



1 **The effects of carbon turnover time on terrestrial ecosystem carbon storage**

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13 **Abstract.** Carbon (C) turnover time is a key factor in determining C storage capacity in various plant
14 and soil pools and the magnitude of terrestrial C sink in a changing climate. However, the effects of C
15 turnover time on C storage have not been well quantified for previous researches. Here, we first
16 analyzed the difference among different definition of mean turnover time (MTT) including ecosystem
17 MTT(MTT_{EC}) and soil MTT (MTT_{soil}) and its variability in MTT to climate changes, and then evaluated
18 the changes of ecosystem C storage driven by MTT changes. Our results showed that total GPP-based
19 ecosystem MTT (MTT_{EC_GPP}:25.0±2.7 years) was shorter than soil MTT (35.5 ±1.2years) and NPP-
20 based ecosystem MTT (MTT_{EC_NPP}:50.8±3 years) ($MTT_{EC_GPP} = C_{pool}/GPP$ &
21 $MTT_{soil} = C_{soil}/NPP$ & $MTT_{EC_NPP} = C_{pool}/NPP$, C_{pool} and C_{soil} referring as the ecosystem or soil
22 carbon storage, respectively). At the biome scale, temperature is still the predictor for MTT_{EC} ($R^2 =$
23 0.77 , $p < 0.001$) and MTT_{soil} ($R^2 = 0.68$, $p < 0.001$). There is no clear improvement in the performance of
24 MTT_{EC} predication when incorporating precipitation into the model ($R^2 = 0.76$, $p < 0.001$). Thus, MTT
25 decreased by approximately 4 years from 1901 to 2011 when temperature just was considered, resulting
26 in a large C release from terrestrial ecosystems. The resultant terrestrial C release driven by MTT
27 decrease only accounted for about 13.5% of than driven by NPP increase (159.3 ± 1.45 vs $1215.4 \pm$
28 11.0 Pg C) due to the diffidence between both of the product factor ($NPP * \Delta MTT$ vs $MTT * \Delta NPP$).
29 Therefore, the larger uncertainties in the spatial variation of MTT than temporal changes would lead in
30 a greater impact on ecosystem C storage from spatial pattern of MTT, which may need to be focused on
31 in the future research.



32 **Key words:** ecosystem, mean turnover time, MAT, MAP, biome scale



33 1 Introduction

34 Rising atmospheric CO₂ concentrations and the resultant climatic warming can substantially impact the
35 global carbon (C) budget (IPCC, 2007), leading to a positive or negative feedback to global climate
36 change (e.g., Friedlingstein *et al.*, 2006; Heimann and Reichstein, 2008). Projections of earth system
37 models (ESMs) show a substantial decrease in terrestrial C storage as the world warms (Friedlingstein
38 *et al.*, 2006), but the decreased magnitude is difficult to quantify due to the complexity of terrestrial
39 ecosystems in response to global change, such as forest dieback (Cox *et al.*, 2004), storms (Chambers
40 and Li, 2007), and land use change (Strassmann *et al.*, 2008). For example, experimental and modeling
41 studies generally showed that elevated CO₂ would enhance NPP and terrestrial C storage (Nemani *et al.*,
42 2003; Norby *et al.*, 2005), but warming may increase soil respiration rates, contributing to reduced C
43 storage, especially in the colder regions (Atkin and Tjoelker, 2003; Karhu *et al.*, 2014). Therefore, the
44 response of terrestrial C storage to climate depends on the response of C influx and how C residence
45 time change in various C pools (i.e., plant, litter and soil pools) (Luo *et al.*, 2003; Xia *et al.*, 2013) as
46 reflected in most of the biogeochemical models (Parton *et al.*, 1987; Potter *et al.*, 1993). Todd-Brown *et*
47 *al.* (2013) validated soil C simulations from CMIP5 earth system models and found that global soil
48 carbon varied 5.9 fold across models in response to a 2.6-fold variation in NPP and a 3.6-fold variation
49 in global soil carbon turnover times. Thus it is key to quantify the time that carbon resides in terrestrial
50 ecosystems and its relationships with climate, and then the resultant change of terrestrial ecosystem C
51 storage driven by turnover time changes.



52 In a given environmental condition, the ecosystem C storage capacity refers to the amount of amount of
53 C that a terrestrial ecosystem can store at the steady state, determined by C influx and turnover time
54 (Xia *et al.*, 2013). External environmental forces, such as climate change and land use change, would
55 dynamically influence both ecosystem C influx and turnover time, and then change terrestrial C storage
56 capacity. Thus, the changed magnitude of ecosystem C storage sink can be expressed by changes in both
57 NPP and mean C turnover time. The spatial variation of NPP changes and the effects of climate change
58 have been relatively well quantified by manipulative experiments (Rustad *et al.*, 2001; Luo *et al.*, 2006),
59 satellite data (Zhao and Running, 2010), and data assimilation (Luo *et al.*, 2003; Zhou and Luo, 2008;
60 Zhou *et al.*, 2012). Todd-Brown *et al.* (2013) also found that differences in NPP contributed
61 significantly to differences in soil carbon across models using a reduced complexity model dependent
62 on NPP and temperature. In contrast, the spatial variation of C turnover time have not well been
63 quantified due to limited data, especially at regional or global scales.

64 Ecosystem C turnover time is the average time that a C atom stays in an ecosystem from entrance to the
65 exit (Barrett, 2002). Several methods have been used to estimate the C turnover time: C balance method
66 by estimating ratios of C pools and fluxes (Vogt *et al.*, 1995), C isotope tracing (Ciais *et al.*, 1999;
67 Randerson *et al.*, 1999), and measurements of radiocarbon accumulation in the undisturbed soils
68 (Trumbore *et al.*, 1996). However, most methods mainly focused on various pools (i.e., leaf, root, soil)
69 and small scale (i.e. C isotope tracing, radiocarbon). The turnover time at region or global scale are



70 often calculated with the ratio of ratios of C storage to flux, such as soil C turnover time (Gill and
71 Jackson, 2000; Chen *et al.*, 2013). Although there are many estimates of global C turnover time, those
72 global C turnover time focused on soil C. Spatial distribute of ecosystem C turnover time is relatively
73 difficult to be estimated (Zhou and Luo, 2008), which needs to incorporate individual plant and soil
74 pools and their C turnover time into ecosystem models. The inverse modeling has been used to estimate
75 ecosystem mean C turnover time in USA and Australia (Barrett, 2002; Zhou and Luo, 2008; Zhou *et al.*,
76 2012). Carvalhais *et al.* (2014) have estimated ecosystem turnover time as the ratio of carbon storage
77 (soil and vegetation C) and influxes and the correlation to climate, which focused on the validation of
78 model-based turnover time and the qualitative relationship with climate. Thompson and Randerson *et al*
79 (1999) has indicated that there were two types of mean C turnover times for terrestrial ecosystems: the
80 GPP-based or the NPP-based mean turnover time according to the terrestrial C models for some models
81 use NPP as their C input and others use just GPP from atmosphere (i.e., NPP is GPP minus autotrophic
82 respiration). However, there was no clear distinction in most pervious researches. For example, Zhou
83 and Luo (2008) and Zhou *et al.* (2012) estimated mean turnover time as the NPP-based one. In most of
84 previous researches, soil turnover time are usually estimated using field sampling as the global turnover
85 time for model validation. However, the difference between different turnover time definitions was still
86 not quantified. Therefore, we considered vegetation and litter C data into soil C to extend the global
87 turnover time and then examined the difference between both. Finally, we focused on the effects of
88 turnover time on ecosystem C storage with the climate changes.



89 Thus, this study was designed to quantify the global pattern of ecosystem mean turnover time and its
90 effects on ecosystem C storage driven by turnover time changes. Meanwhile, we also quantified the
91 difference between different definitions of turnover time. Ecosystem mean turnover time was estimated
92 using the C balance method, which are ratios of C pools and fluxes. Ecosystem C pools include plant,
93 litter and soil, and C fluxes refer to ecosystem respiration or C influx (GPP/NPP). The current datasets
94 from published or unpublished papers have covered all C pools and fluxes, but they were at different
95 spatial scales, so we estimated ecosystem mean turnover time at the grid ($1^{\circ}\times 1^{\circ}$) and biome scale for
96 accuracy and data match. Our objectives are: 1) to estimate the difference between ecosystem and soil
97 mean turnover time, 2) to explore their relationships with climate, and 2) to quantify the ecosystem C
98 storage changes driven by ecosystem turnover time from 1901 to 2011.

99 **2 Materials and methods**

100 2.1 Data collections

101 Three datasets were used to calculate ecosystem mean turnover time and its climate effects on C
102 sequestration, including carbon (C) influx (GPP and NPP), C storage in C pools (soil, plant and litter),
103 and climate factors (temperature, precipitation and potential evapotranspiration). GPP and NPP were
104 extracted from MODIS products (MOD17) on an 8-day interval with a nominal 1-km resolution since
105 Feb. 24, 2000. The multi-annual average GPP/NPP from 2000-2009 with the spatial resolution of 0.083°
106 $\times 0.083^{\circ}$ were used in this study (Zhao and Running, 2010).



107 The harmonized World Soil Database (HWSD) (Hiederer and Köchy, 2012) provided empirical
108 estimates of global soil C storage, a product of the Food and Agriculture Organization of the United
109 Nations and the Land Use Change and Agriculture Program of the International Institute for Applied
110 System Analysis (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012). Hiederer and Köchy (2012) estimated global
111 soil organic carbon (SOC) at the topsoil (0-30cm) and the subsoil layer (30-100cm) from the amended
112 HWSD with estimates derived from other global datasets for these layers. We used the amended HWSD
113 SOC to calculate C turnover time (<http://eusoils.jrc.ec.europa.eu>). However, HWSD just only provided
114 an estimate of soil carbon C storage at the top 1 m of soil and may have largely underestimated total soil
115 carbon. Jobbagy and Jackson (2000) indicated that global SOC storage in the top 3m of soil was 56%
116 more than that for the first meter, which could change estimates of the turnover time estimates
117 dramatically. We will discuss this issue in the discussion section. It is well known that HWSD
118 underestimated soil C in high latitude, so we also estimated turnover time in high latitudes with the
119 Northern Circumpolar Soil Carbon Database (NCSCD), which is an independent survey of soil carbon
120 in this region (Tarnocai *et al.*, 2009). For biomass, Gibbs (2006) estimated the spatial distribution of the
121 above- and below-ground C stored in living plant material by updating the classic study (Olson *et al.*,
122 1983; Olson *et al.*, 1985) with a contemporary map of global vegetation distribution (Global Land
123 Cover database)(Bartholomé and Belward, 2005). Each cell in the gridded data set was coded with an
124 estimate of mean and maximum carbon density values based upon its land cover class, so this dataset
125 mainly represents plant biomass C at a biome level.



126 The litter dataset was extracted from 650 published and unpublished documents (Holland *et al.*, 2005).
127 Each record represents a site, including site description, method, litterfall, litter mass and nutrients. We
128 calculated the mean and median of litter mass for each biome, and then assigned the value for each grid
129 according as the biome types, forming the global pattern of litter C storage using the method of
130 Matthews (1997) in ARCGIS software.

131 Global climate databases produced by the Climate Research Unit (CRU) at the University of East
132 Anglia were used to analyze the climatic effect on ecosystem mean turnover time. We used mean 0.5
133 °×0.5° gridded air temperature, precipitation and potential evapotranspiration, specifically their means
134 from 2000-2009 in CRU_TS 3.20 (Harris *et al.*, 2013).

135 We aggregated all datasets into a biome level for accuracy and data match, so the biome map was
136 extracted from the GLC 2000 (Bartholomé and Belward, 2005) and regulated by MODIS. We assigned
137 22 land cover class among three temperature zones (i.e., tropical, temperate and boreal) by taking the
138 most common land cover from the original underlying 0.083 °×0.083 ° data. Eight typical biomes were
139 zoned with ARCGIS 10 in corresponding to plant function types (PFTs) in CABLE model that Xia *et al*
140 (2013): evergreen needleleaf forest (ENF), evergreen broadleaf forest (EBF), deciduous needleleaf
141 forest (DNF), deciduous broadleaf forest (DBF), tundra, shrubland, grassland and cropland. All of the
142 data were regridded using R software to a common projection (WGS 84) and 1⁰×1⁰ spatial resolution.
143 The regridding approach for C fluxes and pools (i.e., GPP, NPP, soil C and litter C) assumed



144 conservation of mass that a latitudinal degree was proportional to distance for the close grid cells (Todd-
145 Brown *et al.*, 2013). A nearest neighbor approach were used for land cover classes and a bi-linear
146 interpolation were used for climate variables (i.e, temperature, precipitation).

147 2.2 Estimation of ecosystem mean C turnover time

148 C turnover time is commonly estimated with the C balance method by calculating the ratio of C total in
149 a C pool and its outflux. Terrestrial ecosystem includes many C pools with largely varying residence
150 times from days to millennia, but it is difficult to collect the observation-based datasets of C pools and
151 flux for each component (e.g. leaf, wood and different soil C fractions) at the global scale. It thus is
152 impossible to estimate individual pools' turnover time. In this study, we estimated the whole-ecosystem
153 C turnover time as the ratio of C pools to flux based on the observed datasets. Certainly, there are some
154 limitations that the ecosystem is taken as a single pool, which will be discussed in the discussion. For
155 terrestrial ecosystems, the C pools (C_{pool}) is composed of three parts: plant, litter and soil, and C
156 outfluxes include all C losses include autotrophic and heterotrophic respiration (R_a , R_h) and losses by
157 fires and harvest. In the steady state, C outfluxes equal to C influx, which is the carbon uptake through
158 gross primary production (GPP), so ecosystem mean turnover time (MTT_{EC}) can be equivalently
159 calculated as the ratio between C storage in vegetation, soils and litters, and the influx into the pools,
160 GPP:



161

$$MTT_{EC} = \frac{C_{pool}}{GPP} \quad (1)$$

162 The similar method was used to calculate soil MTT (MTT_{soil}):

163

$$MTT_{soil} = \frac{C_{soil}}{NPP} \quad (2)$$

164 However, the steady-state in nature is rare, so we relax the strict steady-state assumption and computed
165 the ratio of C_{pool} to GPP as apparent whole-ecosystem turnover time and interpret the quantity as an
166 emergent diagnostic at ecosystem level (Carvalho *et al.*, 2014). In addition, it is difficult to accurately
167 get the observed respiration (R_a and R_h) in terrestrial ecosystem at the global scale. Therefore, we used
168 multi-year GPP or NPP to calculate MTT in order to reduce the effect of the non-steady state, since it is
169 difficult to evaluate how this assumption affects model results.

170

171 2.3 The climate effects on ecosystem mean C turnover time

172 In order to explore the combining effect of precipitation and temperature on ecosystem mean C turnover
173 time, aridity index (AI) was calculated as follows:

174

$$AI = \frac{MAP}{PET} \quad (3)$$

175 where PET is the potential evapotranspiration and MAP is mean annual precipitation (Middleton and



176 Thomas, 1997). AI is a bioclimatic index including both physical phenomena (precipitation and
 177 potential evapotranspiration) and biological processes (plant transpiration) related with edaphic factors.

178 The relationships were examined between ecosystem mean C turnover time and mean annual
 179 temperature (MAT, °C), mean annual precipitation (MAP, mm) and aridity index (AI) at the biome level.

180 The regression analyses ($MTT = ae^{-bMAT/MAP}$) were performed in STATISTICA 10, where a and b are
 181 the coefficients. The coefficient of determination (R^2) was used to measure the phase correlation
 182 between ecosystem mean C turnover time and climate factors. Here, we calculated a Q_{10} value (i.e., Q_{10} ,
 183 a relative increase in mean turnover time for a 10°C increase in temperature, $Q_{10} = e^{10b}$, b, the
 184 coefficients of $MTT = ae^{-bMAT/MAP}$) that is used in most models to simulate C decomposition. The
 185 relationship between ecosystem mean turnover time and temperature was used to estimate mean C
 186 turnover time in 1901 and 2011.

187 2.4 The effects of turnover time on ecosystem C storage

188 Ecosystem C storage capacity at steady state is represented by $NPP \times MTT$ (Lou *et al.*, 2003), so the
 189 difference of ecosystem C storage from 1901 to 2011 can be calculated as follows:

$$\begin{aligned}
 \Delta C_{pool} &= NPP_{2011} \times MTT_{2011} - NPP_{1901} \times MTT_{1901} \\
 \Rightarrow \Delta C_{pool} &= NPP_{2011} \times MTT_{2011} - (NPP_{2011} - \Delta NPP) \times (MTT_{2011} - \Delta MRT) \quad (4) \\
 \Rightarrow \Delta C_{pool} &= NPP_{2011} \times \Delta MTT + MTT_{2011} \times \Delta NPP - \Delta NPP \times \Delta MTT
 \end{aligned}$$



191 where $NPP_{1901(2011)}$ and $MTT_{1901(2011)}$ refer to NPP and MTT at time 1901 or 2011. ΔC_{pool} (ΔNPP or
192 ΔMTT) is the difference between ecosystem C storage (NPP or MTT) at time 2011 and that at time
193 1901. The first component ($NPP_{2011} \times \Delta MTT$) represents the effects of MTT changes on ecosystem C
194 storage. The second component ($\Delta NPP \times MTT_{2011}$) is the effects of NPP change on ecosystem C storage,
195 and $\Delta NPP \times \Delta MTT$ is the cross-coupling effects.

196 To assess the effects of changes in MTT or NPP on ecosystem C storage, ecosystem MTT in 1901 and
197 2011 was calculated using an exponential equation between mean turnover time and temperature at a
198 biome level. NPP in 2011 was derived from products (MOD17) and NPP in 1901 was averaged from the
199 eight models' simulated results (CanESM2, CCSM4, IPSL-CM5A-LR, IPSL-CM5B-LR, MIROC-
200 ESM, MIROC-ESM-CHEM, NorESM1-M and NorESM1-ME) for modeled NPP is near to MODIS
201 estimated NPP (Yan *et al.*, 2014).

202 2.5 Uncertainty analysis and sensitivity Analysis

203 Limitation of the above datasets is that the uncertainties are poorly quantified. The global mean of C
204 fluxes (GPP and NPP) and pools (soil, litter, and plant) were calculated by 1000 simulations,
205 respectively, through Markov chain Monte Carlo (MCMC) sampling from a gamma distribution in R
206 software. For each variable, the confidence interval (CI) was estimated as the 2.5 and 97.5 percentile of
207 mean values of the 1000 simulations. It was also applied to estimate the confidence interval of



208 ecosystem C storage and ecosystem mean C turnover time.

209 **3 Results**

210 3.1 Ecosystem C storage

211 On average, terrestrial C storage (plant biomass + soil + litter) was 22.0 kg C m^{-2} (with a 95% CI of
212 $21.85\text{-}22.50 \text{ kg C m}^{-2}$) at the global scale, which largely varied with vegetation and soil types (Fig.1d).
213 Among the forest biomes, ecosystem C storage was highest in boreal evergreen needleleaf forest (ENF)
214 with high soil C content and lowest in deciduous broadleaf forest (DBF) with the lowest soil C. Soil C
215 was the largest C pool in terrestrial ecosystems, accounting for more than 60% of ecosystem C storage,
216 while C storages in litter and biomass only represented less than 10% and 30%, respectively (Fig. 1b).
217 Among eight typical biomes associated with plant functional types (PFTs) (Table 1), the order of
218 ecosystem C storage followed as: ENF ($34.84 \pm 0.02 \text{ kg C m}^{-2}$) > deciduous needleleaf forest (DNF,
219 $25.30 \pm 0.03 \text{ kg C m}^{-2}$) > evergreen broadleaf forest (EBF, $22.70 \pm 0.01 \text{ kg C m}^{-2}$) > shrubland (18.29 ± 0.02
220 kg C m^{-2}) > DBF ($16.51 \pm 0.02 \text{ kg C m}^{-2}$) > tundra ($14.16 \pm 0.02 \text{ kg C m}^{-2}$)/cropland ($14.58 \pm 0.01 \text{ kg C m}^{-2}$) >
221 grassland ($10.80 \pm 0.01 \text{ kg C m}^{-2}$).

222 3.2 Mean C turnover time

223 On average, ecosystem mean C turnover time (MTT) was 25.0 years (with a 95% CI of 23.3-27.7 years)
224 based on GPP data and 50.8 years (with a 95% CI of 47.8-53.8 years) on NPP data (Table 1), while soil



225 MTT is smaller than NPP-based MTT with the value of 35.5 years (with a 95% CI of 34.9-36.7 years).
226 MTT varies among biomes due to the different climate forcing (Table 1 and Fig 2). The long MTT
227 occurred in high latitude while the short ones are in tropical zone. Among forest biomes, DNF had the
228 highest MTT with the lowest mean temperature (-7.9 °C), while the lowest MTT was in EBF due to
229 highest temperature (24.5 °C) and precipitation (2143 mm). Although ecosystem C storage was low in
230 tundra (14.16 kg C m⁻²), it has the longest MTT. Therefore, the order of ecosystem MTT among biomes
231 was different from that of ecosystem C storage, with tundra (99.704 ± 6.14 years) > DNF (45.27 ±
232 2.43 years) or ENF (42.23 ± 2.01 years) > shrubland (27.77 ± 2.25 years) > grassland (26.00 ± 1.41 years) >
233 cropland (14.91 ± 0.40 years) or DBF (13.29 ± 0.68 years) > EBF (9.67 ± 0.21 years). Soil MTT had the
234 similar order with ecosystem MTT with the different values (Table 1). In the high latitude, ecosystem
235 MTT could increase up to 145 years if soil C storage was calculated from NCSCD dataset (Fig. 3) due
236 to higher soil C storage (500 Pg C vs 290 Pg C), compared with the global soil C storage HWSD, while
237 the global average of soil MTT increased to 40.8 years when NCSCD dataset was considered.

238 3.3 Climate effects on ecosystem mean turnover time

239 Ecosystem mean C turnover time significantly decreased with mean annual temperature (MAT) and
240 mean annual precipitation (MAP) as described by an exponential equation: $MTT = 57.06e^{-0.07MAT}$
241 ($R^2=0.77$, $P<0.001$) and $MTT = 103.07e^{-0.001MAP}$ ($R^2=0.34$, $P<0.001$, Fig 4), but there was no
242 correlation between ecosystem mean turnover time and aridity index (AI, Fig. 4c). The similar



243 relationships occurred between soil MTT and MAT and MAP ($MTT_{soil} = 58.40e^{-0.08MAT}$, $R^2=0.68$,
244 $P<0.001$) and $MTT_{soil} = 109.98e^{-0.002MAP}$, $R^2=0.48$, $P<0.001$, Fig. 5). There was the different
245 temperature sensitivity of mean turnover time (Q_{10}) for ecosystem MTT ($Q_{10}=1.95$) and soil MTT
246 ($Q_{10}=2.23$) at ecosystem scale, which was estimated as $Q_{10} = e^{10b}$ based on temperature regression
247 function. When MAP was incorporated into a multivariate regression function of ecosystem mean
248 turnover time with MAT, the relationships could not be significantly improved (Fig. 6a). While MAP
249 improved the explanation of variance of soil MTT (R^2 from 0.68 to 0.76, Fig. 6b), although there were
250 the relationships due to the significant covariance of MAP and MAT ($R^2=0.60$). However, the
251 relationship between MTT and AI is not clear due to the scale limit (biome level). When we separated
252 ecosystem MTT into two categories according to aridity index (i.e., $AI > 1$ and $AI < 1$), the relationships
253 between ecosystem MTT and MAT did not significantly change (Figs. 4e, h) compared to that with all
254 data together (Fig. 4b), while the relationship of ecosystem MTT with MAP significantly increased
255 when $AI > 1$, but decreased when $AI < 1$. However, the same regression function of soil MTT with MAT
256 largely improved the explanation of the variance when $AI > 1$ (Fig. 5e, $MTT = 58.67e^{-0.08MAT}$,
257 $R^2=0.76$, $P<0.001$). The relationships between soil MTT and MAP were both improved when $AI > 1$ and
258 $AI < 1$ (Fig. 5e, h).

259 3.4 Temporal variations of ecosystem mean turnover time and C storage

260 The average increase in global air temperature is around 1°C from 1901 to 2011 based on the Climate



261 Research Unit (CRU) datasets, ranging from -2.5 to 5.9 °C. When the function between ecosystem MTT
262 and temperature was used to estimate the change in ecosystem mean turnover time (Fig. 4), the average
263 mean turnover time decreased by approximately 4 years (Fig. 7a). The largest change in ecosystem
264 MTT occurred in the cold zones. In tundra, mean C turnover time decreased by more than 10 years due
265 to the larger increase in temperature (~2°C) than other regions. However, the average NPP increased by
266 approximately $0.3 \pm 0.003 \text{ Kg C m}^{-2} \text{ yr}^{-1}$ over 110 years with most range of 0~0.6 $\text{Kg C m}^{-2} \text{ yr}^{-1}$ (Fig. 7b).
267 The changes in ecosystem MTT and NPP across 110 years would cause decrease or increase in
268 terrestrial C storage. Driven by MTT changes, ecosystem C storage decreased by $159.3 \pm 1.45 \text{ Pg C yr}^{-1}$
269 from 1901 to 2011 ($\Delta \text{MTT} \times \text{NPP}$), with the largest decrease in tundra and boreal forest (more than 12 g
270 $\text{C m}^{-2} \text{ yr}^{-1}$) but little decrease in tropical zones (Fig. 8a). However, the increase in NPP directly raised
271 ecosystem C storage up to $1215.4 \pm 11.0 \text{ Pg C yr}^{-1}$ from 1901 to 2011 with a range of 30-150 $\text{g C m}^{-2} \text{ yr}^{-1}$
272 ¹ in most areas ($\text{MTT} \times \Delta \text{NPP}$, Fig. 8b). The MTT-induced changes in ecosystem C storage only
273 accounted for about 13.5% of that driven by NPP due to the difference between both of the product
274 factor, so the spatial pattern of the NPP-driven changes mostly represented the spatial pattern of the
275 changes in ecosystem C storage (Fig. 6d).

276 4 Discussion

277 4.1 Global pattern of mean turnover time

278 In this study, we estimated spatial patterns of mean turnover time (MTT) with ecosystem C influxes



279 (GPP and NPP) and C pools in plants, litter and soil using the C balance method. Here, we assumed that
280 the nature was the steady state and took the whole ecosystem as a single pool similar in Sanderman *et al*
281 (2003), which have some caveats in the estimation of mean turnover time. Terrestrial ecosystems
282 comprise of compartments varying greatly in their individual turnover times (for example leaves, wood,
283 different soil organic carbon fractions), but we cannot estimate turnover time for each pools using
284 observation datasets. In addition, it is difficult to accurately get the observed respiration (R_a and R_h) in
285 terrestrial ecosystem at the global scale, or carbon allocation between outflux and influx. It is thus
286 difficult to evaluate how this assumption affects model results. Maybe, inverse models would be a valid
287 method to estimate turnover time for the both (e.g., Zhou *et al.*, 2012).

288 The global average of ecosystem MTT was 25.0 years for GPP-based estimation and 50.8 years for
289 NPP-based one and soil MTT was 35.5 years, which was within the global mean turnover times (26-60
290 years) estimated by various experimental and modeling approaches with NPP-based estimation
291 (Randerson *et al.*, 1999; Thompson and Randerson, 1999) mostly focused on soils, but not ecosystem
292 MTT. However, our results indicated that ecosystem MTT (GPP-based estimation) was shorter than soil
293 MTT ($MTT_{EC} = C_{pool}/GPP$ & $MTT_{soil} = C_{soil}/NPP$). According to the equations, the difference
294 between ecosystem and soil MTT depends on the component carbon pools and the ratio of GPP to NPP.
295 Thus, there was subtle difference in patterns of MTT between both. For example, ecosystem MTT in
296 Evergreen Needleleaf forest (ENF) was larger than soil MTT where the decomposition rate in soil C
297 was very slow.



298 The GPP-based MTT were also larger than the result of Carvalhais *et al* (2014) (23 years), probably
299 due to litter C storage included in this study. The ratio of GPP-based and NPP-based MTT (0.49) was
300 smaller than that estimated by Thompson and Randerson (1999) (0.58, 15 year vs. 26 year,
301 respectively). Our NPP-based MTTs for the conterminous USA (37.2 years) and Australia (33.4 years)
302 were shorter than the estimates by the inverse models (46 to 78 years) (Barrett, 2002; Zhou and Luo,
303 2008; Zhou *et al.*, 2012). The NPP-based MTT was lower than the estimated results from Xia *et al.*
304 (2013) using the CABLE model, though the order of MTT across forest biomes is similar. In addition,
305 we only used soil C in the top 1 m to estimate ecosystem MTT, which would be largely underestimated
306 for the important amounts of C stored between 1 and 3m depth (Jobbagy and Jackson, 2000). According
307 to the SOC estimation of Jobbagy and Jackson (2000), the MTT in the top 3 m could increase to 34.63
308 years for GPP-based, 70.68 years for NPP-based and 55.38 years for soil. Therefore, the accurate
309 estimates of total soil C are important to estimate ecosystem MTT.

310 4.2 The sensitivity of turnover time to climate

311 The estimated mean turnover time (MTT) was shortest in tropical zones and increased toward high-
312 latitude zones (Fig. 2), which were often affected by the spatial patterns of temperature and moisture.
313 The results was similar to those the previous studies based on SOC data set (Schimel *et al.*, 1994;
314 Sanderman *et al.*, 2003; Frank *et al.*, 2012; Chen *et al.*, 2013) and root pools (Gill and Jackson, 2000).
315 Ecosystem MTT had negative exponential relationship with MAT (Fig 4), similar to those with soil



316 MTT, probably due to the temperature dependence of respiration (Lloyd and Taylor, 1994; Wen *et al.*,
317 2006). Our results showed that the temperature sensitivity of ecosystem MTT was lower than that of
318 soil C pool (Q_{10} : 1.95 vs. 2.23, Figs. 4 & 5), which was similar to the previous research (Sanderman *et*
319 *al.*, 2003), because wood may decompose at much lower rates than SOM due to the longer MTT of
320 wood (Zhou *et al.*, 2012). Ecosystem MTT was no significant differences between very humid zone
321 ($AI > 1.0$) and other zones ($AI < 1.0$, Fig 4). However, the better relationships between MTT and MAP
322 occurred in very humid zone ($AI > 1.0$) than other zones, which was similar to soil pool, but soil MTT
323 have the higher sensitivity to precipitation than ecosystem MTT under $AI > 1$. SOM decomposition often
324 increased with added moisture in aerobic soils (Trumbore, 1997), because the metabolic loss of various
325 C pools increased under warmer and wetter climates (Frank *et al.*, 2012), resulting in high sensitivity of
326 MTT to MAP. Thus, the fitting regression combined MAT and MAP clearly improved soil MTT
327 ($R^2 = 0.76$, $p < 0.001$, Fig 6b). In arid or semi-humid regions, the increase in C influx with MAP was more
328 rapid than that in decomposition (Austin and Sala, 2002). In addition, water limitation may suppress the
329 effective ecosystem-level response of respiration to temperature (Reichstein *et al.*, 2007). At an annual
330 scale, temperature is still the best predictor of MTT (Chen *et al.*, 2013), which explained up to 77% of
331 variation of MTT (Fig 4). Other ecosystem properties (e.g. ecosystems types, soil nitrogen) may cause
332 the rest of the variation in the estimates of MTT.

333 4.3 Effects of the changes in mean turnover time on ecosystem C storage



334 Terrestrial ecosystems play an important role in regulating C cycling balance to combat global change.
335 Current studies suggest that the terrestrial biosphere is currently a net C sink (Lund *et al.*, 2010), but it
336 is difficult to assess the sustainability of ecosystem C storage due to the complexity of terrestrial
337 ecosystem in response to global change (Luo, 2007). In this study, we first tried to assess the potential
338 shifts of ecosystem C storage capacity by changes in both NPP and ecosystem MTT. Our studies
339 indicated that the decrease in MTT increased ecosystem C loss over time while increased NPP enhance
340 ecosystem C uptake.

341 Current datasets have showed an increase in NPP (e.g., Hicke *et al.*, 2002; Potter *et al.*, 2012), leading
342 to increasing terrestrial C uptake. Driven by NPP changes from 1901 to 2011, our results showed that
343 global C storage would increase by 11.0 Pg C yr⁻¹ and 0.4 Pg C yr⁻¹ at the global scale and conterminous
344 USA, respectively. Our estimated ecosystem C storage in USA was larger than the one from inverse
345 models (Zhou and Luo, 2008; Zhou *et al.*, 2012) but comparable to C sink from atmospheric inversion
346 (0.30-0.58 Pg C yr⁻¹) (Pacala *et al.*, 2001). However, the shortened MTT caused C losses from
347 ecosystems from 1901 to 2011 (about 1.45 Pg C yr⁻¹), indicating that the magnitude of ecosystem C
348 uptake is likely to decrease under warming due to decreased MTT. Ecosystem C losses driven by the
349 decrease in MTT only accounted for 13.5% of ecosystem C uptake compared to that driven by NPP
350 increase, still causing a net sink in terrestrial ecosystem. The largest changes in terrestrial C storage
351 occurred in high latitude, where it is more vulnerable to loss with climate change (Zimov *et al.*, 2006).
352 However, the direct release of CO₂ in high latitude through thawing would be another large source in



353 the decrease of ecosystem C storage under climate warming (Grosse *et al.*, 2011), which cannot be
354 assessed by MTT or NPP. Interestingly, our results suggested that the substantial changes in terrestrial C
355 storage occurred in forest and shrub (50% of total) due to the relatively longer MTT, which caused the
356 larger terrestrial C uptake driven by NPP increase compared with others. Moreover, the largest absolute
357 and relative changes of MTT occurred in high latitude regions (Fig. 7a), which would largely decrease
358 the terrestrial C uptake driven by NPP under global warming. Furthermore, the C uptake in cropland
359 and grassland has been underestimated probably due to the ignorance of the effects of land
360 management.

361 4.4 Limitation in estimating mean turnover time and its effects to climate

362 Estimated MTT in this study were based on C influxes (GPP or NPP) and C pools in plants, litter and
363 soil at the grid scale and can be used to quantify global, regional or biome-specific MTT, which was
364 very important to evaluate terrestrial C storage. However, the balance method and data limitation may
365 cause biases to some degree in estimated ecosystem MTT in a few sources. First, we assumed that
366 ecosystem C cycle is at the steady state, when MTT was estimated. It is difficult to define the steady
367 state, especially soil C dynamics (Luo and Weng, 2011). Actually, steady state is rare in nature and any
368 ecosystem process could be only close to reach the steady state in the short time. For example,
369 permafrost will be thawing both gradually and catastrophically (Schuur *et al.*, 2008). The assumption of
370 the steady state would cause the overestimation or underestimation of ecosystem MTT (Zhou *et al.*,



371 2010). Second, MTT was estimated on the basis of C pool and flux measurements, whose uncertainties
372 in the current datasets of C pools and fluxes would limit the estimated MTT. For example, the
373 amendments of typological data and bulk density had largely improved the estimates of the SOC storage
374 from HWSD (1417 PgC) (Hiederer and Köchy, 2012). Soil C storage calculated from NCSCD dataset
375 would improve the ecosystem MTT in high latitudes (Fig. 3), compared with that from HWSD datasets.
376 However, it is difficult to quantify the uncertainty in MTT caused by uncertainties of the pool and flux
377 datasets due to lack of quantitative uncertainty estimates in these datasets. The calculation of MTT by
378 the ratio of the pool to flux would reduce these uncertainties associated with the pool and flux data sets
379 in some degree.

380 Third, the uncertainties in ecosystem MTT would cause the uncertainties in the relationship between
381 MAT, MAP and ecosystem MTT. To simplify the calculation, we aggregated all datasets into a biome
382 level, leading in a fixed parameters across biomes. However, the response magnitude in soil respiration
383 to warming varied over time and across sites (Rustad *et al.*, 2001; Davidson and Janssens, 2006),
384 resulting in multiple temperature response function. MTT for 1901 and 2011 were estimated using the
385 exponential function between mean turnover time and temperature, resulting in underestimation or
386 overestimation of MTT and the resultant changes on ecosystem C storage.

387 4.5 Implication for land surface models



388 First, this study demonstrated that spatial variability of ecosystem mean C turnover time had higher
389 uncertainties compared to temporal variability, which was mainly caused by the estimation of soil C
390 storage. Further work should focus on the accurate estimation of soil C storage with numerous
391 observational data in estimating the spatial patterns of mean C turnover time at regional or global scale.
392 Land surface model should consider spatial variability of ecosystem mean C turnover time, especially at
393 high latitude.

394 Second, there were the inconsistent responses of ecosystem C turnover time to climate variables in the
395 current global vegetation models (Friend *et al.*, 2013). Our results showed that temperature was the best
396 predictor for ecosystem C turnover time ($R^2 = 0.77$, $p < 0.001$) on annual scale, which declined with
397 rising temperature. Such temperature relationship with mean C turnover time can be incorporated into
398 land surface models to improve the forecast of terrestrial climate-C cycle feedback. Third, our results
399 showed that temperature sensitivity of ecosystem MTT was lower than that of soil C pool while
400 precipitation was less sensitive to ecosystem turnover time than soil C turnover time with different
401 effects in very humid zone and arid zone. Now all global carbon cycle models have considered moisture
402 stress on vegetation, but the incorporation of moisture or precipitation stress into soil decomposition
403 should be strengthened, especially in high-latitude zones with greater warming and increased
404 precipitation.

405



406 Ecosystem C turnover time is crucial in determining terrestrial C storage capacity, so it is necessary to
407 quantify ecosystems turnover time and its relationships with climate. We developed global maps of
408 ecosystem C mean turnover time based on the current datasets from published GPP and C pools in
409 plant, litter and soil. The average ecosystem mean turnover time at the global scale is 25.0 years with a
410 range from about 8 years for spare grassland to 120 years for tundra, which is shorter than soil C pool
411 alone. Our results showed that the temperature sensitivity of ecosystem turnover time was lower than
412 that of soil C pool (Q_{10} : 1.95 vs. 2.23), while the relationship between ecosystem C turnover time and
413 precipitation under low aridity conditions ($AI > 1$) was much stronger than for all or $AI < 1$ conditions at
414 biome scale. MTT decreased by approximately 4 years from 1901 to 2011 when temperature just was
415 considered, resulting in a large C release from terrestrial ecosystems. The resultant terrestrial C release
416 driven by MTT decrease only accounted for about 13.5% of than driven by NPP increase (159.3 vs
417 1215.4 Pg C) due to the diffidence between both of the product factor ($NPP \cdot \Delta MTT$ vs $MTT \cdot \Delta NPP$).
418 Therefore, understanding the response of C turnover time to global warming would be important to
419 assess the sustainability of ecosystem C storage.

420 **Data availability**

421 All of the original elevation data used in this study is referenced in Fig 1 of the manuscript and full
422 citations for data sources are provided.

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427 **References**

- 428 Atkin, O. K. and Tjoelker, M. G. 2003. Thermal acclimation and the dynamic response of plant respiration to
429 temperature. *Trends in Plant Science* **8**, 343-351.
- 430 Austin, A. T. and Sala, O. E. 2002. Carbon and nitrogen dynamics across a natural precipitation gradient in Patagonia,
431 Argentina. *Journal of Vegetation Science* **13**, 351-360.
- 432 Barrett, D. J. 2002. Steady state turnover time of carbon in the Australian terrestrial biosphere. *Global Biogeochemical*
433 *Cycles* **16**.
- 434 Bartholomé, E. and Belward, A. 2005. GLC2000: A new approach to global land cover mapping from Earth
435 observation data. *International Journal of Remote Sensing* **26**, 1959-1977.
- 436 Carvalhais, N., Forkel, M., Khomik, M., Bellarby, J., Jung, M. and co-authors 2014. Global covariation of carbon
437 turnover times with climate in terrestrial ecosystems. *Nature* **514**, 213-217.
- 438 Chambers, C. R. S. and Li, T. 2007. Simulation of formation of a near-equatorial typhoon Vamei (2001). *Meteorology*
439 *and Atmospheric Physics* **98**, 67-80.
- 440 Chen, S., Huang, Y., Zou, J. and Shi, Y. 2013. Mean residence time of global topsoil organic carbon depends on
441 temperature, precipitation and soil nitrogen. *Global and Planetary Change* **100**, 99-108.
- 442 Ciais, P., Friedlingstein, P., Schimel, D. S. and Tans, P. P. 1999. A global calculation of the delta C-13 of soil respired
443 carbon: Implications for the biospheric uptake of anthropogenic CO₂. *Global Biogeochemical Cycles* **13**, 519-
444 530.
- 445 Cox, P. M., Betts, R. A., Collins, M., Harris, P. P., Huntingford, C. and co-authors 2004. Amazonian forest dieback
446 under climate-carbon cycle projections for the 21st century. *Theoretical and Applied Climatology* **78**, 137-156.
- 447 Davidson, E.A., and Janssens, I.A. 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to
448 climate change. *Nature* **440**, 165-173.



- 449 FAO/IIASA/ISRIC/ISSCAS/JRC 2012. Harmonized World Soil Database (version 1.10). *FAO, Rome, Italy and IIASA,*
450 *Laxenburg, Austria.*
- 451 Frank, D. A., Pontes, A. W. and McFarlane, K. J. 2012. Controls on soil organic carbon stocks and turnover among
452 North American ecosystems. *Ecosystems* **15**, 604-615.
- 453 Friedlingstein, P., Cox, P., Betts, R., Bopp, L., Von Bloh, W. and co-authors 2006. Climate-carbon cycle feedback
454 analysis: Results from the C⁴MIP model intercomparison. *Journal of Climate* **19**, 3337-3353.
- 455 Gibbs, H. K. 2006. Olson's major world ecosystem complexes ranked by carbon in live vegetation: An updated database
456 using the GLC2000 land cover product. *NDP-017b* doi: 10.3334/CDIAC/lue.ndp3017.2006 Available at
457 [<http://cdiac.ornl.gov/epubs/ndp/ndp3017/ndp3017b.html>].
- 458 Gill, R. A. and Jackson, R. B. 2000. Global patterns of root turnover for terrestrial ecosystems. *New Phytologist* **147**,
459 13-31.
- 460 Grosse, G., Harden, J., Turetsky, M., McGuire, A.D., Camill, P., and co-authors 2011. Vulnerability of high-latitude
461 soil organic carbon in North America to disturbance. *Journal of Geophysical Research: Biogeosciences* 116,
462 G00K06
- 463 Harris, I., Jones, P. D., Osborn, T. J. and Lister, D. H. 2013. Updated high-resolution grids of monthly climate
464 observations. *International Journal of Climatology* Doi: 10.1002/joc.3711.
- 465 Heimann, M. and Reichstein, M. 2008. Terrestrial ecosystem carbon dynamics and climate feedbacks. *Nature* 451,
466 289-292.
- 467 Hicke, J.A., Asner, G.P., Randerson, J.T., Tucker, C., Los, S., Birdsey, R., Jenkins, J.C., & Field, C. 2002. Trends in
468 North American net primary productivity derived from satellite observations, 1982–1998. *Global*
469 *Biogeochemical Cycles* **16**, 1018
- 470 Hiederer, R. and Köchy, M. 2012. Global soil organic carbon estimates and the Harmonized World Soil Database. *EUR*
471 *Scientific and Technical Research series.*, ISSN 1831-9424 (online), ISSN 1018-5593 (print), ISBN 1978-
472 1892-1879-23108-23107, doi:23110.22788/13267.
- 473 Holland, E. A., Post, W. M., Matthews, E. G., Sulzman, J., Stauffer, R. and co-authors 2005. Global patterns of litterfall



- 474 and litter pool carbon and nutrients. *Data set. Available on-line [http://daac.ornl.gov/] from Oak Ridge*
475 *National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A.*
- 476 IPCC 2007. *Climate change 2007: The physical science basis* (ed. S. Solomon, D. Q., M. Manning, Z. Chen, M.
477 Marquis, K. B. Averyt, M. Tignor and H. L. Miller), Cambridge, UK and New York, NY, USA.
- 478 Jobbagy, E. G. and Jackson, R. B. 2000. The vertical distribution of soil organic carbon and its relation to climate and
479 vegetation. *Ecological Applications* **10**, 423-436.
- 480 Karhu, K., Auffret, M. D., Dungait, J. A. J., Hopkins, D. W., Prosser, J. I. and co-authors 2014. Temperature sensitivity
481 of soil respiration rates enhanced by microbial community response. *Nature* **513**, 81-84.
- 482 Lloyd, J. and Taylor, J. 1994. On the temperature dependence of soil respiration. *Functional ecology*, 315-323.
- 483 Lund, M., Lafleur, P.M., Roulet, N.T., Lindroth, A., Christensen, T.R., and co-authors 2010. Variability in exchange of
484 CO₂ across 12 northern peatland and tundra sites. *Global Change Biology* **16**, 2436-2448
- 485 Luo, Y., Hui, D. and Zhang, D. 2006. Elevated CO₂ stimulates net accumulations of carbon and nitrogen in land
486 ecosystems: A meta-analysis. *Ecology* **87**, 53-63.
- 487 Luo, Y. and Weng, E. 2011. Dynamic disequilibrium of the terrestrial carbon cycle under global change. *Trends in*
488 *ecology & evolution* **26**, 96-104.
- 489 Luo, Y. Q., White, L. W., Canadell, J. G., DeLucia, E. H., Ellsworth, D. S. and co-authors 2003. Sustainability of
490 terrestrial carbon sequestration: A case study in Duke Forest with inversion approach. *Global Biogeochemical*
491 *Cycles* **17**.
- 492 Matthews, E. 1997. Global litter production, pools, and turnover times: Estimates from measurement data and
493 regression models. *Journal of Geophysical Research* **102**, 18771.
- 494 Middleton, N., and Thomas, D. 1997. *World atlas of desertification*. Arnold, Hodder Headline, PLC.
- 495 Nemani, R. R., Keeling, C. D., Hashimoto, H., Jolly, W. M., Piper, S. C. and co-authors 2003. Climate-driven increases
496 in global terrestrial net primary production from 1982 to 1999. *Science* **300**, 1560-1563.
- 497 Norby, R. J., DeLucia, E. H., Gielen, B., Calfapietra, C., Giardina, C. P. and co-authors 2005. Forest response to
498 elevated CO₂ is conserved across a broad range of productivity. *Proceedings of the National Academy of*



- 499 *Sciences of the United States of America* **102**, 18052-18056.
- 500 Olson, J. S., Watts, J. A. and Allison, L. J. 1983. Carbon in live vegetation of major world ecosystems. Oak Ridge
501 National Lab., TN (USA).
- 502 Olson, J. S., Watts, J. A. and Allison, L. J. 1985. Major world ecosystem complexes ranked by carbon in live
503 vegetation: A database, NDP-017. *Oak Ridge Lab., Oak Ridge, Tenn.*
- 504 Pacala, S.W., Hurtt, G.C., Baker, D., Peylin, P., Houghton, R.A., and co-authors 2001. Consistent Land- and
505 Atmosphere-Based U.S. Carbon Sink Estimates. *Science* **292**, 2316-2320
- 506 Parton, W. J., Schimel, D. S., Cole, C. V. and Ojima, D. S. 1987. Analysis of factors controlling soil organic matter
507 levels in Great Plains grasslands. *Soil Sci. Soc. Am. J.* **51**, 1173-1179.
- 508 Potter, C. S., Randerson, J. T., Field, C. B., Matson, P. A., Vitousek, P. M. and co-authors 1993. Terrestrial ecosystem
509 production - a process model-based on global satellite and surface data. *Global Biogeochemical Cycles* **7**, 811-
510 841.
- 511 Potter, C., Klooster, S., and Genovese, V. 2012. Net primary production of terrestrial ecosystems from 2000 to 2009.
512 *Climatic Change* **115**, 365-378
- 513 Randerson, J. T., Thompson, M. V. and Field, C. B. 1999. Linking C-13-based estimates of land and ocean sinks with
514 predictions of carbon storage from CO₂ fertilization of plant growth. *Tellus Series B-Chemical and Physical*
515 *Meteorology* **51**, 668-678.
- 516 Reichstein, M., Papale, D., Valentini, R., Aubinet, M., Bernhofer, C. and co-authors 2007. Determinants of terrestrial
517 ecosystem carbon balance inferred from European eddy covariance flux sites. *Geophysical Research Letters*
518 **34**.
- 519 Rustad, L., Campbell, J., G, M., R, N., M, M. and co-authors 2001. A meta-analysis of the response of soil respiration,
520 net nitrogen mineralization, and aboveground plant growth to experimental ecosystem warming. *Oecologia*
521 **126**, 543-562.
- 522 Sanderman, J., Amundson, R. G. and Baldocchi, D. D. 2003. Application of eddy covariance measurements to the
523 temperature dependence of soil organic matter mean residence time. *Global Biogeochemical Cycles* **17**.



- 524 Schimel, D. S., Braswell, B. H., Holland, E. A., Mckeown, R., Ojima, D. S. and co-authors 1994. Climatic, edaphic,
525 and biotic controls over storage and turnover of carbon in soils. *Global Biogeochemical Cycles* **8**, 279-293.
- 526 Schuur, E. A. G., Bockheim, J., Canadell, J. G., Euskirchen, E., Field, C. B. and co-authors 2008. Vulnerability of
527 permafrost carbon to climate change: Implications for the global carbon cycle. *Bioscience* **58**, 701-714.
- 528 Strassmann, K. M., Joos, F. and Fischer, G. 2008. Simulating effects of land use changes on carbon fluxes: Past
529 contributions to atmospheric CO₂ increases and future commitments due to losses of terrestrial sink capacity.
530 *Tellus Series B-Chemical and Physical Meteorology* **60**, 583-603.
- 531 Tarnocai, C., Canadell, J. G., Schuur, E. A. G., Kuhry, P., Mazhitova, G. and co-authors 2009. Soil organic carbon
532 pools in the northern circumpolar permafrost region. *Global Biogeochemical Cycles* **23**.
- 533 Thompson, M.V., and Randerson, J.T. 1999. Impulse response functions of terrestrial carbon cycle models: method and
534 application. *Global Change Biology* **5**, 371-394
- 535 Todd-Brown, K. E. O., Randerson, J. T., Post, W. M., Hoffman, F. M., Tarnocai, C. and co-authors 2013. Causes of
536 variation in soil carbon simulations from CMIP5 Earth system models and comparison with observations.
537 *Biogeosciences* **10**, 1717-1736.
- 538 Trumbore, S.E., 1997. Potential responses of soil organic carbon to global environmental change. Proceedings of the
539 National Academy of Sciences of the United States of America **94**, 8284–8291
- 540 Trumbore, S. E., Torn, M. S. and Chadwick, O. A. 1996. Recent ams measurements of C-14 in soil organic matter:
541 Understanding controls of carbon storage and turnover in soils. *Abstracts of Papers of the American Chemical*
542 *Society* **211**, 17-Geoc.
- 543 Vogt, K. A., Vogt, D. J., Palmiotto, P. A., Boon, P., O'Hara, J. and co-authors 1995. Review of root dynamics in forest
544 ecosystems grouped by climate, climatic forest type and species. *Plant and soil* **187**, 159-219.
- 545 Wen, X. F., Yu, G. R., Sun, X.M., Li, Q. K., Liu, Y. F. and co-authors 2006. Soil moisture effect on the temperature
546 dependence of ecosystem respiration in a subtropical Pinus plantation of southeastern China. *Agricultural and*
547 *Forest Meteorology* **137**, 166-175.
- 548 Xia, J., Luo, Y., Wang, Y. P. and Hararuk, O. 2013. Traceable components of terrestrial carbon storage capacity in



- 549 biogeochemical models. *Global Change Biology*.
- 550 Yan, Y., Luo, Y., Zhou, X., & Chen, J. 2014. Sources of variation in simulated ecosystem carbon storage capacity from
551 the 5th Climate Model Intercomparison Project (CMIP5). *Tellus Series B-Chemical and Physical Meteorology*
552 **66**, 22568
- 553 Zhao, M. and Running, S. W. 2010. Drought-induced reduction in global terrestrial net primary production from 2000
554 through 2009. *Science* **329**, 940-943.
- 555 Zhou, T. and Luo, Y. Q. 2008. Spatial patterns of ecosystem carbon residence time and NPP-driven carbon uptake in
556 the conterminous United States. *Global Biogeochemical Cycles* **22**.
- 557 Zhou, X., Zhou, T. and Luo, Y. 2012. Uncertainties in carbon residence time and NPP-driven carbon uptake in
558 terrestrial ecosystems of the conterminous USA: A Bayesian approach. *Tellus Series B-Chemical and Physical*
559 *Meteorology* **64**, 17223
- 560 Zimov, S., Davydov, S., Zimova, G., Davydova, A., Schuur, E. and co-authors 2006. Permafrost carbon: Stock and
561 decomposability of a globally significant carbon pool. *Geophysical Research Letters* **33**, L20502
- 562



563 **Table 1.** The density of ecosystem C storage (Kg C m⁻²), mean turnover time (MTT, years), mean
 564 annual temperature (MAT) and precipitation (MAP) for the eight biomes. Ecosystem MTT were
 565 calculated based GPP and NPP, respectively.

Biome	Ecosystem C storage (kg C m ⁻²)	Ecosystem MTT (years)		Soil MTT(years)	MAT (°C)	MAP (mm)
		MTT _{GPP}	MTT _{NPP}			
ENF	34.8±0.02	42.23±2.01	58.54±2.16	39.62±1.22	3.5	760.5
EBF	22.7±0.01	9.67±0.21	18.43±0.43	8.96±0.21	24.5	2143.5
DNF	25.3±0.03	45.27±2.43	75.80±2.71	53.50±1.71	-7.9	401.4
DBF	16.5±0.02	13.29±0.68	22.02±1.00	12.08±0.69	16.1	988.4
tundra	14.2±0.02	99.74±6.14	132.86±4.40	122.88±5.54	-11.1	291.1
Shrubland	18.3±0.02	27.77±2.25	43.41±2.37	36.22±2.01	9.3	643.6
Grassland	10.8±0.01	26.00±1.41	39.51±2.11	34.37±2.20	9.4	605.5
Cropland	14.6±0.01	14.91±0.40	23.06±0.84	17.72±0.58	15.4	885.7

573 *ENF: Evergreen Needleleaf forest; EBF: Evergreen Broadleaf forest; DNF: Deciduous Needleleaf forest; DBF: Deciduous Broadleaf
 574 forest.

575



576 **Figure Caption List**

577 **Figure 1.** Spatial pattern of soil C (a), biome C (b), litter C (c) and ecosystem C storage (d) at grid scale
578 ($1^{\circ}\times 1^{\circ}$). Unit: Kg C m^{-2} . Ecosystem C storage was calculated from biomass, soil and litter C pools.

579 **Figure 2.** Spatial pattern of mean turnover time (MTT, years), calculated based on biome types and
580 GPP (a) or NPP (b) and soil (c) using the C balance methods.

581 **Figure 3.** Spatial pattern of mean turnover time (years) in high latitude. (a) Based on soil C storage
582 from HWSD data, (b) based on soil C storage from NCSCD data.

583 **Figure 4.** Relationships between ecosystem mean turnover time (MTT) and multi-annual temperature
584 (MAT, a), precipitation (MAP, b) at different aridity indexes (AI, c). Each data point stands for average
585 values of each biome. Biomes were assigned into 62 types according to land cover and three
586 temperature zones.

587 **Figure 5.** Relationships between soil mean turnover time (MTT_{soil}) and multi-annual temperature
588 (MAT, a), precipitation (MAP, b) at different aridity indexes (AI, c). Each data point stands for average
589 values of each biome. Biomes were assigned into 62 types according to land cover and three
590 temperature zones.

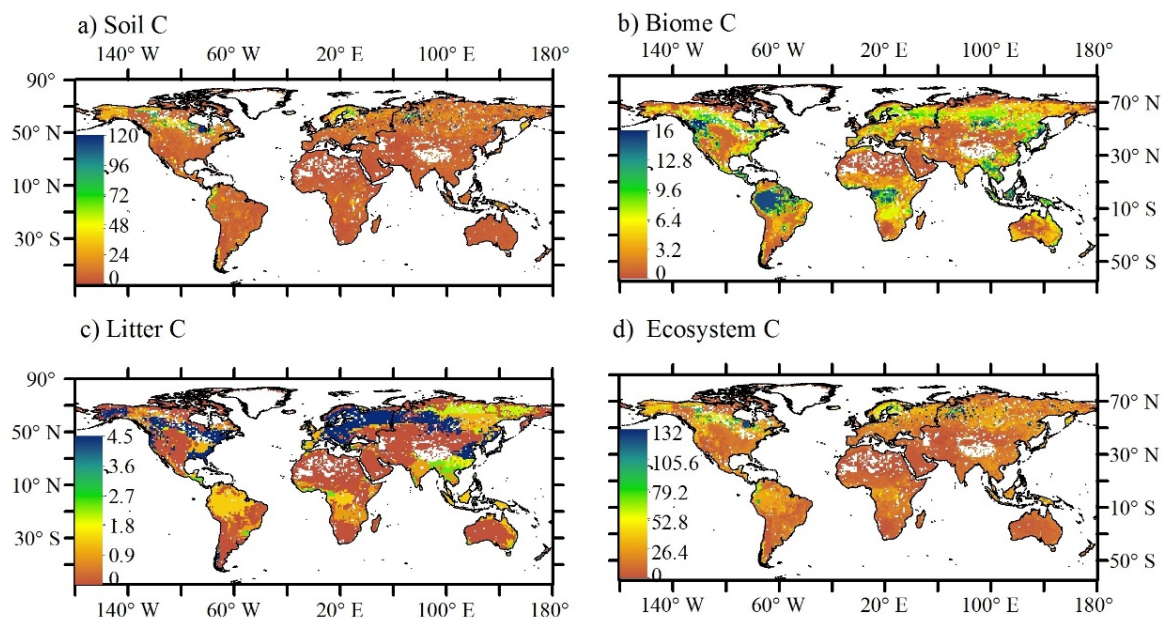
591 **Figure 6.** Surface fitting between mean turnover time and multi-annual temperature (MAT),
592 precipitation (MAP) for ecosystem (a) and soil (b).

593 **Figure 7.** Change values of ecosystem mean ecosystem mean turnover time (MTT, unit: year a) driven
594 by temperature change and NPP (unit: $\text{Kg C m}^{-2}\text{yr}^{-1}$) from 1901 to 2011. MTT for 1901 and 2011 was



595 calculated by the temperature-dependence function showing in Fig. 4. NPP in 1901 and 2011 was
596 derived from models' average and MODIS.

597 **Figure 8.** Change values of ecosystem carbon storage driven by mean turnover time change
598 ($NPP_{2011} \times \Delta MTT$, a), by NPP change ($MTT_{2011} \times \Delta NPP$, b) and by NPP change and MRT change
599 ($\Delta MTT \times \Delta NPP$, c) and total ecosystem C storage changes (d). Unit: $g\ C\ m^{-2}\ yr^{-1}$ ($\Delta C_{pool} = NPP_{2011} \times$
600 $\Delta MTT + MTT_{2011} \times \Delta NPP - \Delta NPP \times \Delta MTT$).



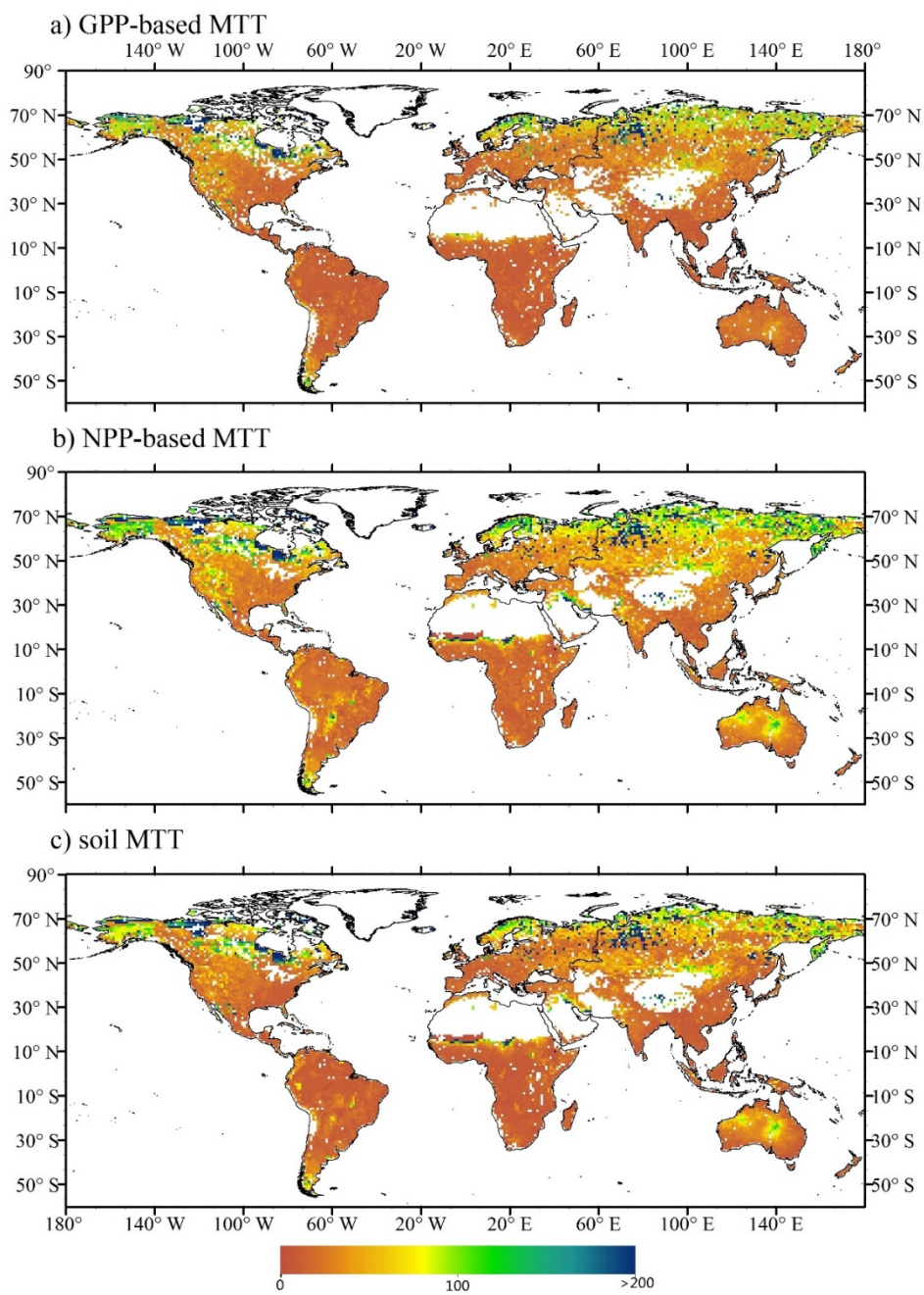
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602 **Figure 1.** Spatial pattern of soil C (a), biome C (b), litter C (c) and ecosystem C storage (d) at grid

603 scale ($1^\circ \times 1^\circ$). Unite: Kg C m^{-2} . Ecosystem C storage was calculated from biomass, soil and litter C

604 pools.

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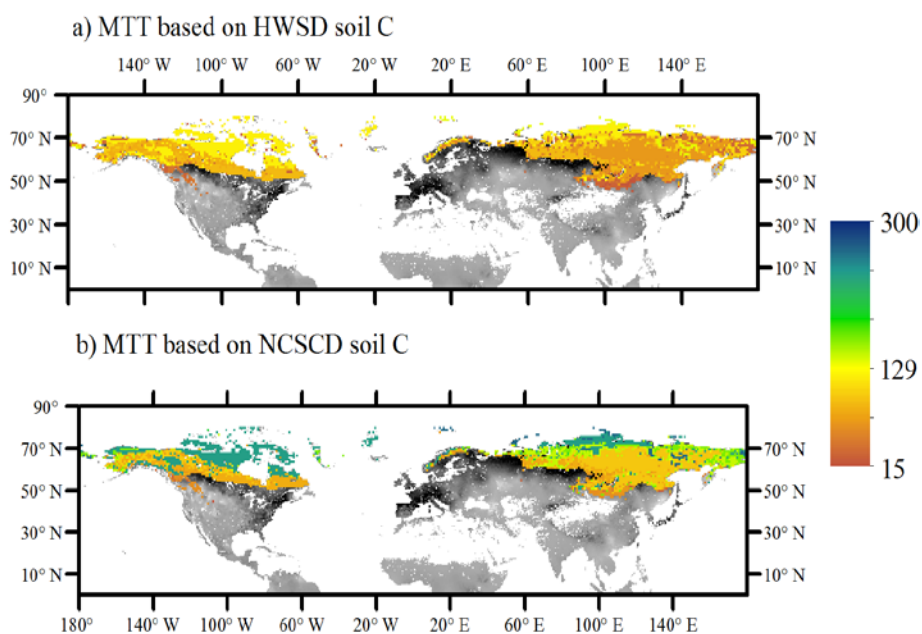
606

607 **Figure 2.** Spatial pattern of mean turnover time (MTT, years), calculated based on biome types and

608 GPP (a) or NPP (b) and soil (c) using the C balance methods.



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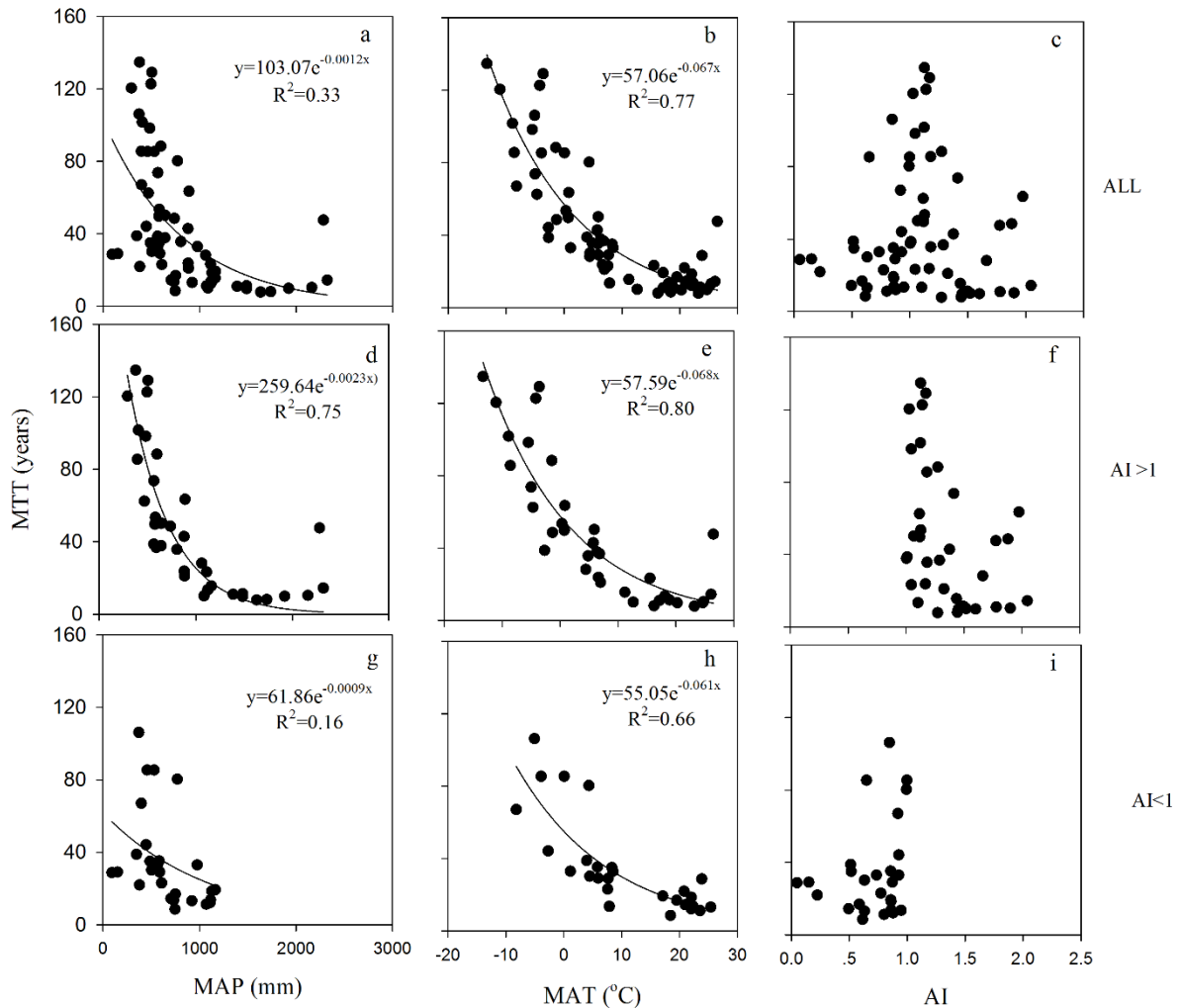


610 **Figure 3.** Spatial pattern of mean turnover time (years) in high latitude. (a) Based on soil C storage
611 from HWSD data, (b) based on soil C storage from NCSCD data.

612



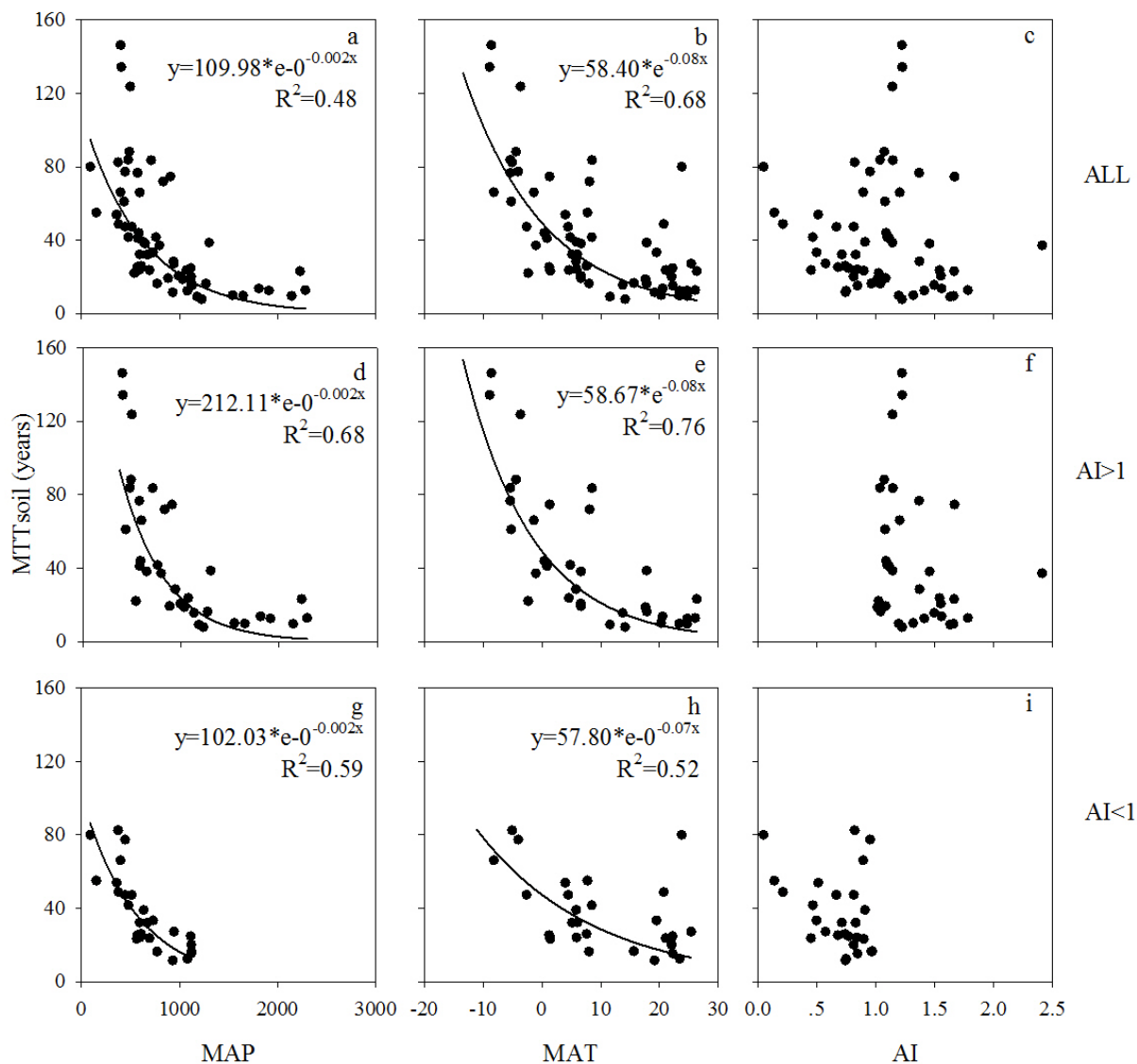
613



614

615 **Figure 4.** Relationships between ecosystem mean turnover time (MTT) and multi-annual
616 temperature (MAT, a), precipitation (MAP, b) at different aridity indexes (AI, c). Each data point stands
617 for average values of each biome. Biomes were assigned into 62 types according to land cover and three
618 temperature zones.

619



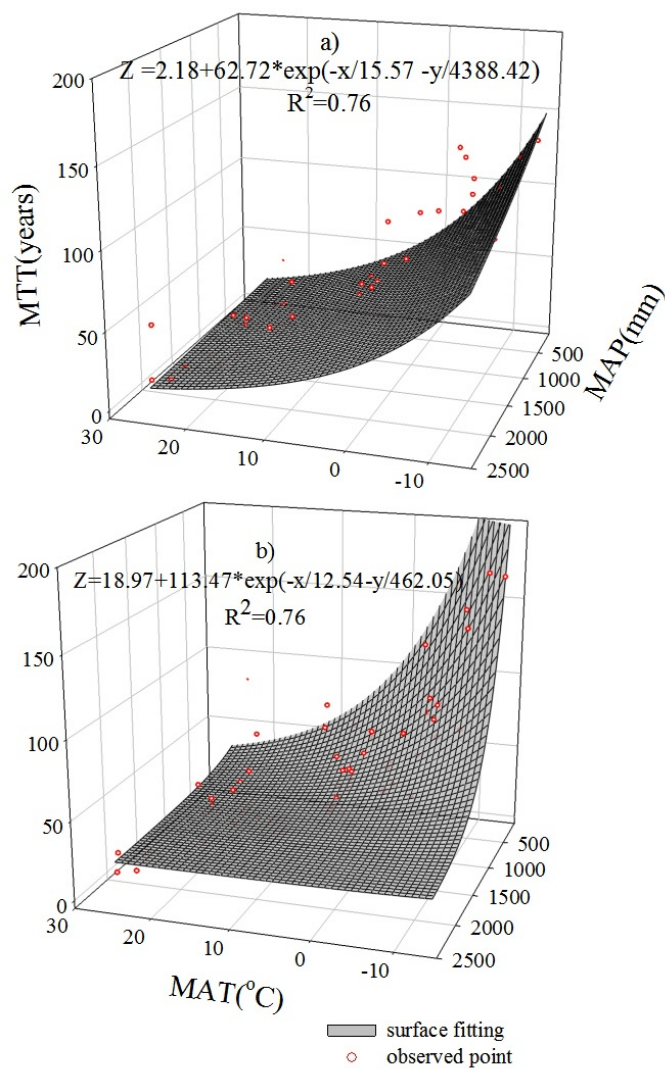
620

621 **Figure 5.** Relationships between soil mean turnover time (MTT_{soil}) and multi-annual temperature

622 (MAT, a), precipitation (MAP, b) at different aridity indexes (AI, c). Each data point stands for average

623 values of each biome. Biomes were assigned into 62 types according to land cover and three

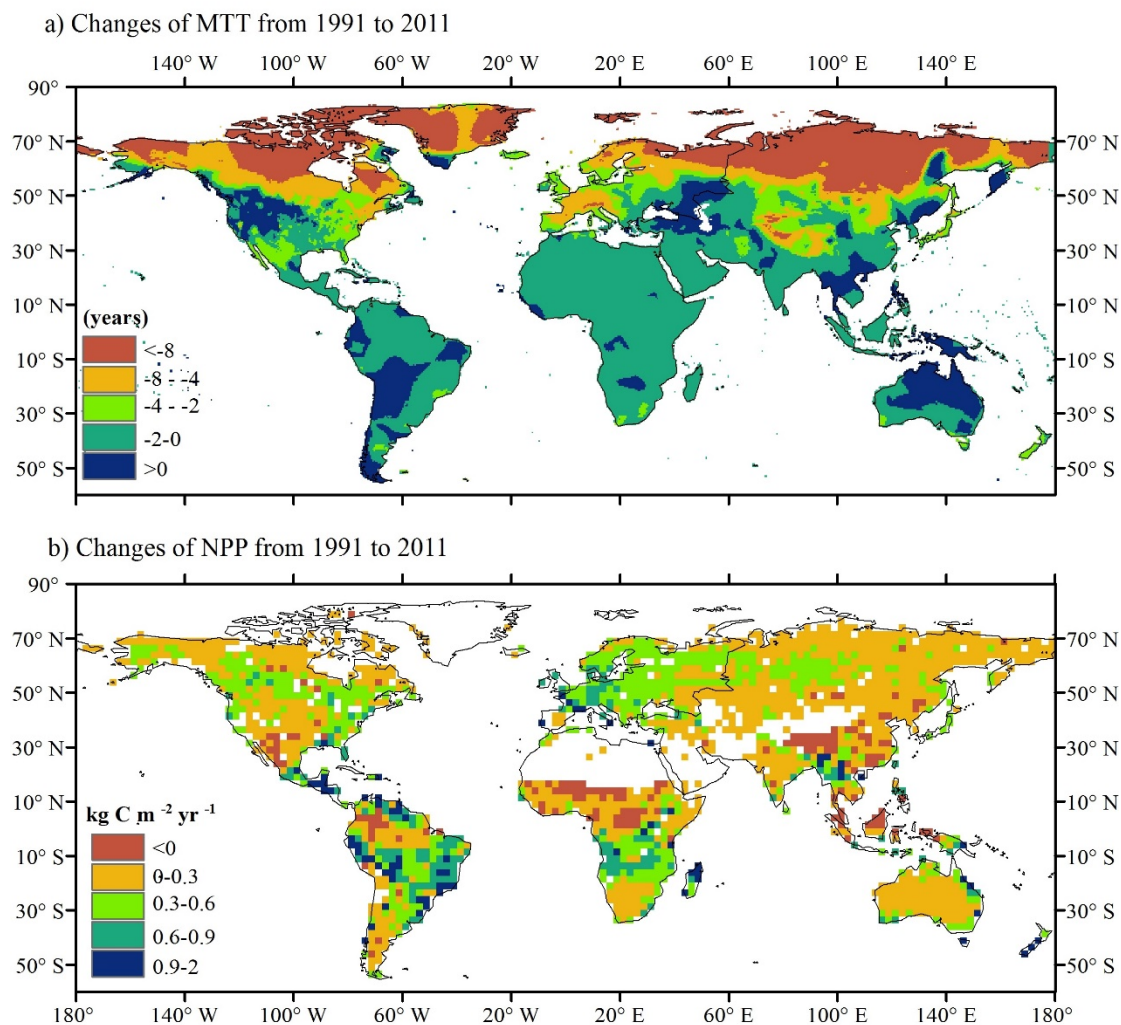
624 temperature zones.



625

626 **Figure 6.** Surface fitting between mean turnover time and multi-annual temperature (MAT),

627 precipitation (MAP) for ecosystem (a) and soil (b).



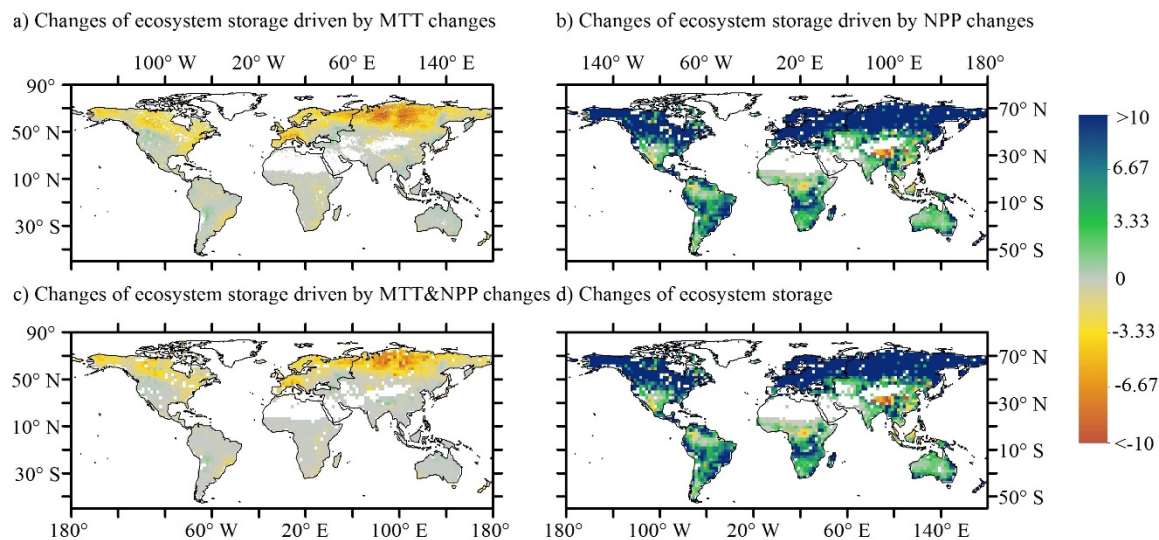
628

629 **Figure 7.** Change values of ecosystem mean ecosystem mean turnover time (MTT, unit: year a)

630 driven by temperature change and NPP (unit: Kg C m⁻²yr⁻¹) from 1901 to 2011. MTT for 1901 and 2011

631 was calculated by the temperature-dependence function showing in Fig. 4. NPP in 1901 and 2011 was

632 derived from models' average and MODIS.



633
634

635 **Figure 8.** Change values of ecosystem carbon storage driven by mean turnover time change

636 ($NPP_{2011} \times \Delta MTT$, a), by NPP change ($MTT_{2011} \times \Delta NPP$, b) and by NPP change and MRT change

637 ($\Delta MTT \times \Delta NPP$, c) and total ecosystem C storage changes (d). Unit: $g\ C\ m^{-2}\ yr^{-1}$ ($\Delta C_{pool} = NPP_{2011} \times$

638 $\Delta MTT + MTT_{2011} \times \Delta NPP - \Delta NPP \times \Delta MTT$).