

1 **Title: Radiocarbon constraints imply reduced carbon uptake by soils during**
2 **the 21st century**

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17**Subheading:** Reduced carbon uptake by soils during the 21st century

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19**One Sentence Summary:**

20Global radiocarbon observations show that Earth system models, lacking carbon stabilization
21mechanisms, overestimate the ~~21st century~~ soil carbon sink by almost two-fold.

22**Abstract:**

23Soil is the largest terrestrial carbon reservoir and may influence the sign and magnitude of carbon

24cycle-climate feedbacks. Changes in soil carbon—the largest terrestrial carbon reservoir—may

25influence the sign and magnitude of climate-carbon cycle feedbacks. Many Earth system models

26(ESMs) estimate a significant soil carbon sink by 2100, yet the underlying carbon dynamics

27determining this response have not been systematically tested against observations. Using We

28used $\delta^{14}\text{C}$ data from 157 globally distributed soil profiles sampled to 1 m depth, we to show that

29ESMs underestimated d the mean age of soil carbon by more than six-fold (430 ± 50 years vs.

30 3100 ± 1800 years). Consequently, ESMs overestimated d the carbon sequestration potential of soils

3121st century soil carbon sequestration by nearly two-fold ($40 \pm 27\%$). These biases/inconsistencies

32suggest that ESMs must better represent carbon stabilization processes and the turnover time of

33slow and passive reservoirs when simulating future atmospheric CO₂ dynamics.

34To improve simulations of future atmospheric CO₂ and carbon storage, ESMs must better

35represent stabilization processes and turnover times for soil carbon pools.

36**Keywords:** soil carbon, earth system models, carbon-concentration feedback, mean age,

37radiocarbon

38Main Text:

39 Soil carbon is a dynamic reservoir that may increase substantially in size during the 21st
40century, as predicted by Earth system models (ESMs), thereby influencing the sign and
41magnitude of carbon cycle feedbacks under climate change (1-4). Under a high radiative forcing
42scenario (Representative Concentration Pathway 8.5), changes in soil carbon estimated by
43different models vary from a loss of 20 Pg C to a gain of more than 360 Pg C (5). These models
44suggest that the global carbon inventory in mineral soils may increase by 30% or more over a
45timespan of about two centuries. The multi-model mean soil carbon accumulation of 109 Pg C
46(5) represents about one decade of global fossil fuel emissions at current rates and 5% of
47cumulative fossil emissions by 2100 for this scenario (6). This soil carbon sink represents a
48negative feedback on CO₂ emissions, and if robust, would slow the rate of climate change.

49 Still, there are substantial uncertainties in the soil carbon sink projected by ESMs (5).
50Rapid rates of carbon sequestration in ESMs contrast with findings from CO₂ and warming
51experiments (7, 8) as well as multiple theoretical and observational constraints indicating slow
52(millennial) rates of soil organic carbon accrual and turnover (9-14). Model uncertainty—as
53measured by inter-model spread—is high for soil carbon turnover time (τ) and exceeds the
54uncertainty estimated for carbon uptake through gross primary production (GPP) (15, 16).

55 In coupled model simulations, the relative sink strength (i.e. percentage change in soil
56carbon) depends on the responses of net primary production (NPP) and soil carbon dynamics to
57increasing atmospheric CO₂ concentrations and to a lesser extent climate change (5). Elevated
58CO₂ increases photosynthesis and NPP, which results in greater carbon inputs to soil pools with
59decadal or longer residence times. Carbon sequestration in soils reduces the build-up of CO₂ in
60the atmosphere (the carbon-concentration feedback). On the other hand, elevated CO₂ also

61warms the climate, which tends to accelerate soil carbon turnover and reduce carbon storage (the
62carbon-climate feedback) (17, 18). Although these feedbacks oppose one another, the carbon-
63concentration feedback is more than 4 times greater on average than the carbon-climate feedback
64in current ESMs at the global scale (3). Differences in the representation of elevated CO₂ versus
65climate effects on ecosystem processes result in substantial variation in soil carbon sequestration
66estimates (19) (Table S1).

67 Without [a strong carbon-concentration feedbacks](#), ESMs would likely project smaller
68gains or larger losses of soil carbon over the 21st century. Our aim was to constrain the magnitude
69of the soil carbon-concentration feedback with soil radiocarbon observations. Radiocarbon
70content ~~can be used to constrain~~[provides information about](#) soil carbon turnover over centuries to
71millennia based on radioactive decay and over decades based on inputs of ¹⁴C from atmospheric
72weapons testing (“bomb carbon”). Accurate carbon turnover times are important for ESM
73projections because pools with short turnover times rapidly adjust to increasing NPP, whereas
74pools with long turnover times (and by inference low rates of inputs) change only slowly,
75possibly beyond the time horizon of effective climate mitigation efforts. [Therefore inaccuracies](#)
76[in the representation of carbon turnover times will have consequences for the rate and magnitude](#)
77[of the carbon-concentration feedback simulated by ESMs. If ESMs omit soil carbon pools with](#)
78[long turnover times, they could overestimate the carbon-concentration feedback effect on soil](#)
79[carbon storage during the 21st century while underestimating soil carbon storage at steady-state](#)
80[\(after millennia\).](#)

81 Here we used $\Delta^{14}\text{C}$ measurements at 157 sites across multiple biomes (Fig 1, Table S2)
82along with carbon inventory data to constrain soil carbon dynamics in five biogeochemically-
83coupled ESM simulations (esmFixClim1) from the Coupled Model Intercomparison Project

84Phase 5 (CMIP5) (20). In these idealized simulations the atmospheric CO₂ mole fraction starts at
85a preindustrial value of 285 ppm and rises at a rate of 1% yr⁻¹, thus quadrupling over 140 yrs. The
86biogeochemical components of each model experience the increasing trajectory of atmospheric
87CO₂, whereas the atmospheric radiation submodels do not, limiting impacts solely to the direct
88effects of CO₂ on plant physiology and thus enabling diagnosis of carbon-sink sensitivity to
89increasing CO₂.

90 Total initial soil carbon in the ESMs was not significantly different from the total amount
91in the top meter of the Harmonized World Soil Database (HWSD; Fig 2a, b) for 4 of the 5
92models (p>0.05, except CESM p=0.03). Therefore we compared ESM-derived $\Delta^{14}\text{C}$ to
93observations derived from soil profiles to a 1 m depth. The carbon and ¹⁴C patterns of the soil
94profiles we used were similar to those reported in a recent synthesis paper (21), and we used
95some of the same profiles in our analysis.

96 Comparing ESM outputs to ¹⁴C observations requires a model analysis approach because
97most ESMs do not yet explicitly simulate $\Delta^{14}\text{C}$ in soils, and no ESMs had reported turnover times
98for soil carbon pools. Therefore we used a reduced complexity (RC) model to approximate soil
99carbon dynamics in each ESM. This approach allowed us to ~~(1)~~ estimate the ¹⁴C ages ~~and~~
100turnover times and $\Delta^{14}\text{C}$ associated with the carbon pools in different ESMs (Table S3), ~~(2)~~
101~~compare with observations, and (3) assess the consequences if ESM parameters were aligned~~
102~~with observations.~~ Where possible, we used a three-pool RC model (with fast, slow, and passive
103pools) to simulate carbon and ¹⁴C dynamics. A multi-pool structure is essential because
104radiocarbon observations show that soil carbon fluxes (NPP inputs and heterotrophic respiration)
105exchange mainly with short-lived pools whereas carbon stocks are dominated by long-lived
106pools (12, 18, 22, 23). The three-pool RC model had five parameters representing turnover times

107of fast, slow, and passive pools (τ_{fast} , τ_{slow} , τ_{passive}) and transfer coefficients (r_f , r_s) that regulated
108carbon flow from the fast to slow, and slow to passive pools (Fig S1). We used a two-pool RC
109model for GDFL-ESM2M because it represents soil carbon with two pools (24) and for
110HadGEM2-ES because it reported carbon for two pools (Table S4). The two-pool RC model had
111three parameters, representing τ_{fast} , τ_{slow} , and r_f (Fig S1). After verifying that the RC model was a
112good approximation of each ESM based on minimization of root-mean-square error, we used the
113RC models to simulate $\delta^{14}\text{C}$ values at each grid cell, with observed atmospheric $\delta^{14}\text{C}$ for the
114past 50 kyr as a boundary condition and, accounting for radioactive decay (see supplementary
115material).

116 We used an inverse analysis to determine the RC model parameters that were most
117consistent with our $\delta^{14}\text{C}$ dataset. In the inversion, we ~~held the total carbon mass in the ESM at its~~
118~~preindustrial value (except in sensitivity analyses where it was matched to HWSD observations);~~
119~~and~~ adjusted the parameters described above to match both the total carbon and radiocarbon
120constraints. With these constraints, turnover time and carbon input rate for each pool were
121coupled such that an increase in turnover time required a compensatory decline in inputs (Fig
122S2). RC parameters derived from the inversion were subsequently used to assess consequences
123of ^{14}C constraints for the carbon-concentration feedback.

124 All ESMs projected an increase in soil carbon over 140 yrs with multi-model mean of
125326% (Table 1). This increase was primarily driven by increasing carbon inputs to soil under the
126quadrupling of CO_2 (Table S3), as temperature increased by only a small amount (mean \pm 1 s.d.
127is was 0.52 ± 0.68 °C) for this set of biogeochemically-coupled simulations. CESM showed the
128smallest soil carbon increase (6.3%) primarily because of low litter inputs relative to other ESMs

129(Table S3). For this time period and set of model runs, storage in soil carbon accounted for
13042±17% of the total accumulation of carbon in the terrestrial biosphere.

131 Both two- and three-pool RC models reproduced the global carbon dynamics of the
132original ESMs (Fig S3-S5; Table S5). The τ_{fast} across all RC models was less than 20 yrs, while
133 τ_{slow} varied from 40 to 600 yrs (Fig S6) with a multi-model mean of 212±104 yrs. The mean $\tau_{passive}$
134for the three-pool RC models from CESM, IPSL and MRI was 1185±123 yrs (Table 1, Fig S7).
135Using the RC model parameters estimated at each grid cell within an ESM, we calculated the
136expected $\Delta^{14}C$. The resulting global average $\Delta^{14}C$ for 1995 (median sample year of site profiles)
137from the RC models was significantly higher than the mean of the observations (-6.4±64‰ vs.
138-211±156‰) (Fig 2c,d, $p<0.001$). $\Delta^{14}C$ values from RC models approximating ESMs with
139passive pools were more negative (-53±35‰) but still significantly higher than the observations
140($p<0.001$). Converting these $\Delta^{14}C$ observations into mean age for the soil profile yielded an
141estimate of 3100±1800 yrs for the observed soil carbon integrated to 1 m and 430±50 yrs for the
142ESMs (Fig 2e,f). These results indicated that the ESMs did not have enough old carbon that had
143experienced significant levels of radioactive decay; concurrently the models assimilated too
144much bomb ^{14}C . Relative to the observations, the ESM-based RCs underestimated the turnover
145time of bulk soil carbon and thus assimilated too much bomb ^{14}C (and/or had too little old soil
146carbon that would be depleted in radiocarbon).

147 ^{14}C -derived mean ages indicates that organic carbon soils is often thousands of years old
148(12-14, 21), which is an order of magnitude older than suggested by ESM turnover parameters.
149This discrepancy is likely a consequence of incomplete representation of key biogeochemical
150processes and difficulties in developing accurate parameterizations for soil carbon at a global
151scale. Most ESMs do not account for stabilization mechanisms whereby mineral interactions and

152 aggregate formation protect soil organic matter from decomposition over centuries to millennia
153 (13, 25-28). Moreover, first-order decay, as represented in ESMs, may not capture the response
154 of mineral-stabilized carbon to changes in soil moisture, temperature, and other conditions (29-
155 31). In addition, some ESM turnover parameters are based on laboratory incubation studies,
156 which are often biased fast compared to *in situ* decomposition rates (32). Finally, this set of
157 ESMs did not explicitly resolve vertical differences in soil organic matter dynamics, which may
158 cause underestimation of turnover times in deep soils with large carbon stocks (21, 25, 33, 34).

159 Because the turnover times derived from ESMs were inconsistent with ^{14}C observations,
160 we optimized the turnover parameters by fitting our RC models to the observations. We could
161 then run the optimized RC models to re-evaluate ~~21st-century~~ soil carbon storage [for the transient](#)
162 [1% yr⁻¹ simulations](#). For this inverse approach, we optimized RC model parameters in each grid
163 cell containing an observation site (Fig 2g, 2h, S8, S9). We optimized the τ of the slowest pool
164 and the corresponding transfer coefficient into this pool based on [the \$^{14}\text{C}\$ observations](#)
165 ~~observations~~ while holding soil inputs and τ for the faster pools at their ESM-derived values. The
166 size of the slowest carbon pool was ~~also~~ constrained by optimizing the turnover time and the
167 transfer coefficient together using both [\$^{14}\text{C}\$ and total carbon](#) ~~and ^{14}C~~ . Consequently the optimized
168 RC model had about the same total carbon stock as the original ESM, thereby maintaining
169 consistency with carbon inventory data. This optimization approach yielded τ_{slow} values of
170 3700 ± 2800 yrs for GFDL and 3500 ± 1300 yrs for HadGEM (using two-pool RC models), which
171 were 16-17 times greater than the turnover times derived from the original ESMs.

172 For ESMs that included a passive pool, the optimization process yielded three distinct
173 outcomes. For CESM, which has the largest passive pool (73% of soil carbon), the optimized
174 τ_{passive} was 4500 yrs, which was 3.7 ± 1.5 times greater than τ_{passive} derived from the original model

175(Table 1). IPSL has a smaller fraction of passive carbon (46%) and therefore required a greater
176 τ_{passive} (16,500 yrs) to obtain agreement with the observed $\Delta^{14}\text{C}$. For MRI, the passive pool size
177was too small (only 13% of soil carbon) to bring $\Delta^{14}\text{C}$ into alignment with the profile
178observations even after parameter optimization (Fig S10, Table S5). To adjust for MRI's
179potential bias in the passive pool size, we optimized r_f together with τ_{passive} and r_s to allow for
180simultaneous changes in slow and passive pool sizes. The resulting RC model for MRI was able
181to match observations (Fig 2 g,h) with a passive pool fraction of 48% (see Methods; Table S5).
182These results indicated that increasing the size and turnover time of the passive pool in ESMs
183would improve agreement with ^{14}C -based mean age estimates.~~In general, increasing the size and~~
184~~turnover time of the passive pool in ESMs would improve agreement with ^{14}C -based age~~
185~~estimates.~~

186 Bringing turnover time and carbon transfer parameters into agreement with ^{14}C
187observations had significant consequences for the magnitude of the carbon-concentration
188feedback. Using the ^{14}C -based parameters, we conducted global transient simulations with each
189of the five RC models. These simulations showed that the soil as a whole (specifically the slow
190and passive pools) stored much less carbon in response to increasing levels of atmospheric CO_2 ,
191primarily as a consequence of reduced flow into the slow or passive pool. The soil carbon sink
192decreased from $32 \pm 18\%$ to $18 \pm 12\%$ (Table 1), corresponding to an absolute sink reduction of
193 $170 \pm 127 \text{ Pg C}$ (Fig 3).~~Relative to the ESMs, these simulations showed much less soil carbon~~
194~~accumulation in response to increasing levels of atmospheric CO_2 because of lower inputs to the~~
195~~slow and/or passive pools. The soil carbon sink decreased from $32 \pm 18\%$ to $18 \pm 12\%$ (Table 1),~~
196~~corresponding to an absolute sink reduction of $170 \pm 127 \text{ Pg C}$ (Fig 3).~~ The magnitude of the soil

197sink reduction varied widely across the different models; those with larger and older passive
198fractions at the onset of the transient simulation (Table 1) generally had smaller sink reductions.

199 To assess the robustness of these sink reductions, we conducted a series of sensitivity
200experiments (see supplementary material). We found that the sink reduction imposed by
201constraining the models with ^{14}C observations ~~is~~ was robust to (1) turnover times optimized
202specifically for different biomes; (2) spatial variation ~~and magnitude of~~ in soil carbon stocks; and
203(3) variations in $\delta^{14}\text{C}$ across measurement sites (Table 2, S6). Sink reductions declined by a
204factor of 2 when the models were fit to an inventory that was 50% larger than the HSWD dataset,
205suggesting that if soil carbon pools were larger in ESMs, ^{14}C -imposed sink reductions would be
206lower (35). Lastly, we used our RC model approach to analyze four fully-coupled ESM runs
207(1pctCO₂) to address potential interactions between the carbon-climate and the carbon-
208concentration feedback. ^{14}C constraints still reduced the sink by at least 40% on average (Fig
209S11, Table S7) in the fully coupled simulations (see supplementary material).

210 We conclude that ~~CMIP5 current~~ ESMs underestimated the mean age of soil carbon,
211especially for slow-cycling pools. By adjusting the turnover times of slow and passive pools to
212bring the models into alignment with ^{14}C observations, the potential for future soil carbon
213sequestration declined by $40 \pm 27\%$. ~~If turnover times of slow and passive pools are adjusted to~~
214bring the ESMs into alignment with ^{14}C observations, the potential for 21st-century soil carbon
215sequestration declines by $40 \pm 27\%$ in the ESMs we evaluated. Although long-lived soil carbon
216pools consistent with old ^{14}C ages ~~imply~~ imply increased a similar potential for carbon storage at
217steady state, the timescale required to reach equilibrium is too long to mitigate the potentially
218damaging climate effects of rising CO₂ concentrations during the 21st century (Fig S2). These
219findings emphasize the need to incorporate ^{14}C and other diagnostics into ESM development and

220evaluation. In addition, models require better representation of long-term mechanisms of soil
221carbon stabilization such as organic matter-mineral interactions. Considered together with
222potential nutrient limitation of NPP inputs to soil (36), our analysis suggests that the
223climatecarbon-concentration feedback may be weaker in the 21st century than currently expected
224from ESMs. Therefore a greater fraction of CO₂ emissions than previously thought could remain
225in the atmosphere and contribute to global warming.

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327Climate Model Diagnosis and Intercomparison at Lawrence Livermore National Laboratory
328(<https://pcmdi.llnl.gov/projects/esgf-llnl/>).

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334**Table 1:** Global soil carbon stocks and carbon uptake for CMIP5 models that experienced a quadrupling of atmospheric CO₂ from a
335preindustrial value of 285 ppm over a period of 140 years.

ESM	Initial SOC (Pg C)	% change in SOC	% change in SOC after ¹⁴ C constraint	¹⁴ C- imposed sink reduction (%)	τ^{slow} (yr) ¹	τ^{passive} (yr)	r_f	r_s	¹⁴ C- imposed correction factors ²			
									τ^{slow}	τ^{passive}	r_f	r_s
CESM1(BGC)	571	6.3	5.1	19	56±16	1310±241	0.06±0.05	0.33±0.05	-	3.7±1.5	-	0.34±0.75
GFDL- ESM2M	1344	26	3.3	87	231±196	-	0.17±0.07	-	16±18	-	0.06±0.14	-
HadGEM2-ES	1028	63	33	46	208±84	-	0.12±0.07	-	17±12	-	0.07±0.32	-
IPSL-CM5A- LR	1340	27	25	5.9	218±82	1181±347	0.06±0.03	0.29±0.07	-	14±8.3	-	0.07±0.14
MRI-ESM1 ³	1403	36	22	40	347±117	1065±257	0.17±0.09	0.10±0.06	-	13±7.2	0.46±0.79	0.34±0.74
Mean⁴	1137±312	32±18	18±12	40±27	212±104	1185±123	0.12±0.06	0.24±0.12	16.5±0.5	10.2±4.6	-	-

336¹ τ_{slow} , τ_{passive} denote the turnover time, and r_f , r_s denote the transfer coefficient from the fast to the slow pool, and from the slow to the
337passive pool respectively. Reported values were estimated as an area-weighted mean and standard deviation of all model grid cells.

338² The mean and standard deviation of the ¹⁴C-imposed correction factors were derived from using the ¹⁴C observations at each site in a
339single optimization, and then averaging these scalar adjustments across the set of 157 optimizations.

340³ The ¹⁴C-constrained sink reduction and correction factor for MRI were based on an inverse analysis that changed the pool size of
341both slow and passive pools. The reported percent change in SOC and sink reduction were derived from transient simulations starting
342at steady state with the reduced complexity model. See methods in supporting material.

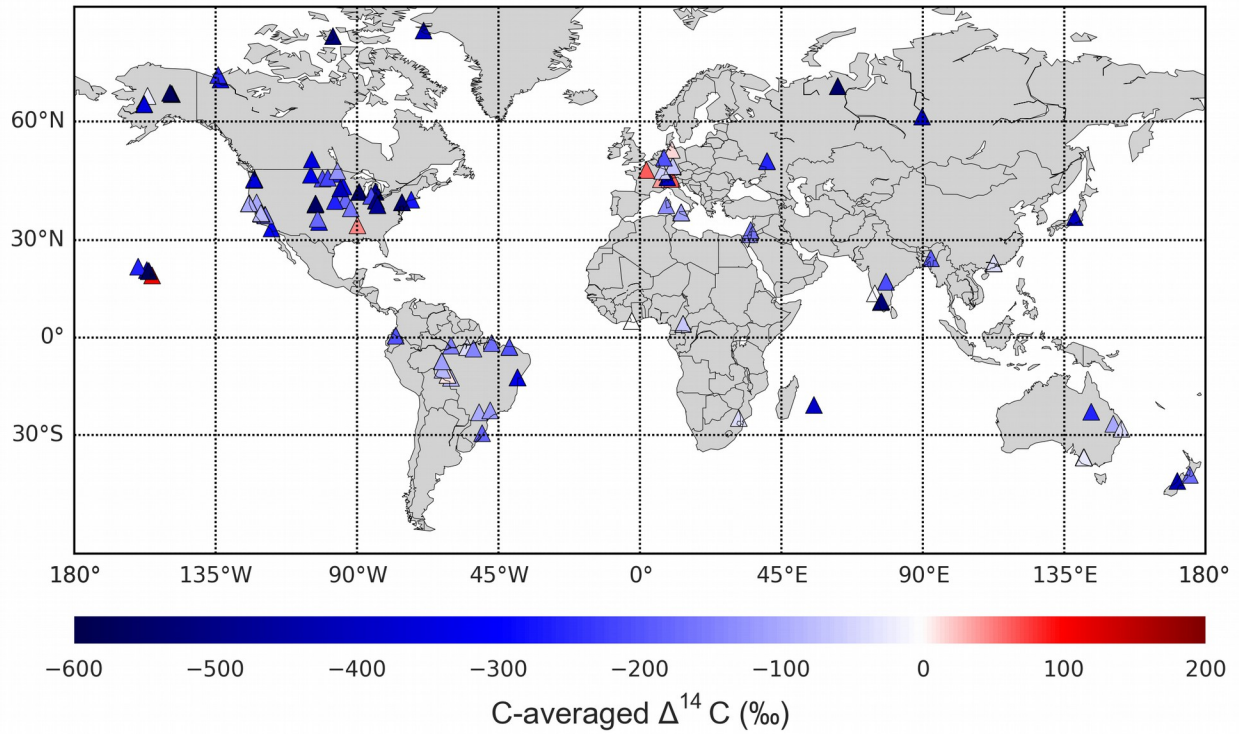
343⁴ The multi-model mean and standard deviation were estimated using the mean value from each of the 5 ESMs.

344**Table 2:** Summary of sensitivity experiments.

Experiment	% change in SOC after ¹⁴ C constraint ¹	¹⁴ C- imposed sink reduction (%) ¹	Correction factor for turnover time ¹	Correction factor for transfer coefficient ¹
Biome-specific inversions	17±11	43±24	-	-
Match SOC with HWSD at sites ²	18±12	31±40	13±4.5	0.19±0.23
Match SOC with 1.5*HWSD at sites ²	21±12	19±42	11±4.5	0.38±0.39
-1 S.D. of inter-site variation	14±9.9	52±23	-	-
+1 S.D. of inter-site variation	23±16	25±25	-	-

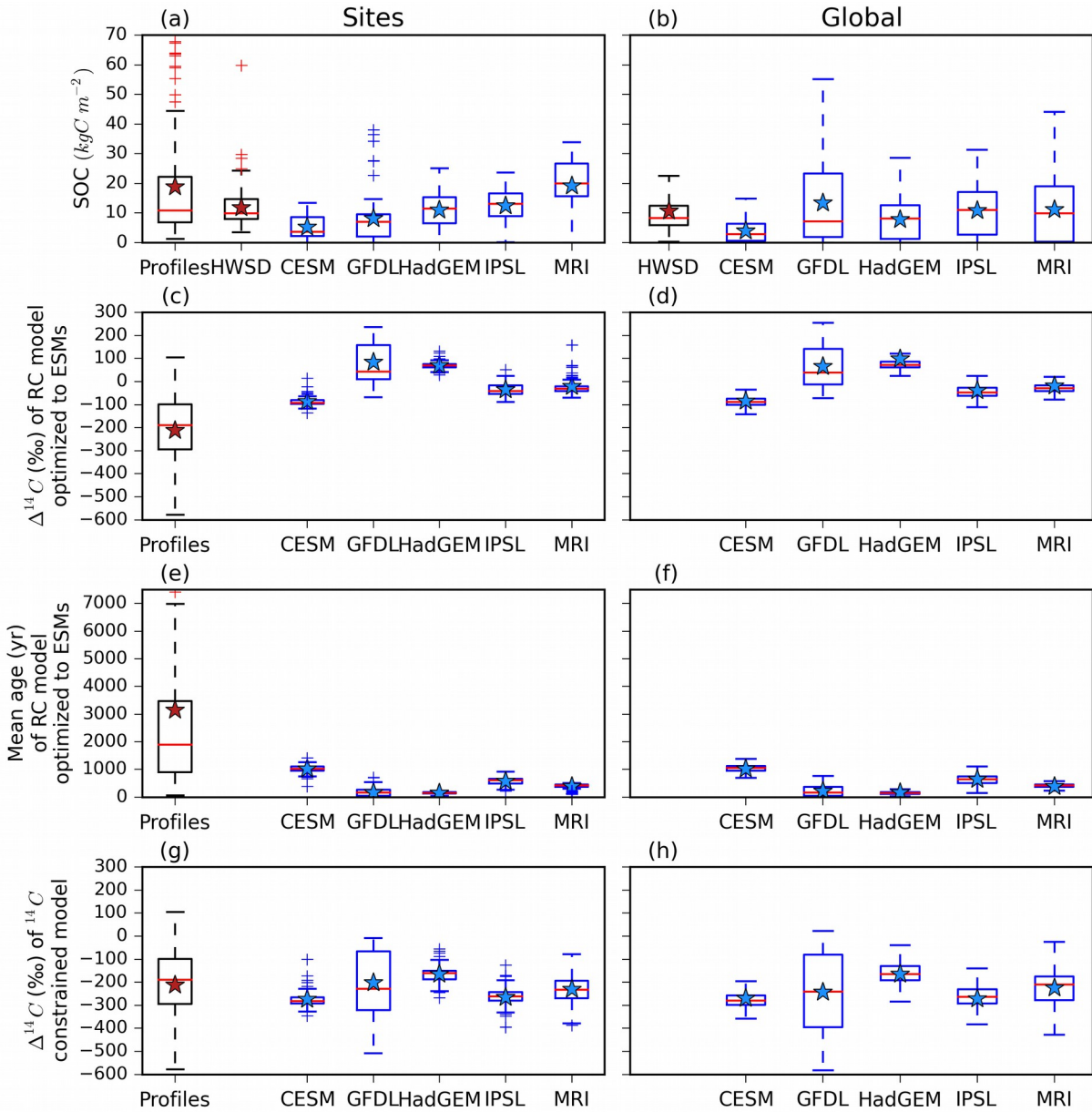
345¹ The mean and standard deviation were estimated from the global mean change of each of the 5
 346 individual ESMs. The correction factors for the turnover time and transfer coefficients are
 347 reported for the slowest carbon pool.

348² The correction factors were obtained at each site, and then the mean scalar across all sites was
 349 applied to the global forward simulation.



350

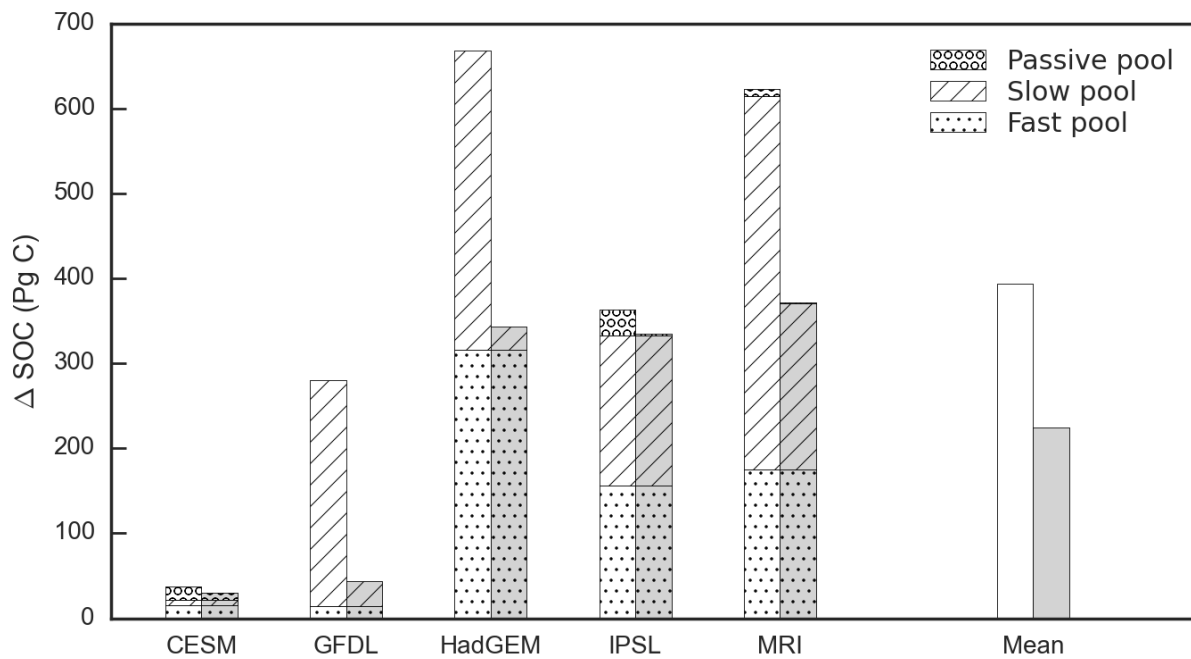
351**Fig 1:** Location of radiocarbon soil profiles used to constrain ESM soil carbon mean ages and
 352turnover times (N=157). The carbon-weighted $\Delta^{14}\text{C}$ to a depth of 1m is denoted with the color
 353shade of each symbol. A summary of the location, sample year, and reference for each site is
 354provided in Table S2.



355

356 **Fig 2:** Soil organic carbon content (a, b) of the original ESMs, $\Delta^{14}C$ of the reduced complexity
 357 model optimized to the original ESMs (c, d), corresponding mean age (e, f), and the $\Delta^{14}C$ of the
 358 ^{14}C -constrained reduced complexity models (g, h). Left column shows the values of the models
 359 sampled at the locations of the individual soil profiles; right column shows the global model
 360 distribution. Data from profile sites and the Harmonized World Soil Database represent carbon

361content in the top 1 m of soil; data from ESMs are the total carbon stock. Star denotes the mean;
362the '+' symbol denotes outliers beyond the 25th and 75th percentiles.



364

365 **Fig 3:** Absolute change in SOC content from the reduced complexity model fit to the original
 366ESM (bars with white background) and the estimate obtained by applying the ^{14}C constraint to
 367the reduced complexity model (bars with gray background). The estimates on the right side show
 368the total carbon content (sum of fast, slow, and passive) averaged across all the models, before
 369and after applying the radiocarbon constraint.

370Supplementary Materials:

371Materials and Methods

372Sensitivity Analysis Results

373Fully-Coupled Simulation Analysis

374Figures S1-S11

375Tables S1-S7

376References 37-1110