Dear Editor,

Thanks so much for sending us two reviews on our manuscript “**The effects of carbon turnover time on terrestrial ecosystem carbon storage**” (ID: bg-2017-183). We are very grateful to the reviewers for their constructive comments and suggested amendments. Their inputs have helped to improve the paper significantly. We have carefully studied the reviews, and revised our manuscript accordingly. As a consequence, our manuscript has been considerably improved.

Here are our detailed responses to the reviews. Please note that the comments are in ***italics*** followed by our responses in **regular** text. In addition, we marked the changes or revision with the **red text** in the whole revised manuscript.

Yours Sincerely,
Xuhui

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Response letter to comments (ID: bg-2017-183)

Referee #1

General comments:

First, what exactly is the advance of this study over Carvalhais et al. (2014)? This wasn't clear to me.

[Response] Thanks so much for your comments. In *Carvalhais et al. (2014),* global C turnover times and its covariation with climate were mainly examined. They also compared global C turnover time calculated by the model results from CIMP5 with those from observed data and showed their trend over latitude. Based on their work, we extended litter C and vegetation C pools from different datasets into ecosystem C storage to estimate ecosystem C turnover time compared to the study of *Carvalhais et al.* (2014). We also focused on the uncertainty from datasets, especially in high latitude (HWSD vs. NCSCD). More importantly, we examined ecosystem C storage over time from changes in C turnover time and/or NPP. In addition, we calculated the GPP-based the NPP-based and soil MTTs to explore their difference and its variability to climate. Therefore, our study advance the understanding of the uncertainty of global C turnover time and ecosystem C storage from C turnover time with updated data. We revised the introduction and discussion to make it clearer for the advance in Lines 83-86, 92-94, 312-319.

Second, this analysis mixes (I believe) spatial and temporal trends, assuming that they're equivalent, but this assumption is never explored or even really discussed.

[Response] Thanks for your suggestions. In this study, we assumed that the spatial correlation between temperature and MTT is similar to the temporal correlation between these variables. We added this assumption and discussed this caveat in Lines 210-211,447-450.

The steady-state assumption is also troubling. I understand why it may be necessary at a global scale, but the authors should at least estimate how much bias this might be introducing. For example, there are gridded disturbance and forest age maps available that could be incorporated into such a calculation.

[Response] Thanks so much for your comments. For an ecosystem, a steady state is defined as GPP equals total ecosystem respiration at a reasonable period of time and there is no net change in total standing crop of living and dead biomass. However, maintaining a steady state without change is rare for a long time and ecosystems could be only close to reach the steady state in the short time.

As we know, disturbance and forest age structure will influence large-scale accumulation of biomass, the partitioning of C into pools with different turnover times, and thereby long-term C sequestration and turnover times. In the past decades, most of previous studies have considered the age-related decline in forest growth and simulated the current-age C flux to some degree (Zaehle et al., 2006), which were involved in the gridded data. Therefore, the gridded disturbance and forest age maps can be used to simulate the current-age ecosystem turnover time using models to compare our results, although it has large uncertainty. However, the specific effects of disturbance and forest age on ecosystem C turnover time are difficult to be examined, which was beyond our study. We thus added the discussion of the disturbance and forest age effects on ecosystem C turnover time in the discussion section as well as the caveat of the steady state (Lines 431-435, 415-420).

The lack of any clear data availability statement is unacceptable. It's 2017, and I expect all code and data to be included as supplementary info, or (better) posted in a repository. It's not acceptable to produce results from a black box.

[Response] Thanks for your suggestions. All of the original data (MOD 17, HWSD, NCSCD, vegetation C production of Gibbs et al (2006) and litter dataset from Holland et al., 2005, climate variables from the Climate Research Unit (CRU_TS 3.20)) are open and shared. We provided full citations for data sources in MS and the download links in the supplemental information.

The download links were as follows:

MOD 17: https://modis.gsfc.nasa.gov/data/dataprod/mod17.php
HWSD: http://eusoils.jrc.ec.europa.eu
NCSCD: http://bolin.su.se/data/ncscd/
Vegetation C: http://cdiac.ess-dive.lbl.gov/epubs/ndp/global_carbon/carbon_documentation.html
litter dataset: https://daac.ornl.gov/VEGETATION/guides/Global_Litter_Carbon_Nutrients.html
the Climate Research Unit: http://www.cru.uea.ac.uk/

The figures should be improved. See comments below.

[Response] See the response as below.

Finally, while I appreciate the difficulties of writing in a foreign language, the current manuscript is riddled with spelling and grammar mistakes. This is doubly frustrating as I know that the senior author, at least, is fluent in English.

[Response] We carefully revised the manuscript, especially for the language editing. Meanwhile, we asked a native speaker: Shahla Hosseini Bai, to carefully revise the whole manuscript. Hope our manuscript has been considerably improved.

Specific comments:

Line 24: Why "Thus"? Doesn't seem to be logically connected

L. 28: "difference"

[Response] Done as suggested.

L. 47: "validated" probably not the best word to use here

[Response] We revised "validated" to "evaluated".

L. 52: "amount of"

[Response] Done as suggested.

L. 62-63: Carvalhais et al. (2014) seems like a needed citation here

[Response] Done as suggested. We added the citation "Carvalhais *et al*. (2014)" in Lines 79-82.

L. 86-87: unclear

[Response] Done as suggested.

L. 90: this language is used frequently in the ms. Is ecosystem C storage really "driven" by MRT? I would say that MTT is an emergent property of changes in fluxes; it can't "drive" anything

[Response] Thanks for your comments. The ecosystem C storage is co-determined by C influx and C turnover time. For example, reduced soil C turnover time resulted in the insignificant net effect of increased atmospheric CO_2 on the equilibrium soil carbon storage (van Groenigen et al., 2014). Here, we referred to the changes in ecosystem C storage from the changes in C turnover time as the changes of ecosystem C storage driven by turnover time, compared to the changes in ecosystem C storage driven by C influx.

As suggested, we also used other words instead of "driven", such as ecosystem C storage over time from changes in MTT, the MTT-induced changes in ecosystem C storage and so on to diversely show it.

L. 116: by the definition above (pool/flux), it definitely would change

[Response] We agreed with your comments. We have carefully discussed the difference between ecosystem and soil C turnover times in the discussion section (Lines 319-321, 332-344).

L. 142: cite R correctly ("citation()"), including version numbers of all packages used

[Response] Sorry for the mistake. We did not use R software to regrid the spatial resolution. Actually we used ARCGIS 10 (ESRI Inc.) and adopted the regridding method from Todd-Brown *et al*. (2013) to regrid the spatial resolution for C fluxes and pool. We have added the citation: ARCGIS 10 and Brown *et al*. (2013), in Lines 152, 154.

L. 166: at the biome level, do you mean?

[Response] Sorry for the confusion. We aggregated ecosystem C turnover time and mean annual temperature (MAT, ^{o}C), mean annual precipitation (MAP, mm) and aridity index (AI) into a biome level.

L. 196-201: first, need to note that you're assuming that the current-day spatial correlation between temperature and MTT is identical to the temporal correlation between these variables. It's not at all obvious this would be true. Second, you're mixing models and remote sensing products; it would be good to document how much divergence these models have from MOD17 in 2011.

[Response] Thanks for your suggestions. We added this assumption in Lines 210-211, and also discussed its limitation in the discussion section (Lines 447-450) as "We assumed that the current-day spatial correlation between temperature and MTT is identical to the temporal correlation between these variables, although such assumption cannot reflect the processes like acclimation of microbial respiration to warming or shifts in plant species over time".

We used NPP in 2011 from MODIS products and NPP in 1901 from models since there was no MODIS GPP in 1901. Our previous paper (Yan *et al.*, 2014) showed that the modeled NPP was near to MODIS-estimated NPP and their difference was mostly less than 0.05 kg C m^{-2} yr^{-1}, so we used the average modeled NPP (CanESM2, CCSM4, IPSL-CM5A-LR, IPSL-CM5B-LR, MIROC-ESM, MIROC-ESM-CHEM, NorESM1-M and NorESM1-ME) for NPP in 1901 and assumed the average modeled NPP was similar to MODIS NPP in 1901. The detail information was described in Yan *et al*. (2014).

L. 211-221: are these really results? Aren't these just the GLC database num- bers?

[Response] The terrestrial C storage was calculated from the global datasets about plant biomass, soil and litter C, which described in the datasets section. GLC database was just used for plant functional types or biome class to aggregate all C into a biome level.

L. 225-: be consistent in using long/short or high/low or large/small in referring to MTT

[Response] Done as suggested. We used long/short in referring to MTT in the whole manuscript.

L. 245: Q_{10} is 1.95 implies that MTT roughly doubles with a 10 ◦C increase? That seems nonsensical

[Response] The previous research reported that Q_{10} for soil or other C pool was near to or larger than 2. For example, Sanderman et al (2003) calculated a Q_{10} value of 2.9 for soil C turnover time using eddy flux. Foereid et al (2014) used Q_{10} value of 1.5~2.27 for soil pool and 1.29~1.66 for litter pool due to pool properties. Compared to those data, we thought that our results were reasonable.

L. 298-299: can you explain this more?

[Response] The mean GPP-based MTT was slightly longer than that from Carvlhais *et al*. (2014, 23 years) with the similar method. The difference may result from two aspects. Firstly, ecosystem C storage in this study was the sum of soil, vegetation and litter C pools, while Carvalhais *et al*. (2014) only considered soil and vegetation C pools.

Secondly, the data source of global vegetation C storage was different with our study from Gibbs (2006) and Carvalhais *et al.* (2014) from a collection of estimates for pan-tropical regions and radar remote-sensing retrievals for northern and temperate forests. We added the more explanations in Lines 312-319.

L. 338-340: see comment 7 above re language and causality

[Response] In this study, we quantified the changes in ecosystem C storage from 1901 to 2011 and partitioned it into three parts from the changes in NPP, in ecosystem MTT, and in both NPP and MTT (seeing equation 3). Our results showed that the decrease in MTT increased ecosystem C loss over time due to the increase in C decomposition rates, while increased NPP enhanced ecosystem C uptake due to the decrease in CO_2 input to atmospheric and the increase of vegetation C stocks. We have revised them in Lines 383-389.

L. 365-366: is it possible to quantify, even in a back-of-the-envelope kind of way, how much error might be introduced by this assumption? That would be interesting

[Response] Thanks for your comments. It is sure that the large uncertainty will be introduced by the steady-state assumption. Currently, most studies still used this assumption to examine ecosystem C capacity and turnover time. For example, there are Carvalhais *et al* (2014), Zhou *et al.* (2012), and Barrett et al. (2006). However, it is very difficult to quantify the uncertainty. It is a big project. We did not have some good approaches to resolve this problem to date. We thus only discussed the limitation of this assumption in our discussion. (See the above response).

L. 389: but you're not measuring temporal variability (much), except for changes over time in the MOD17 product, right?

[Response] Sorry for the confusion. We used an exponential equation between ecosystem MTT and temperature ($MTT = ae^{-bMAT}$) to calculate ecosystem MTT in 1901 and 2011 for the temporal variability of MTT. MOD17 product was for NPP changes over time.

L. 406-419: this is all duplicative and can be removed

[Response] Done as suggested.

L. 421-422: completely inadequate data availability statement. Elevation data?!?

[Response] Sorry for confusion. We revised it as “All of the original data (MOD 17, HWSD, NCSCD, vegetation C production of Gibbs et al (2006) and litter dataset from Holland et al., 2005, climate variables from the Climate Research Unit (CRU_TS 3.20)) are open and shared. We provided full citations for data sources in MS and the download links in the supplemental information.”.

Figures generally: maps are pretty but have limited utility. At least of these might be more informative if gives as e.g. Latitude versus MTT plots

[Response] Thanks for suggested. We have rescaled color and also added the latitude pattern for Figure 7.

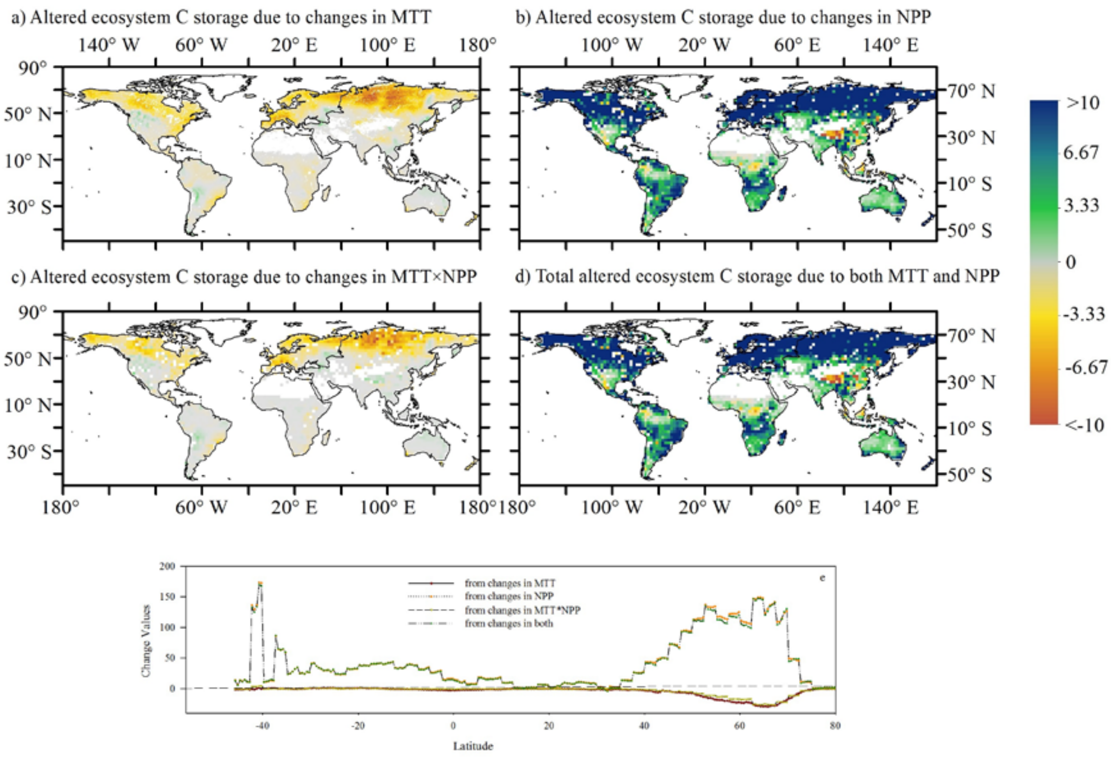


Figure 7. Altered ecosystem carbon storage due to changes in mean turnover time (MTT, NPP2011×ΔMTT, a), net primary production (NPP, MTT2011×ΔNPP, b), and interaction of NPP and MTT (ΔMTT×ΔNPP, c). Panels d and e are total altered ecosystem C storage changes due to changes in MTT, NPP, and MTT×NPP and their latitudinal gradients from panels a-d, respectively. Unit: g C m^{-2} yr^{-1} ($\Delta C_{pool} = NPP_{2011} \times \Delta MTT + MTT_{2011} \times \Delta NPP - \Delta NPP \times \Delta MTT$).

Figure 6: not at all useful in my opinion

. **[Response]** Done as suggested. We deleted it in the revised version.

Referee #2

General comments:

One major issue is that it isn't clear what the major new advance was in this analysis compared to previous, similar analyses. This analysis seems very similar to that of Carvalhais et al (2014), which is cited several times in the manuscript. In fact, Carvalhais et al was arguably more comprehensive than this analysis because it included direct comparisons to earth system model simulations. I think there were some new features in this analysis, such as the inclusion of litter estimates, comparing whole ecosystem vs. soil MTT, and looking at changes over the 20th century, but I think the paper could do a better job of highlighting which things are new and how they changed the results relative to previous, similar studies. If the litter estimates are new, then maybe there could be more discussion of how and why including that pool changed the results relative to previous analyses.

[Response] Thanks for your comments and suggestions. In *Carvalhais et al. (2014)*, global C turnover times and its covariation with climate were mainly examined. They also compared global C turnover time calculated by the model results from CIMP5 with those from observed data and showed their trend over latitude. Based on their work, we extended litter C and vegetation C pools from different datasets into ecosystem C storage to estimate ecosystem C turnover time compared to the study of *Carvalhais et al.* (2014). We also focused on the uncertainty from datasets, especially in high latitude (HWSD vs. NCSCD). More importantly, we examined the changes in ecosystem C storage over time from changes in C turnover time and/or NPP. In addition, we calculated the GPP-based, the NPP-based and soil MTTs to explore their difference and its variability to climate. Therefore, our study advances the understanding of the uncertainty of global C turnover time and ecosystem C storage from C turnover time with updated data. We revised the introduction and discussion to make it clearer for the advance in Lines 83-86, 92-94, 312-319.

Another issue is the potential for bias in some of the results due to the datasets used for GPP and NPP. While MODIS-derived GPP is constrained by satellite observations, it also depends on assumptions about climatic and environmental factors that affect plant growth and photosynthesis. For example, the efficiency parameter that converts absorbed light into GPP varies with VPD and temperature. MODIS NPP includes maintenance respiration that is calculated based on estimates of plant biomass and a temperature-dependent Q10 relationship. This raises questions about the temperature *and moisture relationships shown in Figures 4, 5, and 6, as well as the related estimates of changes in MTT over time. It is difficult to tell how much these relationships are affected by the underlying assumptions of the MODIS NPP algorithm. Since the estimates are not completely measurement based, it is harder to be confident about their meaning.*

[Response] Thank for your comments. Mean turnover time (MTT) was calculated as the ratio of C storage and C influx (e.g., GPP or NPP), so the relationships could be affected by the relationships of GPP or NPP with temperature and VPD. The MODIS NPP algorithm would affect the estimates of MTT, which were discussed in the previous paper (Zhao et al., 2005; Zhao, M. and Running, S. W. 2010) but the uncertainty was within the allowable range. We thus thought that the uncertainty from the underlying assumptions of MODIS NPP algorithm was not considered in this study.

Specifically, the MDOIS NPP algorithm is expressed as: $\mathrm{NPP} = \sum_{i=1}^{365} PsnNet - (R_{mo} + R_g)$, where PsnNet is net photosynthesis ($\mathrm{PsnNet} = \mathrm{GPP} - \mathrm{R}_{ml} - \mathrm{R}_{mr}$). R_{ml} and R_{mr} are maintenance respiration by leaves and fine roots, respectively. R_{mo} is maintenance respiration by all other living parts except leaves and fine roots (e.g., livewood), and R_g is growth respiration. GPP was calculated as: $\mathrm{GPP} = \varepsilon * \mathrm{FPAR} * \mathrm{PAR}$, where ε is the radiation use efficiency of the vegetation determined by maximum ε in each biome and temperature and soil moisture. All the parameters were abstained from the MOD17 Biome Parameter Look-Up Table (BPLUT). Therefore, the performance of the algorithm can be largely influenced by algorithm itself as well as the uncertainties from upstream inputs, such as land cover, FPAR/LAI, the meteorological data. For C5 MOD17, the BPLUT and the upstream inputs were be improved, so the MOD17 NPP is comparable to the Ecosystem Model–Data Intercomparison (EMDI) NPP data set, and global total MODIS GPP and NPP are inversely related to the observed atmospheric CO_2 growth rates, and MEI index, indicating that MOD17 are reliable products (Zhao et al., 2005). For example, direct comparison of MODIS annual GPP (MOD17A3) with observations for 37 site-years has resulted in a higher correlation and lower bias (r^2=0.6993, relative error=19%, unpublished data) than MODIS annual GPP calculated using tower meteorology (r^2=0.595, relative error=2%).

The estimates of changes in MTT over the 20th century are also problematic because NPP in 1901 was modeled rather than measurement-based. This means that all the changes in NPP from 1901 to 2011 are based on a comparison between average output from several models (1901) to a measurement-based (but partially modeled) estimate

(MODIS in 2011). How much of the difference was due to climatic factors that changed over that time period and how much was due to differences between the different sets of NPP estimates? I wonder whether the results in Figure 7b (difference between models in 1901 and MODIS NPP in 2011) would look compared to the change in NPP from the model ensemble between 1901 and 2011. In the end, if models of NPP are being compared, what is the advantage of this MTT approach compared to just analyzing the change in carbon stocks from the actual model output over time?

[Response] Thank for your comments. We used NPP in 2011 from MODIS products and NPP in 1901 from models, which were no MODIS GPP in 1901. Our previous paper (Yan *et al*., 2014) showed that the modeled NPP was near to MODIS NPP and their difference was mostly less than 0.05 kg C m^{-2} yr^{-1}. We thus used the average modeled NPP (CanESM2, CCSM4, IPSL-CM5A-LR, IPSL-CM5B-LR, MIROC-ESM, MIROC-ESM-CHEM, NorESM1-M and NorESM1-ME) for NPP in 1901 and assumed that the average model NPP was similar to MODIS NPP in 1901. Since the details had been described in Yan *et al*., (2014), we did not add the detailed comparison of between NPP of model ensemble in 1901 and MODIS NPP in 2011 and NPP from the model ensemble between 1901 and 2011 in this study. To clarify the information, we added the relevant description and references in Lines 212-216, 622.

The analysis depends on a space-for-time substitution (developing temperature and precipitation relationships based on spatial patterns and assuming they also apply to changes over time). What is the potential for bias in this assumption? Processes like acclimation of microbial respiration to warming or shifts in plant species ranges could make changes over time quite different from those that would be expected from observed spatial patterns.

[Response] Thank for your comments. We assumed that the current-day spatial correlation between temperature and MTT is identical to the temporal correlation between these variables in the revised MS, because there is no time series of data between MTT and temperature at the global scale. However, such assumption cannot reflect the processes like acclimation of microbial respiration to warming or shifts in plant species ranges as suggested by the reviewer, which could make changes over time. In the revised MS, we added the limitation for this assumption in the discussion section (Lines 447-450).

Comparing GPP and NPP as separate and independent metrics doesn’t make much *sense since both are derived from the same MODIS product. The difference between GPP and NPP is entirely determined by the assumptions of the MODIS NPP algorithm, so I'm not sure I would expect that distinction to provide much useful information in this type of analysis.*

[Response] Thanks so much for your comments and suggestions. Thompson and Randerson et al (1999) has indicated that there were two types of mean C turnover times for terrestrial ecosystems: the GPP-based or the NPP-based mean turnover time according to the terrestrial C models with GPP or NPP as their C inputs, respectively (i.e., NPP is GPP minus autotrophic respiration). However, there was no clear distinction in most pervious researches, so we calculated the both MTTs for comparison. In addition, NPP-based MTT is more available in comparison with soil MTT than GPP-based MTT in the literature. The difference between GPP-based and NPP-based MTT was determined by the ratio of GPP and NPP, which largely influenced by the assumptions of the MODIS NPP algorithm. We added their difference in the discussion sections (Lines 319-321).

In general, I think the Discussion doesn't say enough about why this analysis is useful compared to existing models and previous analyses. The suggestions given for incorporating these results into earth system models and land models are not very useful because most of these factors (e.g., temperature dependence of turnover rates) are already included in all existing models. I do think that there are some useful outcomes from this type of analysis, but I think the Discussion needs some more interpretation of the specific results in the context of ecological factors rather than general statements about how models should take these results into account.

[Response] Thanks for your comments and suggestions. In the Discussion section, we added two examples (e.g., the lifetime and decomposition) to the context of ecological factors in the revised MS as "The difference between NPP-based ecosystem and soil MTT was the turnover time of vegetation and litter, which was related to plant functional types (PFTs). For instance, the difference between NPP-based and soil MTTs in Australia was small (33.4 and 29.8 years, respectively) compared to that in other regions, because one of the PFTs accounting for a large space of Australia was spare grass with short turnover time (3.5 years on average). In addition, within a specific PFT, different ecosystems may have diverse turnover time due to climate effects. NPP-based and soil MTTs for boreal neadleaf evergreen forest were about 116 years and 98 years, respectively, while both for tropical ones were about 12 years and 8 years, although ecosystem C in boreal and tropic zone was in the same order of magnitude (~34 vs. 40

kg C m-2) with the similar vegetation C storage (~3.5 kg C m-2). High temperature and humidity in tropical zone, which promote decomposition processes, contribute to the short turnover time compared to those in boreal zone (Sanderman et al., 2003).” in Lines 332-344.

The manuscript also could use some proofreading for English usage.

[Response] We carefully revised the manuscript, especially for the language editing. Meanwhile, we asked a native speaker: Shahla Hosseini Bai, to carefully revise the manuscript. Hope our manuscript has been considerably improved.

Specific comments*:*

Line 56-57: This analysis generally discusses NPP and mean C turnover time as independent, but they could also be related. For example, faster plant growth could accelerate soil C turnover via priming effects, or there could be correlations between plant growth rates and the longevity of vegetation.

[Response] Thanks for comments. The transient C storage is determined by the MTT and NPP. If climate increases C influx (NPP) into an ecosystem but does not change C transient times (MTT), the C sequestration rate of the ecosystem increases due to the fact that more C stays in the ecosystem for the same length of time, which could be correlated between growth C plant growth rates and the longevity of vegetation. Certainty, climate would increases C influx and also accelerate soil C turnover, so the C sequestration rate of the ecosystem increases, which is determined by both the amounts of C influx and their MTT. Therefore, in this study, we firstly partitioned the changes in the C storage into three parts: from the changes in NPP, MTT and both (seeing equation 3), and secondly, the NPP and MTT in 1901 and 2011 were used to estimate the changes in ecosystem C storage over time, and finally we discussed the spatial pattern of ecosystem C storage changes and the possible reasons.

Line 62-63: It seems like Carvalhais et al (2014), which this analysis largely follows, did do a pretty good job of quantifying this spatial variation at global scales.

[Response] Thanks for your comments. Based on their works (Carvalhais et al (2014)), we extended litter C and vegetation C pools from different datasets into ecosystem C storage to estimate C turnover time and evaluate their uncertainty from datasets. We mainly focused on comparing different versions of MTTs and quantifying the spatial variation in ecosystem C storage over time from the changes in C turnover time and/or C flux.

Line 66-68: Another recent radioisotope paper to cite is He et al (2016)

[Response] Thanks you for providing the new reference.

Line 78-82: This suggests that the main contribution of this paper is comparing different versions of MTT calculations. But it's not really clear later on if that is meant to be the focus or not. The paper is also about changes in MTT over time, but doesn't really connect these two parts together.

[Response] In this study, we focused on comparing different versions of MTT and its effects to climate as well as quantifying the changes in ecosystem C storage due to ecosystem MTT. The changes in MTT over time was used to estimate the ecosystem C storage changes caused by MTT (equ. 3), which was calculated by the relationship between MTT and climate.

Line 165-166: "interpret the quantity as an emergent diagnostic at the ecosystem level": What does this emergent diagnostic actually tell us? There isn't any discussion of how it should be interpreted or what kind of bias would occur as a result of the steady state assumption being violated.

[Response] If the ecosystem is not at the steady state, the C turnover time cannot be calculated by the ratio of C storage and C flux. We thus followed the assumption of Carvalhais *et al*. (2014) and have discussed the limitation of steady-state in MS (Lines 415-420).

Line 180: The equation for MTT looks like it's fitting a ratio of MAT/MAP, but I think this is actually meant to say either MAT or MAP. It's very confusing the way it's currently written.

[Response] Done as suggested. We revised it as $\mathrm{MTT} = \mathrm{a}e^{-bMAT\ or\ MAP}$.

Line 214-216: If most of the carbon was in soil, then total ecosystem MTT would be largely determined by soil MTT. What are the implications of this when comparing those two estimates?

[Response] $\mathrm{MTT}_{EC} = \frac{Cpool}{GPP} = \frac{C_{soil+}C_{veg+}C_{litter}}{NPP/\varepsilon} = \varepsilon * MTT_{soil} + \varepsilon * \frac{C_{veg+}C_{litter}}{NPP}$ （$\varepsilon = \frac{NPP}{GPP}, MTT_{soil} = \frac{C_{soil}}{NPP}$）. If most of the C was in soil, the ratio of NPP to GPP is the key to determine the difference between GPP-based ecosystem MTT and soil MTT and NPP-based MTT is similar to soil MTT. We have discussed the difference versions of MTTs in Lines 319-321, 332-344.

Line 220: I would expect permafrost soils to have much larger C stocks in places with very deep organic soils. It's not unusual for deep permafrost to have >100 kgC/m2 (Schuur et al., 2015). Could that lead to bias in these results?

[Response] In this study, ecosystem MTT was calculated as the ratio of C storage and influx ($\mathrm{MTT}_{EC} = \frac{Cpool}{GPP} = \frac{C_{soil+}C_{veg+}C_{litter}}{GPP}$). When the deep permafrost is considered, the ecosystem MTT would become longer. If we assumed that soil C in deep permafrost is 100 kg C/m^2 and GPP is 0.2 kg C m^2 yr^{-1}, the MTT is 500 years.

Line 224-225: He et al (2016) used radiocarbon analysis to estimate a mean soil C residence time of about 3000 years, which they found to be consistent with several other published estimates. What explains the 2 order of magnitude difference from the estimates here? Turnover time for tundra also seems very short, given that permafrost soils are known to have been steadily accumulating carbon for thousands of years.

[Response] In our MS or Carvalhais et al. (2014), we assumed that ecosystem was in the steady state and calculated MTT as the ratio of C pool and C flux. Here, we did not separate C pools into fast, slow, or passive, which could largely underestimate the ecosystem MTT. Another factor is that the current soil dataset such as HWSD underestimate the soil C storage, especially for permafrost soils. In the discussion section, we discussed the limitation of the assumption of the steady-state and the difference soil datasets effects on the estimate of ecosystem turnover time (Lines 415-420, 421-429).

Line 256: It doesn't seem like the increase in R2 was really that significant.

[Response] Sorry for the confusion. R^2 for the regression function of soil MTT with MAT was 0.76 when AI>1, while R^2 was 0.52 when AI<1 (Fig. 5e & h)

Line 261-262: It would be nice to include a map of temperature changes along with

MTT and NPP changes so all driving factors could be compared. Also, why was only temperature and not precipitation included in this part of the analysis, even though both looked like they had significant relationships with MTT?

[Response] Done as suggested. We added a map of temperature changes in Figure 7 (Figure 6 in the revised MS, seeing the below). There is no change in R^2 when MAP was incorporated into the regression function of ecosystem MTT with MAT, so we just considered the temperature changes included in this part of the analysis.

Line 268 and 271: I think these units should be PgC, not PgC/year

[Response] Sorry for the mistake. Thanks so much for your correlation. This unit is Pg C for the change of C storage from 2011 to 1901. We have revised it in Lines 293, 296.

Lines 270-275: This might be a good place to discuss whether the whole ecosystem patterns differed from the soil C patterns if there were any interesting patterns there

[Response] Thanks for your suggestions. Patterns of ecosystem and soil C storage can determined by NPP and MTT, so the difference between the whole ecosystem and the soil C patterns was determined by the difference between ecosystem and soil MTT. In our study, MTT in 1901 and 2011 was calculated using the relationship between MTT and temperature, so the difference of temperature functions determined the difference of both MTT and then the C storage patterns. Therefore, we added the limitation of MTT calculation in the discussion section (Lines 436-447). When the relationship between soil MTT and temperature was used ($MTT_{soil} = 58.40e^{-0.08MAT}$), the changes on ecosystem C storage caused by MTT could decrease 161.42 Pg C and that driven by NPP could be 1125.6 Pg C, with the similar spatial pattern as the ecosystem.

Line 293-297: I think a lot more could be said about the ecology behind these results. What features of dominant plant species and soil contributed to these differences? Differences in plant lifetime? Tissue lifetime? Susceptibility to decomposition?

[Response] Thanks so much for suggestions. The difference between NPP-based ecosystem and soil MTT was the turnover time of vegetation and litter, which was related to plant functional types (PFTs). We have added some ecological information behind these results (e.g., plant lifetime, decomposition as suggested) in Lines 332-344 as “The difference between NPP-based ecosystem and soil MTT was the turnover time of vegetation and litter, which was related to plant functional types (PFTs). For instance, the difference between NPP-based and soil MTTs in Australia was small (33.4 and 29.8 years, respectively) compared to that in other regions, because one of the PFTs accounting for a large space of Australia was spare grass with short turnover time (3.5 years on average). In addition, within a specific PFT, different ecosystems may have diverse turnover time due to climate effects. NPP-based and soil MTTs for boreal neadleaf evergreen forest were about 116 years and 98 years, respectively, while both for tropical ones were about 12 years and 8 years, although ecosystem C in boreal and tropic zone was in the same order of magnitude (~34 vs. 40 kg C m-2) with the similar vegetation C storage (~3.5 kg C m-2). High temperature and humidity in tropical zone, which promote decomposition processes, contribute to the short turnover time compared to those in boreal zone (Sanderman et al., 2003).”.

Line 299: Since the ratio of GPP to NPP is entirely determined by the assumptions of the MODIS NPP algorithm, I don’t think this result has a lot of real-world meaning.

[Response] Two types of mean C turnover times has been suggested for terrestrial ecosystems: the GPP-based or the NPP-based mean turnover time according to the terrestrial C models with GPP or NPP as their C inputs, respectively (Thompson and Randerson *et al*., 1999, NPP is GPP minus plant respiration). However, there was no clear distinction in most pervious researches, so we calculated the both two for comparison and NPP-based MT is more available in comparison with soil MTT than GPP-based MTT. In our study, the difference between GPP-based and NPP-based MTT was determined by the ratio of GPP and NPP, which largely influenced by the assumptions of the MODIS NPP algorithm. We added these information in Lines 319-321.

Line 377-379: Why would this reduce the uncertainties?

[Response] Sorry for the confusion. We deleted this sentence in the revised version after we carefully considered the sources of uncertainties.

Line 381-382: Doesn’t aggregating everything to the biome level violate the assumptions behind calculating change in MTT over time? This would suggest that MTT could only change if the spatial extent of different biomes was shifting.

[Response] The original data, including MOD 17, HWSD, vegetation C production of Gibbs *et al*. (2006), and litter dataset from Holland *et al.* (2005), were created based on the plant functional types (PFTs) or biomes by the assumptions of algorithm, so we aggregated MTT into a biome level to estimate the change in MTT over time for data match.

Line 390-391: This would be a good place to discuss alternative soil databases like Hengl et al (2014) - available at soilgrids.org

[Response] Thanks for your suggestions. We have discussed the uncertainty caused by the different datasets (in Lines 347-349, 425-429) and also added the soil databases of Hengl et al (2014). (If SoilGrids (Hengl et al., 2014) was used, the MTT in the top 1 m could increase to 30.3 years for GPP-based, 66.9 years for NPP-based and 45.7 years for soil.)

Line 392-393: This is arguably the primary purpose of all land surface models. They all already consider this.

[Response] Thanks for your comments. We have deleted it.

Line 397-398: All land surface models already include temperature functions that affect pool turnover times.

[Response] Thanks for your comments. It is sure that all land surface models already included temperature functions that affected C pools and fluxes via plant photosynthesis and respiration. These effects probably directly affected turnover times of C pools to some degree. Carvalhais *et al.* (2014) examined the covariation of climate with turnover times. In this study, we emphasized the effects of moisture or precipitation on soil decomposition, especially in high-latitude zones with greater warming and increased precipitation.

Line 401-404: Land surface models already include these processes. In general, this whole section about improvements to land models isn't supported by any comparison between this study and actual land model output. Carvalhais et al (2014) did explicitly compare their MTT results to earth system model simulations, and I don't think it makes sense to discuss these model-related suggestions without doing a similar comparison here.

[Response] Thanks for your comments and suggestions. Compared with Carvalhais *et al*. (2014), we mainly discussed the difference of the climate effects between on ecosystem MTT and soil MTT, especially for moisture. Our results also showed that the temperature sensitivity of ecosystem turnover time was lower than that of soil C pool (Q_{10}: 1.95 vs. 2.23), while moisture stress on soil MTT was significant, especially under low aridity conditions. Current land surface models have considered moisture stress on vegetation, but the incorporation of moisture or precipitation stress into soil decomposition should be strengthened, especially in high-latitude zones with greater warming and increased precipitation. To make it clear, we have rewrote these sentences (Lines 461-469).

Line 421-422: Data availability would require putting all the MTT data somewhere that readers can access it.

[Response] All of the original data (MOD 17, HWSD, NCSCD, vegetation C production of Gibbs et al (2006) and litter dataset from Holland et al., 2005, climate variables from the Climate Research Unit (CRU_TS 3.20)) are open and shared. We provided full citations for data sources in MS and the download links in the supplemental information.

The download links were as follows:

MOD 17: https://modis.gsfc.nasa.gov/data/dataprod/mod17.php

HWSD: http://eusoils.jrc.ec.europa.eu
NCSCD: http://bolin.su.se/data/ncscd/
Vegetation C: http://cdiac.ess-dive.lbl.gov/epubs/ndp/global_carbon/carbon_documentation.html
litter dataset: https://daac.ornl.gov/VEGETATION/guides/Global_Litter_Carbon_Nutrients.html
the Climate Research Unit: http://www.cru.uea.ac.uk/

Figure 1: The colors need to be rescaled, especially for soil C. It's really hard to see anything in that map. Also, the soil C has some obvious artifacts, like the sharp change in soil C on the border between Alaska and Canada. What does this mean for the results? It would also be nice to have a map of NPP here s ons.

[Response] Done as suggested. We have rescaled the colors for map (Figure 1).

Soil C storage in Alaska is near 30 kg C, while that in Canada is less than 10 kg C, forming the sharp change in soil MTT on the border between Alaska and Canada. Here, soil MTT in Alaska ranges among 70~95 years and that in Canada on the border is less than 20 years.

Figure 1 showed the C storage in different C pools (soil, vegetation, litter and ecosystem). Since NPP is not our focus in this study, we put NPP map in Supplemental information.

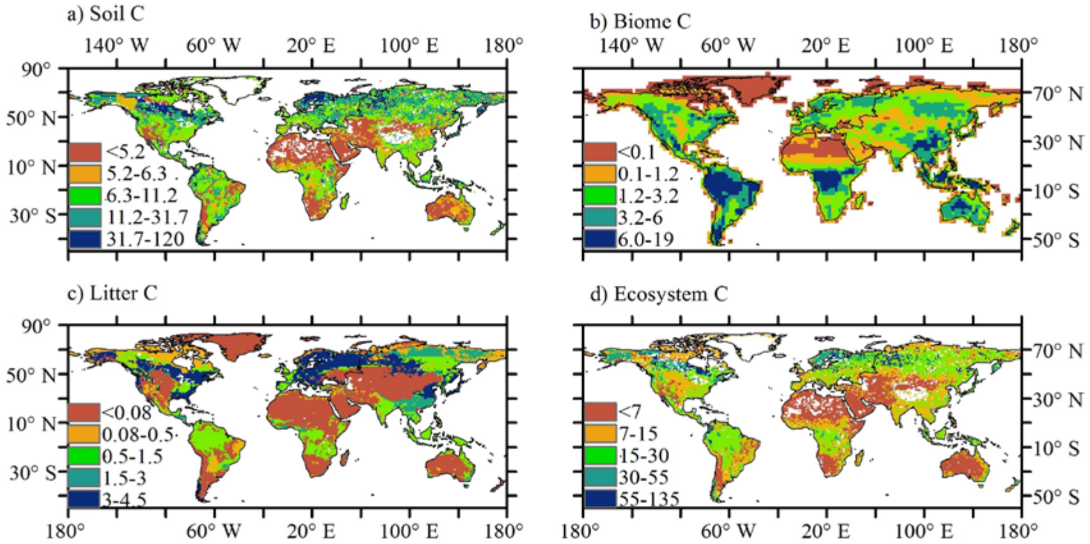
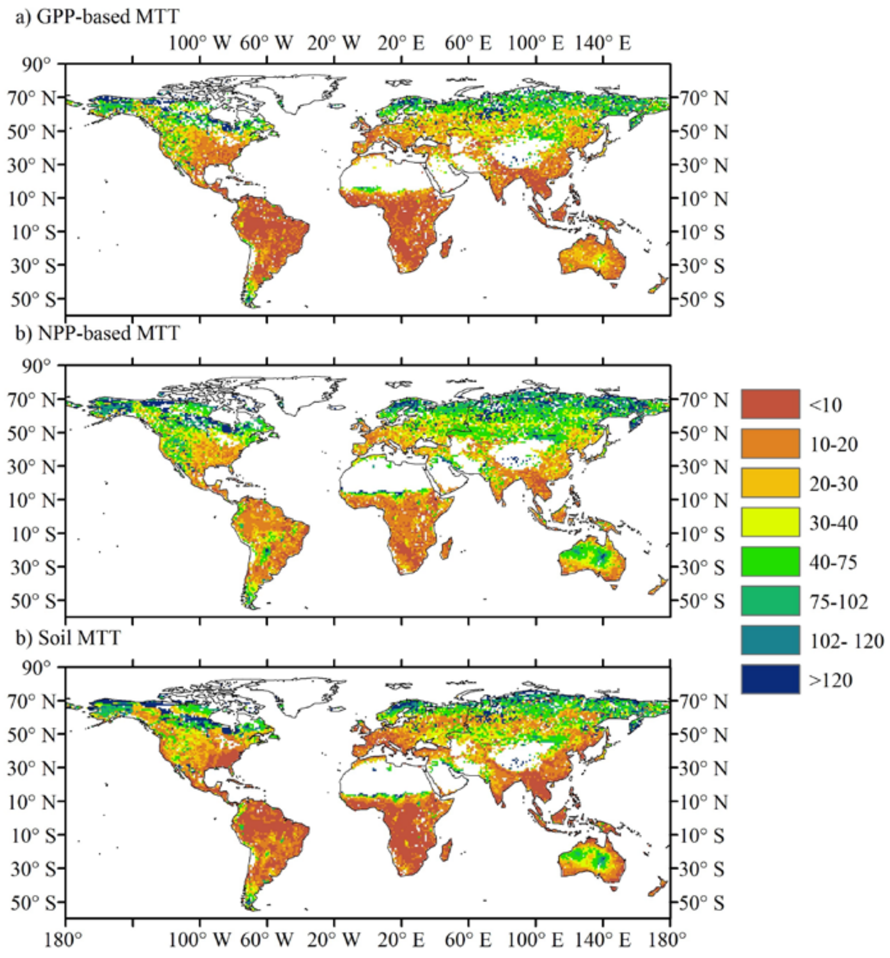


Figure 2: Since all three of these look about the same, I don't really see the point in including all of them as separate metrics

[Response]Thanks for your comments. The colors have been rescaled to strengthen



the difference among three of these.

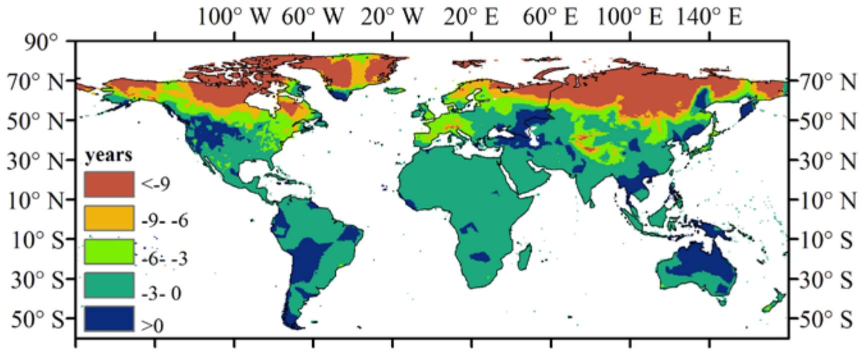
Figure 4: Panel a: The regression looks like it underestimates the slope of the curve by a lot. Panel d: The exponential fit does not do very well at the high precipitation end. What does this mean for the results?

[Response] We agree that the curve fit does not do very well at the high precipitation end at Panel a or Panel b**.** If the high precipitation (>2000mm) was neglected, the exponential fit would do better. For example, R^2 would increase to 0.86 at Panel d.

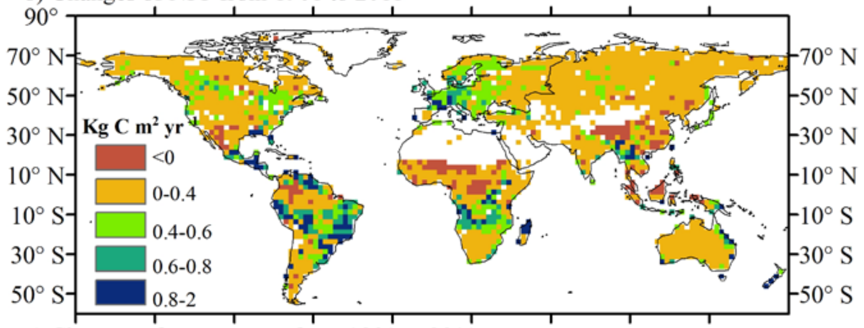
Figure 7: The titles on the figure say from 1991 to 2011, but the text says it goes from 1901 to 2011.

[Response] We have revised the titles on the figure from 1901 to 2011.

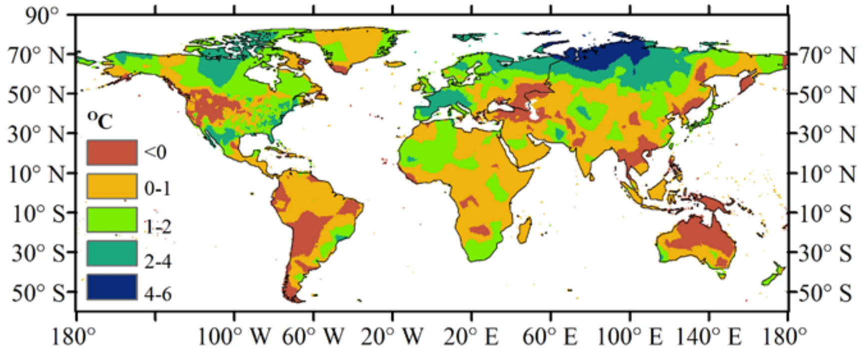
a) Changes of MTT from 1901 to 2011



b) Changes of NPP from 1901 to 2011



c) Changes of temperature from 1901 to 2011



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The effects of carbon turnover time on terrestrial ecosystem carbon storage

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Abstract. Carbon (C) turnover time is a key factor in determining C storage capacity in various plant and soil pools and the magnitude of terrestrial C sink in a changing climate. However, the effects of C turnover time on ecosystem C storage have not been well quantified~~ for previous researches~~. Here, we ~~first analyzed ~~compared~~ the different versions of ~~ ~~different versions of ~~mean turnover times~~s~~ ~~(MTT) of different components ~~ (MTTs~~s~~) of ~~,~~ ~~including ~~ecosystem ~~MTT (MTT$_{EC}$) based on GPP [MTT$_{EC\_GPP}$] and NPP [MTT$_{EC\_NPP}$] ~~and soil~~ MTTs~~ ~~[(MTT$_{soil}$])~~), examined~~ and~~ ~~its ~~their variability to ~~ in MTT to ~~climate~~ changes~~, and then ~~evaluated the changes of ecosystem C storage driven by MTT changes ~~quantified the spatial variation in ecosystem C storage over time from changes in C turnover time and/or NPP. Our results showed that mean~~total~~ GPP-based ecosystem MTT (MTT$_{EC\_GPP}$ = C_{pool}/GPP~~:~~, 25.0±2.7 years) was shorter than soil MTT (MTT$_{soil}$ = C_{soil}/NPP, 35.5 ±1.2 years) and NPP-based ecosystem MTT (MTT$_{EC\_NPP}$ = C_{pool}/NPP,~~:~~ 50.8±3 years~~)~~ ~~($MTT_{EC\_GPP} = C_{pool}/GPP$ & $MTT_{soil} = C_{soil}/NPP$ & $MTT_{EC\_NPP} = C_{pool}/NPP$;~~, C_{pool} and C_{soil} ~~referr~~referred to ~~ing as the ~~ecosystem or soil ~~carbon ~~C storage, respectively). At the biome scale, temperature is ~~still ~~the best predictor for MTT$_{EC}$ ($R^2 = 0.77$, $p<0.001$) and MTT$_{soil}$ ($R^2 = 0.68$, $p<0.001$), while the inclusion of precipitation in~~to~~ the model did not improve ~~. There is no clear improvement in ~~the performance of MTT$_{EC}$ ~~predication when~~

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~~incorporating precipitation into the model~~ ($R^2 = 0.76$, $p<0.001$). ~~Thus,~~ Ecosystem MTT decreased by approximately 4 years from 1901 to 2011 when temperature ~~just~~ was just considered, resulting in a large C release from terrestrial ecosystems. The resultant terrestrial C release caused by the decrease in MTT ~~decrease~~ only accounted for about 13.5% of that ~~driven~~ due to~~by~~ the change~~s~~ in ~~increase in NPP~~NPP uptake ~~increase~~ (159.3 ± 1.45 vs 1215.4 ± 11.0Pg C)~~ due to the differencet between both of the product factorweights (NPP * ΔMTT vs MTT * ΔNPP)~~. ~~Therefore~~However, the larger uncertainties in the spatial variation of MTT than temporal changes would lead ~~in~~to a greater impact on ecosystem C storage ~~from spatial pattern of MTT~~, which may deserve to the ~~need to~~ further study ~~pay pay attention be focused on~~ in the future ~~research~~.

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

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1 Introduction

Rising atmospheric CO_2 concentrations and the resultant climatic warming can substantially impact the global carbon (C) budget (IPCC, 2007), leading to a positive or negative feedback to global climate change (e.g., Friedlingstein *et al.*, 2006; Heimann and Reichstein, 2008). Projections of earth system models (ESMs) show a substantial decrease in terrestrial C storage as the world warms (Friedlingstein *et al.*, 2006), but the decreased magnitude is difficult to be ~~quantify~~ quantified due to the complexity of terrestrial ecosystems in response to global change~~, such as forest dieback (Cox *et al.*, 2004), storms~~ (Chambers and Li, 2007~~), and land use change (~~; Strassmann *et al.*, 2008). For example, experimental and modeling studies ~~generally~~ showed that elevated CO_2 would enhance NPP and terrestrial C storage (Nemani *et al.*, 2003; Norby *et al.*, 2005), but warming ~~may~~ could increase ecosystem ~~soil respiration rates~~C release, contributing to reduced C storage, especially in the colder regions (Atkin and Tjoelker, 2003; Karhu *et al.*, 2014). Therefore, the response of terrestrial C storage to climate change depends on the responses of C ~~influx~~ flux and ~~how~~ C ~~residence~~ turnover time ~~change in~~in various C pools (i.e., plant, litter and soil pools) (Luo *et al.*, 2003; Xia *et al.*, 2013) as reflected in most of the biogeochemical models (Parton *et al.*, 1987; Potter *et al.*, 1993). Todd-Brown *et al.* (2013) evaluated results of soil C simulations from CMIP5 earth

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system models and found that global soil ~~carbon~~ C varied 5.9 folds across models in response to a 2.6-fold variation in NPP and a 3.6-fold variation in global soil ~~carbon~~ C turnover times. ~~Thus, it is key necessary to quantify the time that carbon resides C turnover time in terrestrial ecosystems and its relationships with climate, and then examine the resultant changes of terrestrial in ecosystem C storage from changes in turnover time.~~

In a given environmental condition, the ecosystem C storage capacity refers to the amount of C that a terrestrial ecosystem can store at the steady state, determined by C influx and turnover time (Xia *et al*., 2013). External environmental forces, such as climate change and land use change, would dynamically influence both ecosystem C influx and turnover time, and then change terrestrial C storage capacity. Thus, the changed magnitude of ecosystem C storage ~~sink~~ can be expressed by changes in both NPP and mean C turnover time. The spatial variation of NPP changes over time and the effects of climate change have been relatively well quantified by manipulative experiments (Rustad *et al*., 2001; Luo *et al*., 2006), satellite data (Zhao and Running, 2010), and data assimilation (Luo *et al*., 2003; Zhou and Luo, 2008; Zhou *et al*., 2012). Todd-Brown *et al*. (2013) ~~also~~ found that differences in NPP contributed significantly to differences in soil ~~carbon~~ C across models using a reduced complexity model with ~~dependent on~~ NPP and temperature. In contrast, the spatial variation of C turnover time

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in terrestrial ecosystems and its contribution to C storage have not well been quantified, especially~~have not well been quantified due to limited data, especially at regional or global scales.~~ at the regional or global scale.

Ecosystem C turnover time is the average time that a C atom stays in an ecosystem from entrance to the exit (Barrett, 2002). Several methods have been used to estimate the C turnover time, such as C balance method by estimating ratios of C pools and fluxes (Vogt *et al*., 1995), C isotope tracing (Ciais *et al*., 1999; Randerson *et al*., 1999), and measurements of radiocarbon accumulation in the undisturbed soils (Trumbore *et al*., 1996). However, most methods mainly focused on various pools (i.e., leaf, root, soil) and at small scale (i.e. C isotope tracing, radiocarbon). ~~The turnover time at region or global scale are often calculated with the ratio of ratios of C storage to flux, such as soil C turnover time (Gill and Jackson, 2000; Chen *et al*., 2013). Although there are many estimates of global C turnover time, those global C turnover time focused on soil C.~~ Spatial ~~distribute~~ pattern of ecosystem C turnover time is relatively difficult to be estimated (Zhou and Luo, 2008), which needs to incorporate individual plant and soil C pools and their C turnover time into ecosystem models. The inverse modeling has been used to estimate ecosystem mean C turnover time in USA and

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Australia (Barrett, 2002; Zhou and Luo, 2008; Zhou *et al*., 2012). The ratio of C storage to flux ~~has been used to~~is another common method to estimate ~~soil~~ecosystem turnover time at region or global scale ~~(~~(Gill and Jackson, 2000; ~~Sanderman et al., 2003;~~ Chen et al., 2013). For example, Carvalhais et al. (2014) ~~have~~ ha~~s~~d ~~firstly~~ estimated ecosystem C turnover time as the ratio of ~~carbon~~ C storage (soil and vegetation C) and ~~influxes~~ GPP– and examined ~~as well as and gross primary production (GPP) and~~ their correlations to climate, which mainly focused on the ~~the validation of model-based turnover time and the qualitative relationship with climate~~ comparison of global C turnover time calculated by model results from CIMP5 with those from observed data as well as their trend over latitude. ~~However,~~In our study, ~~–the quality of current datasets adopted determines the accurate of C turnover time estimates using the ratio of C storage to flux. Therefore,~~ we extended litter C and vegetation C pools from different datasets into ecosystem C storage ~~for~~to ~~the~~ estimate~~s of~~ C turnover time and evaluate~~d~~ their uncertainty from datasets. ~~Simultaneously,~~ –We~~we~~ also examined the changes in ecosystem C storage over time from changes in C turnover time and/or NPP~~due to the changes of ecosystem turnover time~~.

In past decades, ~~Thompson and Randerson *et al* (1999) has indicated that there were~~ two types of mean C turnover times has been ~~indicat~~suggested for terrestrial ecosystems: the

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GPP-based or the NPP-based mean turnover time according to the terrestrial C models with GPP or NPP as their C inputs, respectively (Thompson and Randerson *et al*., 1999~~), where~~ ~~for some models use~~d ~~NPP as their C input and others use~~d ~~just GPP~~ ~~from atmosphere~~ ~~(i.e.~~, NPP is GPP minus ~~autotrophic~~ plant respiration). ~~However, there was no clear distinction in most pervious researches. For example, Zhou and Luo (2008) and Zhou *et al*. (2012) estimated mean turnover time as the NPP-based one.~~ In addition, ~~In most of previous researches,~~ soil C turnover time are usually estimated using field sampling as the global turnover time for model validation. However, the difference among different versions of turnover times ~~(NPP- and GPP-based ecosystem turnover time and soil turnover time)~~ w~~as~~ere still unclear. ~~.~~ Therefore, ~~In Carvalhais et al. (2014), global C turnover times and its covariation with climate were mainly examined. They also compared global C turnover time calculated by the model results from CIMP5 with those from observed data as well as their trend over latitude. Based on their work, we focused on the uncertainty from different observed data (HWSD vs. NCSCD), especially in high latitude. Litter data was updated compared to the study of Carvalhais et al. (2014).~~ We ~~also~~ calculated ~~estimated~~ the GPP-based, ~~–~~ ~~the~~ NPP-based ecosystem and soil turnover times~~MTT~~ through the similar method to explore their difference ~~among them. More importantly, we examined ecosystem C storage over time from changes in~~

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~~C turnover time and/or NPP. Therefore, our study advance the understanding of the uncertainty of global C turnover time (especially in high latitude) and ecosystem C storage from C turnover time with updated data.~~ and its ~~effects~~variability to climate~~s~~.

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~~we examined compared the difference of turnover times between both and also consideredbased on soil, vegetation, and litter C data into soil C to extend the global turnover time, and then . Finally, we focused onquantified the effects of turnover time on ecosystem C storage with the climate changes.~~

Thus, our objectives are:, 1) to estimate the difference between GPP- and NPP-based ecosystem and soil mean turnover time, 2) to explore their relationships with climate, and 3) to quantify ecosystem C storage over time from changes in ecosystem C turnover time from 1901 to 2011.~~this study was designed to quantify the global pattern of ecosystem mean turnover time and its effects on ecosystem C storage caused by change in turnover time changes. Meanwhile, we also quantified the difference among different versions of turnover time.~~ Ecosystem~~Ecosystem mean~~ C turnover time was estimated using the C balance method~~, which are~~ with the ratios of C pools and fluxes. Ecosystem C pools include plant, litter and soil, and C fluxes refer to ecosystem respiration or C influx (GPP/NPP). The current

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datasets from published or unpublished papers have covered all C pools and fluxes~~,~~ but ~~they were at~~with different spatial scales. We thus ~~, so we estimated~~regridded ecosystem mean turnover time at the grid (1°×1°) ~~and biome scale~~ for the ~~accuracy and data match~~comparison.

~~Our objectives are: 1) to estimate the differentce between GPP- and NPP-based ecosystem and soil mean turnover time, 2) to explore their relationships with climate, and 3) to quantify the ecosystem C storage changes caused by change in ecosystem turnover time from 1901 to 2011.~~

2 Materials and methods

2.1 Data collections

Three datasets were used to calculate ecosystem and soil mean turnover times, examine their variability to climate, and investigate ~~its climate~~ effects of C turnover time on ecosystem C ~~sequestration~~storage, including carbon (C) influx (GPP and NPP), C storage in C pools (soil, plant and litter), and climate ~~factors~~ variables (temperature, precipitation and potential evapotranspiration). GPP and NPP were extracted from MODIS products (MOD17) on an 8-day interval with a nominal 1-km resolution since Feb. 24, 2000. The multi-annual average GPP/NPP from 2000-2009 with the spatial resolution of 0.083° ×0.083° were used in this

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study (Zhao and Running, 2010).

The harmonized World Soil Database (HWSD~~) (~~, Hiederer and Köchy, 2012) provided empirical estimates of global soil C storage, a product of the Food and Agriculture Organization of the United Nations and the Land Use Change and Agriculture Program of the International Institute for Applied System Analysis (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012). Hiederer and Köchy (2012) estimated global soil organic carbon (SOC) at the topsoil (0-30cm) and the subsoil layer (30-100cm) from the amended HWSD with estimates derived from other global datasets for these layers. We used the amended HWSD SOC to calculate C turnover time (http://eusoils.jrc.ec.europa.eu). However, HWSD just ~~only~~ provided an estimate of soil ~~carbon~~ C storage at the top 1 m of soil and ~~may~~ have largely underestimated total soil ~~carbon~~C. Jobbagy and Jackson (2000) indicated that global SOC storage in the top 3 m of soil was 56% more than that for the first meter, which could change estimates of the turnover time~~ estimates dramatically~~. We will discuss this ~~issue~~ caveat in the discussion section. It is well known that HWSD has underestimated soil C in high latitude. We thus ~~, so we also~~ estimated turnover time in high latitudes with the Northern Circumpolar Soil Carbon Database (NCSCD), which is an independent survey of soil ~~carbon~~ C in this region (Tarnocai *et al*., 2009). For biomass, Gibbs (2006) estimated the spatial distribution of the above- and

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below-ground C stored in living plant material by updating the classic study (Olson *et al*., 1983; Olson *et al*., 1985) with a contemporary map of global vegetation distribution (Global Land Cover database, ~~)(~~Bartholomé and Belward, 2005). Each cell in the gridded data set was coded with an estimate of mean and maximum ~~carbon~~ C density values based ~~up~~on its land cover class, so this dataset mainly represents plant biomass C at a biome level.

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

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

We aggregated all datasets into a biome level for ~~accuracy and~~ data match, so the biome map was extracted from the GLC 2000 (Bartholomé and Belward, 2005) and regulated by MODIS. We assigned 22 land cover class among three temperature zones (i.e., tropical, temperate and boreal) by taking the most common land cover from the original underlying 0.083 °×0.083 ° data. Eight typical biomes ~~plant function types (PFTs)~~ were zoned with ARCGIS 10 ~~(ESRI Inc.)~~ in corresponding to ~~plant function types (PFTs)~~ plant function types (PFTs)~~PFTs~~ in CABLE model that Xia *et al* (2013): evergreen needleleaf forest (ENF), evergreen broadleaf forest (EBF), deciduous needleleaf forest (DNF), deciduous broadleaf forest (DBF), tundra, shrubland, grassland and cropland. All of the data were regridded by ARCGIS 10 –to a common projection (WGS 84) and $1^0 \times 1^0$ spatial resolution ~~(Todd-Brown *et al*., 2013)~~. The regridding approach for C fluxes and pools (i.e., GPP, NPP, soil C and litter C) assumed conservation of mass that a latitudinal degree was proportional to distance for the close grid cells (Todd-Brown *et al*., 2013). A nearest neighbor approach were used for land cover classes and a bi-linear interpolation were used for climate variables (i.e., temperature, precipitation).

2.2 Estimation of ecosystem mean C turnover time

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~~C turnover time is commonly estimated with the C balance method by calculating the ratio of C total in a C pool and its outflux.~~ Terrestrial ecosystem includes many C pools with largely varying turnover times from days to millennia, but it is difficult to collect the observed ~~observation-based~~ datasets of C pools and flux for each component (e.g., leaf, wood and different soil C fractions) at the global scale. It thus is impossible to estimate individual pools' turnover time. In this study, we estimated the whole-ecosystem C turnover time as the ratio of C pools to flux based on the observed datasets. Certainly, there are some limitations that the ecosystem is taken as a single pool, which will be discussed in the discussion section.

For terrestrial ecosystems, the C pools (C_{pool}) is composed of three parts: plant, litter and soil, and C outfluxes include all C losses ~~include (~~autotrophic [R_a] and heterotrophic respiration [R_h] ~~(R_a, R_h)~~ ~~and losses~~as well as by fires and harvest. However, it is difficult to accurately get the observed respiration (R_a and R_h) in terrestrial ecosystem at the global scale. At~~In~~ the steady state, C outflux~~es~~ equals to C influx, which is the ~~carbon~~ C uptake through GPP, so ecosystem C mean turnover time (MTT_{EC}) can be equivalently calculated as the ratio between C storage in vegetation, soils and litters, and the influx into the pools, GPP:

$$\mathrm{MTT}_{\mathrm{EC}} = \frac{C_{pool}}{\mathrm{GPP}} \qquad (1)$$

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

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~~$\mathrm{MTT}_{soil}=\frac{C_{soil}}{\mathrm{NPP}}$ (2)~~

However, the steady-state in nature is rare, so we relax the strict steady-state assumption and computed the ratio of C$_{pool}$ to GPP as apparent whole-ecosystem turnover time and interpret the quantity as an emergent diagnostic at the ecosystem level (Carvalhais *et al*., 2014).~~ In addition, it is difficult to accurately get the observed respiration (R$_a$ and R$_h$) in terrestrial ecosystem at the global scale.Therefore we~~We used multi-year GPP ~~or NPP~~ to calculate MTT in order to reduce the effect of the non-steady state, since it is difficult to evaluate how this assumption affects model results. To make better comparison, we also estimated the NPP-based ecosystem MTT (MTT$_{EC\_NPP}$ = C$_{pool}$/NPP). The similar method was used to calculate soil MTT (MTT$_{soil}$ = C$_{soil}$/NPP)~~:~~.

~~$\mathrm{MTT}_{soil}=\frac{C_{soil}}{\mathrm{NPP}}$ (2)~~

2.3 The climate effects on ecosystem mean C turnover time

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

$$\mathrm{AI}=\frac{\mathrm{MAP}}{\mathrm{PET}} \qquad (\cancel{3}2)$$

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where PET is the potential evapotranspiration and MAP is mean annual precipitation (Middleton and Thomas, 1997). AI is a bioclimatic index including both physical phenomena (precipitation and potential evapotranspiration) and biological processes (plant transpiration) related with edaphic factors.

The relationships were examined between ~~ecosystem mean C turnover time~~MTT and mean annual temperature (MAT, ^{o}C), ~~mean annual precipitation (~~MAP~~,~~ (mm), and ~~aridity index (~~AI~~)~~ at the biome level. The regression analyses ($MTT = ae^{-bMATorMAP}$) were performed in STATISTICA 10 (StatSoft Inc., 2011), where a and b are the coefficients. The coefficient of determination (R^2) was used to measure the phase correlation between ~~ecosystem mean C turnover time~~MTT and climate factors. Here, we calculated a Q_{10} value (i.e., Q_{10}, a relative increase in mean turnover time for a 10^{o}C increase in temperature, $Q_{10} = e^{10b}$, b, the coefficients of $MTT = ae^{-bMAT\cancel{/}orMAP}$), which ~~that~~ is used in most models to simulate C decomposition.

~~The relationship between ecosystem mean turnover time and temperature was used to estimate mean C turnover time in 1901 and 2011. Here, we assumed that the spatial~~

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~~correlation between temperature and MTT is identical to the temporal correlation between these variables.~~

2.4 The effects of turnover time on ecosystem C storage

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

$$\begin{aligned}&\Delta \text{Cpool} = \text{NPP}_{2011} \times \text{MTT}_{2011} - \text{NPP}_{1901} \times \text{MTT}_{1901} \\ &\Rightarrow \Delta \text{Cpool} = \text{NPP}_{2011} \times \text{MTT}_{2011} - (\text{NPP}_{2011} - \Delta \text{NPP}) \times (\text{MTT}_{2011} - \Delta \text{MRT}) \\ &\Rightarrow \Delta \text{Cpool} = \text{NPP}_{2011} \times \Delta \text{MTT} + \text{MTT}_{2011} \times \Delta \text{NPP} - \Delta \text{NPP} \times \Delta \text{MTT}\end{aligned} \quad (3)$$

where NPP$_{1901(2011)}$ and MTT$_{1901(2011)}$ refer to NPP and MTT at time 1901 or 2011. ΔC$_{pool}$ (ΔNPP or ΔMTT) is the difference between ecosystem C storage (NPP or MTT) at time 2011 and that at time 1901. The first component (NPP$_{2011}$×ΔMTT) represents the effects of changes in –MTT ~~changes~~ on ecosystem C storage. The second component (ΔNPP×MTT$_{2011}$) is the effects of changes in NPP ~~change~~ on ecosystem C storage, and ΔNPP×ΔMTT is the ~~combined~~interactive effects of both changes in NPP and MTT~~PP changes~~~~cross-coupling effects.~~.

To assess ecosystem C storage from the changes in MTT or NPP~~the effects of changes in~~

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~~MTT or NPP on ecosystem C storage~~, ecosystem MTT in 1901 and 2011 was calculated using an exponential equation between ecosystem MTT and temperature ($MTT = ae^{-bMAT}$). Here, we assumed that the spatial correlation between temperature and MTT is identical to the temporal correlation between these variables.~~using an exponential equation between mean turnover time and temperature at a biome level.~~ NPP in 2011 was derived from products (MOD17) and NPP in 1901 was averaged from the eight models' simulated results (CanESM2, CCSM4, IPSL-CM5A-LR, IPSL-CM5B-LR, MIROC-ESM, MIROC-ESM-CHEM, NorESM1-M and NorESM1-ME). Our previous study found that ~~-fo~~the~~r~~ modeled NPP was~~is~~ near to MODIS~~-~~estimated NPP and their difference was mostly less than 0.05 kg C m^{-2} yr^{-1} (Yan *et al.*, 2014).

2.5 Uncertainty analysis and sensitivity Analysis

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

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applied to estimate the confidence interval of ecosystem C storage and ecosystem mean C turnover time.

3 Results

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3.1 Ecosystem C storage

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

3.2 Mean C turnover time

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~~On average, e~~Ecosystem mean C turnover time (MTT) was 25.0 years (with a 95% CI of 23.3-27.7 years) 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 MTT ~~is~~ was ~~smaller~~ shorter than NPP-based MTT with the value of 35.5 years (with a 95% CI of 34.9-36.7 years). MTT ~~varies~~ varied among biomes due to the different climate forcing (Table 1 and Fig 2). The long MTT occurred in high latitude while the short one~~s are~~ was in tropical zone. Among the forest biomes, DNF had the longest MTT with the lowest mean temperature (-7.9 ^{o}C), while the shortest ~~lowest~~ MTT was in EBF due to highest temperature (24.5 ^{o}C) and precipitation (2143 mm). Although ecosystem C storage was low in tundra (14.16 kg C m^{-2}), it ~~has the~~had the longest MTT. Therefore, the order of GPP-based ecosystem MTT among biomes was different from that of ecosystem C storage, with tundra (99.704±6.14 years) > DNF (45.27± 2.43years) or ENF (42.23±2.01 years) > shrubland (27.77±2.25 years) > grassland (26.00±1.41 years) > cropland (14.91±0.40years) or DBF (13.29± 0.68years) > EBF (9.67±0.21 years). Soil MTT had the similar order ~~with~~to ecosystem MTT with the different values (Table 1). In the high latitude, ecosystem MTT could increase up to 145 years if soil C storage was calculated from

NCSCD dataset (Fig. 3) due to higher soil C storage (500 Pg C vs 290 Pg C), compared with the global soil C storage HWSD, while the global average of soil MTT increased to 40.8 years when NCSCD dataset was considered.

3.3 Climate effects on ecosystem mean turnover time (MTT)

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Ecosystem ~~mean C turnover time~~MTT significantly decreased with mean annual temperature (MAT) and mean annual precipitation (MAP) as described by an exponential equation: $MTT = 57.06e^{-0.07MAT}$ (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 correlation between ecosystem ~~mean turnover time~~MTT and aridity index (AI, Fig. 4c). The similar relationships occurred between soil MTT and MAT and MAP ($MTT_{soil} = 58.40e^{-0.08MAT}$, R^2=0.68, P<0.001) and $MTT_{soil} = 109.98e^{-0.002MAP}$~~–~~, R^2=0.48, P<0.001, Fig. 5). There was the different temperature sensitivity of mean turnover time (Q_{10}) for ecosystem MTT (Q_{10}=1.95) and soil MTT (Q_{10}=2.23) at the ~~ecosystem~~ biome scale~~, which was estimated as $Q_{10} = e^{10b}$ based on temperature regression function~~. When MAP was incorporated into a multivariate regression function of ecosystem ~~mean turnover time~~MTT with MAT, the relationships could not be significantly improved~~ (Fig. 6a)~~. While MAP improved the explanation of variance of soil

MTT (R^2 from 0.68 to 0.76~~, Fig. 6b~~), although there ~~were the relationships due to~~was the significant covariance of MAP and MAT (R^2=0.60). However, the relationship between MTT and AI is not clear due to the scale limit~~ (biome level)~~. When we separated ecosystem MTT into two categories according to aridity index (i.e., AI >1 and AI< 1), the relationships between ecosystem MTT and MAT did not significantly change (Figs. 4e, h) compared to that with all data together (Fig. 4b).~~, while t~~ The relationship of ecosystem MTT with MAP significantly increased when AI > 1, but decreased when AI <1. However, the same regression function of soil MTT with MAT largely improved the explanation of the variance when AI>1 (Fig. 5e, $MTT = 58.67e^{-0.08MAT}$, R^2=0.76, P<0.001-). The relationships between soil MTT and MAP were both improved when AI>1 and AI<1 (Fig. 5e, h).

3.4 Temporal variations of ecosystem mean turnover time and C storage

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The average increase in global air temperature is around 1°C from 1901 to 2011 based on the Climate Research Unit (CRU) datasets, ranging from -2.5 to 5.9 °C (Fig. 6c). When the regression function between ecosystem MTT and MAT~~temperature~~ was used to estimate ~~the change in ecosystem mean turnover time~~ecosystem MTT in 1901 and 2011 (Fig. 4), the ecosystem MTT~~average mean turnover time~~ decreased by approximately 4 years on ~~(~~average

(Fig.~~7a~~6a). The largest change in ecosystem MTT occurred in the cold zones. In tundra, ~~mean C turnover time~~ ecosystem MTT decreased by more than 10 years due to the larger increase in temperature (~2°C) than other regions. ~~However, t~~The average NPP increased by approximately 0.3±0.003 Kg C m^{-2} yr^{-1} over 110 years with most range of 0~0.6 Kg C m^{-2} yr^{-1} (Fig. ~~7b~~6b).

The changes in ecosystem MTT and NPP across 110 years would cause decrease or increase in terrestrial C storage. ~~Caused by MTT changes, e~~ Ecosystem C storage decreased by 159.3 ± 1.45 Pg C ~~yr^{-1}~~ from 1901 to 2011 (ΔMTT × NPP) ~~due to~~from the decrease in MTT ~~changes~~, with the largest decrease in tundra and boreal forest (more than 12 g C m^{-2} ~~yr^{-1}~~) ~~but~~ and little decrease in tropical zones (Fig. 7a & e ~~Fig. 8a~~). ~~, and that caused by t~~The ~~combined~~ interactive ~~co-~~changes of both NPP and MTT caused a decrease~~d by~~ of 129.4±1.31 Pg C (ΔMTT × ΔNPP) with the similar spatial pattern (Fig. ~~8c~~7c). However, the increase in NPP directly raised ecosystem C storage up to 1215.4 ± 11.0 Pg C ~~yr^{-1}~~ from 1901 to 2011 with a range of 30-150 g C m^{-2} ~~yr^{-1}~~ in most areas (MTT × ΔNPP, Fig. ~~8b~~7b). The MTT-induced changes in ecosystem C storage only accounted for about 13.5% of that driven by NPP due to the different weights (ΔMTT × NPP vs. MTT × ΔNPP). ~~due to the difference between both of the product factor, so t~~The spatial pattern of the NPP-driven changes mostly represented the

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spatial pattern of the changes in ecosystem C storage (Fig. ~~6d~~7e).

4 Discussion

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~~In Carvalhais et al. (2014), global C turnover times and its covariation with climate were mainly examined. They also compared global C turnover time calculated by the model results from CIMP5 with those from observed data as well as their trend over latitude. Based on their work, we focused on the uncertainty from different observed data (HWSD vs. NCSCD), especially in high latitude. Litter data was updated compared to the study of Carvalhais et al. (2014). We also estimated the GPP-based the NPP-based and soil MTT to explore the difference among them. More importantly, we examined ecosystem C storage over time from changes in C turnover time and/or NPP. Therefore, our study advance the understanding of the uncertainty of global C turnover time (especially in high latitude) and ecosystem C storage from C turnover time with updated data.~~

4.1 Global pattern of mean turnover time

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In this study, we used the ratio of C storage to C flux to calculate the GPP-based, the NPP-based and soil MTT and compared their difference. ~~we estimated spatial patterns of mean turnover time (MTT) with ecosystem C influxes (GPP and NPP) and C pools in plants, litter~~

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

~~–~~The global average of ecosystem MTT was 25.0 years for GPP-based estimation and 50.8 years for NPP-based one, and soil MTT was 35.5 years, which were~~was~~ within the global mean turnover times (26-60 years) estimated by various experimental and modeling approaches with NPP-based estimation (Randerson *et al*., 1999; Thompson and Randerson, 1999)~~ mostly focused on soils, but not ecosystem MTT~~. ~~However, our results indicated that ecosystem MTT (GPP-based estimation) was shorter than soil MTT ($MTT_{EC} = Cpool/GPP$ & $MTT_{soil} = Csoil/NPP$). According to the equations, the difference~~

~~between ecosystem and soil MTT depends on the component carbon pools and the ratio of GPP to NPP. Thus, there was subtle difference in patterns of MTT between both. For example, ecosystem MTT in Evergreen Needleleaf forest (ENF) was larger than soil MTT where the decomposition rate in soil C was very slow.~~ The mean GPP-based MTT ~~are~~ was slightly longer than ~~the result of~~that from Carvalhais *et al*. (2014~~) (~~, 23 years) with the similar method. The difference may result from two aspects. ~~There are two possible factors explaining their difference.~~ Firstly, ecosystem C storage in this study was the sum of ~~the~~ soil, vegetation and litter C pools, while Carvalhais *et al*. (2014) ~~just~~only considered ~~the~~ soil and vegetation C pools. Secondly, the data source of global vegetation C storage was different with our study from ~~global vegetation C storage came from the result of~~ Gibbs (2006) and ~~,~~ ~~while~~ Carvalhais *et al*. (2014) ~~used~~from ~~–~~a collection of estimates for pan-tropical regions and radar remote-sensing retrievals for northern and temperate forests. ~~remote sensing based carbon stock estimates for tropical and Northern Hemisphere vegetation. Here, t~~The difference between GPP-based and NPP-based MTT was determined by the ratio of GPP and NPP, which was ~~entirel~~largely ~~y determin~~influenced by the assumptions of the MODIS NPP algorithm. The ratio of GPP-based and NPP-based MTT (0.49) was smaller than that estimated by Thompson and Randerson (1999, ~~) (~~0.58, 15 year

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vs. 26 year, respectively)~~.~~, largely resulting from different model assumptions for GPP-based (higher normalized storage response function for low turnover time) and NPP-based MTT (for high turnover time) in Thompson and Randerson (1999). –Our NPP-based MTTs for the conterminous USA (37.2 years) and Australia (33.4 years) were shorter than the estimates by the inverse models (46 to 78 years) (Barrett, 2002; Zhou and Luo, 2008; Zhou *et al*., 2012). The NPP-based MTT was shorter than the estimated results from Xia *et al*. (2013) using the CABLE model, although the order of ecosystem MTT across forest biomes was~~is~~ similar.– This is because, in the inverse or CABLE model, ecosystem was often separated into several plant and soil C pools with their distinct C turnover time compared to that with one pool in our study.

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The spatial patterns of ecosystem and soil MTTs ~~is~~were similar~~ The spatial pattern of ecosystem MTT was similar to soil MTT for soil C storage accounted for a large amount of ecosystem C storage. ~~. The difference between NPP-based ecosystem and soil MTTs was ~~depended on ~~the ~~ residence ~~turnover time of vegetation and litter, ~~a trait ~~which ~~was~~was related to plant functional types (PFTs). For instance, the difference between NPP-based and soil MTTs in Australia was ~~small~~shorter (~~as ~~33.4 and 29.8 years, ~~33.4~~respectively) compared

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to that in other regions~~.~~, because ~~Here,In our study,~~ one of the PFTs accounting for a large space of Australia was spare grass with short ~~residence time~~turnover time (~~average value:~~ 3.5 years on average)~~, accounting for a large space of Australia~~. In addition, ~~Within~~ within a specific ~~vegetation~~PFT, different ~~biomes~~ ecosystems may have ~~different~~ diverse ~~residence times~~turnover time due to climate effects. NPP-based and soil MTTs for boreal neadleaf evergreen forest were about 116 years and 98 years, respectively, while both for tropical ~~needleaf evergreen~~ones were about 12 years and 8 years, although ecosystem C in boreal and tropic zone was in the same order of magnitude (~34 vs. 40 kg C m^{-2}) with the similar vegetation C storage (~3.5 kg C m^{-2}). H~~Probably, Highest~~~~h~~igh temperature and humidity-~~temperature and precipitation~~ in tropical zone, which promote decomposition processes, may largely contribute to ~~resulting in~~ the short turnover time compared to those in boreal zone (Sanderman et al., 2003).

~~at the ecosystem level.may contribute to the low turnover time due to is the crucial factor for~~high ~~C decomposition.~~ ~~In addition,~~ ~~We used the same method (the ratio of total C storage to GPP) as Carvalhais et al (2014) to calculate the GPP-based MTT, but two main factors resulted in the difference between both. Firstly, ecosystem C storage in this study was the sum of the soil, vegetation and litter C storage, while Carvalhais et al (2014)~~

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~~just considered the soil and vegetation C. Secondly, vegetation C came from the result of Gibbs (2006) while Carvalhais et al (2014) used remote sensing based carbon stock estimates for tropical and Northern Hemisphere vegetation. The ratio of GPP-based and NPP-based MTT (0.49) was smaller than that estimated by Thompson and Randerson (1999) (0.58, 15 year vs. 26 year, respectively). Our NPP-based MTTs for the conterminous USA (37.2 years) and Australia (33.4 years) were shorter than the estimates by the inverse models (46 to 78 years) (Barrett, 2002; Zhou and Luo, 2008; Zhou *et al*., 2012). The NPP-based MTT was shorter than the estimated results from Xia *et al*. (2013) using the CABLE model, though the order of MTT across forest biomes is similar. The difference between GPP-based and NPP-based MTT was determined by the ratio of GPP and NPP which entirely determined by the assumptions of the MODIS NPP algorithm. In addition,~~ In our study, we only used soil C in the top 1 m to estimate ecosystem MTT, which would be ~~largely~~ underestimated for the important amounts of C stored between 1 and 3m depth (Jobbagy and Jackson, 2000). According to the SOC estimation of Jobbagy and Jackson (2000), the MTT in the top 3 m could increase to 34.63 years for GPP-based, 70.68 years for NPP-based and 55.38 years for soil. ~~If SoilGrids (Hengl et al., 2014) was used to estimate C MTT, the MTT in the top 1 m could increase to 30.3 years for GPP-based, 66.9 years for NPP-based and 45.7 years for soil.~~

Therefore, the C storage in deep soil layers (>1m) should be considered to estimate ecosystem MTT and the accurate estimate of the deep soil C storage, which deserves to the further study in the future.

~~the accurate estimates of total soil C are important to estimate ecosystem MTT.~~

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4.2 The sensitivity of turnover time to climate

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The estimated ~~mean turnover time (MTT)~~MTT was shortest in tropical zones and increased toward high-latitude zones (Fig. 2), which were often affected by the spatial patterns of temperature and moisture. The results was similar to those the previous studies based on SOC data set (Schimel *et al*., 1994; Sanderman *et al*., 2003; Frank *et al*., 2012; Chen *et al*., 2013) and root C pools (Gill and Jackson, 2000). Ecosystem MTT had negative exponential relationships with MAT (Fig 4), similar to those with soil MTT, ~~probably~~ due to temperature dependence of ~~decomposition and~~ respiration rates~~the temperature dependence of respiration~~ (Lloyd and Taylor, 1994; Wen *et al*., 2006). Our results showed that the temperature sensitivity of ecosystem MTT was lower than that of soil C pool (Q_{10}: 1.95 vs. 2.23, Figs. 4 &5), which was similar to the previous research (Sanderman *et al*., 2003), because wood would~~may~~ decompose at much lower rates than SOM due to the longer MTT of wood (Zhou *et al*., 2012). Ecosystem MTT ~~was~~ had no significant differences between very humid zone

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(AI>1.0) and other zones (AI<1.0, Fig 4). However, the better relationships between MTT and MAP occurred in very humid zone (AI>1.0) than other zones, which was similar to soil pool, but soil MTT have the higher sensitivity to precipitation than ecosystem MTT under AI>1. SOM decomposition often increased with added moisture in aerobic soils (Trumbore, 1997), because the metabolic loss of various C pools increased under warmer and wetter climates (Frank *et al*., 2012), resulting in high sensitivity of MTT to MAP. Thus, the fitting regression combining~~ed~~ MAT and MAP clearly improved soil MTT ($R^2=0.76$, $p<0.001$). In arid or semi-humid regions, the increase in C influx with MAP was more rapid than that in decomposition (Austin and Sala, 2002). In addition, water limitation ~~may~~ could suppress the effective ecosystem-level response of respiration to temperature (Reichstein et al., 2007). At an annual scale, temperature is still the best predictor of MTT (Chen et al., 2013), which explained up to 77% of variation of MTT (Fig 4). Other ecosystem properties (e.g., ecosystems types, soil nitrogen) ~~may~~ could explain ~~cause~~ the rest of the variation in the estimates of MTT.

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

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Terrestrial ecosystems play an important role in regulating C ~~cycling~~ balance to combat global change. Current studies suggest that the terrestrial biosphere is currently a net C sink (Lund *et al*., 2010), but it is difficult to assess the sustainability of ecosystem C storage due to the complexity of terrestrial ecosystem in response to global change (Luo, 2007). In this study, we ~~first tried to assess the potential shifts of ecosystem C storage capacity by changes in both NPP and ecosystem MTT.~~ quantified the changes ~~of~~in ~~the~~ ecosystem C storage ~~changes~~ from 1901 to 2011 and partitioned ~~separated~~ it into three parts~~:~~ ~~caused by~~from the changes in NPP, in ~~the changes in~~ ecosystem MTT, and ~~ecosystem MTT, and~~ ~~the combined changes of~~ in both NPP and MTT ~~the combined - changes inof both NPP and MTT~~(seeing equation 3). Our results ~~indicated~~ showed that the decrease in MTT increased ecosystem C loss over time due to the increase in C decomposition rates, while increased NPP enhanced ecosystem C uptake ~~from 1901 to 2011~~due to the decrease in CO_2 input to atmospheric and the increase of vegetation C stocks.

Current datasets have showed an increase in NPP (e.g., Hicke *et al*., 2002; Potter *et al*., 2012), leading to increasing terrestrial C uptake. Our results showed that the NPP increased by approximately 0.3 k~~K~~g C m^{-2} yr^{-1} ~~Driven by NPP changes~~ from 1901 to 2011~~,~~ and the resultant terrestrial C uptake is 1215.4 Pg C (with average year of 11.0 Pg C yr^{-1}), ~~our results showed that global C storage would increase by 11.0 Pg C yr^{-1} and~~ The ecosystem C storage

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in conterminous USA increased 0.4 Pg C yr^{-}~~^{1}~~^{1}~~at the global scale and conterminous USA, respectively~~, which was larger than ~~. Our estimated ecosystem C storage in USA was larger than the one~~that from inverse models (Zhou and Luo, 2008; Zhou *et al*., 2012) and was ~~–but~~ comparable to C sink from atmospheric inversion (0.30-0.58 Pg C yr^{-1}~~)~~ ~~(~~, Pacala *et al*., 2001). ~~However, t~~The shortened MTT caused C losses from ecosystems from 1901 to 2011 (about 1.45 Pg C yr^{-1}), indicating that ecosystem C storage decreased with ~~world~~climate warmings ~~due to the decreased MTT~~ (Fig. 7e). ~~, indicating that the magnitude of ecosystem C uptake is likely to decrease under warming due to decreased MTT.~~However, ecosystem ~~Ecosystem~~ C ~~release caused by~~losses from the decrease in MTT ~~decrease~~ only accounted for 13.5% of that driven by changes in NPP ~~increase~~, so terrestrial ecosystem was still a net sink~~still causing resulting in a net sink in terrestrial ecosystem~~. The largest changes of MTT occurred in high latitude regions (Fig. 6a), resulting in the largest loss of terrestrial C (Fig. 7e)~~The largest changes in terrestrial C storage occurred in high latitude~~, where it is more vulnerable to ~~loss with~~ climate change (Zimov *et al*., 2006). However, the direct release of CO_2 in high latitude through thawing would be another large source ~~in the decrease of~~ of decreasing ecosystem C storage ~~losses~~ under climate warming (Grosse *et al*., 2011), which cannot be assessed by MTT or NPP. Interestingly, our results suggested that the substantial changes in terrestrial C storage occurred in forest and shrubland (50% of total) due to the relatively longer MTT, ~~which caused~~~~causing~~leading to the larger terrestrial C uptake driven by NPP increase compared with others. In addition, ~~Moreover, the largest absolute and relative changes of MTT occurred in high latitude regions (Fig. 6a), which would largely decrease the terrestrial C uptake driven by NPP under global warming. Furthermore,~~ the C uptake in cropland and grassland ~~has been~~ could be underestimated probably due to the ignorance of the effects of land management.

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

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Estimated MTT in this study were based on C influxes (GPP or NPP) and C pools in plants, litter and soil at the grid scale and can be used to quantify global, regional or biome-specific MTT, which was very important to evaluate terrestrial C storage. However, the balance method and data limitation ~~may~~ could cause biases to some degree in estimated ecosystem MTT~~ in a few sources~~. First, ~~Here, we assumed that the nature was at the steady state and took the whole ecosystem as a single pool similar in Sanderman *et al* (2003), which have some caveats in the estimation of mean turnover time.~~ we assumed that ecosystem ~~C cycle~~ is at the steady state~~,~~ when MTT was estimated. It is difficult to define the steady state,

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especially for soil C dynamics (Luo and Weng, 2011). Actually, maintaining a steady state~~-~~ ~~without change~~ is rare ~~in nature~~ for a long time and ~~any~~ ecosystems ~~process~~ could be only close to reach the steady state in the short time. For example, permafrost will be thawing both gradually and catastrophically (Schuur *et al*., 2008). The assumption of the steady state would cause the overestimation or underestimation of ecosystem MTT (Zhou *et al*., 2010). Second, MTT was estimated on the basis of C pool and flux measurements~~,~~. The quality of the current datasets would determine the accuracy of ecosystem MTT estimates.~~whose uncertainties in the current datasets of C pools and fluxes would limit influence the estimated MTT.~~ For example, the amendments of typological data (derived from the global ISRIC-WISE datasets) and soil bulk density had largely improved the estimates of the SOC storage from HWSD (1417 PgC) (Hiederer and Köchy, 2012). Soil C storage calculated from NCSCD dataset would improve the ecosystem MTT in high latitudes (Fig. 3), compared with that from HWSD datasets. Compared to HWSD dataset, the MTT in the top 1m could increase to 30.3 years for GPP-based, 66.9 years for NPP-based and 45.7 years for soil when ~~If~~ SoilGrids was used (Hengl et al., 2014)~~ was usedused to estimate C MTT,~~. ~~the MTT in the top 1 m could increase to 30.3 years for GPP-based, 66.9 years for NPP-based and 45.7 years for soil.~~However, it is difficult to quantify the uncertainty in MTT caused by uncertainties of

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~~the pool and flux datasets~~the current datasets due to lack of quantitative uncertainty ~~estimates~~ in these datasets. In addition, disturbance and forest age structure will influence large-scale accumulation biomass, the partitioning of C into pools with different turnover times and thereby the estimates of long-term C ~~sequestration~~ storage and turnover time (Zaehle et al., 2006), which cannot be reflected in the current algorithms. Probably, the inverse modeling can be a feasible method to evaluate the effect of ~~Combining the current~~the disturbance and forest age ~~structure into models should improve the estimate of turnover time~~on the estimates of turnover time. ~~The calculation of MTT by the ratio of the pool to flux would reduce these uncertainties associated with the pool and flux data sets in some degree.~~

Third, the uncertainties in the relationships of ecosystem MTT with MAT and MAP would influence the estimates of ecosystem MTT, ~~ecosystem MTT would influence cause the uncertainties in their relationships with between MAT, and MAP,~~ causing the propagation of uncertainty in ecosystem C storage. ~~and ecosystem MTT.~~ To simplify the calculation, we aggregated all datasets into a biome level, leading ~~in~~ to a fixed parameters across biomes. However, the response magnitude in soil respiration to warming varied over time and across sites (Rustad *et al*., 2001; Davidson and Janssens, 2006), resulting in multiple temperature response function. Changes in MTT for 1901and 2011 were estimated using the exponential

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function between ~~mean turnover time~~MTT and temperature, resulting in underestimation or overestimation of MTT and the resultant changes on ecosystem C storage. ~~f~~For example, when the relationship between soil MTT and temperature was used ($MTT_{soil} = 58.40e^{-0.08MAT}$), ~~the changes on~~ the soil C storage from MTT changes ~~ecosystem C storage caused by MTT~~could decrease ~~-could decrease to~~ 161.42 Pg C and that driven by NPP uptake could increase 1125.6 Pg C with the similar spatial pattern to the ecosystem. In addition, we assumed that the current-day spatial correlation between temperature and MTT was identical to temporal correlation between these variables, although~~. However,~~ ~~Moreover,~~ such assumption cannot reflect some~~the~~ processes like acclimation of microbial respiration to warming or shifts in plant species over time.

4.5 Implication for land surface models

Our results may provide insights as to how MTT and ecosystem C storage varied with climate and over time.~~Our study quantified the spatial variation in ecosystem C storage over time from changes in C turnover time and/or NPP and indicate that the larger uncertainties in the spatial variation of MTT than temporal changes would lead to a greater impact on the estimates of ecosystem C storage~~ Our ~~results~~study could thus offer several suggestions for

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future experimental and modeling research with the goals to improve estimates of ecosystem C storage. First, ~~this study demonstrated that spatial variability of ecosystem mean C turnover time had higher uncertainties compared to temporal variability, which was mainly caused by the estimation of soil C storage.~~ our~~this study demonstrated that~~ the substantial changes in terrestrial C storage occurred in forest and shrubland covering large area with ~~these regions with~~ the relatively long turnover ~~,compared with othersbecause~~time, because~~ covering large area.~~ MTT~~ C turnover time~~ dominated~~s~~ the uncertainty in the estimates of terrestrial C storage~~, but~~ and ~~the spatial variability of ecosystem mean C turnover time had higher uncertainties compared to temporal variability~~. These uncertainties ~~, which was~~were largely ~~mainly caused by~~resulted from ~~the estimation of soil C storage~~. Therefore, further work should focus on the accurate estimation of ~~soil C storage~~C turnover time –with numerous observational data ~~in estimating the spatial patterns of mean C turnover time~~ at regional or global scale and the evaluation of uncertainty from datasets and the assumption (e.g., ~~likely~~ the steady-state). ~~Land surface model should consider spatial variability of ecosystem mean C turnover time, especially at high latitude.~~

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Second, there were the inconsistent responses of ecosystem C turnover time to climate variables in the current global vegetation models (Friend *et al*., 2013). Our results showed that ~~that temperature was the best predictor for ecosystem C turnover time (R^2 = 0.77, $p<0.001$) on annual scale, which declined with rising temperature. Such temperature relationship with mean C turnover time can be incorporated into land surface models to improve the forecast of terrestrial climate-C cycle feedback.~~the temperature sensitivity of ecosystem C turnover time was lower than that of soil C pool (Q_{10}: 1.95 vs. 2.23), while the relationship between ecosystem C turnover time and precipitation under low aridity conditions (AI>1) was much stronger than those for all or AI<1 conditions. Although ~~all~~ global carbon models have currently considered moisture stress on vegetation, ~~but~~ the incorporation of moisture or precipitation stress into soil decomposition should be strengthened, especially in high-latitude zones with greater warming and increased precipitation. ~~Third, our results showed that temperature sensitivity of ecosystem MTT was lower than that of soil C pool while precipitation was less sensitive to ecosystem turnover time than soil C turnover time with different effects in very humid zone and arid zone. Now all global carbon cycle models have considered moisture stress on vegetation, but the incorporation of moisture or precipitation stress into soil decomposition should be strengthened, especially in high-latitude zones with greater warming and increased~~

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~~precipitation.~~

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

Data availability

All of the original ~~elevation~~ data (MOD 17, HWSD, NCSCD, vegetation C production of Gibbs *et al*. (2006), ~~and~~ litter dataset from Holland *et al*.~~,~~ (2005), climate variables from the Climate Research Unit (CRU_TS 3.20)) used in this study ~~is~~ are open and shared. ~~are~~ We provided full citations for data sources in MS and the download links in the supplemental information.

~~referenced in Fig 1 of the manuscript and full citations for data sources are provided.~~

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Table 1. The density of ecosystem C storage (k~~K~~g C m^{-2}), mean turnover time (MTT, years), mean annual temperature (MAT), and precipitation (MAP) for the eight biomes. Ecosystem MTT were calculated based on 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

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

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Broadleaf forest.

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Figure Caption List

Figure 1. Spatial pattern of soil C (a), biome C (b), litter C (c), and ecosystem C storage (d) at the grid scale (1°×1°). Unit~~e~~: k~~K~~g C m^{-2}. Ecosystem C storage was calculated from plant biomass, soil, and litter C pools.

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

Figure 3. Spatial pattern of mean turnover time (years) in high latitude ~~. (a)~~ b~~B~~ased on~~–~~ soil C storage from HWSD data (a) and ~~, (b) based on soil C storage from~~ NCSCD data (b).

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

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

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

Figure ~~7~~6. Changes in~~ values of~~ ~~ecosystem~~ mean ecosystem mean turnover time (MTT, unit: year~~ a~~) driven by temperature change (a), changes in ~~ and~~ NPP (unit: ~~K~~kg C m^{-2}yr^{-1}, b), and changes in temperature (°~~(°~~C, c) from 1901 to 2011. Changes in MTT from~~for~~ 1901 and 2011 were~~as~~ calculated by the temperature-dependence function showing in Fig. 4. Changes in NPP from~~in~~ 1901 and 2011 ~~was~~ were derived from models' average and MODIS.

Figure ~~8~~7. Altered ecosystem carbon storage due to changes in mean turnover time (MTT, NPP2011×ΔMTT, a), net primary production (NPP, MTT2011×ΔNPP, b), and interaction of NPP and MTT (ΔMTT×ΔNPP, c). Panels d and e are total altered ecosystem C storage changes due to changes in MTT, NPP, and MTT×NPP and their latitudinal gradients from panels a-d, respectively.~~Change values of ecosystem carbon storage caused by mean turnover time change (NPP$_{2011}$×ΔMTT, a), by NPP change (MTT$_{2011}$×ΔNPP, b) and by NPP change and MRT change (ΔMTT×ΔNPP, c) and total ecosystem C storage changes (d) latitudinal gradients of whole ecosystem carbon storage change values for a, b, c and d (e).~~. Unit: g C m^{-2} yr^{-1} ($\Delta C_{pool} = NPP_{2011} \times \Delta MTT + MTT_{2011} \times \Delta NPP - \Delta NPP \times \Delta MTT$).

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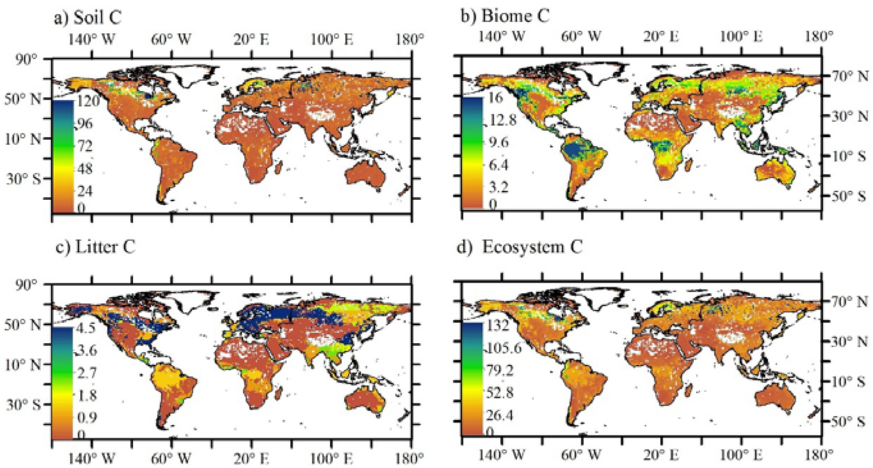

a) Soil C
b) Biome C
c) Litter C
d) Ecosystem C
140° W
60° W
20° E
100° E
180°
90°
50° N
10° N
30° S
70° N
30° N
10° S
50° S
120
96
72
48
24
0
16
12.8
9.6
6.4
3.2
0
4.5
3.6
2.7
1.8
0.9
0
132
105.6
79.2
52.8
26.4
0

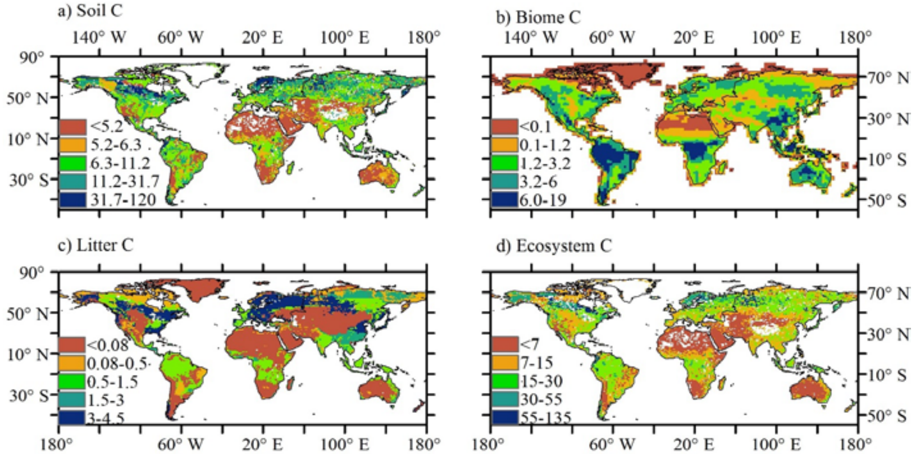
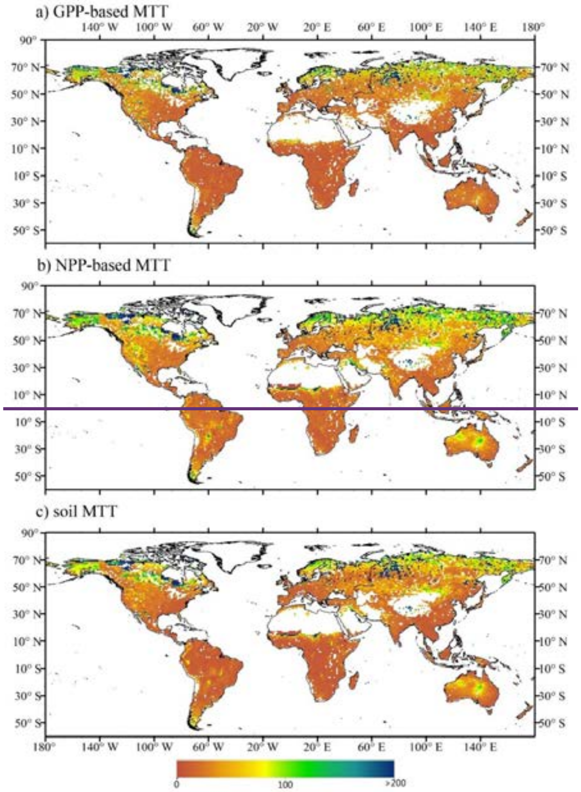

a) Soil C
b) Biome C
c) Litter C
d) Ecosystem C
140° W
60° W
20° E
100° E
180°
90°
50° N
10° N
30° S
70° N
30° N
10° S
50° S
<5.2
5.2-6.3
6.3-11.2
11.2-31.7
31.7-120
<0.1
0.1-1.2
1.2-3.2
3.2-6
6.0-19
<0.08
0.08-0.5
0.5-1.5
1.5-3
3-4.5
<7
7-15
15-30
30-55
55-135

Figure 1. Spatial pattern of soil C (a), biome C (b), litter C (c), and ecosystem C storage (d) at the grid scale (1º×1º). Unit: k~~K~~g C m^{-2}. Ecosystem C storage was calculated from plant biomass, soil, and litter C pools.


a) GPP-based MTT
b) NPP-based MTT
c) soil MTT
140° W
100° W
60° W
20° W
20° E
60° E
100° E
140° E
180°
90°
70° N
50° N
30° N
10° N
10° S
30° S
50° S
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100
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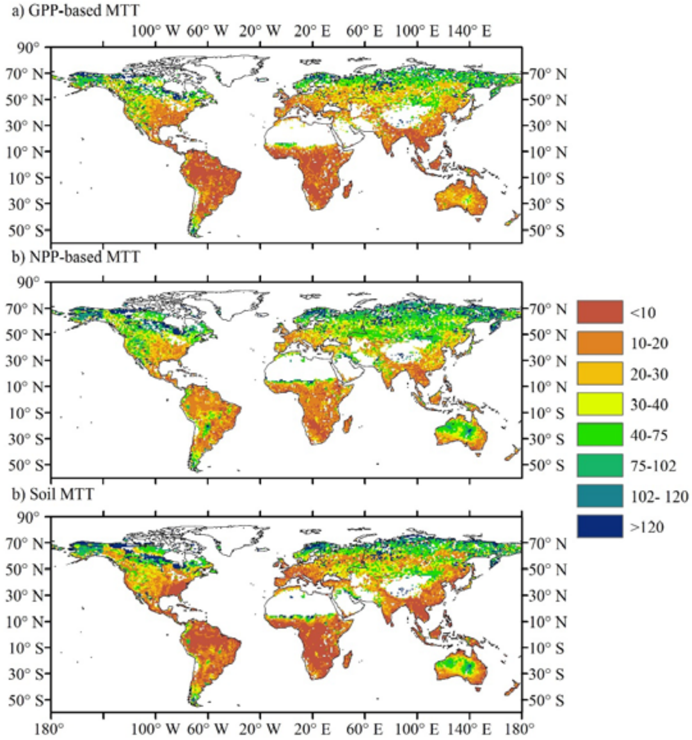

Figure 2. Spatial pattern of mean turnover time (MTT, years)~~, calculated~~ based on biome types and GPP (a) or NPP (b) and soil C (c) using the C balance methods.

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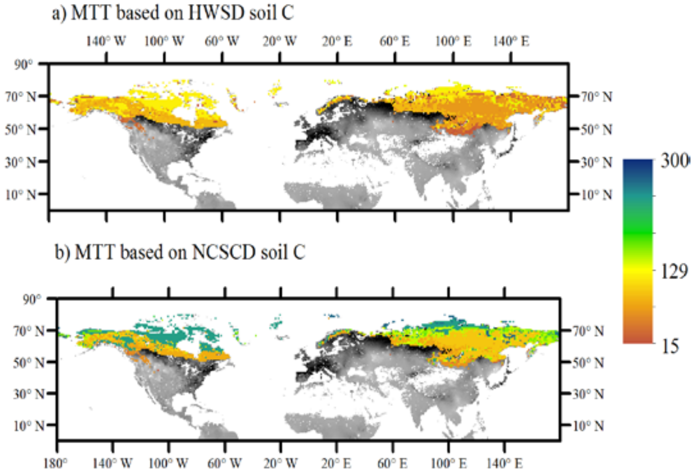

Figure 3. Spatial pattern of mean turnover time (years) in high latitude~~. (a) B~~ based on soil C storage from ~~–~~HWSD data (a)~~,~~ ~~(b) based on soil C storage from~~and NCSCD data (b).

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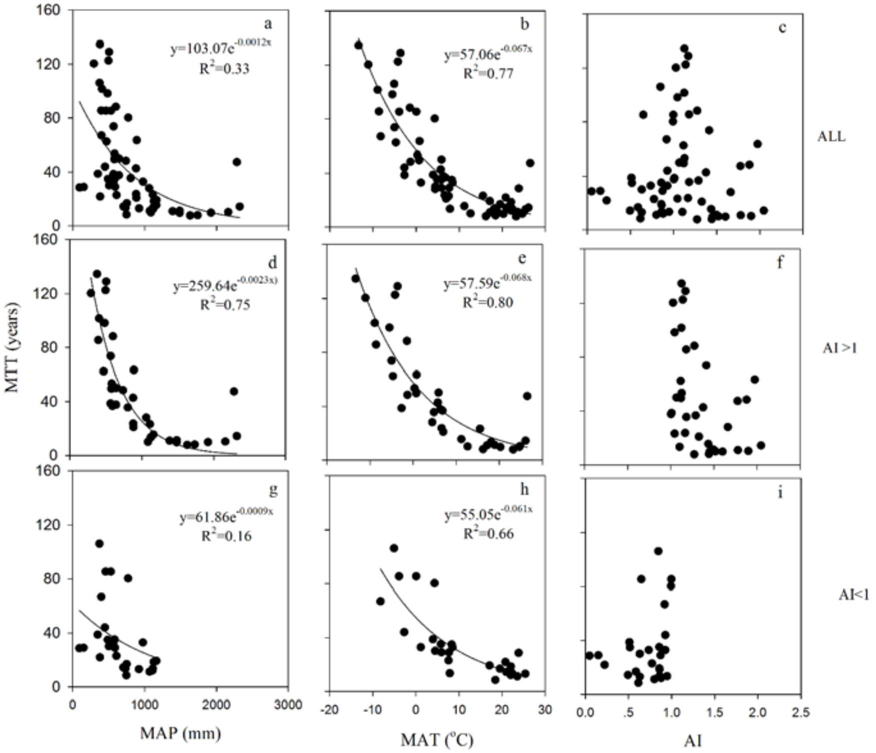

Figure 4. Relationships between ecosystem mean turnover time (MTT) and multi-annual temperature (MAT, a) or ~~,~~precipitation (MAP, b) at different aridity indexes (AI, c). Each data point stands for average values of each biome. Biomes were assigned into 62 types

according to land cover and three temperature zones.

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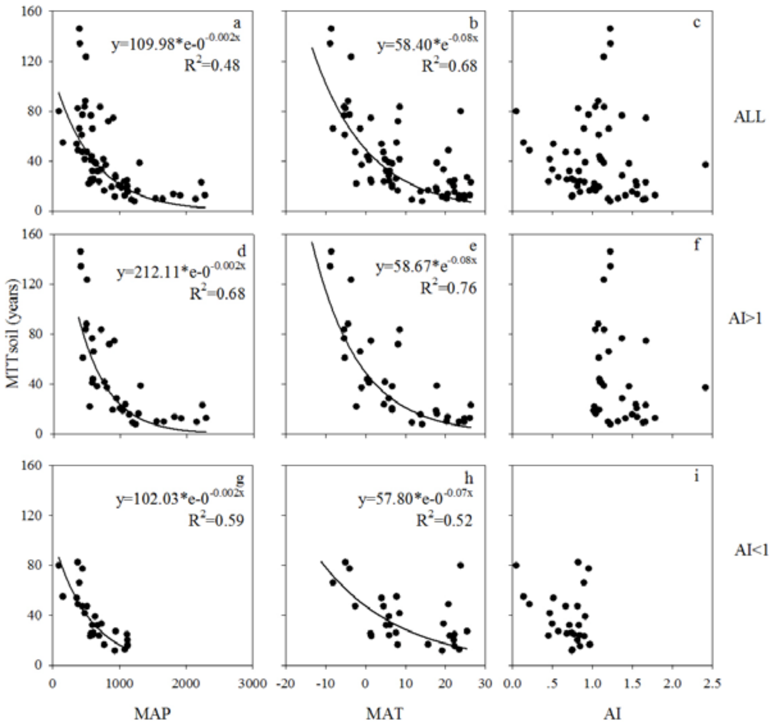

Figure 5. Relationships between soil mean turnover time (MTT_{soil}) and multi-annual temperature (MAT, a)~~,~~ or precipitation (MAP, b) at different aridity indexes (AI, c). Each data point stands for average values of each biome. Biomes were assigned into 62 types according to land cover and three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

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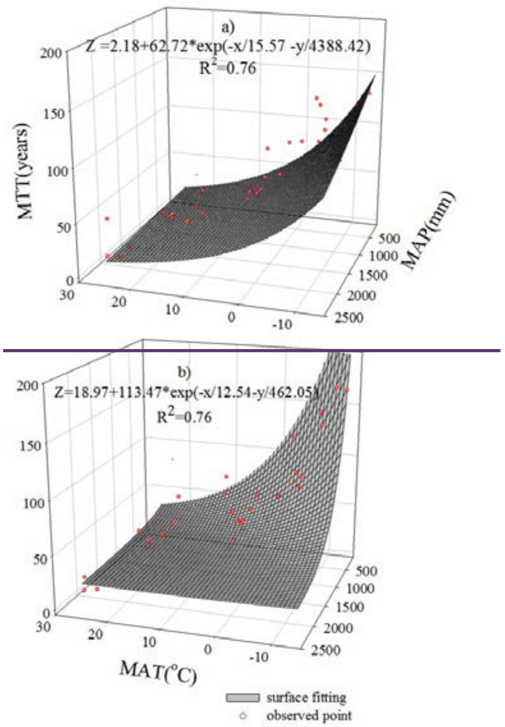

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~~Figure 6~~~~. Surface fitting between mean turnover time and multi-annual temperature (MAT), precipitation (MAP) for ecosystem (a) and soil (b).~~

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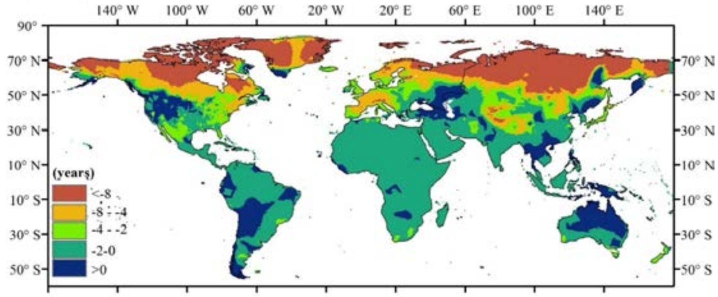
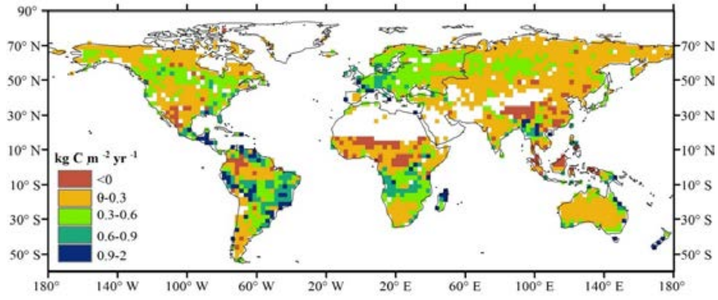
a) Changes of MTT from 1991 to 2011



b) Changes of NPP from 1991 to 2011



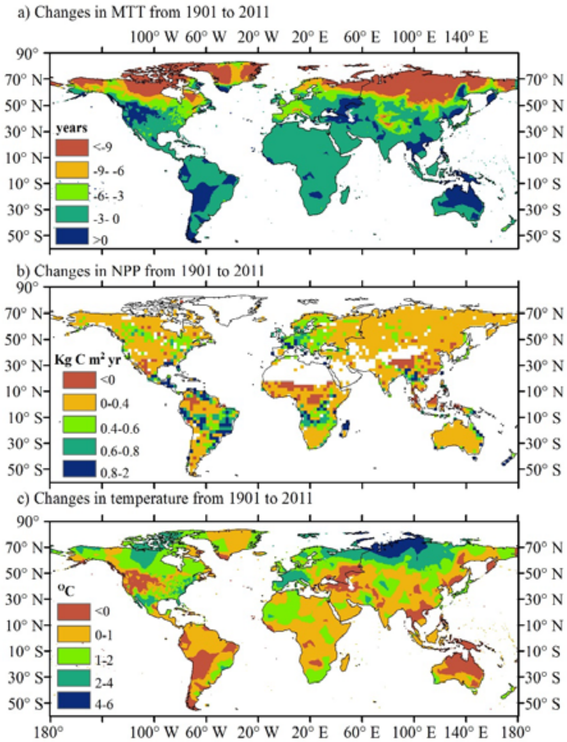


Figure 6. ~~Change~~Altered~~ values of ecosystem ~~ mean ecosystem mean turnover time (MTT, unit: year~~r a~~) driven by temperature change ~~change~~(a),~~ and~~ changes in NPP (unit: Kg C m^{-2}yr^{-1}, b), and changes in temperature (ºC, c)~~(ºC)~~ from 1901 to 2011. Changes in MTT for 1901 and 2011 w~~as~~ere calculated by the temperature-dependence function showing in Fig. 4.

Changes in NPP in 1901 and 2011 were~~as~~ derived from models’ average and MODIS.~~**Figure 7.** Change values of ecosystem mean ecosystem mean turnover time (MTT, unit: year a) driven by temperature change and NPP (unit: Kg C m^{-2} yr^{-1}) from 1901 to 2011. MTT for 1901 and 2011 was calculated by the temperature-dependence function showing in Fig. 4. NPP in 1901 and 2011 was derived from models’ average and MODIS.~~

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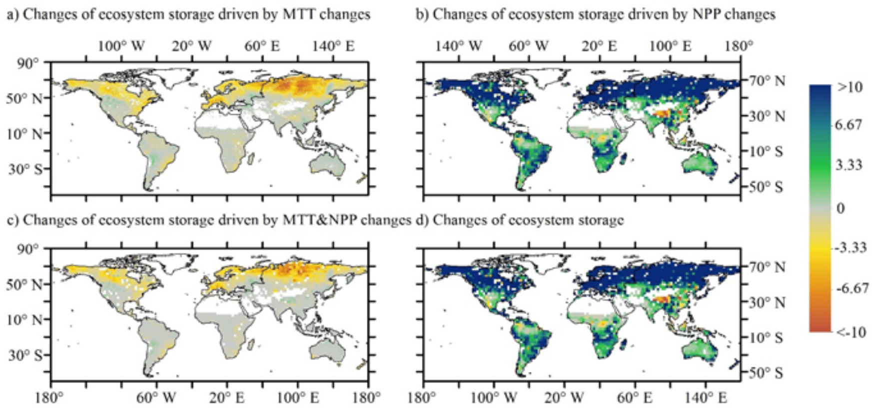

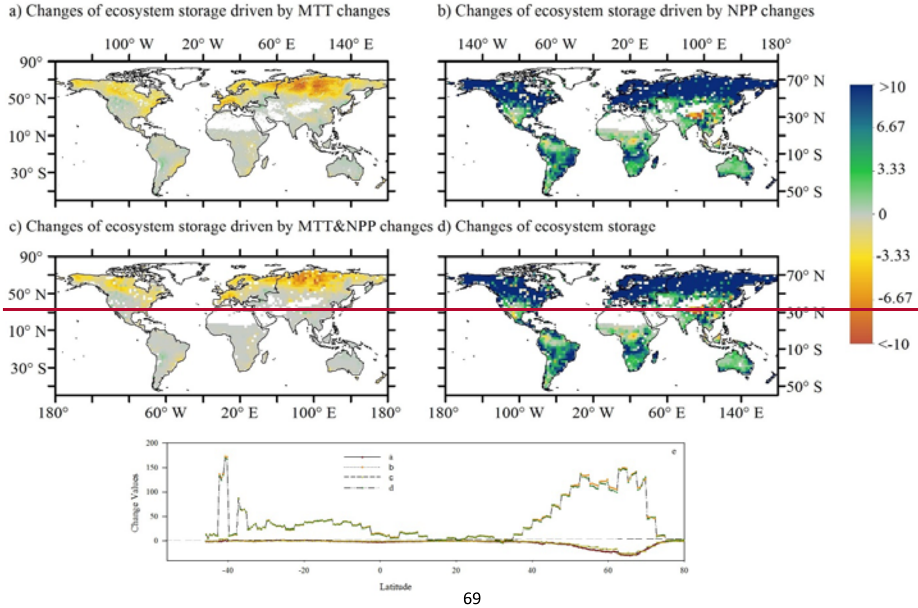

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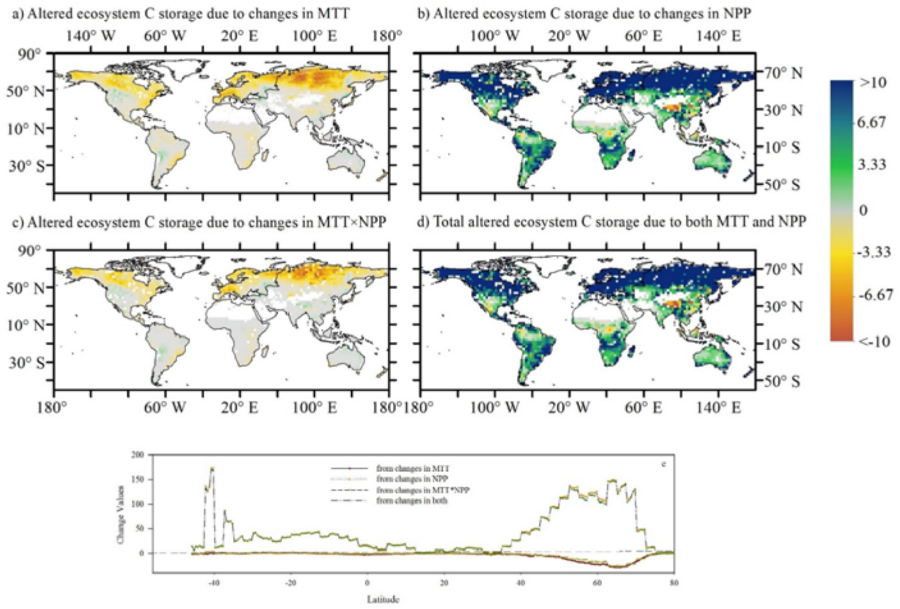

Figure 7. Altered ecosystem carbon storage due to changes in mean turnover time (MTT, NPP2011×ΔMTT, a), net primary production (NPP, MTT2011×ΔNPP, b), and interaction of NPP and MTT (ΔMTT×ΔNPP, c). Panels d and e are total altered ecosystem C storage changes due to changes in MTT, NPP, and MTT×NPP and their latitudinal gradients from panels a-d, respectively. Unit: g C m^{-2} yr^{-1} ($\Delta C_{pool} = NPP_{2011} \times \Delta MTT + MTT_{2011} \times \Delta NPP - \Delta NPP \times \Delta MTT$). ~~Change values of ecosystem carbon storage caused by mean~~

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~~turnover time change (NPP2011×ΔMTT, a), by NPP change (MTT2011×ΔNPP, b) and by NPP change and MRT change (ΔMTT×ΔNPP, c) and total ecosystem C storage changes (d), and latitudinal gradients of whole ecosystem carbon storage change values for a, b, c and d (e). Unit: g C m^{-2} yr^{-1} ($\Delta C_{pool} = NPP_{2011} \times \Delta MTT + MTT_{2011} \times \Delta NPP - \Delta NPP \times \Delta MTT$).~~

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