the need to account for the dependence of forest growth on climate. To account  
31 for long term effects of wood harvest as integrated in IAMs, we added a life cycle analysis  
32 showing that the higher supply with MF as an adaptive forest harvesting rule may improve the  
33 net mitigation effects of forest harvest during the 21<sup>st</sup> century by sequestering carbon in  
34 anthropogenic wood products.

35

36 **Keywords:** Adaptation to climate change, Mitigation, Mortality, Carbon forestry, sustainable  
37 forest management, Global forest model

38

39 1. Introduction

40 Forest ecosystems play a major role in taking up global CO<sub>2</sub> emissions and affect global climate  
41 conditions through a range of complex biophysical and biogeochemical processes. Forests are  
42 the main source of biomass production from solar energy through photosynthesis and are  
43 estimated to take up globally around  $2.4 \pm 0.4 \text{ PgCy}^{-1}$  (Pan et al., 2011). A large part of this  
44 uptake can be attributed to direct and indirect human interference: Direct human impact by  
45 forest management creates young forests sequestering carbon during regrowth (Houghton et al.,  
46 2012), and provides material for fossil-fuel substitution (Nabuurs et al., 2007). However, forest  
47 utilization and interaction of management with large-scale natural disturbances, such as forest  
48 fires, may emit tonnes of CO<sub>2</sub> immediately to the atmosphere and act as a source of CO<sub>2</sub>  
49 emissions (Bonan, 2008). Indirect human impact alters environmental conditions, in particular  
50 climate and atmospheric CO<sub>2</sub> concentrations, which historically has caused a carbon uptake by  
51 the terrestrial vegetation (Le Quéré et al., 2018). Any change in environmental conditions  
52 affects forest growth, risks of hazards, and productivity and, consequently, the amount of wood  
53 that can be harvested (Temperli et al., 2012; Sohngen and Tian, 2016).

54 The effects of changes in environmental conditions on the state of the biosphere are represented  
55 in state-of-the-art Earth system models (ESMs). However, the description of forest management  
56 in these models is largely independent of environmental changes: So far, ESMs employ  
57 prescribed wood harvest amounts. These are derived from national statistics for the historical  
58 period and from global integrated assessment models (IAMs) for future scenarios. IAMs  
59 determine the wood harvest rates based on the supply of woody materials from vegetation and  
60 demands of regional industries and population (van Vuuren et al., 2011). However, changes in  
61 the supply via forest growth and changed structural conditions especially under climate change  
62 and increasing CO<sub>2</sub> concentrations are ignored. The main drivers of these models are economic,  
63 i.e. market price, and population growth scenarios and forest harvest decisions are only reactive

64 to the assumed socioeconomic scenarios and do not take forest ecosystem dynamics and growth  
65 into account.

66 In this study we investigate the relevance of changes in environmental conditions for the growth  
67 potential of forests and subsequently their harvest potentials. Moreover, we explore the  
68 ecological potential of world forest resources for wood production and the implications for  
69 carbon mitigation. To assess growth and harvest potentials, we investigate forest growth under  
70 various future climate scenarios. We allow forests to be harvested and to regrow in response to  
71 the respective changes in environmental conditions, in all scenarios such that the growth  
72 increment is removed each year, i.e. the biomass stocks are neither reduced nor increased. We  
73 call this “growth-based” harvesting (GB). Removing the annual increment mirrors the forest  
74 management concept of “sustained yield”. Managing for sustained yield is a strong  
75 sustainability policy applied in sustainable forest management, which aims to maintain forest  
76 stocks as natural capital and controls wood extraction (Luckert and Williamson, 2005).  
77 According to the sustained yield concept, the maximum wood harvest rate to utilize forest  
78 resources equals the actual rate of forest growth. Exceeding regrowth rates would result in the  
79 exploitation of forest ecosystems and would decrease forest yield and productivity. On the other  
80 hand, minimalistic usage, i.e. falling below regrowth rates, would not be an optimal allocation  
81 of forest resources from the perspective of production. However, the traditional concept of  
82 sustained yield management, as defined above, does not account for changes in the growth rates  
83 (Luckert und Williamson, 2005), although forest growth rates are highly dependent on the  
84 environmental conditions (Collins et al., 2018). It has been noted before that any decision about  
85 forest management should take into account the effects of changes in climate and CO<sub>2</sub>  
86 concentrations on forest growth (Yousefpour et al., 2012; Hickler et al., 2015; Sohngen and  
87 Tian, 2016; Sohngen et al., 2016) and consequently on the harvest rate (Temperli et al., 2012;  
88 Jönsson et al., 2015). Here we demonstrate how altered growth potentials translate into higher  
89 harvest potentials under an adaptive growth-based harvest. We idealize the concept for this



90 study in that GB is applied world-wide irrespective of the accessibility of the forest for forest  
91 management activities, but allowing for dependence of wood harvest on altered climate  
92 conditions and CO<sub>2</sub> concentrations. To link these results to actual harvest potentials, we overlay  
93 information on the accessibility of forest areas represented as managed forest area (Kraxner et  
94 al., 2017).



95 Keeping in mind the above-mentioned problem of not accounting for changing environmental  
96 conditions in global forest utilization modelling, the goal of this study is to establish a modeling  
97 framework that allows harvesting rates to respond interactively to environmental changes. We  
98 further assess the maximum potential of global forest resources for wood production and the  
99 long term CO<sub>2</sub> mitigation effects of wood harvest, which are implicit or explicit drivers of forest



100 utilization in IAMs. We compare the outcome of the growth-based harvest with the outcome  
101 when applying prescribed wood harvest amounts from three different Representative  
102 Concentration Pathways (RCPs) realized by IAMs and commonly used by ESMs as an external  
103 forcing (Hurtt et al., 2011). Since harvested material is used in the IAMs to estimate the amount  
104 of bioenergy wood, which in turn is needed in the IAMs to analyze energy and carbon mitigation  
105 policies, we perform a first-order assessment of the CO<sub>2</sub> consequences of altering the harvest  
106 rates in response to climate. Similarly and to determine the mitigation potential by wood  
107 products we allocate the harvested material to products of different lifetimes according to FAO  
108 country-specific statistics (FAOSTAT, 2016). The change in atmospheric carbon content  
109 resulting from the release of CO<sub>2</sub> by the decay of these products is quantified accounting for



110 compensating fluxes by the ocean and the terrestrial vegetation (Maier-Reimer und  
111 Hasselmann, 1987). The net mitigation effect of wood harvest is then defined as the difference  
112 between the total amount of harvested material and the change in atmospheric carbon content.

## 113 2. Materials and methods

### 114 2.1. Dynamic global vegetation model JSBACH

115 We implemented the GB harvesting rule in JSBACH, the land component of the MPI-ESM  
116 (Reick et al., 2013). In the applied version of JSBACH vegetation is represented by 12 plant  
117 functional types (PFTs) including six woody PFTs. Each PFT is globally endowed with  
118 properties in relation to integrated processes in JSBACH and PFT-specific phenology, albedo,  
119 morphology, and photosynthetic parameters (Pongratz et al., 2009). Organic carbon is stored in  
120 three vegetation pools: living tissue as “green”, woody material as “wood”, sugar and starches  
121 as “reserve pool”, and two soil pools with a fast (about 1 year) and a slow (about 100 years)  
122 turnover time (Raddatz et al., 2007). Wood harvest activities do not change the area or  
123 characteristics of different PFTs, but affect the carbon pools of woody PFTs (forests and shrubs)  
124 by removing carbon from the wood pool, resembling trees’ stem and branches removal via  
125 harvesting (Reick et al., 2013). Harvest thus affects the vegetation carbon stocks, but the model  
126 does not represent a feedback of the harvest activity on the forest productivity.

127 We applied JSBACH in ‘offline’ mode, i.e. not coupled to the atmosphere, but driven by the  
128 CMIP5 output of the MPI-ESM (Giorgetta et al., 2013) from experiments with CO<sub>2</sub> forcing  
129 according to three different RCP scenarios (RCP2.6, RCP4.5 and RCP8.5) for the year 2006-  
130 2100. We used a T63/1.9° horizontal resolution and conducted our simulations with  
131 disturbances due to fire and wind. The simulations were conducted without dynamic vegetation  
132 and without land-use transitions to prevent changes in the areas occupied by the different PFTs  
133 and to be thus able to isolate the effects of forest management activities. Further details on the  
134 model version and the simulation setup are given in the supplementary material (S1).

### 135 2.2. RCPs wood harvest

136 The current standard module for anthropogenic land cover and land-use change in JSBACH is  
137 based on the harmonized land-use protocol (Reick et al., 2013), which provides land-use

138 scenarios for the period 1500-2100 (Hurtt et al., 2011). As part of this protocol, a set of globally  
139 gridded harvest maps from the **IAM implementations** of the RCPs is provided (Hurtt et al.,  
140 2011). In JSBACH simulations, the harvest prescribed in these maps is fulfilled taking above-  
141 ground carbon of all vegetation pools and all PFTs proportionally to the different pool sizes. In  
142 this study, however, we concentrate on the carbon harvested from the wood pool of the woody  
143 PFTs, which by far contributes most of the harvested volume.



### 144 2.3. Growth-based (GB) harvesting rule to estimate growth potentials

145 As an alternative for the prescribed harvest maps, we implemented the GB harvesting rule,  
146 which allows for adaptive wood harvesting reacting to changes in wood increments, and  
147 accordingly dependent on climate and CO<sub>2</sub> conditions. We define the GB rule as the allowance  
148 to harvest specific volumes of wood to the extent of the average increment (i.e. the average  
149 annual growth). Applying GB, we aim to stabilize the wood carbon pool in the woody PFTs at  
150 the level of a selected reference period. In the current paper we selected the maximum level for  
151 the present period (1996-2005) simulated with JSBACH (see S1). Using a reference level  
152 determined from the last ten years of the historical simulation allows us to keep the standing  
153 wood on the present level and to account for the dependence of forest growing stocks (carbon  
154 pools) to disturbances, silvicultural interventions and varying environmental conditions. Under  
155 the GB harvesting rule, the wood harvest is only allowed to reduce the wood carbon pool down  
156 to the reference level. Aside from environmentally driven decreases, the wood carbon pool thus  
157 nearly remains constant over the whole simulation time.

158

### 159 2.4. Simulation runs with JSBACH

160 We conducted six simulations (Table 1) from 2006-2100, all starting from the same initial state  
161 (see S1). The simulations differ in the applied harvest rule and in their climate and CO<sub>2</sub> forcing.  
162 While the different RCP harvest maps were applied in simulations with the corresponding MPI-

163 ES-M RCP forcing, each MPI-ES-M RCP forcing was additionally run applying the GB  
164 harvesting rule.

165 **Table 1**

166 2.5. Growth-based harvesting restricted to managed forests (MF)

167 To infer from the growth potentials simulated under GB how much biomass could potentially  
168 be harvested (harvest potentials), we conduct a post-processing step overlaying a map that  
169 masks out forest areas subject to conservation, infrastructural limits, or not being influenced by  
170 human activities so far due to other reasons (Kraxner et al., 2017). Applying nearest neighbor  
171 interpolation on the 1 km<sup>2</sup> spatially explicit map of primary forest intensity (0%-100%; Fig. 6  
172 in Kraxner et al., 2017) we derived a T63 map of primary forest area. This static map was used  
173 to filter the growth-based harvest determined in the GB simulations for 2006 to 2100, to only  
174 account for managed forests (MF) in the mitigation assessment.

175 2.6. Analysis of wood harvest impacts on forest disturbances and natural mortality

176 To analyze the mechanisms driving differences in GB and RCP wood harvest amounts we can  
177 formulate changes in above-ground wood carbon stocks over time ( $dC_w/dt$ ) as carbon gains  
178 from net primary production allocated to the wood pools ( $NPP_w$ ) minus losses due to natural  
179 disturbances and anthropogenic management (i.e., wood harvest,  $h$ ):

180 
$$\frac{dC_w}{dt} = NPP_w - \frac{C_w}{\tau} - h \quad (1)$$

181 In this conceptual formulation, the loss due to natural disturbances depends on the size of the  
182 carbon stock and a time constant ( $\tau$ ). As net primary production in our model does not depend  
183 on harvest, GB growth potentials ( $p_{GB}$ ) and RCP harvest can be related as

184 
$$p_{GB} = h_{RCP} + \left( \frac{C_{wRCP}}{\tau_{RCP}} - \frac{C_{wGB}}{\tau_{GB}} \right) + \left( \frac{dC_{wRCP}}{dt} - \frac{dC_{wGB}}{dt} \right) \quad (2)$$



185 The amount of growth potential under GB can thus be split into several terms: The first term is  
186 the reference harvest rate of the RCPs. The second term accounts for the difference in loss due  
187 to natural disturbances in the RCP and the GB simulation. In JSBACH this can further be split  
188 into differences in losses due to background mortality, such as self-thinning of forests, due to  
189 fire, and due to windbreak. JSBACH explicitly integrates two modules for the simulation of  
190 fire and wind disturbances depending on climate and carbon pools. The third term accounts for  
191 the changes in the above-ground wood pool realized over time in the simulations. As shown  
192 below, the RCP harvest results in an increase of above-ground woody biomass over the 21<sup>st</sup>  
193 century for all three scenarios. For GB, on the other hand,  $dC_{WGB}/dt$  should theoretically be  
194 close to zero over time as GB aims to sustain the above-ground carbon pools of woody PFTs;  
195 however, reductions in NPP due to less favorable climatic conditions or increased disturbances  
196 can entail negative  $dC_{WGB}/dt$ . To summarize, GB includes the RCP wood harvest and,  
197 moreover, makes use of additionally accumulated carbon and eventually reduced mortalities to  
198 adapt harvest decisions to the novel climate and forest growing conditions.

## 199 2.7. Accounting for the mitigation potential of forest management in the Earth system

200 We account for long term effects of wood harvest, as in IAMs, by approaching a life cycle  
201 analysis. Many wood products have lifetimes of decades to centuries. Here, we assess the effect  
202 on atmospheric carbon content when harvested carbon is transferred, at least to a part, to longer-  
203 lived product pools, instead of entering the atmosphere immediately. We compare this  
204 “mitigation effect” achievable by the wood products harvested under the GB concept after the  
205 map of managed forest area is overlaid (MF) to those achievable according to the three RCP  
206 harvest maps. To this end, we distinguish three anthropogenic wood product pools -- bioenergy,  
207 paper, and construction -- with 1, 10, and 100 year life times, respectively, as are typically  
208 assumed in global modeling studies (Houghton et al., 1983; McGuire et al., 2001).

209 To allocate the wood biomass harvested in our JSBACH simulations to different product pools,  
 210 we made use of FAO country-specific statistics reporting wood production in fourteen different  
 211 categories (FAOSTAT, 2016). For our analysis, we assume that the production technology and  
 212 allocated percentage of each country’s total wood production to these fourteen categories  
 213 remains constant at 2005 levels over the 21<sup>st</sup> century and used these percentages to allocate  
 214 wood biomass harvest from JSBACH (remapped to countries - see a calculus example in  
 215 supplementary material S2). The fourteen categories are then assigned to the three distinguished  
 216 anthropogenic wood product pools. We assume that the harvested material entering one of these  
 217 three product pools in a year decays at a rate of 1/lifetime, i.e. that all material used for  
 218 bioenergy is respired to the atmosphere within the same year it is harvested, while the material  
 219 entering the paper and construction pool is emitted at a constant rate over the following 10 or  
 220 100 years, respectively. The emissions at a given year for paper and construction pools are  
 221 therefore composed of a fraction of that year’s harvest, but also of the legacy of material  
 222 harvested earlier, yielding annual emissions  $E$  from all three product pools as follows:

$$223 \quad E(t) = f_b h(t) + \sum_{s=t-9}^t \frac{1}{10} f_p h(s) + \sum_{s=t-99}^t \frac{1}{100} f_c h(s) \quad (1)$$

224 Here,  $f$  for bioenergy (b), paper (p), and construction wood (c) are the fractions with which the  
 225 harvested biomass is assigned to the product pools (see S2). We call  $E$  “emissions from product  
 226 decay” in the following.

227 To account for the fact that the emissions from product decay leave the atmosphere over time  
 228 to be taken up by the terrestrial biosphere and the ocean, we apply the response function (Eq.  
 229 2) by Maier-Reimer and Hasselmann (1987). Convolution of this response function with the  
 230 time series of annual emissions from product decay until year  $t$  results in the change in  
 231 atmospheric carbon content in that year,  $C(t)$  (Eq. 3).

232

$$233 \quad G(t) = A_0 + \sum_{p=1}^4 A_p \exp^{-t/\tau_p} \quad (2)$$

234  $C(t) = \int_0^t G(t-s) \cdot E(s) ds$  (3)

235

236 Emissions are present in the atmosphere as they occur and, therefore,  $G(0) = 1$  and  $A_0 = 1 -$   
237  $\sum_p A_p$ . The constants  $A_p$  and the time constants  $\tau_p$  are fitted for  $p > 0$  using one of the best fits  
238 found by Maier-Reimer und Hasselmann (1987): the sum of four exponential terms with time  
239 constants  $\tau_1, \tau_2, \tau_3$  and  $\tau_4$  of approximately 1.9, 17.3, 73.6, and 362.9 years, and constants  $a_1,$   
240  $a_2, a_3$  and  $a_4$  of 0.098, 0.249, 0.321, and 0.201. Accordingly, Equation 2 is an exponential  
241 function that accounts for the uptake of CO<sub>2</sub> by ocean and land over time and Eq. (3) integrates  
242 the accumulated amount of total CO<sub>2</sub> concentrations in the atmosphere at each time step  
243 regarding past and present emissions. The mitigation effect of wood products is then determined  
244 as the difference between the harvested material and the change in atmospheric carbon content.

### 245 3. Results

#### 246 3.1. Comparison of GB and RCP harvesting

247 Above-ground woody biomass is simulated to increase by the end of the 21<sup>st</sup> century for the  
248 RCP wood harvest (Figure 1a), despite an increase of the amounts of wood harvest (Figure 1b).  
249 This implies that the changes in environmental conditions lead to a larger accumulation of  
250 woody biomass than is removed by the increased harvest. Depending on the RCP, the simulated  
251 increase in above-ground woody biomass may reach 133% (425 PgC in 2100) of the initial  
252 level in 2005 (320 PgC) for RCP8.5 and substantially higher levels of 128% and 117% for  
253 RCP4.5 and RCP2.6, respectively (Figure 1a). The temporal pattern of this increase, with strong  
254 increase only in the first half of the century for RCP2.6 or throughout the century for RCP8.5,  
255 reflects the projected evolution of changes in CO<sub>2</sub> and climate (Collins et al., 2018).

256 For the GB rule, woody biomass remains more or less constant over time (Figure 1a), as the  
257 average annual increment is removed by harvest by definition of the GB rule (see Methods).

258 Consequently, the growth potential of global forest resources under GB is simulated to be as  
259 high as 9 PgCy<sup>-1</sup> at the end of the century subject to the realization of RCP8.5 climatic  
260 conditions, or about 4 to 6 PgCy<sup>-1</sup> for the other two scenarios (Figure 1b). About two thirds of  
261 the growth potential lie in managed forest areas and are thus potentially harvestable (Figure 1b,  
262 MF-harvest curves). The MF harvest potentials are thus twice to three times (3-7 PgCy<sup>-1</sup>) as  
263 high as those of prescribed wood harvest simulated by IAMs for the RCPs. Note that, as  
264 described in the methods, managed forest areas refer to the present-day state and may expand  
265 in the future, which would further increase the harvest potential. These figures are harvestable  
266 wood biomass amount and differ from commercially useable timber including bioenergy, paper,  
267 and construction woody biomass (see 2.7 and 3.3).

268 We map the geographical distribution of RCP harvest as well as growth and harvest potential  
269 under the GB harvesting rule applied to all global forest (GB) and managed forest areas (MF)  
270 to recognize regional hotspots (Figure 2). Central Latin America including the accessible parts  
271 of the Amazon forests, large parts of North America, the accessible parts of central Africa,  
272 eastern Asia and Europe including Russia can be recognized under all climate scenarios as  
273 hotspots for allocation of simulated harvest activities. The large harvest potentials of the supply-  
274 based harvest in the tropics contrast with the patterns of the demand-based RCP harvest; in  
275 particular in RCP2.6 and RCP4.5 much of the global harvest is provided from eastern North  
276 America, central Europe and East Asia. A reasonable proportion of GB harvest amount in the  
277 tropics is masked out in MF as inaccessible forest area; nevertheless the tropics contribute a  
278 large harvest potential from wood supply side in both GB and MF.

279 **Figure 1**

280 **Figure 2**

281 3.2.Separation of the processes underlying the growth potentials under future climate  
282 scenarios

283 The harvest potential under the GB harvesting rule in JSBACH exceeds RCPs wood harvest  
284 defined by IAMs not only because of taking into account changes in growth rates caused by  
285 changed environmental conditions, but also due to avoided mortality and disturbances (see  
286 methods section). Figure 3 shows the separation of the growth potential underlying the GB  
287 harvest into changes in standing wood as compared to RCP harvest, avoided background  
288 mortality, natural fire, and wind disturbances, and the amount prescribed originally by RCPs.  
289 The largest contribution to the growth potential under the GB harvesting rules exceeding the  
290 RCP harvest is the lower background mortality, which is directly related to lower accumulation  
291 of woody biomass (see Figure 1a). This lower accumulation also leads to the decreased carbon  
292 losses from fire and wind disturbances. Depending on the climate scenario (RCPs) the simulated  
293 reduction of mortality and disturbances add up to 2-5 PgCy<sup>-1</sup> at the end of the century. Under  
294 the RCP harvest, woody biomass is simulated to mostly increase beyond what is required by  
295 the increasing harvest rates (see Figure 1). Harvesting this “surplus”, i.e. the increase of  
296 standing biomass over time by applying RCP harvest rates and harvesting less biomass than the  
297 annual increment provides, also contributes to the larger growth potentials under the GB  
298 harvesting rule. The temporal evolution is different from that of avoided mortality and  
299 disturbances, reflecting the projected changes in CO<sub>2</sub> and climate. Greater fluctuation of the  
300 growth potential compared to the RCPs’ annual wood harvest amounts is because of the direct  
301 dependency of the forest’s productivity on climate fluctuations.

302 **Figure 3**

303 3.3.Mitigation potential of GB versus RCP wood harvest

304 We show the mitigation potential of forest resources in the 21<sup>st</sup> century under growth-based  
305 harvesting of global forest (GB) and managed forest (MF) areas versus the RCP wood harvest

306 prescribed from IAMs in Figure 4. Due to the larger harvested amounts, the mitigation potential  
307 is higher for GB and MF compared to RCP harvest and the magnitude depends on the  
308 underlying climate scenario. The advantage of growth-based harvesting lies in storing a larger  
309 amount of carbon in wood products whilst keeping above-ground woody carbon pools constant.  
310 These aspects are largely ignored by IAMs. Table 2 below shows the net mitigation potentials  
311 of world forest resources (GB and MF against RCP harvest) by wood harvest at the middle and  
312 end of the 21<sup>st</sup> century (2050 and 2100). The highest mitigation effect is achieved in the GB8.5  
313 scenario with 140.6 PgC and 379.1 PgC up to 2050 and 2100, respectively. These figures  
314 account for 278% and 287% more global carbon storage than in the RCP8.5 scenario with  
315 prescribed RCP wood harvest with 50.6 and 132.1 PgC mitigation up to 2050 and 2100,  
316 respectively. Only considering current managed forests, the mitigation effect realized for MF8.5  
317 still reaches a maximum mitigation potential of 109.3 and 295.8 PgC up to 2050 and 2100,  
318 respectively.

## 319 **Table 2**

## 320 **Figure 4**

### 321 4. Discussion



322 RCPs define wood harvest in each region according to scenarios realized by IAMs about social  
323 and economic developments in the 21<sup>st</sup> century, but independent of ecological capacities of  
324 forest ecosystems. Although the growth-based harvesting rule realizes potentially a larger wood  
325 harvest amount than the RCPs, it remains as per definition a sustained-yield forest harvesting  
326 approach and guarantees sustainability of the current ecological conditions at each region with  
327 respect to standing biomass. However, as a consequence, regions with low standing biomass,  
328 for example due to extensive historical harvest, will maintain these low biomass levels. Below  
329 we discuss the effectivity of GB in adapting to new environmental conditions and the mitigation  
330 potential and highlight the missing issues in our simulation analysis, especially about the

331 provisioning of multiple goods and services (e.g. biodiversity, forest health), and the future  
332 research themes about integration of diversified management strategies in ESMs.

333 Accounting for the climate state in simulating future forest harvest is crucial (Temperli et al.,  
334 2012; Sohngen and Tian, 2016). Accordingly, the novelty of the applied GB in this study is the  
335 dynamic nature of this management approach based on the ecology of forest ecosystems and  
336 climatic and atmospheric conditions. According to Schelhaas et al. (2010), an accelerated level  
337 of wood harvest to reduce the vulnerability of European old forests to wind and fire disturbances  
338 is needed to stop the current built-up of growing stock. Applying GB in this study realized an  
339 increased wood harvest rate for European forests (see Figure 2) showing first signs of carbon  
340 sink saturation and high vulnerability to natural disturbances (Nabuurs and Maseret, 2013).  
341 Global studies of this nature are largely missing due to the lack of data and forest ecosystems  
342 complexity on global scale. Our idealized simulations suggest that GB does not only effectively  
343 safeguard sustainability of the current forest biomass on the global scale, but also positively  
344 affects the resistance of forest resources against natural disturbances and efficiently utilizes  
345 forest growth and productivity potentials (see Figure 3). Our estimates are, of course, sensitive  
346 to the choice of reference level: In this study, we applied the maximum current (1996-2005)  
347 above-ground wood biomass as the reference level. Any changes in this reference may affect  
348 the realized harvest potentials and should be carefully defined regarding ecological potentials  
349 and economic implications.

350 In our simulations, future environmental changes are mostly beneficial for accumulation of  
351 forest biomass, apparent from increasing standing biomass in the RCP harvest scenarios or the  
352 increase of GB and MF harvest rates over the 21<sup>st</sup> century. This is in line with other studies  
353 projecting above-ground forest carbon storage to increase in the future (e.g. Tian et al., 2016).  
354 These effects of environmental changes on forest growth are largely missing in the IAMs  
355 providing the wood harvest scenarios to dynamic global vegetation models (DGVMs) and

356 ESMS. The RCP wood harvest rates are based on the demand for wood and bioenergy as the  
357 main driver of decisions by IAMs on forest harvest. For example, RCP8.5 applies the forest  
358 sector model DIMA (Riahi et al., 2011), which is a spatial model for simulating forestry  
359 processes to meet specific regional demand on wood and bioenergy. RCP4.5 bases wood  
360 harvest rates solely on the price of carbon affected by emissions and mitigation potentials of  
361 forestry and agricultural activities (Hurtt et al., 2011). Finally, RCP2.6 relies on the forecasted  
362 demand on timber and fuelwood from forest resources and applies a series of forest  
363 management rules (plantation, clear cutting, selective logging) to meet this demand as the only  
364 driver of wood harvest rate in the IMAGE model (Stehfest et al., 2014). IAMs do not account  
365 for the fact that the demand side may also be influenced by the availability of the resource and,  
366 accordingly, the increased biomass stocks projected for the future would likely lead to larger  
367 wood harvest rates than IAMs simulate by assuming present-day growth conditions. The extent  
368 to which accounting for environmental changes may influence estimates of harvestable material  
369 (e.g. apparent from comparisons of GB and MF harvest potentials under RCP2.6 as compared  
370 to RCP8.5, see Figure 1) highlights the need to include these effects in models, such as IAMs,  
371 that estimate future wood harvest. Our study is limited to considering biomass growth, albeit in  
372 interaction with soil conditions also responding to the altered climate. In reality, harvest  
373 decisions would consider further variables that depend on environmental conditions, such as  
374 the maximum soil expectation value, which are not explicitly simulated neither in our model  
375 nor in IAMs.

376 Note that the estimates of GB wood harvest as provided by our model are not meant as plausible  
377 estimates of actual future harvest, which as described before depends not just on resource  
378 availability and accessibility of areas, but is demand driven by other economic and political  
379 considerations. Limiting GB to available managed forest area, MF realized less harvest  
380 potential than GB, however, still a larger amount than RCP and with a higher mitigation  
381 potential (see Table 2). Also, actual future harvest will interact with other land-use decisions



382 such as changes in forest cover due to agricultural expansion, but also afforestation. We have  
383 further not accounted for the effects of wood harvest on biodiversity, forest health, and other  
384 ecosystem services. Chaudhary et al. (2015) state that the effect of forest management on the  
385 species richness, for example, highly depends on the management regime applied. They refer  
386 to literature reporting a positive effect of logging activities on species richness as a result of  
387 establishing early successional colonizers. Additionally, applying selective logging approaches  
388 (e.g. future crop trees of targeted species) for forest management may enhance forest recovery  
389 and reduce unintended changes in species composition (Luciana de Avila et al., 2017). Instead  
390 of actual forest harvest that considers all these aspects in its decision-making, our study  
391 provides an estimate of the ecological potentials for wood harvest. However, the change in  
392 resource potentials with climate change forms the ecological basis for realistic decision-making.

393 There is uncertainty in simulating ecosystem response to environmental changes. Regional  
394 forest inventories show an increase in biomass due to historical environmental changes  
395 (excluding effects of land-use change) (Pan et al., 2011). The largest sinks are found by these  
396 studies to be in the tropical regions, coinciding with our simulated regions of largest potentials  
397 for additional wood harvest. Also the other regions showing larger potential for wood harvest  
398 under GB and MF than RCP, such as North America, Europe, Russia and East Asia, currently  
399 exhibit carbon uptake due to historical environmental changes. This gives some confidence in  
400 the robustness of our results, in particular since most models project the carbon sink in  
401 vegetation to continue for the future; however, its magnitude is uncertain (Sitch et al., 2008). A  
402 large source of uncertainty is the strength of the CO<sub>2</sub>-fertilization effect (Kauwe et al., 2013;  
403 Hickler et al., 2015;), which reflects in a large spread across models in estimates of global total  
404 (vegetation plus soil) terrestrial carbon stocks (Arora et al., 2013) and of vegetation productivity  
405 (Zaehle et al., 2014). To better assess these effects, we additionally simulated the future GB  
406 and MF harvest potentials under present-day climate and CO<sub>2</sub> conditions (see simulations of  
407 GBpd and MFpd in the supplementary material (S1)). These simulations led to a wood harvest

408 potential larger than that with RCPs harvest rates and rather constant harvest over time (~3.2  
409 and 2.7 PgC annually for GBpd and MFpd, respectively, see S1-Figure 1). The harvest amount  
410 of GBpd is equal to RCP8.5 harvest amount at the end of the century in our simulations.  
411 Differences between GBpd and MFpd and the simulations forced by the different RCPs as well  
412 as differences among the latter illustrate the effects of changes in climate and CO<sub>2</sub> concentration  
413 on forest growth and resulting harvest potentials. The differences in wood harvest amounts  
414 between the harvest simulations based on GB and MF and those with prescribed RCP wood  
415 harvest rates in the first simulation year show differences of applying the supply-based harvest  
416 rule (GB and MF) versus the demand-based RCPs under current environmental conditions. The  
417 geographic allocation of growth and harvest potentials for GBpd and MFpd (see S1-Figure 2)  
418 resembles those under RCPs, however, with higher global values. That the GBpd and MFpd  
419 harvest potential are higher than the RCP harvest implies that the larger potentials as compared  
420 to RCP harvest are partly attributable to the harvest simulated by IAMs not using the full  
421 sustained, ecological potential (e.g. due to real-world demand). However, the harvest potentials  
422 under RCP climate all grow substantially larger than the harvest potential under present-day  
423 climate. This depicts the isolated effect of environmental changes, particularly CO<sub>2</sub> fertilization,  
424 on the simulated potential harvest.

425

426 A further uncertainty in the model we used is that our model did not explicitly account for a  
427 nitrogen cycle. Nitrogen may become a limiting factor for the additional uptake of carbon in  
428 vegetation, although future climate change might also lead to higher nutrient availability due to  
429 faster decomposition rates (Friedlingstein and Prentice, 2010). Further, nitrogen deposition may  
430 reduce nitrogen limitation (Churkina et al., 2010), and it is not predictable if artificial  
431 fertilization of managed forests may find wide-spread application in the future. Overall,  
432 therefore, quantifications of effects of future climate change on global carbon stocks derived  
433 from individual models have to be treated with care. Our model includes present-day nitrogen

434 limitation implicitly by choice of photosynthetic parameters and includes structural limits  
435 prohibiting development of wood densities beyond observational values. Tests with a similar  
436 model version as ours but representing an explicit nitrogen cycle suggest a rather small  
437 sensitivity of the land carbon cycle to nitrogen limitation under CO<sub>2</sub> increases and climate  
438 changes in the range of the RCP scenarios investigated here (Goll et al., 2017). The increase in  
439 gross primary production (GPP) over the industrial era of our model (or similar versions) lie at  
440 the high end, but within the range of a wide range of other models (Anav et al., 2013); recent  
441 evidence from long-term atmospheric carbonyl sulfide (COS) records shows that models with  
442 high GPP growth are most consistent with observations (Campbell et al., 2017). The location  
443 of the largest potentials of GB and partly MF harvest simulated in our study being in the tropical  
444 forests is consistent with the large carbon sinks derived from inventories for past environmental  
445 change (Pan et al., 2011).

446 GB harvest was simulated to mitigate 255-380 PgC, depending on the realized RCP, through  
447 wood product usage for the period 2006-2100 from global forest resources. Moreover, it  
448 accounted for sustaining the above-ground wood carbon pool at the reference level of 1996-  
449 2005. A comprehensive mitigation study, however, should take into account the total carbon  
450 balance of forest ecosystems including soil plus litter carbon. Growth enhanced by  
451 environmental changes, as simulated to lead to accumulation of woody biomass in the RCP  
452 harvest simulations (Fig. 1a), may lead to larger input to the soil (if not removed by wood  
453 harvest). However, soil carbon pools respond differently to environmental changes than forest  
454 biomass. In particular, soil carbon models generally assume enhanced soil respiration under  
455 higher temperatures (Friedlingstein et al., 2006), which may substantially offset the additional  
456 carbon uptake by the vegetation (Ciais et al., 2013). As these processes act the same in our  
457 simulations of GB, MF and RCP harvesting rules (as they share the same climate scenarios),  
458 effects of environmental changes on soil carbon will likely not substantially affect our  
459 comparison of GB, MF and RCP harvest in relative terms, but may alter the net carbon balance

460 in each of them. Further, the usage of wood products implies removal of carbon off-field. This  
461 can lead to depletion of soil plus litter carbon stocks. Observational data generally found small  
462 decreases of soil carbon, but substantial reduction of deadwood material (Erb et al., 2017). Such  
463 effects must be expected to be stronger for GB and MF harvest with its larger harvested biomass  
464 than for RCP harvest, reducing on-site carbon stocks, but consequently also soil respiration.  
465 Estimating a mitigation potential based on the net carbon balance of vegetation, soil plus litter  
466 and product pools therefore would depend on the actual size of soil and vegetation carbon pools  
467 and the lifetimes of products relative to the lifetimes of the on-site carbon, which are further  
468 subject to a changing climate. There is not a unique life time for anthropogenic wood products  
469 pools in the literature. Lifetime of construction wood, for example, spanning from 67 years in  
470 Härtl et al. (2017), up to 160-200 years in van Kooten et al. (2007) are applied in recent studies.  
471 Regarding global variation of carbon turnover rate, Carvalhais et al. (2013) find mean turnover  
472 times of 15 and 255 years for carbon residing in vegetation and soil near to Equator and higher  
473 Latitude over 75°, respectively. Regarding the uncertainty about life time of anthropogenic  
474 wood pools, we stay consistent with the applied figures in FAO statistics (FAOSTAT, 2016)  
475 and other land carbon budget studies (Houghton et al., 1983; McGuire et al., 2001).  
476 Despite carbon fluxes being the focus of land-use change as mitigation tool (e.g., UNFCC,  
477 2012), forest management may enhance or mitigate climate change by a range of other  
478 mechanisms such as a change in surface albedo (e.g., Rautiainen et al., 2011; Otto et al., 2014)  
479 or turbulent heat fluxes (e.g., Miller et al., 2011). Such biogeophysical effects needed to be  
480 accounted for in a complete assessment of the mitigation potentials, as has been done for global  
481 land cover change (Pongratz et al., 2011) or for forest management on local (Bright et al., 2011)  
482 or regional scale (Naudts et al., 2016). These biogeophysical effects are particularly important  
483 for the local climate (Winckler et al., 2017). In our study, we restrict estimates of mitigation  
484 potential to carbon fluxes only and thus focus on the perspective of mitigating global

485 greenhouse gas concentrations. This further allows for a direct comparison of the wood harvest  
486 scenarios provided as part of the RCPs.

487 Different from economic models, ESMs do not consider costs associated with early mitigation  
488 measures and thereby implicitly assume a zero social discount rate, meaning that there is no  
489 preference for immediate mitigation. However, the discount rate plays a major role to find  
490 economically the most efficient mitigation action (Stern, 2007). van Kooten et al. (1999)  
491 analyzed the sensitivity of investments for carbon sequestration to discount rate in western  
492 Canada and found that applying zero discount may not provide enough incentive for increasing  
493 carbon storage. However, most forest carbon cost studies are inconsistent in using terms,  
494 geographic scope, assumptions, program definitions, and methods (Richards and Stokes, 2004)  
495 and may not truly assess carbon sequestration potentials of forest ecosystems. Therefore, if  
496 there were a social preference for prompt climate change mitigation, carbon sinks later in the  
497 century should be discounted. Regarding the discussion on discount rate, Johnston and van  
498 Kooten (2015) argue that applying sufficiently high discount rates in substituting biomass for  
499 fossil fuels never leads to carbon neutrality.

## 500 5. Conclusions

501 We recommend that future research on integration of management strategies in DGVMs and  
502 ESMs should regard ecological sustainability as well as socio-economic challenges. In reality  
503 and today, forest management is more of a gamble than a scientific debate (Bellassen and  
504 Luysaert, 2014) and there is no consensus in applying a certain forest harvest rule (e.g. GB)  
505 among forest owners, decision-makers and local users. The rationale to manage forest resources  
506 sustainably and efficiently is generally recognized and implemented (Luckert and Williamson,  
507 2005; Elbakidze et al., 2013). However, the process of forest management decision-making is  
508 based on the past experiences with a business-as-usual strategy (BAU). Adaptation to future  
509 environmental change and minimizing the risks associated with climate change impacts is

510 recently fully integrated in forest research (Lindner et al., 2014), however, remains in  
511 experimental level in implementation (Yousefpour and Hanewinkel, 2015). Mitigation, in turn,  
512 is of public interest and there are some attempts internationally to account for mitigation effects  
513 of forest management in carbon policy. International programs such as the Kyoto protocol  
514 encourage forest managers to store carbon in the forest stocks on the ground applying financial  
515 instruments such as tax reduction and direct purchase of carbon offsets. Therefore, inclusion of  
516 financial aspects in global forest management modelling and decision-making may help to put  
517 scientific results into practice (Hanewinkel et al., 2013). This suggestion is in line with van  
518 Vuuren et al. (2011) about the necessity of strengthening the cooperation between integrated  
519 assessment models (IAMs) and Earth system modelling communities to improve the  
520 understanding of interactions and joint development of environmental and human systems. Our  
521 study is the first implementation to account for the climate-dependence of forest growth on  
522 global scale for harvest potentials. It suggests the importance of considering this dependence:  
523 the growth-based harvest approach (GB) as applied in this study may realize wood harvest  
524 potentials twice to four times as high as those of prescribed wood harvest simulated by IAMs  
525 for the RCPs and would closely triple the net mitigation effects of wood products. By limiting  
526 GB to managed forests (MF), we simulated a lower harvest potential than GB, still two to three  
527 times more than in the IAMs, which could double the net mitigation effect of wood harvest  
528 potential in the 21<sup>st</sup> century. To move from estimates of potentials to actual harvest rates,  
529 climate-dependent forest growth needs to be integrated with socio-economic factors to fully  
530 incorporate economic aspects of forestry practices within a dynamic forest growth and yield  
531 modelling system.

532 Code availability

533 Scripts used in the analysis and other supplementary information that may be useful in  
534 reproducing the authors' work are archived by the Max Planck Institute for Meteorology and  
535 can be obtained by contacting [publications@mpimet.mpg.de](mailto:publications@mpimet.mpg.de).

536 Data availability

537 Primary data are archived by the Max Planck Institute for Meteorology and can be obtained by  
538 contacting [publications@mpimet.mpg.de](mailto:publications@mpimet.mpg.de).

539 Sample availability

540 None

541 Appendices

542 None

543 Supplement link (will be included by Copernicus)

544 Supplementary includes two main files: a word document S1 on the “details on JSBACH, the  
545 model version, the simulation setup, and the additional simulation with present day forcing”  
546 and a zipped excel file S2 as an example of how “mitigation potentials of woody products in  
547 their life time” are calculated.

548 Team list

549 See authors list

550 Author contribution

551 R.Y. and J.P. initiated the study. R.Y. performed the model simulations. J.N. implemented the  
552 code changes. All authors contributed to analyzing the simulations and writing the manuscript.

553 Competing interests

554 The authors declare that they have no conflict of interest.

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764 Figure's Captions

765 **Figure 1 Development of global standing wood carbon pools forced by three different RCP**  
766 **scenarios and subject to the harvesting rules of the representative concentration pathways**  
767 **(RCP2.6, RCP4.5 and RCP8.5) or subject to growth-based harvesting (GB2.6, GB4.5, and**  
768 **GB8.5) (1a). Development of RCP wood harvest rates, of the growth potential of forests**  
769 **under GB, and of the harvest potential under GB limited to global managed forest area**  
770 **(MF2.6, MF4.5, and MF8.5) (1b). All lines are smoothed over 10 years.**

771 **Figure 2 Spatial distribution of the harvest realized in JSBACH when harvest rates are**  
772 **prescribed from the representative concentration pathways (left panels), of the harvest**  
773 **potential applying the growth-based harvesting rule to available managed forest area**  
774 **(right panels) and of the underlying growth potential (middle panels). All values are**  
775 **summed over the entire simulated period (2006-2100).**

776 **Figure 3 Composition of growth-based harvest (GB) forced by different climate change**  
777 **scenarios (RCP2.6, RCP4.5, and RCP8.5 in figures a, b, and c, respectively).  $dCw/dt$  refers**  
778 **to the difference in changes in above-ground woody biomass between representative**  
779 **concentration pathways' and GB harvest (where changes in biomass in GB are by**  
780 **construction of the harvest rule close to 0), BGmort refers to the difference in woody**  
781 **carbon losses between RCP and GB harvest due to background mortality, Fire to that due**  
782 **to fire disturbance, and Wind to that due to wind disturbance. GB and RCP harvest are**  
783 **as in Figure 1b.**

784 **Figure 4 Net mitigation potentials from the growth potential under the growth-based**  
785 **harvesting rule (GB) (a, b, c), representative concentration pathways' (RCP) harvest (d,**  
786 **e, f), and GB harvest limited to managed forest area (MF) (g, h, i). Left axes show the**  
787 **annual carbon fluxes due to harvested material and product decay changing atmospheric**

788 **CO<sub>2</sub> concentration, and the mitigation potential of wood products as the difference of**  
789 **both. Right axes accumulate the annual figures over time.**

790 **Table 1: JSBACH simulations conducted in this study with the applied harvesting rule**  
791 **and climate and CO<sub>2</sub> forcing.**

Name	Harvest rule	MPI-ESM forcing
GB2.6	GB	RCP2.6
GB4.5	GB	RCP4.5
GB8.5	GB	RCP8.5
RCP2.6	RCP2.6 map	RCP2.6
RCP4.5	RCP4.5 map	RCP4.5
RCP8.5	RCP8.5 map	RCP8.5

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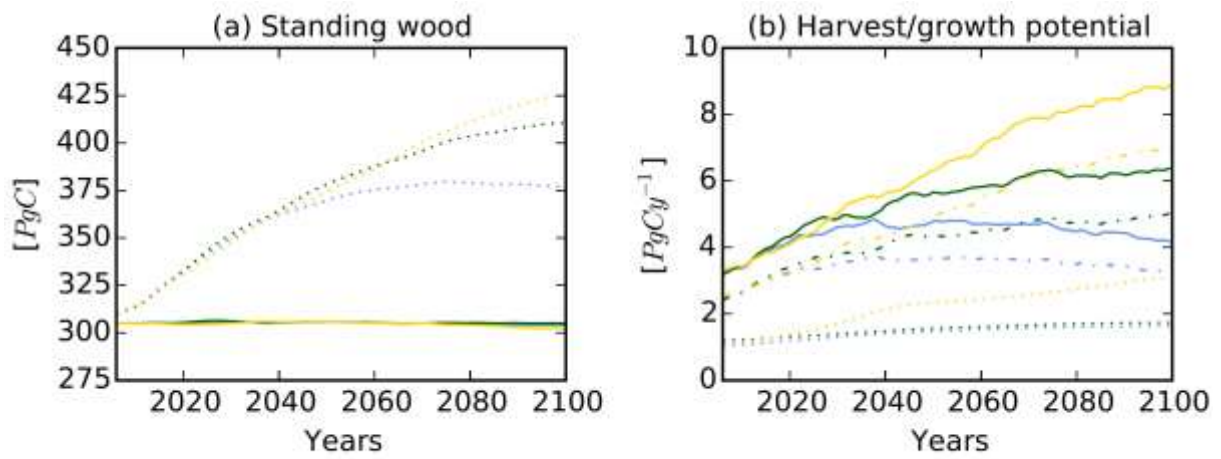
794 **Table 2 Net mitigation potentials of GB, MF and RCP harvest at the middle and end of**  
 795 **the 21st century**

Applied harvest rule	Harvested wood (PgC)		Mitigation effect (PgC)	
	2050	2100	2050	2100
RCP2.6	58.1	137.6	38.3	85.1
RCP4.5	62.9	147.2	40.7	90.2
RCP8.5	76.5	211.8	50.6	132.1
GB2.6	192.7	421.3	124.5	255.0
GB4.5	210.0	513.9	136.4	314.7
GB8.5	215.0	609.4	140.6	379.1
MF2.6	148.3	324.3	96.6	199.5
MF4.5	161.6	395.1	105.6	244.9
MF8.5	166.4	472.9	109.3	295.8

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797

798 **Figure 1**

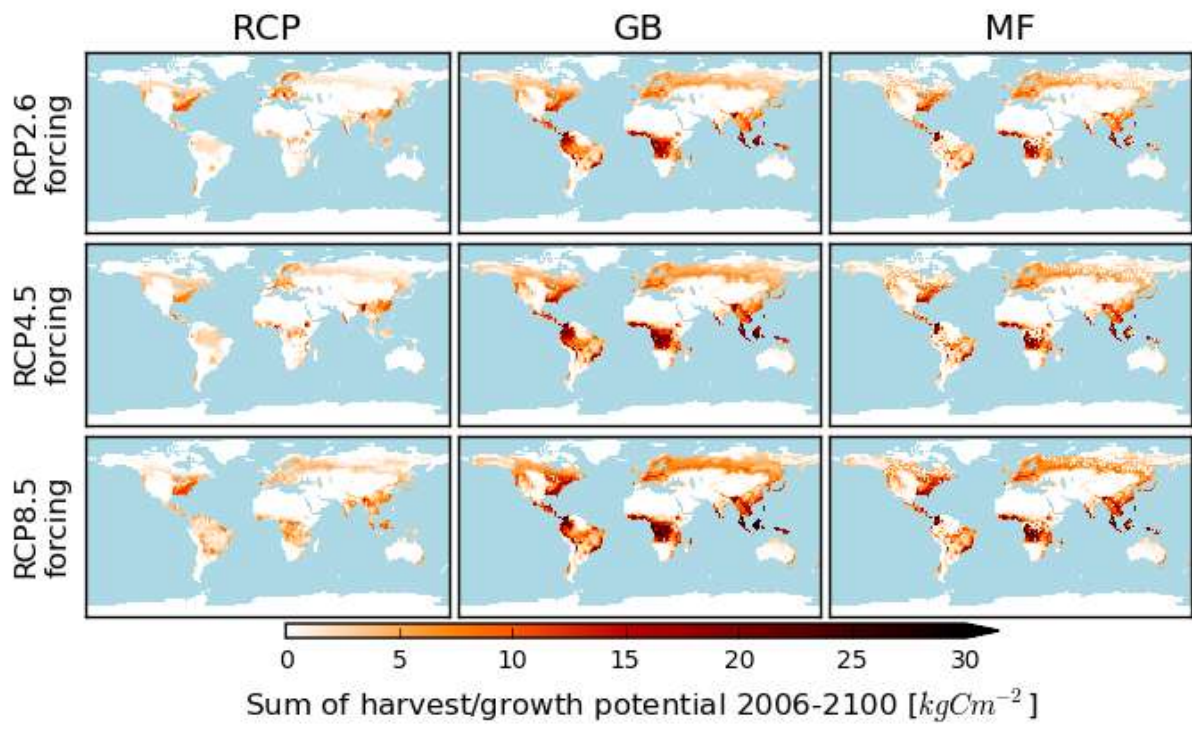


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801 **Figure 2**

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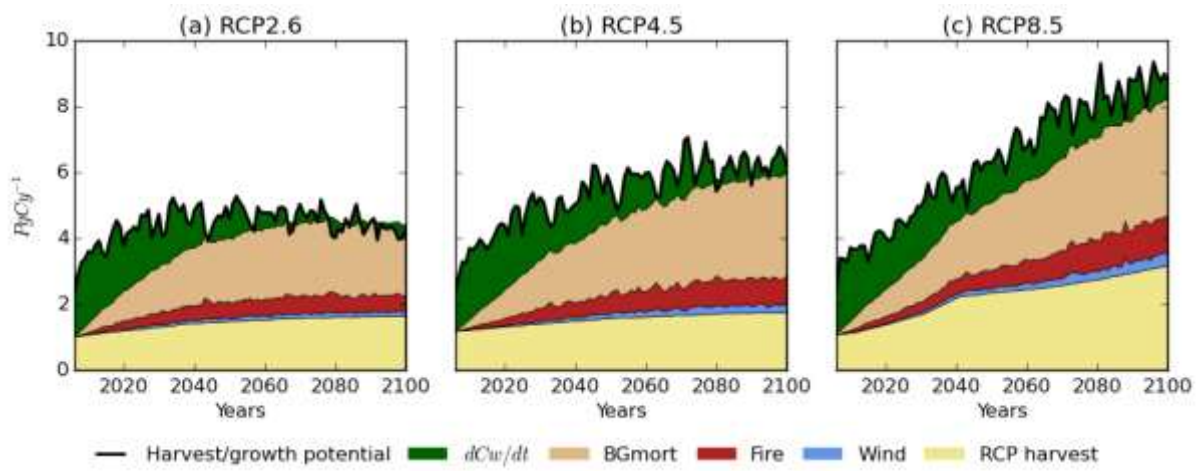


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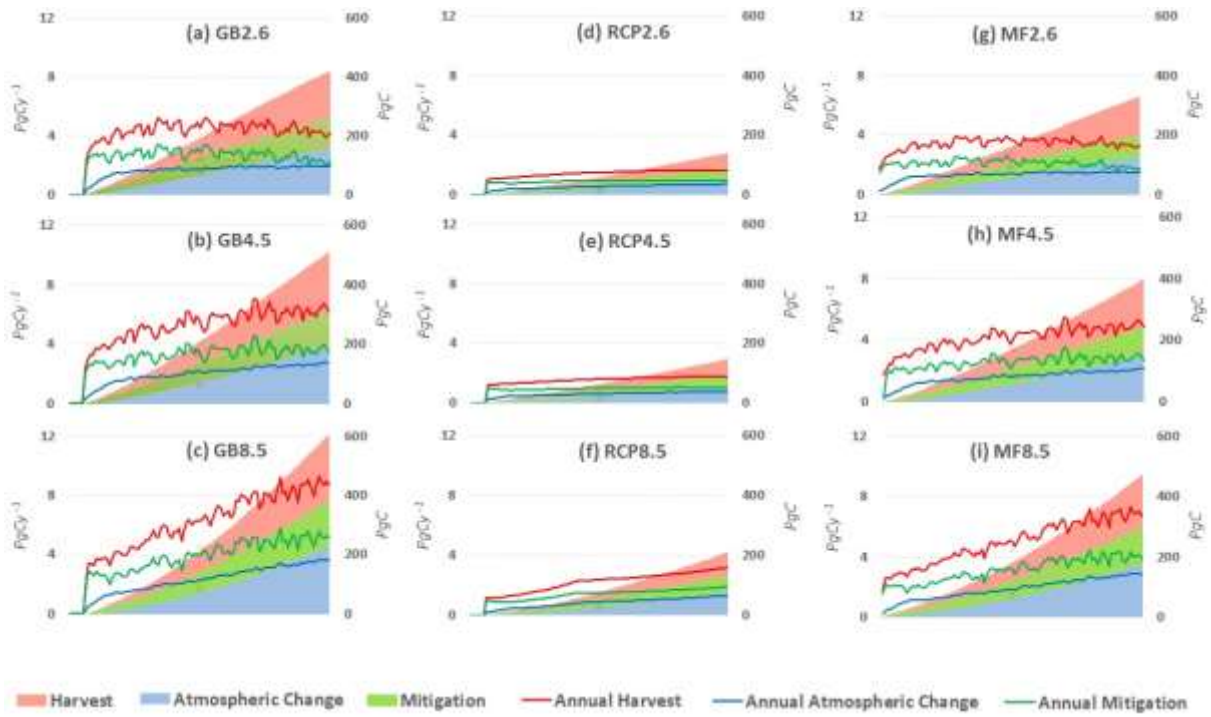
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805 **Figure 3**

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809 **Figure 4**



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