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# 1 **Atmosphere–soil carbon transfer as a function of soil depth**

2 Jérôme Balesdent<sup>1\*</sup>, Isabelle Basile-Doelsch<sup>1</sup>, Joël Chadoeuf<sup>2</sup>, Sophie Cornu<sup>1</sup>, Delphine Derrien<sup>3</sup>, Zuzana  
3 Fekiacova<sup>1</sup> & Christine Hatté<sup>4</sup>

4 <sup>1</sup>Aix-Marseille Univ, CNRS, IRD, INRA, Coll France, CEREGE, Aix en Provence, France.

5 <sup>2</sup>INRA UR 1052, Avignon, France.

6 <sup>3</sup>INRA UR Biogéochimie des Ecosystèmes Forestiers, Nancy, France.

7 <sup>4</sup>Laboratoire des Sciences du Climat et de l'Environnement, UMR 8212 CEA-CNRS-UVSQ, Université Paris-  
8 Saclay, Gif-sur-Yvette, France.

9 \*e-mail: jerome.balesdent\_a\_inra.fr

10  
11 **The exchange of carbon between soil organic carbon (SOC) and the atmosphere affects**  
12 **the climate<sup>1,2</sup> and—because of the importance of organic matter to soil fertility—**  
13 **agricultural productivity<sup>3</sup>. The dynamics of topsoil carbon has been relatively well**  
14 **quantified<sup>4</sup>, but half of the soil carbon is located in deeper soil layers (below**  
15 **30 centimetres)<sup>5-7</sup>, and many questions remain regarding the exchange of this deep carbon**  
16 **with the atmosphere<sup>8</sup>. This knowledge gap restricts soil carbon management policies and**  
17 **limits global carbon models<sup>1,9,10</sup>. Here we quantify the recent incorporation of**  
18 **atmosphere-derived carbon atoms into whole-soil profiles, through a meta-analysis of**  
19 **changes in stable carbon isotope signatures at 112 grassland, forest and cropland sites,**  
20 **across different climatic zones, from 1965 to 2015. We find, in agreement with previous**  
21 **work<sup>5,6</sup>, that the deeper 30–100 centimetres of soil (the subsoil) contains on average 47 per**  
22 **cent of the top metre's SOC stocks. However, this subsoil accounts for just 19% of the**  
23 **SOC that is newly incorporated (within the past 50 years) into the top metre. Globally,**  
24 **the median depth of recent carbon incorporation in mineral soil is 10 centimetres.**  
25 **Variations in the relative allocation of carbon to deep soil layers are better explained by**  
26 **the aridity index than by mean annual temperature. Land use for crops reduces the**  
27 **incorporation of carbon into the soil surface layer, but not into deeper layers. Our results**  
28 **suggest that SOC dynamics and its responses to climatic control or land use are strongly**  
29 **dependent on soil depth. We propose that using multilayer soil modules in global carbon**  
30 **models, tested with our data, could help to improve our understanding of soil–atmosphere**  
31 **carbon exchange.**

32           The size of the Earth SOC reservoir is estimated to be around 1,500 gigatonnes of  
33 carbon (Gt C) in the first metre, excluding permafrost areas<sup>6</sup>, making it a huge potential source  
34 or sink for atmospheric carbon (which increases by +4.4 Gt C per year)<sup>11</sup>. The future response  
35 of this soil compartment could substantially affect not only the climate but also global food  
36 production (through the role of organic matter in soil fertility), as well as the stability or  
37 resilience of ecosystems<sup>3</sup>. About half of this carbon is located at depths below 30 cm (refs. <sup>5,6</sup>).  
38 However, although the dynamics of topsoil carbon has been relatively well quantified,  
39 especially thanks to long-term experiments carried out over generations<sup>4</sup>, major questions  
40 remain about how to estimate changes in deep-soil carbon and the processes involved.  
41 Decision-makers and ecosystem managers are thus deprived of any references for the  
42 management of the deep carbon stock. Similarly, when modelling the Earth system and the  
43 global carbon cycle, the scientific community also constantly faces the problem of modelling  
44 the dynamics of deep carbon<sup>9,10,12</sup>.

45           Neither absolute changes in carbon stocks nor carbon fluxes in the deep soil horizons  
46 can be quantified by direct measurement. Owing to the very low carbon concentrations (on  
47 average less than 5 g kg<sup>-1</sup> at depths of 80 cm), spatial heterogeneity and slow changes, temporal  
48 variations in stocks are smaller than measurement accuracy. Evidence for deep carbon changes  
49 is therefore exceptional<sup>13,14</sup>. Information on incoming fluxes resulting from root mortality and  
50 exudation by living roots is not accessible without tracers. In addition, in situ quantification of  
51 the outflow from the organic reservoir—which occurs mainly through heterotrophic respiration  
52 of the organic matter decomposers, in the form of CO<sub>2</sub> production—is very difficult, if not  
53 impossible, because the CO<sub>2</sub> efflux mixes up heterotrophic respiration and root autotrophic  
54 respiration<sup>15</sup>. Isotopic methods are therefore appropriate for tracing deep carbon dynamics. The  
55 radiocarbon age of deep carbon is indicative of its slow turnover<sup>16-19</sup>, but <sup>14</sup>C dating, which  
56 provides mean ages, does not estimate the exact proportions of active and stable carbon<sup>17-20</sup>.  
57 Here we propose a stable-isotope-based observation of the actual depth distribution of soil  
58 carbon ages. It relies on sites that are marked by a natural change in the <sup>13</sup>C/<sup>12</sup>C ratio of the  
59 vegetation at a known date. This is equivalent to the continuous in situ labelling of the  
60 atmospheric carbon atoms that have been incorporated into soil organic matter for a known  
61 duration, have eventually replaced pre-existing organic carbon, and have been retrieved at the  
62 date of sampling<sup>21</sup>.

63           We conducted a meta-analysis of 112 such sites (Extended Data Fig. 1), where the  
64 labelling ranged from 4 to 4,000 years. At each site, the technique provides an indication of

65 carbon age—that is, the proportion of carbon that is younger than the labelling duration; meta-  
66 analysis of similar sites with varied durations provides an age probability distribution<sup>17</sup>. Our  
67 study includes most of the world’s biomes except boreal zones, and is evenly distributed among  
68 forests, grasslands and croplands.

69 We quantified carbon distribution in the two-dimensional age–depth continuum<sup>22</sup>, the  
70 depth distribution of carbon incorporation in soil over the past 50 years, and the dependence of  
71 these factors on climate and land use. We also summarized depth distributions in terms of two  
72 layers, 0–30 cm (topsoil) and 30–100 cm (subsoil)—an arbitrary cut-off, but one that is often  
73 used in carbon inventories<sup>6</sup>. Our results, which are based on original observations, are  
74 independent of any data sets or modelling results from other studies.

75 Figure 1 depicts individual data showing the proportion of new carbon—that is, the  
76 proportion of SOC that derives from new vegetation—as a function of time. At all depths, a  
77 minor proportion of soil carbon is renewed rapidly (within ten years). Nine sites at which a  
78 vegetation signature change occurred more than 1,000 years ago reveal the incomplete  
79 replacement of carbon, that is, the presence of millennia-old soil carbon, at depth but not in the  
80 topsoil.

81 The rate of carbon incorporation in the topsoil was, as expected, strongly dependent on  
82 environmental variables, in particular land use ( $P < 0.001$ ) and mean annual temperature  
83 (MAT;  $P < 0.05$ ) (Extended Data Table 1). For the subsoil, by contrast, we found no  
84 relationship between carbon age and land use, and only a weak relationship with temperature  
85 ( $P = 0.1$ ); instead, carbon age was more affected by the ratio of precipitation to potential  
86 evapotranspiration<sup>23</sup> ( $P < 0.01$ ; Extended Data Table 2). This observation reinforces the results  
87 of ref. <sup>9</sup>, which showed that the relationship between ecosystem carbon turnover time and  
88 precipitation is pervasive and underestimated by models.

89 To analyse the age distribution with depth under comparable environmental conditions,  
90 we selected a homogeneous subset of sites, namely a group of forests and grasslands under  
91 warm and moist climates (with MATs higher than 17 °C, annual precipitation of more than  
92 1,000 mm, and precipitation/evapotranspiration ratios greater than 0.8). Figure 2 and Extended  
93 Data Table 3 depict the detailed depth distribution of carbon ages throughout this panel of soils.  
94 This description of carbon dynamics in time–depth space highlights its strong dependence on  
95 both variables. The dynamics of subsoil carbon is around seven times slower than that of topsoil  
96 carbon (that is, it takes seven times longer to reach the same proportion of renewed carbon;  
97 Extended Data Fig. 2). In deep layers, the age distribution reveals the small but non-negligible

98 direct incorporation of photosynthetically fixed carbon through deep roots or soluble carbon  
99 (for the youngest carbon), and the predominance of carbon that is older than 1,000 years. Mid-  
100 profile horizons (20–70 cm) are dominated by carbon of intermediate ages (100 to 1,000 years),  
101 which can be considered to result from the slow downward movement of carbon<sup>16,24</sup>. Carbon  
102 incorporation in the 100–200-cm layer has been quantified in only a few studies and averaged  
103  $5 \pm 3\%$  (1 standard deviation) of soil carbon after 50 years.

104 We calculated the amount of carbon incorporated into each layer ( $C_{\text{new}}$ , in units of  
105  $\text{kg C m}^{-2}$ ) for each site. In our database, the SOC found in the subsoil layer represents 47% of  
106 the total stock found in the entire top metre of soil, in agreement with the percentage of 47% to  
107 52% reported globally<sup>5,6</sup>. To express the incorporation of new carbon in depth on the basis of a  
108 single indicator, we chose the ratio  $R_{30-100}$ , which is  $C_{\text{new}}(30-100 \text{ cm})/C_{\text{new}}(0-100 \text{ cm})$ , and  
109 analysed its dependence on land use, climate and time in the 0- to 200-year-old sites (Extended  
110 Data Table 4). We found that  $R_{30-100}$  is strongly dependent on land use ( $P < 0.001$ ). The mean  
111 values of  $R_{30-100}$  (50 years) are 19%, 21% and 29% for forests, grasslands and croplands,  
112 respectively. The relatively deeper carbon incorporation in croplands concerns all layers below  
113 a depth of 10 cm and cannot be explained only by soil mixing due to ploughing, as the depth of  
114 this mixing does not exceed 30 cm (Fig. 3). Croplands incorporate less new carbon in their  
115 topsoils than do forests and grasslands, whereas in subsoil the amount of incorporated carbon  
116 is similar (Extended Data Tables 1 and 2). This is consistent with the general reduction in  
117 carbon input at the soil surface<sup>25</sup> that results from the removal of above-ground biomass during  
118 harvesting.  $R_{30-100}$  also depends on the precipitation/evapotranspiration index ( $P < 0.005$ ), and  
119 is weakly dependent on MAT ( $P < 0.1$ ; Extended Data Table 4), in accordance with the deeper  
120 rooting that takes place under dry climates, and possibly the more frequent occurrence of deep  
121 soils at low latitudes. The world average value of  $R_{30-100}$  (50 years) is 19% ( $\pm 4\%$ ; 95%  
122 confidence interval) (Fig. 3). The overall shallow incorporation of carbon can be expressed by  
123 the median depth of carbon incorporated in the last 50 years:  $9 \pm 1 \text{ cm}$  ( $\pm 95\%$  confidence  
124 interval) in forests,  $10 \pm 2 \text{ cm}$  in grasslands and  $17.5 \pm 1.5 \text{ cm}$  in croplands in our panel ( $9.7 \pm$   
125  $1.2 \text{ cm}$  on average globally; Extended Data Table 5). Taking into account the 100–200-cm layer  
126 (when observed) would lower this median depth by 0.5 cm.

127 This study provides an unprecedented estimate of, first, the SOC age distribution over  
128 the soil profile (Fig. 2), and, second the depth distribution of the carbon transferred from the  
129 atmosphere to soils (Fig. 3). The carbon-incorporation profiles can be compared with existing  
130 profiles of root biomass and above-ground inputs. The proportion of carbon that we found to

131 be allocated to the subsoil is higher than the corresponding proportion of root biomass compiled  
132 in meta-analyses<sup>5,26</sup>. This can be explained on the one hand by the contribution of root exudates  
133 in addition to root mortality<sup>27</sup>, and on the other hand by reduced decay rates at depth<sup>24</sup>. The  
134 reduced decay rates could be related to several interacting processes, for example, reduced and  
135 scattered microbial biomass<sup>8</sup>, stabilization by minerals<sup>8,18</sup>, and reduced priming effect (the latter  
136 being the stimulation of SOC decomposition by the supply of fresh carbon)<sup>28</sup>.

137 We measured the depth distribution of atmosphere-derived carbon incorporation over  
138 the past 50 years (50-year input). The depth distribution of the net change in soil carbon in the  
139 same time interval also depends on the loss of carbon older than 50 years during the period (50-  
140 year output). In steady-state systems, the depth distribution of outputs would perfectly equal  
141 the depth distribution of inputs. But real systems are transient as a result of global changes in  
142 either carbon inputs (for example, increased net primary production, reduced carbon returns  
143 because of land-use change) or decay rates (for example, because of warming). On the basis of  
144 our meta-analysis, we argue that the depth distributions of carbon output and of carbon  
145 incorporation are very similar even in transient systems, for the following reason. In non-  
146 steady-state systems, the delay associated with the downward movement of carbon may be  
147 suspected to result in 50-year outputs that are deeper than 50-year inputs, in a ‘conveyor-like’  
148 dynamic system. But the  $R_{30-100}$  ratio increases very slowly with time (by less than 0.001 per  
149 year; Extended Data Table 4). This means that the movement of carbon is slow and affects only  
150 long-term carbon dynamics, far later than the change expected in future decades. The depth  
151 distribution of net changes could differ from our distribution of new carbon only under the  
152 pressure of a driving force that affects old carbon in a very different way to the new carbon,  
153 such as de-freezing<sup>29</sup> or major changes in deep carbon inputs leading to additional priming  
154 effects<sup>28</sup>.

155 Our study also reveals that the steep age gradient with depth (Fig. 2) could be a source  
156 of bias in the representation of carbon dynamics if depth is not handled properly. For instance,  
157 if we consider three commonly used reference layers—0–10 cm, 0–20 cm and 0–30 cm—we  
158 find that their median ages differ considerably, being 23, 50 and 92 years, respectively.  
159 Projecting the decay-rate parameters observed in the topmost part of soils onto thicker layers  
160 would bias future projections of changes in carbon. The kinetics of carbon incorporation further  
161 reveals a substantial turnover over the time range of centuries (Figs. 1, 2 and Extended Data  
162 Fig. 2)—that is, between the ‘decadal’ and ‘millennial’ compartments of present carbon

163 models<sup>1,7,30</sup>—arguing for a more realistic description of carbon storage in terms of continuous  
164 time ranges<sup>30</sup>.

165 Our results show that SOC dynamics and their responses to climatic control or land use  
166 are strongly depth dependent. A better representation of deep carbon dynamics has been called  
167 for, together with other processes, to improve ecosystem carbon models<sup>7,12,19</sup>. Our observations  
168 support the use of multilayer SOC modules in Earth system models, which our data could help  
169 to test.

170 **Online content** Any Methods, including any statements of data availability and Nature Research reporting  
171 summaries, along with any additional references and Source Data files, are available in the online version of the  
172 paper

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240 **Author contributions** J.B. led the study and drafted the manuscript. All authors contributed equally to data  
241 provision and processing, and commented on and provided edits to the original manuscript. J.C. supervised the  
242 statistical analysis.

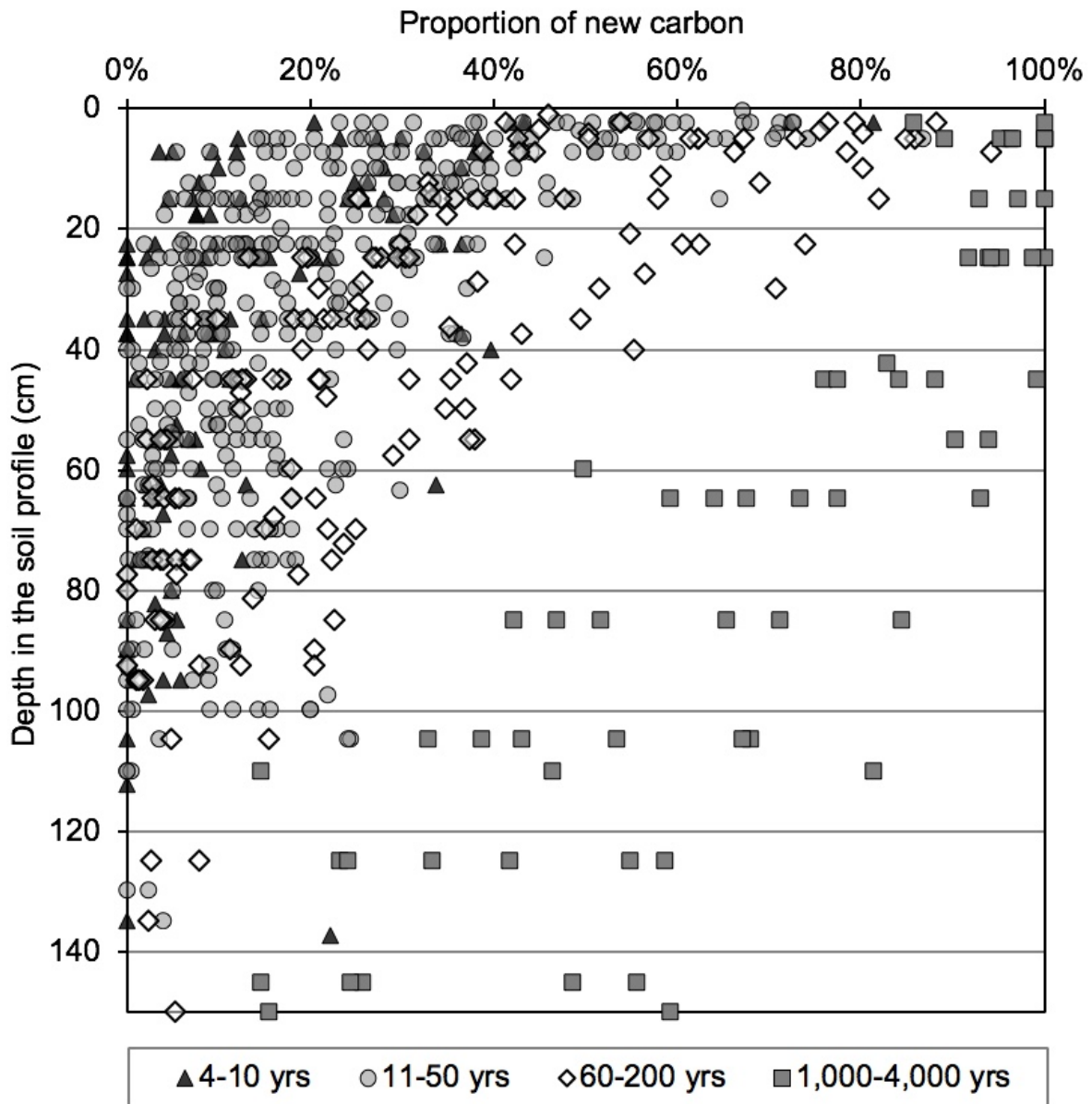
243 **Competing interests** The authors declare no financial competing interests.

244 **Extended data** is available for this paper

245 **Supplementary information** is available for this paper

246 **Correspondence and requests for materials** should be addressed to J.B.

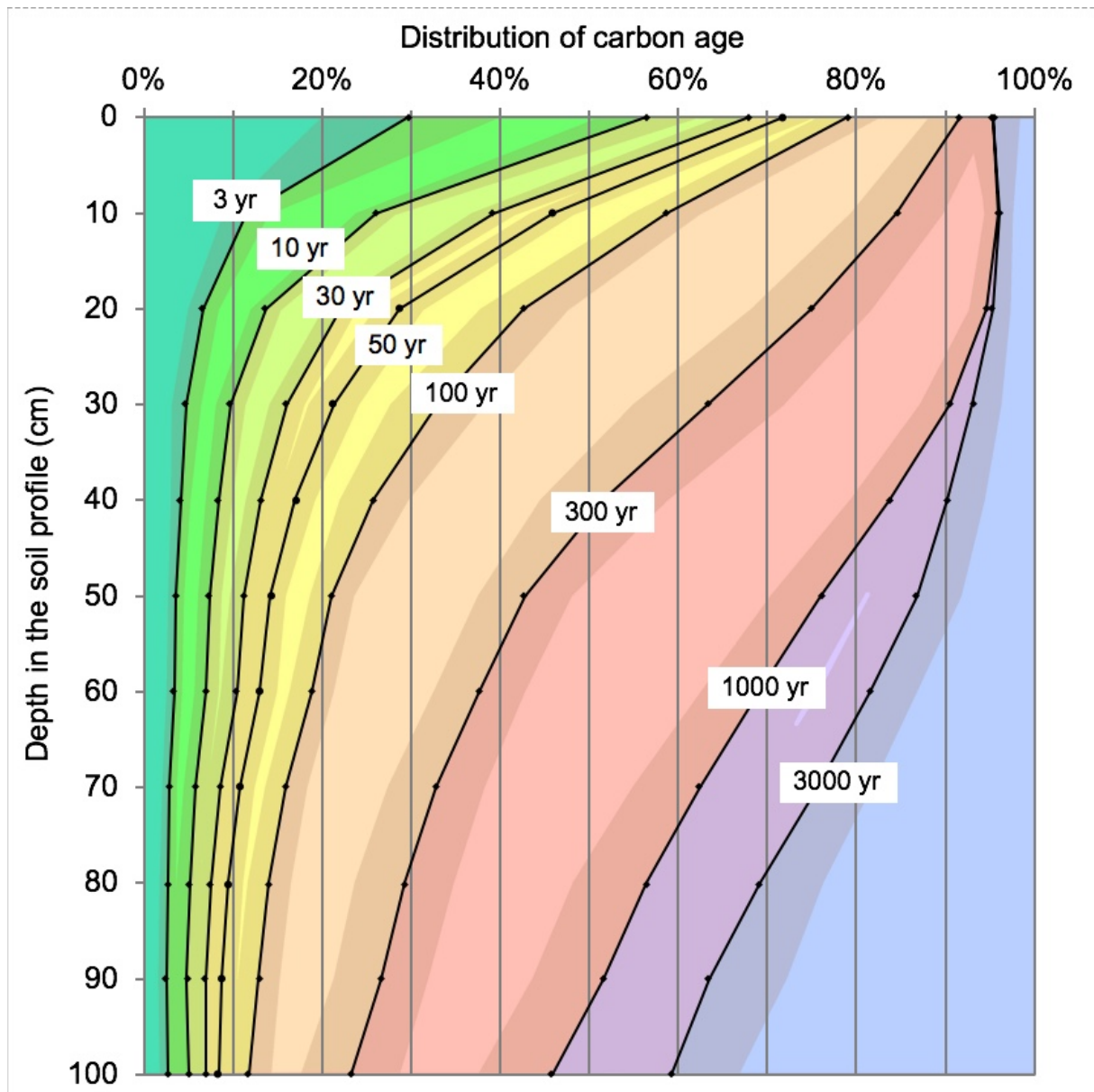
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248

249 **Fig. 1 | Observed proportions of new carbon in 112 soil profiles.** In each soil sample, the  
 250 proportion  $p$  of new carbon atoms was determined by the change in the soil carbon  $^{13}\text{C}$  signature  
 251 following a change in the  $^{13}\text{C}$  signature of the vegetation for a given duration  $t$ ;  $p$  is the  
 252 proportion of carbon younger than  $t$ <sup>21</sup>. Data are presented in four classes of duration  $t$ .

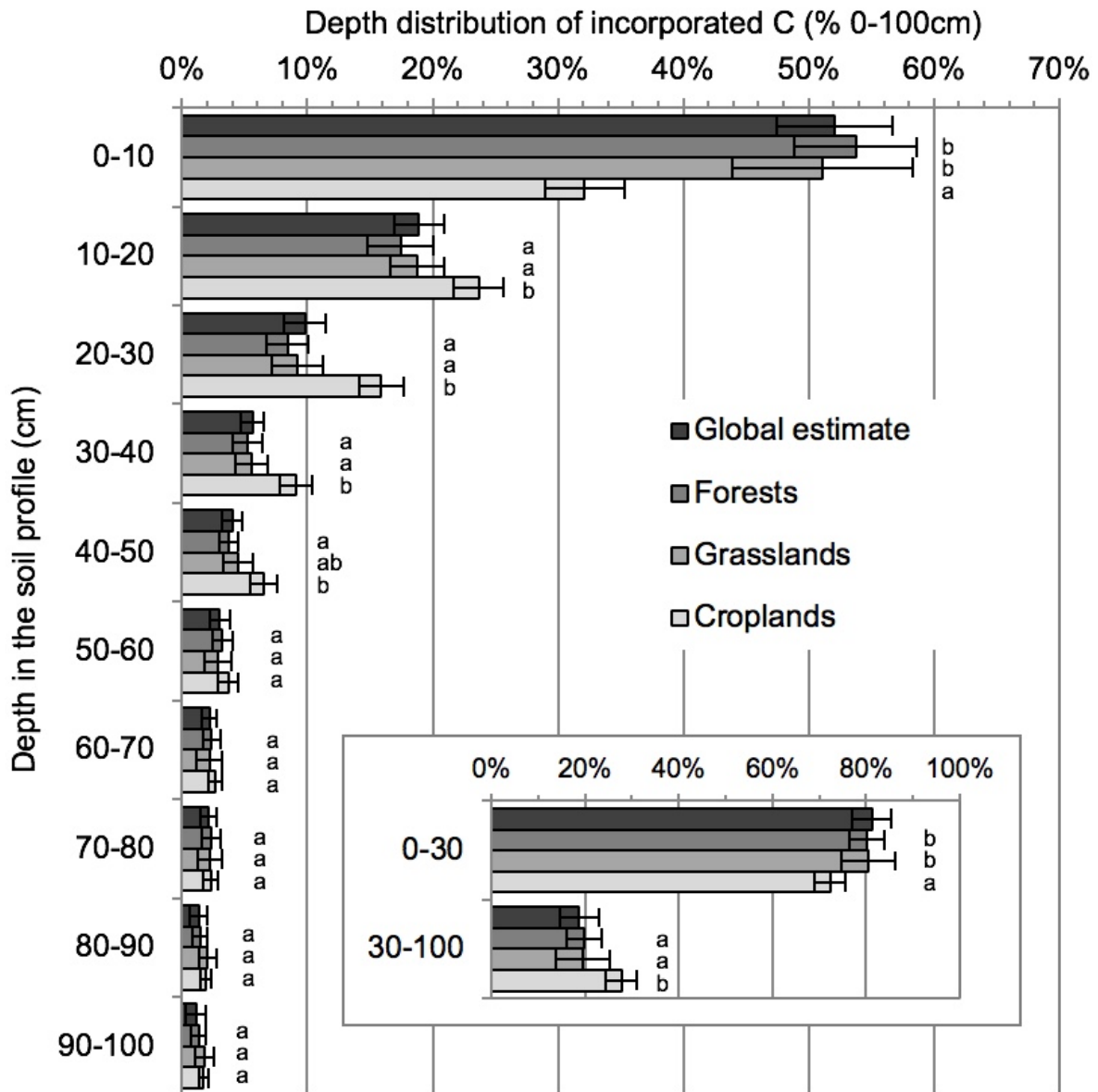
253



254

255 **Fig. 2 | Meta-analysis of carbon age distribution over 55 tropical grassland and forest soil**  
 256 **profiles.** At each depth, the proportion of carbon aged less than time  $t$  (3 years, 10 years and so  
 257 on) was fitted by a bi-exponential regression of  $t$  (Extended Data Table 3). Grey bands represent  
 258  $\pm 1$  standard error of the estimated mean. The median age of soil carbon increases from seven  
 259 years at depth 0 cm to 1,250 years at 100 cm. Integration of the carbon content in each layer  
 260 demonstrates that the carbon of age less than 50 years represents 45% of topsoil carbon (0–  
 261 30 cm) and 13% of deep carbon (30–100 cm).

262



263

264 **Fig. 3 | Depth distribution of the carbon that has been transferred from the atmosphere**  
 265 **to soil organic matter between 1965 and 2015.** The amount of carbon per 10-cm increment  
 266 is expressed as a proportion of the total carbon incorporated in the top metre. The value for each  
 267 land use is the mean of the observed profiles, and the value for the whole Earth was estimated  
 268 by multivariate linear model extrapolation to the world's biomes. Error bars represent the 95%  
 269 confidence interval of the mean or estimate; within each increment, land uses followed by the  
 270 same letter (a or b) do not differ significantly. The small shift between the global estimate and  
 271 the observed values reflects the differences in soil-climate conditions between the global  
 272 average and the observation panel.

273

## 274 **METHODS**

### 275 **Study sites**

276 We compiled published data sets from 47 peer-reviewed articles, together with original data,  
277 on mineral soil  $^{13}\text{C}/^{12}\text{C}$  changes in places where the  $^{13}\text{C}/^{12}\text{C}$  ratio of the vegetation has been  
278 shifted for known durations (see Supplementary Information). We analysed a total of 112 pairs  
279 of mineral soil profiles: 108 pairs in which the predominant vegetation has changed from the  
280 C3 photosynthetic type to the C4 type, or vice versa, and four pairs from free-air carbon-  
281 enrichment (FACE) experiments, where the  $^{13}\text{C}$  signature of added carbon dioxide has labelled  
282 plant-derived material (Extended Data Fig. 1; see references in Supplementary Information. At  
283 each site, two plots with a common history (one with changed and one with unchanged  
284 vegetation) were analysed. The isotopic difference between the two profiles was used to  
285 calculate the proportion of new carbon through an isotope-mixing equation, which is not biased  
286 by additional isotopic effects in soils<sup>21</sup>.

287 Most of the world's biomes are represented; the land uses include grasslands and  
288 savannas (34%), forests and woodlands (30%), and annual and perennial crops (36%), from 24  
289 countries between latitudes 29° S and 57° N (Extended Data Fig. 1). We selected studies that  
290 fulfil the following criteria: the age of change should be known or estimated; the observed depth  
291 should be more than 60 cm or reach bedrock; and the difference in the  $\delta^{13}\text{C}$  of the vegetation  
292 between the reference and the study site should be 5‰ or more in the case of mixed vegetation  
293 that include both photosynthetic types. The duration of vegetation change ranged from 4 years  
294 to 4,000 years. Authors estimated the dates of change through controlled experiments,  
295 enquiries, historical records, or airborne surveys. Changes in isotope signature that occurred  
296 more than 1,000 years ago (nine sites) were associated with interacting climate- and man-  
297 induced changes in vegetation. In those cases, dates were estimated by the authors from local  
298 or regional proxies of palaeovegetation change (for example, pollen/charcoal combined with  
299 radiocarbon dating). When the period after vegetation change was expressed by the authors as  
300 a range (for changes older than 200 years), we used the mid-value of the range.

301 Mean climatic data were obtained either from data reported in the article ( $n = 103$ ) or,  
302 if missing ( $n = 9$ ), from the CRU Group/Oxford/International Water Management Institute  
303 (IWMI) 10-minute mean climate grids for global land areas for the period 1961 to 1990 (ref.<sup>31</sup>).  
304 We compared grid versus declared climatic data in the database: for annual precipitation, the  
305 mean CRU grid/declared ratio is  $0.98 \pm 0.15$  (standard deviation); for MAT, the mean  
306 difference between CRU grid and declaration is  $-0.15 \pm 1.1$  °C. Topsoil clay content was either

307 obtained from authors' statements or assumed to be the median value of the texture class  
308 mentioned. Mean annual aridity indexes, P/PET (annual precipitation/potential  
309 evapotranspiration)<sup>23</sup>—a better indicator of hydric impact on both net primary production and  
310 microbial activity than precipitation alone—were obtained from the Food and Agriculture  
311 Organization 10-minute mean climate grids for global land areas for the period 1950 to 2000  
312 (ref.<sup>23</sup>).

### 313 **Proportion of new carbon and data pre-processing**

314 For each site, the natural <sup>13</sup>C-labelling technique uses two plots, which were initially identical,  
315 and have been differentiated during the last  $t$  years by two types of vegetation that differ in their  
316  $\delta^{13}\text{C}$ . We use the terms 'reference' ('ref') for the plot at which the vegetation type at the date  
317 of sampling is the closest to that of the initial vegetation, and 'studied plot' ('s') for the plot  
318 with the new type of vegetation. Most authors described carbon content and isotopic data  
319 profiles as successive layers, each one sampled between two depths ( $z_1, z_2$ ). For each layer ( $z_1,$   
320  $z_2$ ), we define  $C$  as the carbon stock in the horizon (in  $\text{kg m}^{-2}$ );  $f_{\text{new}}$  as the proportion of new  
321 carbon (that is, derived from the new vegetation) (Fig. 1); and  $C_{\text{new}}$  as the stock of new carbon  
322 in the horizon (in  $\text{kg m}^{-2}$ ).  $C, f_{\text{new}}$  and  $C_{\text{new}}$  were either obtained from the authors' papers  
323 ( $n = 30$ ), or calculated from observed variables as follows.  $C$  was calculated from carbon  
324 concentration,  $[C]$  (in  $\text{mg g}^{-1}$ ), and bulk density,  $\rho$ , according to  $C = [C] \times \rho \times (z_2 - z_1)$ , where  
325  $\rho$  was either from the authors' data or (in 41 cases) estimated from  $[C]$  according to  
326 Alexander's<sup>32</sup> equation.  $f$  and  $C_{\text{new}}$  were calculated according to the equations<sup>21</sup>:

$$327 \quad f_{\text{new}} = (\delta\text{soil}_s - \delta\text{soil}_{\text{ref}}) / \Delta\delta\text{veg} \quad (1)$$

$$328 \quad C_{\text{new}} = f_{\text{new}} \times C$$

329 where  $\delta\text{soil}_s$  and  $\delta\text{soil}_{\text{ref}}$  are the  $\delta^{13}\text{C}$  values of SOC from the study and reference plots; and  
330  $\Delta\delta\text{veg}$  is the difference in vegetation  $\delta^{13}\text{C}$  between the study and reference plots and was  
331 determined from plant or litter samples. The  $\delta\text{soil}_{\text{ref}}$  in each horizon was obtained from the  
332 reference soil collected at the same depth as the soil of the study plot. In accordance with the  
333 limit of resolution of the method, 27 horizons in deep layers had negative  $f_{\text{new}}$  values; in this  
334 case, we considered  $C_{\text{new}}$  to be 0. The resulting overestimation of average new carbon was  
335 negligible. In cases in which the sampling depth differed at the reference and studied plots, we  
336 calculated  $\delta\text{soil}_s$  by linear interpolation of the two nearest observed depths. Equation (1)  
337 typically accounts for the various <sup>13</sup>C enrichments that occur during organic carbon decay or  
338 historical changes<sup>21</sup>, with the sole criterion that these enrichments are similar in the study and

339 reference soils. Equation (1) neglects the dark fixation of carbon atoms<sup>33</sup> that would have the  
340 isotopic composition of atmospheric CO<sub>2</sub>.

### 341 **Depth distribution of new carbon**

342 We calculated depth distributions for the subset of sites whose labelling duration was 200 years  
343 or less ( $n = 99$ ; Fig. 3). The mean duration was 35 years. In order to compare similar depth  
344 intervals, we calculated the three variables  $f_{\text{new}}$ , cumulative carbon stock with depth  $C(0, z)$  and  
345  $C_{\text{new}}(0, z)$  10-cm increments by linear interpolation of the observed horizons. For each 10-cm  
346 depth interval ( $z, z + 0.1$  m), we computed the ratio  $R = C_{\text{new}}(z, z + 10 \text{ cm})/C_{\text{new}}(0, 100 \text{ cm})$ .  
347 When bedrock or the R horizon was described, a nil carbon content was attributed to these  
348 horizons. When profiles were not described down to a depth of one metre ( $n = 31$ ; most often  
349 80 cm),  $C(0, 100 \text{ cm})$  was extrapolated from the maximum depth  $z_{\text{max}}$  using the linear  
350 regression  $C(0, 100 \text{ cm}) = a \times C(0, z_{\text{max}}) + b$  over the entire data set and similarly for  $C_{\text{new}}(0,$   
351  $100 \text{ cm})$ .

352 The median depth  $z_{\text{median}}$  of new carbon was calculated for individual profiles as  $C_{\text{new}}(0,$   
353  $z_{\text{median}}) = C_{\text{new}}(0, 100 \text{ cm})/2$ , by linear interpolation in the observed  $C_{\text{new}}(0, z)$  function.

354 The variance of the ten ratios  $R = C_{\text{new}}(z, z + 10 \text{ cm})/C_{\text{new}}(0, 10 \text{ cm})$  at the ten depths  
355  $z = 0, 10, \dots, 90$  cm, the ratio for the whole subsoil  $C_{\text{new}}(30, 100 \text{ cm})/C_{\text{new}}(0, 100 \text{ cm})$  and the  
356 median depth of new carbon were analysed by multivariate linear regression of time, land use  
357 and climatic variables (Extended Data Tables 3–5). Given that the average start date of labelling  
358 was 1965, we consider that the regression value of  $R$  for time = 50 years stands for carbon  
359 incorporated in the time interval 1965–2015. World average values of carbon incorporation in  
360 deep soil layers, excluding permafrost areas, were obtained by weighting multivariate linear  
361 regression estimates of new carbon (Extended Data Tables 1, 2, 4 and 5) by the biome soil  
362 carbon inventories in ref. 5. Multivariate linear regression used the mean value of each of the  
363 112 observed profiles, with no weighting for the number of replicates or horizons, leading to  
364 less precise but unbiased estimation. When replicated, profile variability is provided in the  
365 database in the Supplementary Information. We used bootstrap procedures<sup>34</sup> to express  
366 confidence on the estimated depth distribution or median age for the globe (Fig. 3 and Extended  
367 Data Table 6), or on the depth distribution of ages in tropical grasslands and forests (Fig. 2 and  
368 Extended Data Table 3). For that purpose, we drew  $N = 100,000$  independent profile bootstrap  
369 samples from the observed profiles. For each bootstrap sample, relationships with P/PET,  
370 MAT, land use and time were recomputed and used to calculate the values of the variables of

371 interest. Standard deviations were then estimated as the standard deviation of these 100,000  
372 values.

373 Statistical analyses were performed using the R packages Boot and Stats version 3.4.3.

#### 374 **Analysis of the inference of vegetation change on the results**

375 The naturally labelled sites experienced varying degrees of perturbation compared with pristine  
376 ecosystems. Vegetation change may modify input or decay rates, leading to transient carbon  
377 dynamics. To investigate whether these changes themselves affect the depth distribution of new  
378 carbon, we tested the dependence on two additional variables that characterize the observed  
379 sites: the previous type of vegetation—either crops, grassland or forest, known for 109 sites—  
380 and the relative difference in carbon stock between study and reference plots, when known and  
381 when the reference resembled the previous vegetation type ( $n = 88$  sites). The relative change  
382  $\Delta C_{rel}$  is calculated as:

$$383 \Delta C_{rel} = [C(0, 100 \text{ cm})_{\text{studied site}} - C(0, 100 \text{ cm})_{\text{reference site}}] / C(0, 100 \text{ cm})_{\text{reference site}}$$

384  $\Delta C_{rel}$  is nil on average in the database, that is, it corresponds to the steady state  
385 ( $\Delta C_{rel} = 0.004 \pm 0.026$ ,  $\pm$  s.e.m.); however, it does vary as a result of changes in inputs or  
386 dynamics in different directions. Mean durations of change are independent of previous  
387 vegetation in the statistical analysis: 31 years for previous grassland, 37 years for previous  
388 crops and 40 years for previous forests (excluding durations of more than 1,000 years, which  
389 involve no crop).  $\Delta C_{rel}$  is not correlated with the duration of the change either.

390 Concerning the depth distribution of new carbon, that is,  $R_{30-100} = C_{new}(30 \text{ to}$   
391  $100 \text{ cm}) / C_{new}(0 \text{ to } 100 \text{ cm})$ ,  $R_{30-100}$  is not correlated with  $\Delta C_{rel}$  either in the whole data set  
392 ( $r^2 = 0.002$ ;  $n = 88$ ), or within the subsets of crops ( $r^2 = 0.01$ ;  $n = 31$ ), grasslands ( $r^2 = 0.02$ ;  
393  $n = 24$ ) or forests ( $r^2 = 0.13$ ;  $n = 33$ ). We also tested the previous vegetation type as an  
394 explanatory variable of  $R_{30-100}$  in addition to the other variables of climate, present land use and  
395 time (that is, the variables in Extended Data Table 4). The additional variable was not a  
396 significant factor (previous forest versus previous crop:  $P = 0.88$ ; previous grassland versus  
397 previous crop:  $P = 0.52$ ; previous grass versus previous forest:  $P = 0.47$ ) and did not improve  
398 the model.

399 Concerning the proportion of new carbon in either topsoil or subsoil (that is,  $f_{new}$ ), the  
400 previous vegetation type added as an explanatory variable in the statistical models of Extended  
401 Data Tables 1 and 2 was not a significant factor either ( $P = 0.49$  to  $0.99$ ). By contrast, as an  
402 additional variable,  $\Delta C_{rel}$  was highly significant for topsoil ( $P < 0.01$ ) but was not for subsoil



403 ( $P = 0.12$ ). The effect is obvious given that both carbon change and new carbon are first driven  
404 by the relative change in inputs. This effect typically explains one of the results, namely the  
405 lower proportion of new carbon in cropland topsoils (Extended Data Table 1).

406 Concerning the age distribution in the subset of tropical grasslands and forests (Fig. 2  
407 and Extended Data Table 3), the mean value of  $\Delta C_{rel}$  is very low ( $0.02 \pm 0.03$ ;  $\pm$  s.e.m.), close  
408 to steady state, and  $\Delta C_{rel}$  does not depend on time, and therefore does not affect the estimated  
409 mean age distribution, but does contribute to the random dispersion of results.

410 Finally, we included neither previous vegetation as an explanatory variable in the  
411 statistical models of the proportion of new carbon, nor carbon change, because of the covariance  
412 of  $\Delta C_{rel}$  with land use. Furthermore, sites with previous or present croplands may have  
413 experienced a complex land-use history involving ancient primary forests and possibly pasture  
414 events. Taking all land-use histories into account would become a case-by-case study.

415 On the basis of this analysis of the inference of vegetation changes, we conclude that  
416 perturbation did not bias our estimates of the mean depth distribution of new carbon; that is,  
417 this depth distribution depends on the present vegetation and conditions, and not on previous  
418 vegetation, nor is it affected by non-steady-state conditions, in any systematic direction. The  
419 impact of perturbation on the proportion of new carbon in topsoils nevertheless prevented us  
420 from integrating our data towards global estimates of the absolute amount of new carbon or  
421 global carbon turnover. We thus restricted global integration to the depth distribution and  
422 median depth of new carbon.

#### 423 **Data availability**

424 The raw primary data, calculated data and ancillary information analysed and generated here  
425 are available in the INRA public repository (<http://dx.doi.org/10.15454/KMNR6R>). No  
426 statistical methods were used to predetermine sample size.

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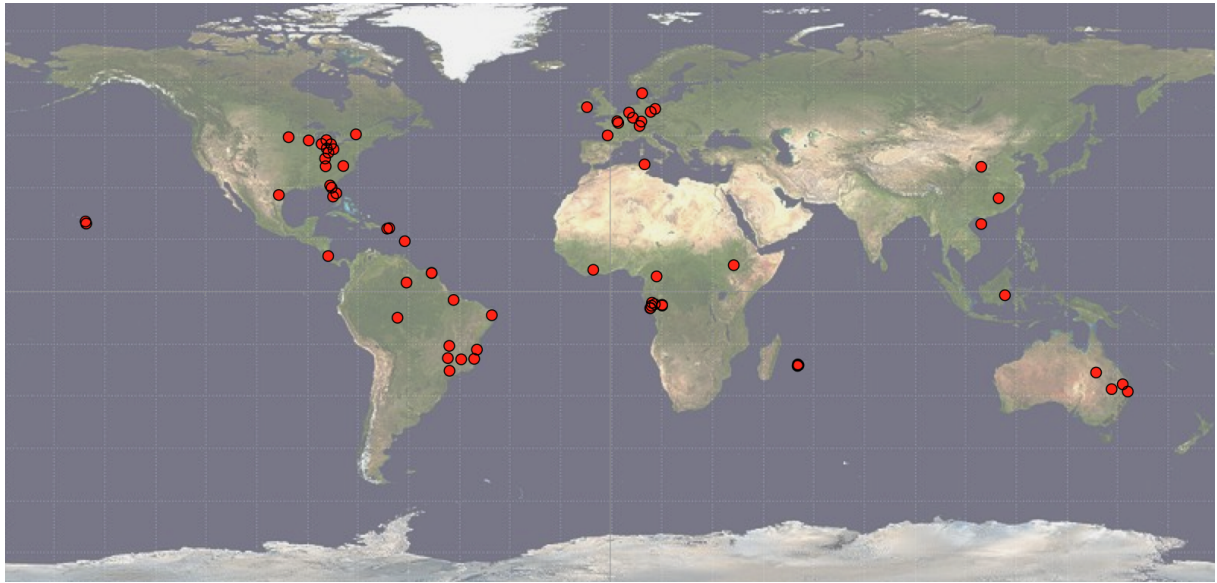
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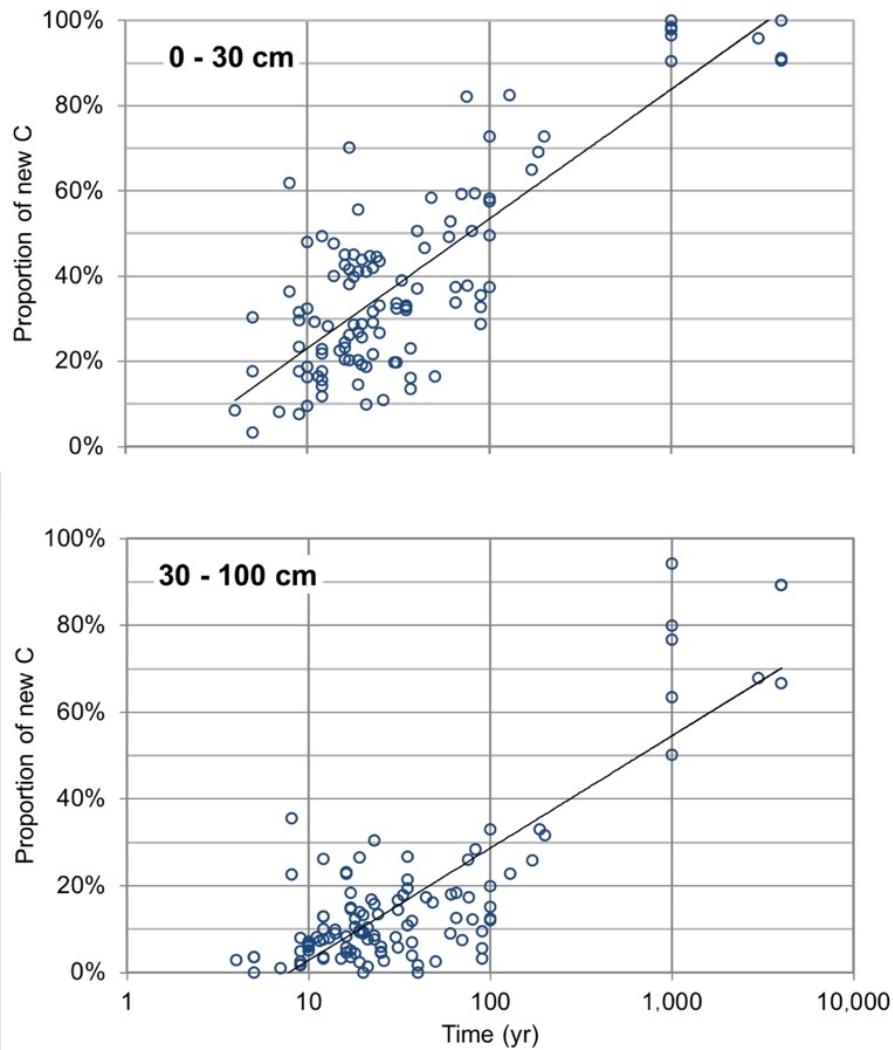
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**Extended Data Fig. 1 | Locations of the study sites.** Source of background image: Visible Earth, NASA.



440

441 **Extended Data Fig. 2 | Kinetics of new-carbon incorporation for the depth layers 0–30 cm**  
 442 **and 30–100 cm.** The respective logarithmic regressions  $y = 0.30 \times \log_{10}(x) - 0.07$  for 0–30 cm  
 443 and  $y = 0.26 \times \log_{10}(x) - 0.23$  for 30–100 cm indicate that the duration required to replace one-  
 444 third of the carbon is on average seven times longer in the subsoil than the topsoil.

445

	Coefficient estimate	Standard error	T value	Pr(> T )	
Intercept = Forest	-0.00250	0.0728	-0.034	0.973	
Grassland	-0.0531	0.0405	-1.311	0.193	
Cropland	-0.0951	0.0328	-2.896	0.00472	**
Log10(time)	0.258	0.038	6.865	7.6e-10	***
MAT	0.00595	0.00234	2.540	0.0128	*
P/PET	-0.0441	0.0337	-1.306	0.1954	
Clay	-0.000566	0.000693	-0.816	0.417	

447

448 **Extended Data Table 1 | Proportion of new carbon in topsoil: multivariate linear**  
 449 **regression**

450 The dependent variable is the ratio of new carbon (derived from the vegetation after time  $t$ ) to  
 451 total organic carbon in the topsoil layer. The explanatory variables are land use (grassland or  
 452 cropland),  $\log_{10}(t)$  (in years), mean annual temperature (MAT, in °C), ratio of annual  
 453 precipitation to evapotranspiration (P/PET), and topsoil clay content (as a percentage). The  
 454 reference land use (intercept) is forest.  $T$  is the value of Student's statistics;  $\text{Pr}(>|T|)$  is the  
 455 probability value of the Student's test.

456 \* $P < 0.05$ ; \*\* $P < 0.01$ ; \*\*\* $P < 0.001$ .

457 Residual standard error, 0.1249 on 92 degrees of freedom; multiple  $R^2$ , 0.4781; adjusted  $R^2$ ,  
 458 0.444;  $F$ -statistic, 14.04 on 6 and 92 degrees of freedom;  $P$ -value,  $2.768 \times 10^{-11}$ .

459

	Coefficient estimate	Standard error	T value	Pr(> T )	
Intercept = Forest	0.0205	0.0433	0.474	0.637	
Grassland	-0.0136	0.0241	-0.564	0.574	
Cropland	0.0024	0.0195	0.121	0.904	
Log10(time)	0.0849	0.0223	3.806	0.00025	***
MAT	0.00216	0.00139	1.551	0.124	
P/PET	-0.0516	0.0201	-2.570	0.0118	*
Clay	0.000018	0.000412	0.045	0.965	

460

461 **Extended Data Table 2 | Proportion of new carbon in subsoil: multivariate linear**  
462 **regression**

463 The dependent variable is the ratio of new carbon (derived from the vegetation after time  $t$ ) to  
464 total organic carbon in the subsoil layer. See Extended Data Table 1 for further definitions.  
465 Residual standard error, 0.07424 on 92 degrees of freedom multiple  $R^2$ , 0.2561; adjusted  $R^2$ ,  
466 0.2076;  $F$ -statistic, 5.279 on 6 and 92 degrees of freedom;  $P$ -value, 0.0001028

467

Depth	$a_1$	$k_1$ (yr <sup>-1</sup> )	$a_2$	$k_2$ (yr <sup>-1</sup> )	$a_1 + a_2$	Standard deviation of residuals
0 cm	0.614 (0.47, 0.75)	0.21 (0.11, 2.8)	0.34 (0.2, 0.49)	0.0073 (0.0024, 0.0158)	0.95 (0.92, 1.0)	0.18
10 cm	0.287 (0.19, 0.40)	0.15 (0.08, 0.5)	0.67 (0.56, 0.77)	0.0059 (0.0028, 0.0083)	0.96 (0.94, 1.0)	0.11
20 cm	0.108 (0.05, 0.19)	0.23 (0.09, 1.5)	0.85 (0.78, 0.92)	0.0047 (0.0025, 0.0072)	0.95 (0.92, 1.0)	0.09
30 cm	0.074 (0.02, 0.13)	0.24 (0.13, 1.5)	0.86 (0.8, 0.93)	0.0035 (0.0020, 0.0064)	0.93 (0.88, 1.0)	0.10
40 cm	0.070 (0.03, 0.13)	0.23 (0.09, 1.0)	0.83 (0.74, 0.93)	0.0026 (0.0014, 0.0041)	0.90 (0.83, 1.0)	0.10
50 cm	0.066 (0.04, 0.11)	0.21 (0.10, 0.5)	0.80 (0.70, 0.95)	0.0020 (0.0010, 0.0030)	0.87 (0.79, 1.0)	0.09
60 cm	0.065 (0.03, 0.11)	0.20 (0.10, 0.4)	0.75 (0.65, 0.89)	0.0018 (0.0008, 0.0028)	0.82 (0.73, 0.94)	0.10
70 cm	0.052 (0.02, 0.09)	0.22 (0.13, 0.5)	0.71 (0.62, 0.88)	0.0016 (0.0007, 0.0024)	0.76 (0.67, 0.95)	0.10
80 cm	0.044 (0.01, 0.08)	0.25 (0.15, 3.2)	0.65 (0.54, 0.92)	0.0016 (0.0005, 0.0024)	0.70 (0.60, 0.93)	0.11
90 cm	0.042 (0.01, 0.08)	0.25 (0.14, 3.5)	0.60 (0.46, 0.99)	0.0016 (0.0003, 0.0025)	0.64 (0.51, 1.0)	0.11
100 cm	0.048 (0.01, 0.08)	0.25 (0.14, 3.3)	0.55 (0.44, 0.99)	0.0014 (0.0002, 0.0025)	0.60 (0.48, 1.0)	0.11

468

469 **Extended Data Table 3 | Age distribution of carbon over 55 tropical grassland and forest**  
470 **soil profiles**

471 These data were used to generate Fig. 2. At each depth, the proportion  $f_{\text{new}}$  of carbon aged less  
472 than  $t$  was fitted by a nonlinear regression of time  $t$  using the equation  
473  $f_{\text{new}} = a_1.[1 - \exp(-k_1 \times t)] + a_2.[1 - \exp(-k_2 \times t)]$ . Such bi-exponential functions<sup>30</sup> describe  
474 carbon age distribution, with carbon divided into three age classes,  $a_1$  being the proportion of  
475 ‘young’ carbon,  $a_2$  the proportion of ‘old’ carbon, and  $(1 - a_1 - a_2)$  the proportion of carbon  
476 with an infinite age.  $1/k_1$  and  $1/k_2$  are the mean ages of young and old carbon, respectively.  
477 Numbers in parentheses denote the 95% confidence intervals of the estimated parameters. The  
478 median environmental conditions of the soil set are: MAT = 23.6 °C; annual  
479 precipitation = 2,100 mm; P/PET (ref.<sup>23</sup>) = 1.44 and topsoil clay content = 37%.

480

	Coefficient estimate	Standard error	T value	Pr(> T )	
Intercept = Forest	0.193	0.049	3.979	0.00014	***
Grassland	0.0218	0.03499	0.624	0.534	
Cropland	0.105	0.029	3.646	0.00044	***
Time (yr)	0.000369	0.000320	1.155	0.251	
MAT (°C)	0.00381	0.00206	1.848	0.0677	
P/PET	-0.0996	0.0297	-3.354	0.00116	**
Clay (%)	0.000638	0.000608	1.049	0.297	

481

482 **Extended Data Table 4 | Depth incorporation of new carbon in subsoil: multivariate linear**  
483 **regression**

484 The dependent variable is the ratio of the amount of new carbon (derived from the vegetation  
485 after time  $t$ , in  $\text{kg m}^{-2}$ ) in the subsoil layer to the amount of new carbon in the entire top metre—  
486 that is,  $R_{30-100} = C_{\text{new}}(30 \text{ to } 100 \text{ cm})/C_{\text{new}}(0 \text{ to } 100 \text{ cm})$ . See Extended Data Table 1 for further  
487 definitions. Note the dependence on time: the maximum value of the coefficient at the 95%  
488 confidence level (estimate + 2 s.e.m.) is  $0.001 \text{ yr}^{-1}$ . Residual standard error, 0.11 on 92 degrees  
489 of freedom; multiple  $R^2$ , 0.2387; adjusted  $R^2$ , 0.1891;  $F$ -statistic, 4.808 on 6 and 92 degrees of  
490 freedom;  $P$ -value, 0.0002618

491



	Coefficient estimate	Standard error	T value	Pr(> T )	
Intercept = Forest	11.3	2.183	5.174	1.31e-06	***
Grassland	3.93	1.463	2.689	0.00849	**
Cropland	8.77	1.28	6.842	8.18e-10	***
Time (yr)	0.0201	0.0137	1.466	0.146	
MAT (°C)	0.183	0.089	2.045	0.0437	*
P/PET	-5.11	1.32	-3.871	0.000202	***

492

493

**Extended Data Table 5 | Median depth of new carbon: multiple linear regression.**

494

The dependent variable is the median depth (in cm) of the amount of new carbon (carbon derived from the vegetation after time  $t$ , in  $\text{kg m}^{-2}$ ) of each profile. See Extended Data Table 1 for further definitions. Residual standard error, 4.963 on 93 degrees of freedom; multiple  $R^2$ , 0.3985; adjusted  $R^2$ , 0.3662;  $F$ -statistic, 12.32 on 5 and 93 degrees of freedom;  $P$ -value:  $3.551 \times 10^{-9}$ .

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500

	Observed Forests	Observed Grasslands	Observed Croplands	Global estimate
0-10 cm	0.538 (0.048)	0.511 (0.071)	0.321 (0.032)	0.521 (0.046)
10-20 cm	0.174 (0.026)	0.188 (0.021)	0.237 (0.019)	0.189 (0.020)
20-30 cm	0.084 (0.016)	0.092 (0.020)	0.159 (0.017)	0.098 (0.017)
30-40 cm	0.052 (0.012)	0.056 (0.012)	0.091 (0.013)	0.056 (0.009)
40-50 cm	0.037 (0.007)	0.045 (0.011)	0.065 (0.010)	0.040 (0.008)
50-60 cm	0.032 (0.007)	0.028 (0.010)	0.037 (0.007)	0.030 (0.008)
60-70 cm	0.024 (0.006)	0.022 (0.010)	0.026 (0.005)	0.022 (0.006)
70-80 cm	0.023 (0.007)	0.022 (0.009)	0.023 (0.005)	0.021 (0.006)
80-90 cm	0.014 (0.006)	0.020 (0.007)	0.019 (0.004)	0.013 (0.007)
90-100 cm	0.013 (0.005)	0.018 (0.007)	0.017 (0.004)	0.011 (0.008)

501

502 **Extended Data Table 6 | Depth distribution of carbon transferred from atmosphere to**  
503 **SOM in 1965–2015**

504 These data were used to generate Fig. 3. The amount of new carbon transferred from the  
505 atmosphere to SOM in 1965 to 2015 (< 50 yr carbon) in each 10-cm layer is expressed as a  
506 proportion of the total new carbon < 50 yr in the first metre. The data shown are mean values  
507 for observed forests, grasslands and croplands, and global estimates; the numbers in parentheses  
508 are the 95% confidence intervals on the mean or estimate.

509

510