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# Global fire emissions buffered by the production of recalcitrant pyrogenic carbon

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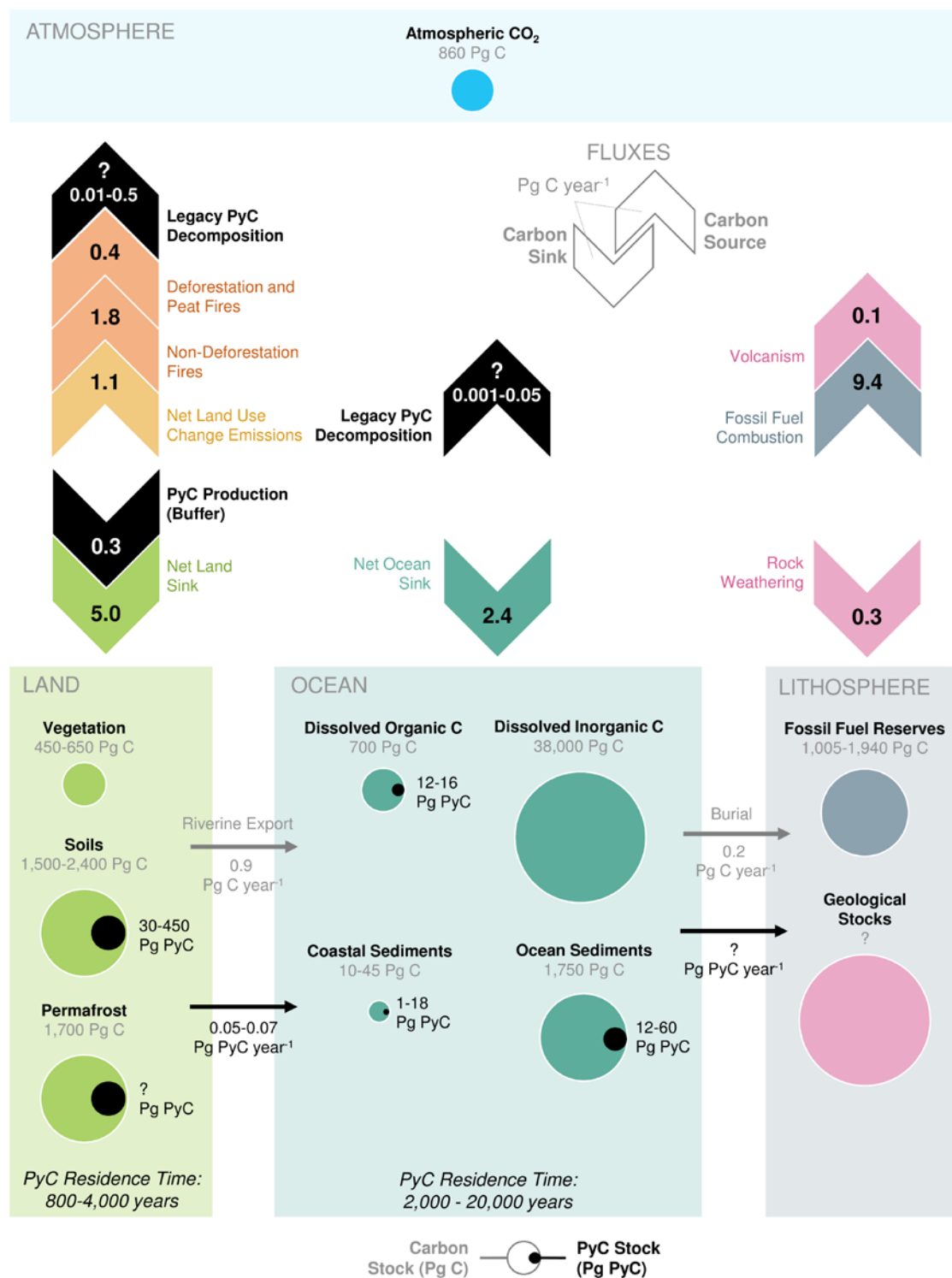
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Landscape fires burn an estimated 3-5 million km<sup>2</sup> of the Earth's surface annually, emitting 2.2 Pg C year<sup>-1</sup> to the atmosphere while also converting a significant fraction of the carbon in burnt biomass to pyrogenic carbon (PyC) contained in combustion by-products. PyC can be stored in terrestrial and marine pools for centuries to millennia, buffering short-term emissions of carbon to the atmosphere by persisting as a recalcitrant pool of carbon during and following vegetation recovery. PyC stocks are routinely ignored in global models of the carbon cycle, leading to systematic errors in carbon accounting. Here we present a comprehensive new dataset of PyC production factors and merge this with the Global Fire Emissions Database (GFED4s+PyC) to quantify the global PyC production flux. GFED4s+PyC suggests that 256 (196-340) Tg C year<sup>-1</sup> was converted to PyC by biomass burning in the period 1997-2016, 91% of which occurred in the (sub)tropics. While savannah fires were consistently the largest source of PyC (49% on average), variation in tropical forest burning, driven by the El Niño Southern Oscillation, was the dominant driver of inter-annual variability in global PyC production. Our global estimate equates to 12% of the carbon emitted annually by landscape fires, indicating that the fate of a substantial fraction of the vegetation carbon stocks affected annually by fire is misrepresented in fire-enabled global models. We estimate that the cumulative production of PyC since 1750 (60 Pg C) is equivalent to ~33-40% of the global losses of biomass carbon due to land use change in the same period. Our results show that PyC production creates capacity for a quantitatively significant sink for atmospheric CO<sub>2</sub> that is presently missing from global carbon budget assessments.

32 Globally, landscape fires including wildfires, deforestation fires, and agricultural burns  
33 emit approximately 2.2 Pg C year<sup>-1</sup> to the atmosphere (1997-2016)<sup>1</sup>. This emission flux  
34 includes ~0.4 Pg C year<sup>-1</sup> due to tropical deforestation and peatland fires, which contribute to  
35 net global emissions of carbon due to land use change (~1.1-1.5 Pg C year<sup>-1</sup>; Figure 1)<sup>2-4</sup>.  
36 The emission fluxes resulting from biomass fires and land use change are outweighed by the  
37 re-sequestration flux of carbon to undisturbed and re-growing vegetation (~5.0 Pg C year<sup>-1</sup>;  
38 Figure 1)<sup>5-8</sup>. These global carbon budget estimates are generated by models that represent  
39 the temporally distinct processes of immediate carbon emission from burned areas and  
40 decadal-scale re-sequestration through vegetation (re-)growth in a spatially explicit  
41 manner<sup>1,9,10</sup>. However, such models routinely overlook the coincident flux of biomass carbon  
42 to recalcitrant by-products of fire, which can be stored in terrestrial and marine pools for  
43 centuries to millennia, and thus provide a long-term buffer against fire emissions (Figure  
44 1)<sup>7,11-14</sup>. Consequently, the legacy effects of fire that operate on the longest timescales are  
45 systematically excluded from models of the carbon cycle and from global carbon budgets<sup>13,15</sup>.

46 These legacy effects are due to the incomplete combustion of vegetation during  
47 landscape fires, which transforms organic carbon (OC) in biomass to a continuum of  
48 thermally-altered products that are collectively termed pyrogenic carbon (PyC)<sup>11,13,16</sup>. The  
49 majority of the PyC produced during vegetation fires remains initially on the ground in  
50 charcoal particles of varying size and is subsequently transferred to its major global stores in  
51 soils<sup>17-19</sup>, sediments<sup>20,21</sup> and ocean waters<sup>22,23</sup>. A smaller fraction of fire-affected vegetation  
52 carbon is emitted as PyC in smoke and has been studied extensively for its influence on  
53 Earth's atmospheric and cryospheric radiative balances<sup>24,25</sup>. PyC includes labile products of  
54 depolymerisation reactions as well as aromatic molecules that result from condensation  
55 reactions, the latter of which are depleted in functional groups and thus chemically and  
56 biologically recalcitrant<sup>26-28</sup>. The enhanced resistance of PyC to biotic and abiotic  
57 decomposition leads to its preferential storage in terrestrial and marine pools<sup>16,21</sup> and a  
58 residence time that is typically one to three orders of magnitude greater than that of its  
59 unburnt precursors<sup>13</sup>. This makes PyC one of the largest groups of chemically discernible  
60 compounds in soil with a contribution to soil organic carbon (SOC) stocks of 14% globally<sup>17</sup>.  
61 PyC is also conserved across the land-to-ocean aquatic continuum and thus contributes  
62 approximately 10% of riverine dissolved organic carbon<sup>29</sup>, 16% of riverine particulate organic  
63 carbon<sup>30</sup>, and 20-50% of the organic carbon in ocean sediments<sup>14</sup>.



64

65 **Figure 1:** A simplified schematic of the global carbon cycle including the buffer and legacy roles of PyC. Stock  
 66 values are expressed in Pg C (1 Pg C = 1 × 10<sup>15</sup> g of carbon) and flux values are expressed in Pg C year<sup>-1</sup>. The  
 67 global carbon cycle is represented by values from the Global Carbon Budget assessment of the decade 2008–  
 68 2017 (ref. <sup>2</sup>) including: stocks of carbon in vegetation, soil, permafrost, ocean dissolved organic and inorganic  
 69 matter, coastal and oceanic sediments, and fossil fuel reserves; fluxes of carbon due to the net land sink

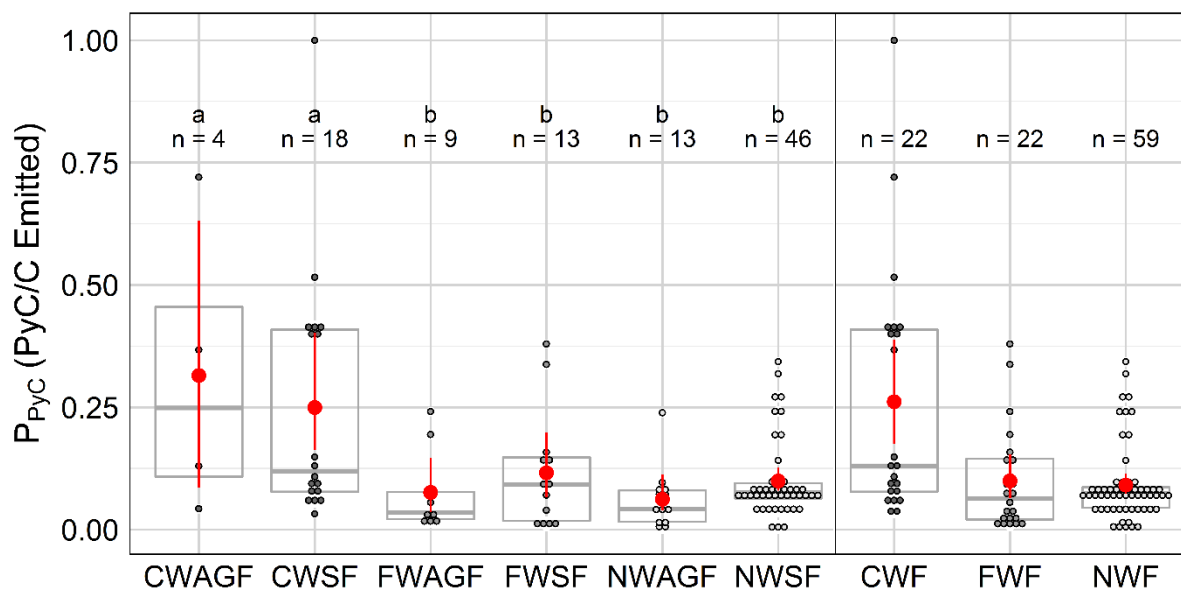
70 (modified to exclude non-deforestation fire emissions), fossil fuel combustion, the net ocean sink, and net land  
71 use change emissions (modified to exclude deforestation fire emissions). Emission estimates from deforestation  
72 and peat fires, and from non-deforestation fires derive from GFED4s and relate to the period 1997-2016 (ref. 1;  
73 deforestation fires are restricted to the tropics). Carbon fluxes due to volcanism and rock weathering derive from  
74 the IPCC AR5 assessment and relate to the period 2000-2009 (ref. 4). Pyrogenic carbon production fluxes due  
75 to deforestation and non-deforestation fires are based on estimates from GFED4s+PyC and relate to the period  
76 1997-2016 (this study). PyC stocks in soils, oceanic DOC and ocean sediments are based on representative  
77 PyC/OC ratios from references 17, 31, and 14 applied to the Global Carbon Budget 2018 estimates of OC stocks  
78 and fluxes. PyC fluxes through rivers are the sum of global dissolved and particulate PyC export fluxes from  
79 references 29 and 30. Residence times shown for soils derive from references 32 and 26. Residence times for  
80 oceanic PyC pools derive from references 20 and 33. Maximum (and minimum) legacy PyC decomposition fluxes  
81 for land and ocean stocks are calculated as the product of high-end (and low-end) total stock magnitudes in  
82 each domain and the reciprocal of the low-end (and high-end) estimate for residence time.

83  
84 A series of reviews and data syntheses have recognised the potential of PyC  
85 production to invoke a drawdown (sink) of photosynthetically-sequestered CO<sub>2</sub> to pools that  
86 are stable on timescales relevant to anthropogenic climate change and its  
87 mitigation<sup>7,11,13,14,34–37</sup>. Owing to the relative recalcitrance of PyC, the conversion of biomass  
88 carbon to PyC represents an extraction of carbon from a pool cycling on decadal timescales  
89 to a pool cycling on centennial or millennial timescales<sup>14,20,21,26,38</sup>. This storage potential  
90 contrasts with that of dead vegetation, which otherwise contributes to post-fire emissions on  
91 annual to decadal timescales or enters soil pools with a shorter residence time than that of  
92 PyC<sup>9,12,26,39,40</sup>. Consequently, post-fire PyC pools emit carbon to the atmosphere over a  
93 significantly longer time period than would be the case in the absence of PyC production,  
94 meanwhile providing a buffer that moderates atmospheric CO<sub>2</sub> stocks (Figure 1)<sup>7,13,14</sup>. At  
95 present, the fire-enabled vegetation models that are used to make global carbon budget  
96 calculations account for short-term fire emissions but routinely exclude fluxes of carbon from  
97 biomass to PyC or the delayed emission of carbon from legacy PyC stocks to the atmosphere  
98 (Figure 1)<sup>9,10,15,41,42</sup>. This introduces systematic errors to global carbon budgets through  
99 misrepresentation of modern and historical fire effects on the net exchange of carbon  
100 between the atmospheric and terrestrial-marine pools<sup>13–15</sup>.

101 While PyC has been recognised as a major component of post-fire carbon stocks for  
102 a number of decades<sup>11,37</sup>, quantification of its production rate at the global scale has been  
103 problematic and estimates vary by roughly an order of magnitude (50-379 Tg C year<sup>-1</sup>)<sup>13,14,36</sup>.

104 A cause of the large range of production estimates is that calculations have previously relied  
 105 on incomplete information regarding the spatial distribution and type of fires, the allocation of  
 106 carbon amongst biomass fuel components in burned areas and the specific PyC production  
 107 factors for these distinct biomass fuel components. To alleviate these issues, we enhanced  
 108 the Global Fire Emissions Database version 4 with small fires (GFED4s)<sup>1</sup>, which is one of the  
 109 principal process-based models used to make estimates of carbon emission from open  
 110 biomass burning<sup>41,43,44</sup>. Specifically, PyC production was incorporated by following a three-  
 111 step approach consisting of: (i) the assembly of the most comprehensive global database of  
 112 PyC production factors ( $P_{PyC}$ ; g PyC g<sup>-1</sup> C emitted) compiled to date; (ii) the assignment of  
 113 production factors for individual fuel classes stratified as coarse or fine and as woody or non-  
 114 woody (Figure 2), and; (iii) the application of production factor ( $P_{PyC}$ ) values to fuel-stratified  
 115 carbon emissions (CE; g C emitted) modelled by the native fuel consumption model in  
 116 GFED4s. The output is the first global gridded dataset for monthly PyC production at a  
 117 resolution of 0.25° × 0.25°, covering the years 1997-2016.

118



119

120 **Figure 1:** Box plots showing the distributions of PyC production factor ( $P_{PyC}$ ) values for each of the biomass  
 121 component classes in the production factor dataset. Abbreviations are: CWAGF, coarse woody aboveground  
 122 fuels; CWSF, coarse woody surface fuels; FWAGF, fine woody aboveground fuels; FWSF, fine woody surface  
 123 fuels; NWAGF, non-woody aboveground fuels; NWSF, non-woody surface fuels; CWF, coarse woody fuels  
 124 (includes both CWSF and CWAGF); FWF, fine woody fuels (includes both FWAGF and FWSF); NWF, non-  
 125 woody fuels (includes both NWAGF and NWSF). Dots mark the distribution of  $P_{PyC}$  values across 1% intervals

126 on the y-axis. Red dots show mean  $P_{\text{PyC}}$  values while red lines show the bootstrapped 95% confidence interval  
127 (see methods). Boxes illustrate the median and interquartile range of values. Letters a and b indicate biomass  
128 components with statistically similar  $P_{\text{PyC}}$  distributions at the 95% confidence level according to Tukey HSD  
129 tests. The number of data entries (n) is also shown.

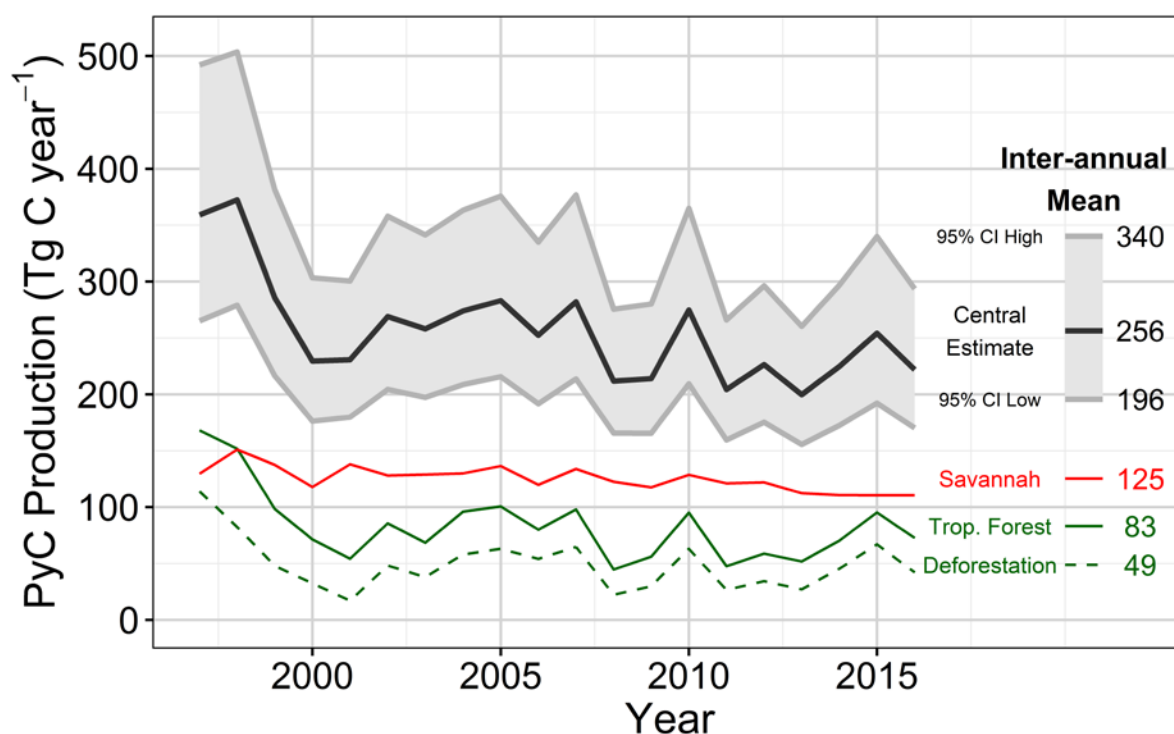
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## 131 **Global PyC Production**

132 Our central estimate for global PyC production in the period 1997-2016 was 256 Tg C  
133 year<sup>-1</sup> with an uncertainty range based on production factors of 196-340 Tg C year<sup>-1</sup> (Figure  
134 3). Inter-annual variability in global PyC production, expressed as the standard deviation  
135 around the mean, was 47 Tg C year<sup>-1</sup> and was most strongly associated with variability in  
136 woody fuel combustion, including standing wood and coarse woody debris (CWD;  
137 supplementary information text S1 and Figure S1). Coarse woody fuels produce PyC at a  
138 greater rate than finer fuels (Figure 2) and consequently forest fires have disproportionate  
139 potential to influence global rates of PyC production (supplementary Figure S2).

140 The El Niño Southern Oscillation (ENSO) is the primary driver of inter-annual variability  
141 in burned area in the tropics<sup>45</sup> and previous analyses conducted with GFED have shown that  
142 carbon emissions from tropical forest ecosystems more than doubled on average during  
143 positive (El Niño) phases relative to negative (La Niña) ENSO phases<sup>46</sup>. Correspondingly, we  
144 calculated that global rates of PyC production in tropical forests were 111% greater during  
145 the main fire season of El Niño phases than La Niña phases (supplementary Table S1). As  
146 rates of PyC production by non-forest fires did not show a significant response to ENSO at  
147 the global scale (supplementary Table S1), the response of forest fires was the major driver  
148 of inter-annual variability in total PyC production (Figure 3). The production of PyC was  
149 anomalously high in 1997-1998 (366 Tg C year<sup>-1</sup>), aligning with a particularly strong positive  
150 El Niño phase which promoted extensive burning of (tropical) forests in South and Central  
151 America and in Southeast and Equatorial Asia<sup>1,46</sup>.

152



153

154 **Figure 3:** Annual global PyC production estimates from GFED4s+PyC. The black line plots the modelled rate  
155 of production based on central  $P_{PyC}$  ratios ( $g\ PyC\ g^{-1}\ C\ emitted$ ) from the global dataset. The shaded area  
156 indicates the uncertainty range of modelled values based on the 95% confidence intervals of  $P_{PyC}$  values (see  
157 Figure 2). The contributions of savannah burning and tropical forest burning to global production totals are  
158 shown, the latter of which includes deforestation fires (also shown; dashed line).

159

## 160 Major Production Regions

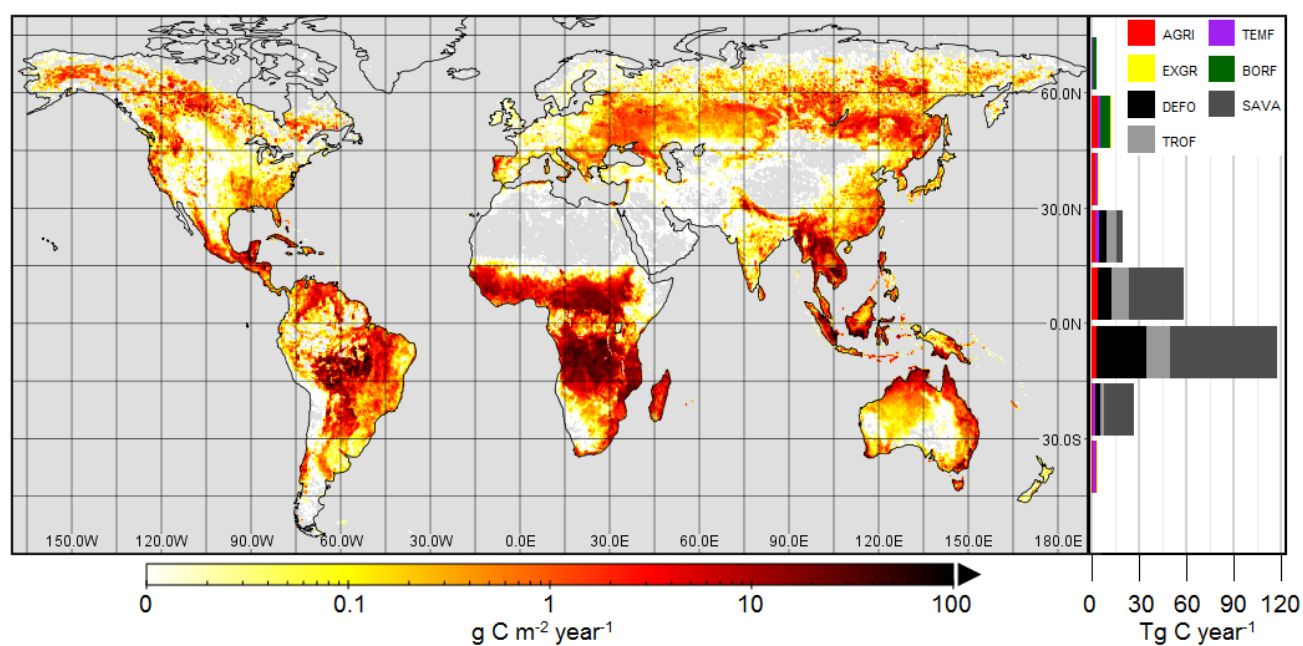
161 The PyC production rates modelled by GFED4s+PyC conformed to a latitudinal  
162 pattern (Figure 4), with the tropical latitudes clearly dominating production at the global scale.  
163 91% of global production occurred in the tropics and subtropics ( $0-30^{\circ}\ N/S$ ), while temperate  
164 ( $30-60^{\circ}\ N/S$ ) and high-latitude regions ( $60-90^{\circ}\ N$ ) provided small contributions to the global  
165 total (8% and 1%, respectively).

166 The global distribution of PyC production also showed intricate regional patterns driven  
167 by variation in both the frequency at which fuel stocks were exposed to fire and the magnitude  
168 of the fuel stocks that were combusted during the fires that occurred (supplementary Figures  
169 S3 and S4). Fire frequency was ultimately the key determinant of PyC production rate and  
170 this explains why the tropics and subtropics were the dominant source regions. Although  
171 savannah fires affected low fuel stocks ( $0.2\ kg\ C\ km^{-2}$  on average; supplementary information



172 text S2), these fires occurred frequently and were spatially extensive (supplementary Figure  
173 S5 and table S2). They thus made the largest contribution to the global PyC production flux  
174 ( $125 \text{ Tg C year}^{-1}$  on average). Although tropical deforestation fires affected approximately 1%  
175 of the area of savannah fires, they affected large stocks of fuel ( $8.7 \text{ kg C km}^{-2}$  on average;  
176 supplementary table S2) and were thus second largest driver of global PyC production,  
177 contributing  $49 \text{ Tg C year}^{-1}$ . The area affected by non-deforestation tropical forest fires was  
178 more than a factor of 4 larger than that of deforestation fires, however fuel consumption was  
179 relatively low ( $2.3 \text{ kg C km}^{-2}$  on average; supplementary table S2). These fires provide the  
180 third major component of the global PyC production flux ( $34 \text{ Tg C year}^{-1}$ ). Overall, 81% of  
181 total global PyC production in the period 1997-2016 occurred in savannahs (49%) and  
182 tropical forests (32%).

183



184  
185

186 **Figure 4:** Annual average PyC production rates for the period 1997-2016 from GFED4s+PyC, based on central  
187 production factors (see Figure 2). **(Left panel)** The global distribution of PyC production expressed in  $\text{g C m}^{-2}$   
188  $\text{year}^{-1}$ . **(Right panel)** The total production of PyC ( $\text{Tg C year}^{-1}$ ) in  $15^\circ$  latitudinal bands segregated according to  
189 the fire type, including: savannah fires (SAVA); non-deforestation tropical forest fires (TROF); tropical  
190 deforestation fires (DEFO); agricultural fires (AGRI); temperate forest fires (TEMF); extratropical grassland fires  
191 (EXGR), and; boreal forest fires (BORF).

192  
193

## 194 **Global Carbon Budget Implications**

195 Here we have quantified the global gross sink of atmospheric carbon caused by the  
196 transfer of photosynthetically-sequestered biomass carbon to stocks of PyC during  
197 vegetation fires. Our central global PyC production flux estimate (256 Tg C year<sup>-1</sup>) is nontrivial  
198 within the context of the global carbon cycle (Figure 1), equating to 12% of the global carbon  
199 emissions flux due to biomass burning and around 8% of the land sink for atmospheric CO<sub>2</sub>  
200 (~3.0-3.2 Tg C year<sup>-1</sup>)<sup>2,4</sup>. This flux is in addition to the smaller global flux of 2 Tg C year<sup>-1</sup>  
201 caused by the emission of PyC in smoke from vegetation fires (according to estimates made  
202 using GFED4s in the years 1997-2016)<sup>1</sup>.

203 The magnitude of our global estimate for PyC production indicates that the  
204 transformation of biomass carbon to PyC in vegetation fires has the potential to significantly  
205 influence the atmospheric stock of carbon. A net sink of atmospheric carbon to stocks of PyC  
206 can be expected to develop if the flux associated with its production is unmatched by re-  
207 mineralisation fluxes from legacy PyC stocks in terrestrial and marine pools (Figure 1). Earth  
208 System Models (ESMs) are the most sophisticated tools available to quantify the exchange  
209 of carbon between the atmosphere and these pools in time periods for which robust empirical  
210 data is sparse or unavailable. Despite foregoing attempts to highlight the importance of PyC  
211 production for carbon storage over timescales relevant to anthropogenic climate change and  
212 its mitigation<sup>36,37,47</sup>, the absence of the PyC cycle from ESMs has restricted the scope for  
213 quantifying its role in the carbon cycle<sup>15</sup>. The method introduced here allows for the routine  
214 integration of PyC production into fire-enabled vegetation models in a manner that  
215 systematically considers the spatial distribution of fire, the composition of the fuel stocks  
216 affected and the specific PyC production factors that apply to individual fuel components.  
217 This procedure would be relatively simple to implement in other fire-enabled vegetation  
218 models used by ESMs, meaning that the major outstanding challenge to quantifying the net  
219 exchange of carbon between the atmosphere and PyC stocks with ESMs will be to improve  
220 constraints over its storage and residence time in terrestrial and marine pools (Figure 1)<sup>14,15</sup>.

221 We also show that the PyC cycle must be integrated into ESMs if they are to accurately  
222 represent the more general role of fire in the carbon cycle. At present, the fate of 11% of the  
223 global biomass carbon stocks affected annually by fire is misrepresented in global models.  
224 Recent estimates suggest that total carbon emissions from biomass burning in the period

225 1750-2015 amounted to around 500 Pg C (averaging 1.9 Pg C year<sup>-1</sup>)<sup>41</sup>. Under the  
226 assumption that the modern global PyC production flux maintained a constant ratio with the  
227 carbon emissions flux throughout this period, we estimate that approximately 60 Pg C was  
228 transferred to PyC stocks since the beginning of the industrial revolution. This value is  
229 equivalent to 33-40% of the carbon lost from biomass pools due to land use change in the  
230 same time period (145-180 Pg C)<sup>4,48</sup>.

231 The production flux of PyC represents the quantity of carbon that models would  
232 otherwise treat as unburned dead or living vegetation with a residence time in terrestrial pools  
233 on the order of months to decades<sup>9,12,26,39,40,49</sup>. This misrepresentation of the legacy effects  
234 of fire thus introduces potentially significant errors to carbon accounting exercises. Moreover,  
235 as PyC dynamics are not represented in the ESMs used to make global carbon budget  
236 calculations, this pool may represent a missing sink or source of carbon to the  
237 atmosphere<sup>15,50</sup>. Our PyC production estimate is equivalent to 41% of the global carbon  
238 budget imbalance caused by overestimated emissions and/or underestimated sinks in the  
239 past decade (600 Tg C year<sup>-1</sup>)<sup>2</sup>, suggesting that errors resulting from the absence of PyC  
240 from ESMs may contribute significantly to global carbon accounting uncertainties.

241 The production of PyC may also become an increasingly important process for global  
242 carbon cycling in future centuries. Although global burned area has declined in at least the  
243 past two decades due predominantly to the conversion of savannah and grassland to  
244 agriculture<sup>51,52</sup>, recent fire modelling studies generally agree that this decline is unlikely to  
245 continue past the year 2050<sup>53-55</sup>. It is also likely that a higher fraction of global burned area  
246 will be distributed in forests where significant stocks of vegetation carbon are held<sup>54,56,57</sup>. As  
247 woody fuels generate more PyC per unit of biomass carbon than other fuels (Figure 1), the  
248 spread of fire into forests can be expected to disproportionately enhance global PyC  
249 production (supplementary Figure S2). Although it is less clear how fire prevalence will  
250 change in tropical and temperate forests owing to a stronger human control over burning in  
251 these regions<sup>51,54</sup>, recent increases in fire extent caused by increasing drought frequency in  
252 Amazonia are already counteracting reductions in the extent of deforestation fires<sup>58</sup>.  
253 Notwithstanding the significant uncertainty that exists in model predictions of future fire  
254 regimes, there are strong indications that PyC production rates will increase in some of the  
255 Earth's most carbon-dense regions in response to a changing climate<sup>7,9,59</sup>. This implies that

256 the buffer for atmospheric CO<sub>2</sub> emissions resulting from PyC production will grow in future  
257 centuries.

## 258 **Methods**

### 259 ***Global Fuel Consumption Modelling in GFED4s***

260 In GFED4s, carbon emissions to the atmosphere are quantified based on burned area  
261 and fuel consumption per unit burned area. Burned area is derived from satellite<sup>60</sup> and fires  
262 that are too small to be detected by regular burned area algorithms are derived statistically  
263 based on active fire detections and relations with vegetation indices<sup>61</sup>. Fuel consumption is  
264 modelled using a satellite-driven biogeochemical model<sup>1</sup> and tuned to match observations<sup>62</sup>.  
265 Most of the underlying satellite input datasets have a 500 × 500 m resolution but are  
266 aggregated to the model resolution of 0.25° × 0.25°. Total fuel consumption is based on fuel  
267 consumption of several fuel components including leaves, grasses, litter, fine woody debris,  
268 coarse woody debris (CWD), and standing wood. For more information on the GFED4s  
269 modelling approach, the reader is directed to reference<sup>1</sup>.

270 To calculate PyC production within GFED4s we added a production factor, P<sub>PyC</sub>, which  
271 quantifies the production of PyC per unit carbon emitted (g PyC g<sup>-1</sup> C emitted). Until now, the  
272 principle obstacle to performing a global modelling exercise of this type has been the lack of  
273 a sufficiently rich and standardised dataset with which to constrain representative values for  
274 P<sub>PyC</sub>. The remainder of this section details how representative PyC production factors were  
275 collated and summarised and subsequently integrated into the fuel consumption model of  
276 GFED4s.

277 Our estimates of uncertainty in PyC production relate only to variability in PyC  
278 production factors and do not include uncertainty in fuel consumption propagating from  
279 GFED4s. Uncertainties in GFED4s fuel consumption are discussed in great detail in ref. <sup>1</sup>  
280 and are predominantly the result of uncertainties in the satellite detection of small fires using  
281 thermal anomalies and burn scars. Based on the level of agreement with regional-level  
282 estimates it is estimated that the burned area data used in GFED have a 1 standard deviation  
283 uncertainty range of 50% but are probably underestimated due to the difficulty in capturing  
284 small fire burned area and the choice of a conservative approach in ref. <sup>61</sup>. As carbon  
285 emissions and PyC production are co-dependent on burned area, estimation errors relating

286 to fire detection introduce scalar uncertainties. Uncertainty in fuel consumption is a smaller  
287 component of the overall uncertainty in GFED4s<sup>1</sup> emission estimates and has been reduced  
288 from previous versions through its incorporation of a global dataset of fuel consumption  
289 estimates<sup>62</sup>.

## 290 ***Collating a Global Dataset of PyC Production Factors***

291 We compiled a new database of P<sub>PYC</sub> factors from a global collection of 21 published  
292 studies which reported on PyC production in 91 burn units, as well as two new datasets  
293 produced by the authors with 23 burn units reported for the first time here, and standardised  
294 their reporting. All studies used one of the following two broad approaches to quantifying the  
295 impacts of fire on the biomass carbon stocks, either: pre-fire and post-fire stocks of biomass  
296 carbon and PyC are measured, or; space-for-time substitution is used to constrain burned  
297 and unburned stocks of biomass carbon and PyC, which are assumed to be equivalent to  
298 pre-fire and post-fire stocks, respectively. Hereafter, the terms “pre-fire” and “post-fire” are  
299 used to refer to both types of assessment. Here we focus only on PyC present in charcoal  
300 and ash on the ground following fire<sup>63</sup> as well as charred vegetation. PyC emitted with smoke,  
301 transported in the atmosphere and deposited over a distant area is not included as this  
302 process has been studied in separate dedicated studies conducted by atmospheric  
303 scientists<sup>24</sup> and represents a relatively small flux in comparison (<5%)<sup>13,14</sup>.

304 The P<sub>PYC</sub> values were calculated for each of six classes of widely used biomass  
305 components: coarse woody surface fuels (CWSF), including coarse woody debris or downed  
306 wood defined by typical diameter thresholds of >7.6 cm or >10 cm<sup>64,65</sup>; fine woody surface  
307 fuels (FWSF), including fine woody debris or any other woody debris with diameters below  
308 the thresholds for CWSF; coarse woody aboveground fuels (CWAGF), including trees or  
309 branches with diameters greater than the thresholds for CWSF; fine woody aboveground  
310 fuels (FWAGF), including material described as shrubs, trees or branches with diameters  
311 below the thresholds for CWSF; non-woody surface fuels (NWSF), including litter, understory  
312 vegetation, grass, root mat and any other form of non-woody material directly in contact with  
313 the ground surface<sup>65,66</sup>, and finally; non-woody aboveground fuels (NWAGF), including  
314 foliage, leaves, needles, crown fuels and any other form of non-woody material that attaches  
315 to standing wood structures above the ground surface.

316 For each biomass component, P<sub>PYC</sub> was calculated using the following equation (1):

317

$$P_{PyC} = \frac{C_{Py}}{C_{PRE} - C_{POST}}$$

318

319

320

321

where  $C_{Py}$  is the mass of PyC created during the fire that was attributed to the component,  $C_{PRE}$  was the pre-fire stock of biomass carbon in the component, and  $C_{POST}$  was the post-fire stock of biomass carbon in the component.  $C_{Py}$ ,  $C_{PRE}$  and  $C_{POST}$  were all expressed in the units g C km<sup>-2</sup>.

322

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Criteria were applied as filters to the dataset in order to ensure that  $P_{PyC}$  could be calculated in a consistent and representative manner. Specifically,  $P_{PyC}$  was calculated if the following conditions were met: first, both pre-fire and post-fire biomass stocks were reported and carbon content (%) was either measured or assumed based on representative values from the literature; second, post-fire stocks of pyrogenic organic matter (charcoal, ash and charred vegetation) were reported and their PyC content (%) was either measured or assumed based on representative values from the literature; third, the type of fire that occurred was representative of a widespread regional fire type (e.g. wildfires, slash-and-burn deforestation, and prescribed fire); fourth, in experimental fires, the biomass carbon stock was designed to replicate the density and structure of biomass carbon stocks observed in the field and the burning efficiency was not optimised or adapted as a factor of the study design; fifth, the post-fire sampling exercise was completed within 3 months of the fire such that losses of PyC through erosion and mineralisation were minimised.

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Like biomass carbon, total PyC stocks are distributed across several components including charcoal and ash on the ground, charcoal attached to coarse woody debris, and charcoal attached to aboveground vegetation<sup>13</sup>. The majority of the studies included in the production factor dataset matched the studied PyC components to individual biomass carbon components from which they were known to derive. However, as some individual components of PyC stocks can have a mixture of sources that are indistinguishable from their location or appearance alone, it was occasionally necessary to make assumptions about the biomass components that were sources of these components. This was done on a study-by-study basis. In cases where the source of each PyC component was not explicitly stated, the following procedural steps were adhered to. On a first basis, the PyC component was assigned to a biomass component according to the most probable source inferred, but not explicitly stated, in the primary literature. Second, where more than one biomass component

347 was inferred to be a source of the PyC stock in the primary literature, the PyC stock was  
348 weighted proportionally to the pre-fire stock of carbon present in each of the implicated  
349 biomass components. Otherwise, if no sources of PyC were inferred in the primary literature  
350 it was necessary to make independent assumptions about the source of PyC in a manner  
351 that was consistent with the other studies included in the dataset and our collective  
352 experience of quantifying PyC production in the field.

### 353 ***Summarising Production Factor Values for use in GFED4s+PyC***

354 Our global database suggested that coarse woody surface fuels (CWSF) and  
355 aboveground fuels (CWAGF) produce significantly more PyC, relative to carbon emitted, than  
356 other fuel classes ( $P_{\text{PyC}}$  averaged 0.25 and 0.31 g PyC g<sup>-1</sup> C emitted, respectively; Figure 2).  
357 In contrast, the mean  $P_{\text{PyC}}$  values for fine woody surface fuels (FWSF) and fine woody  
358 aboveground fuels (FWAGF; 0.12 and 0.076 g PyC g<sup>-1</sup> C emitted, respectively) did not differ  
359 significantly from those of non-woody surface fuels (NWSF) or non-woody aboveground fuels  
360 (NWAGF; 0.099 and 0.062 g PyC g<sup>-1</sup> C emitted, respectively). These results are consistent  
361 with previous studies, which suggest that large-diameter woody fuels burn less completely  
362 and produce PyC in greater proportions than finer fuels<sup>23,36,67</sup>.

363 For each class, the mean PyC production factor was used as the central estimate for  
364  $P_{\text{PyC}}$ , while the confidence interval around the mean  $P_{\text{PyC}}$  was calculated through a  
365 bootstrapping procedure. Specifically, the available PyC production factors from the dataset  
366 were resampled 50,000 times, the mean  $P_{\text{PyC}}$  was calculated for each resample, and the  
367 95% confidence interval was calculated as the middle 95% of the observed 50,000 means  
368 (i.e. those ranked 1,250<sup>th</sup> to 48,750<sup>th</sup>).

369 According to analysis of variance (ANOVA) with a Tukey Honest Significant Difference  
370 post-hoc test, no significant differences in mean  $P_{\text{PyC}}$  were observed between the  
371 distributions of  $P_{\text{PyC}}$  for coarse, fine, and non-woody fuels positioned at the ground surface  
372 and those same fuels located above the ground surface. Therefore, the  $P_{\text{PyC}}$  values applied  
373 in GFED4s+PyC were based on the distribution of values in three simplified fuel classes  
374 (Figure 2): coarse woody fuels (CWF: mean 0.26 g PyC g<sup>-1</sup> C; 95% confidence interval 0.18-  
375 0.39 g PyC g<sup>-1</sup> C), fine woody fuels (FWF: mean 0.096 g PyC g<sup>-1</sup> C; 95% confidence interval  
376 0.064-0.15 g PyC g<sup>-1</sup> C) and non-woody fuels (NWF: mean 0.091 g PyC g<sup>-1</sup> C; 95%  
377 confidence interval 0.074-0.11 g PyC g<sup>-1</sup> C).

## 378 ***Assigning PyC Production Factors in GFED4s+PyC***

379  $P_{PYC}$  values were assigned to each of the native fuel classes of GFED4s<sup>1</sup>, which are:  
380 leaves; grasses; surface fuels (including litter and fine woody debris); coarse woody debris  
381 (CWD), and; standing wood (including trunks, stems and branches). Mean  $P_{PYC}$  values and  
382 bootstrapped confidence interval values for CWF, FWF and NWF from the global dataset  
383 were used to define representative  $P_{PYC}$  values for each of the GFED4s fuel classes (Figure  
384 2). Full details regarding the assignment of  $P_{PYC}$  values to each GFED4s fuel class are  
385 provided in the supplementary information (text S3 and table S3). Briefly: leaf, litter, grass  
386 were assigned the relevant  $P_{PYC}$  values of NWF; fine woody debris and coarse woody debris  
387 were assigned the values of FWF and CWF, respectively, and;  $P_{PYC}$  values for standing wood  
388 were applied in a spatially explicit manner as weighted combinations of the  $P_{PYC}$  values for  
389 CWF (for carbon in trunks) and FWF (for carbon in branches). The weighted CWF:FWF ratio  
390 was assigned according to empirical relationships defining biomass carbon apportionment to  
391 branches and trunks in the various forest types of the GFED4s land cover scheme  
392 (supplementary information text S3 and table S4)<sup>68</sup>.

## 393 ***Quantifying ENSO Impacts on PyC Production***

394 To investigate the influence of pan-tropical climatic variability driven by the El Niño  
395 Southern Oscillation on the production of PyC, we replicated the analysis presented by Chen  
396 et al. (ref. <sup>46</sup>) with a focus on PyC production rather than carbon emissions. The pan-tropics  
397 were defined as consisting of Central America (CEAM); Northern Hemisphere South America  
398 (NHSA); Southern Hemisphere South America (SHSA); Northern Hemisphere Africa (NHAF);  
399 Southern Hemisphere Africa (SHAF); Southeast Asia (SEAS); Equatorial Asia (EQAS), and;  
400 Australia (AUST; supplementary Figure S6). PyC production in El Niño and La Niña phases  
401 was compared for the major fire season periods defined in each tropical region by Chen et  
402 al. (ref. <sup>46</sup>); the reader is referred to their study for a thorough explanation of the rationale for  
403 selecting these comparison periods. We summed PyC production in the major fire season  
404 period of each region and disaggregated this total to forest and non-forest fires according to  
405 the dominant land cover type in the GFED4s land cover scheme (based on the MODIS Land  
406 Cover Type Climate Modelling Grid product MCD12C1)<sup>69</sup>.



## 407 **Apportioning Sources of PyC**

408 Following GFED4s+PyC model runs, PyC production was assigned to specific sources  
409 following a method developed previously for use in GFED4s model runs<sup>1,70</sup>. Specifically, PyC  
410 production occurring as a result of non-deforestation fires was disaggregated in each cell to  
411 tropical forest, savannah/grassland, boreal forest, temperate forest, and agricultural fires  
412 using an existing algorithm that utilises fractional tree cover, climate and fire persistence  
413 variables. The reader is referred to ref. <sup>70</sup> for a full discussion of this algorithm. We added an  
414 additional latitudinal constraint (30 °N-30 °S) to further disaggregate the savannah  
415 compartment, which thus separates tropical savannahs and grasslands from extratropical  
416 grasslands.

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585 **Supplementary Information** is linked to the online version of the paper at  
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## 598 **Author Contributions**

599 MJ, CS and SD designed the study. SD led the Leverhulme Trust grant funding the  
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601 and SD provided unpublished PyC production data. GW provided access to the GFED4s  
602 code. MJ adapted the GFED4s code to include PyC production with the support of GW. MJ  
603 conducted the formal analysis of production factor dataset and model outputs. All authors  
604 contributed to the interpretation of the results. MJ wrote the manuscript text and produced all  
605 figures. All authors contributed to the refinement of the manuscript text.

## 606 **Author Information**

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608 authors declare no competing interests. Correspondence and requests for materials should  
609 be addressed to [matthew.w.jones@swansea.ac.uk](mailto:matthew.w.jones@swansea.ac.uk). The global dataset of PyC production  
610 factors is available as supplementary data file (GlobalPyC\_supplementarydataset.xls) and  
611 will also be made publicly available through submission to the Pangaea Data Publisher for  
612 Earth & Environmental Science. Supplementary information text S4 contains full reference to  
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