Response to comments from reviewer #2

Dear editor:

Thank you very much for handling our manuscript. We really appreciate the reviewer for the invaluable suggestions and comments on our manuscript. Below, we address all the comments from reviewer #2 point-by-point. The comments are italicized and our response follow in blue, and we hope we could address the concerns from reviewer.

Reply to Reviewer #2

General comments:

Comment 1B: Erqian Cui et al. studied the annual NEP and the inter-annual variability of NEP and intended to provide local indicators to better understand their spatial patterns at the FLUXNET site level. I find this study relevant as it is important to have a better understanding of the factors controlling the spatial and inter-annual variability of NEP. However, I have some concerns about some aspects of the method and how the results are presented (see More specific comments section). In addition, there are some results presented in this study that do not provide ay significant new information compared to the available literature (e.g. spatial patterns of annual NEP and IAV of NEP at the global scale). Plus, most of the analysis is done at FLUXNET site level, therefore I do not really the point of using the FLUXCOM and CLM4.5 for the presented study. In short, although I find the presented study suitable for the scope of Biogeosciences, the manuscript is still in its early stage to be accepted as it is, therefore I suggest to make major revisions before potential acceptance.

Response: Thanks for the valuable suggestions. Based the reviewer's comment, we have made a substantial revision on both of the *Method* and *Results* sections.

First, we have deleted Figure 1 from *Results*, and moved the related content to the *Introduction Section* as the background of our study.

Second, we have showed the major findings with FLUXNET observations and the atmospheric inversion product (i.e. new results in Figure 1B). Then as suggested by the reviewer, we have benchmarked the simulations from the compiled global product and the process-based global model both at the global scale and at the FLUXNET site level (i.e. new results in Figure 4B).

Specific comments:

Comment 2B: L. 3-4 The title is very confusing and does not really reflect the findings of the analysis. Please try to rephrase the title so that it matches the message the analysis is trying to convey.

Response: Thanks, we have revised the title as "Spatial variations in terrestrial net ecosystem productivity and its local indicators"

Comment 3B: L. 38 "machine-learning-derived database." This concept seems odd and confusing. What about something like "based on a compiled global dataset and a machine learning method". The use "'machine-learning-derived database' is also not entirely true because, as far as I understood, only the FLUXCOM dataset is based on machine learning approaches. FLUXNET in-situ data and the CLM4.5 product are not using any machine-learning methods.

Response: We have rephrased the relevant statement as "the compiled global product and the process-based global model.".

Comment 4B: L. 65 "is related to the strength of carbon sink". It can also relate to the strength of the carbon source. Consider rephrasing to be more generic.

Response: Thanks, we have rephrased this sentence as "is related to the strength of carbon exchange" .

Comment 5B: L. 68 Not convinced by the use of 'asynchronously' all over the manuscript, particularly because the results presented in the manuscript do not provide evidence that the spatial patterns of annual NEP or IAV_NEP are not simultaneous or concurrent in time.

Response: Thanks, we have deleted the word "asynchronously" all over the manuscript and replaced it with "variation".

Comment 6B: L. 76-77 'environmental fluctuations among years'. Musavi et al., 2017 attributed the year-to-year variation to species richness and stand age. In the same line, Besnard et al. 2018 attributed most of the annual NEP variation to forest age.

Response: Thanks, we have revised this sentence as "Many previous analyses have attributed the IAV_{NEP} at the site level to the different sensitivities of ecosystem photosynthesis and respiration to environmental drivers (Gilmanov et al., 2005; Reichstein et al., 2005) and biotic controls (Besnard et al., 2018; Musavi et al., 2017).".

Comment 7B: L. 82-84 Can this sentence be merged with the 1st sentence of the paragraph (L.71-72)? They seem quite redundant.

Response: Thanks. Sorry for the misunderstanding of these two sentences. The first sentence illustrates the decomposition of NEP as the difference between photosynthesis and respiration, while the last sentence leads to the decomposition of NEP directly into CO_2 uptake flux and CO_2 release flux. To make these points clearer, we have rephrased this sentence as:

> "Alternatively, the annual NEP of a given ecosystem can be also directly decomposed into CO_2 uptake flux and CO_2 release flux (Gray et al., 2014), which are more direct components for NEP (Fu et al., 2019). It is still unclear whether ecosystem CO_2 uptake and release fluxes could be attributed to some simple indicators for the spatially varying NEP and IAV_{NEP} in terrestrial ecosystems."

Comment 8B: L. 84-86 The last sentence of this paragraph seems a bit out of the context of the whole paragraph. Consider improving the transition between the last sentence of the paragraph and the entire paragraph.

Response: Thanks, we have rephrased this section and strengthened our points by adding the following sentences:

> "However, despite the previous efforts in a predictive understanding of the land-atmospheric C exchanges, the multi-model spread has not changed over time (Arora et al., 2019). Therefore, it is imperative to explore the potential indicators for the spatially varying NEP, which could help attribute the spatial variation of NEP and IAV_{NEP} into different processes and provide valuable constraints for the global C cycle. Alternatively, the annual NEP of a given ecosystem can be also directly decomposed into CO_2 uptake flux and CO_2 release flux (Gray et al., 2014), which are more direct components for NEP (Fu et al., 2019). It is still unclear whether ecosystem CO_2 uptake and release fluxes could be attributed to the spatially varying NEP and IAVNEP in terrestrial ecosystems."

Comment 9B: L. 85 "could be integrated into some simple indicators". I would use the term 'decompose' instead of 'integrated'. After all, the authors want to decompose the contribution of a series of carbon uptake and carbon release metrics to annual NEP and IAV_NEP.

Response: Thanks, done as suggested.

Comment 10B: L. 98-99 Not sure that FLUXCOM products are the best to assess IAV_NEP. Please check Jung et al. 2020 to understand the issues of such products when looking at IAV_NEP. Why not using NEE derived from atmospheric inversions though (e.g. JenaCarboScope (Rödenbeck et al., 2018), CAMSv17r1 (Chevallier et al., 2005, 2019) and CarbonTracker-EU (Peters et al., 2010)). At least, we know that this data capture some processes that contribute to IAV_NEP, which are not being captured with eddy-covariance data (e.g. fire, CO_2 fertilization).

Response: Thanks for the suggestion. We have verified the relationship derived from FLUXNET sites with the Jena CarboScope CO_2 Inversion, and find that the relationship between annual NEP and $\frac{U}{R}$ is robust in most global grid cells. We have added these new analyses in the *Results Section* and Figure 2 to strengthen our findings:

> "In addition, the relationship between NEP and $\frac{U}{R}$ was also verified by the atmospheric inversion product (i.e., Jena CarboScope Inversion). The control of $\frac{U}{R}$ on annual NEP was robust in most global grid cells (i.e. $0.6 < R^2 < 1$). The explanation of $\frac{U}{R}$ was higher in 80% of the regions, but lower in North American (Fig. 2). These two datasets both showed that the indicator $\frac{U}{R}$ could successfully capture the variability in annual NEP."

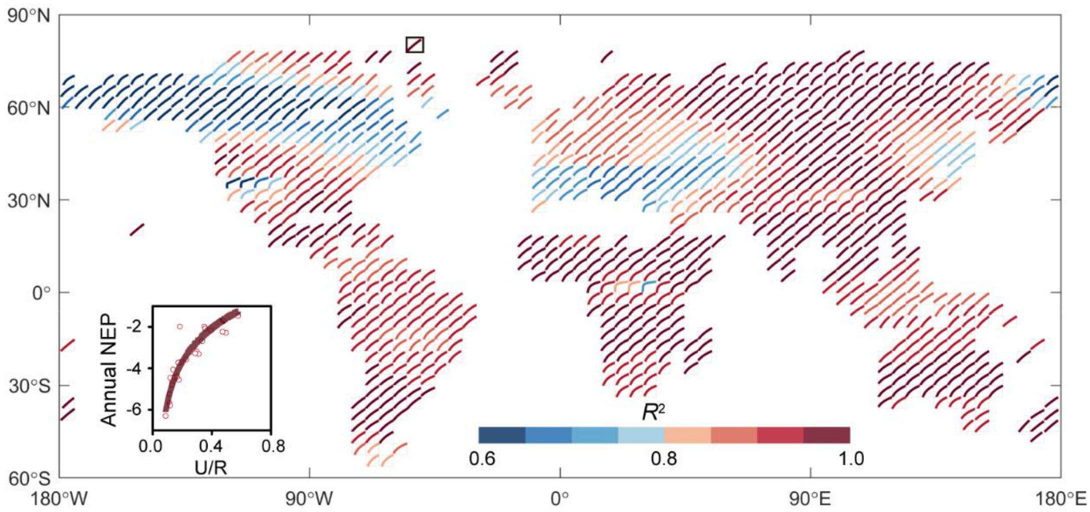

Figure 1B. Relationship between annual NEP and $\frac{U}{R}$ for Jena Inversion product (of the form $\mathrm{NEP} = \beta \cdot \ln\left(\frac{U}{R}\right)$). The black box indicates the location of the sample.

Comment 11B: L. 122-129 It might be relevant to specify that you use the FLUXCOM RS-meteo products for which the inter-annual variability is only driven by climatic conditions as they used the mean seasonal cycle of remote sensing products. This basically means that there is no inter-annual variability directly related to the state of vegetation.

Response: Thanks, we have rephrased the description of FLUXCOM product by adding the following sentences in *Method Section* (Lines x-x):

> "It should be noted that the inter-annual variability of FLUXCOM product is only driven by climatic conditions, the effects of land use and land cover change are not represented."

Comment 12B: L. 124 why only using the CRUNCEPv6 product. In my understanding, FLUXCOM uses more than one meteorological forcing as well as different machine-learning methods. Using all the FLUXCOM RS-meteo products could additionally provide uncertainty estimates for the presented indicators.

Response: Thanks for this comment. We used the CRUNCEPv6 product mainly due to two reasons. First, the simulations from CLM4.5 and Jena Inversion in this study are both driven by CRUNECP meteorological forcing. Therefore, in order to reduce the uncertainty caused by meteorological forcing, we would prefer to choose the CRUNCEPv6 product. Second, we have averaged all the FLUXCOM CRUNCEPv6 products with different machine-learning methods to avoid the uncertainty caused by machine-learning methods. To illustrate our consideration clearer, we have detailed the selection of the product in *Method Section* (Lines x-x):

> "To be consistent with the meteorological forcing of Jena Inversion product and the CLM4.5 model, we used the FLUXCOM CRUNCEPv6 products. In addition,

in order to reduce the uncertainty caused by machine-learning methods, we averaged all the FLUXCOM CRUNCEPv6 products with different machine-learning methods."

Comment 13B: L. 122-136 If one of the aims is to compare FLUXCOM and CLM4.5, I would suggest comparing the two products during the same time period (i.e. 1990-2010).

Response: Thanks for this suggestion, we have adjusted the time period of all the global products to 1985-2010.

Comment 14B: L. 133 'match the available FLUXCOM dataset.' Spatially or temporally? As far as I know, the FLUXCOM products have a spatial resolution of either 0.5 or 0.0833 degrees (http://www.fluxcom.org/CF-Products/).

Response: Thanks, we have adjusted the global products to the same time period and specified their spatial resolution in the *Method Section*.

Comment 15B: L. 140 equation 1: So U is conceptually GPP and R ecosystem respiration, right? I would be curious to see how GPP compared to U when U is computed as in equation 4 for a sanity check. Are they the same? In principle yes, right? Same for ER and R.

Response: Sorry for the misunderstanding. We have drawn a concept figure to shown the decomposition of NEP in our study. The annual NEP is determined by vegetation photosynthesis and ecosystem respiration, but here we decompose the annual NEP into its more direct components: CO_2 uptake flux and CO_2 release flux. To describe the decomposition process more clearly, we have modified the decomposition process of NEP in *Method Section*.

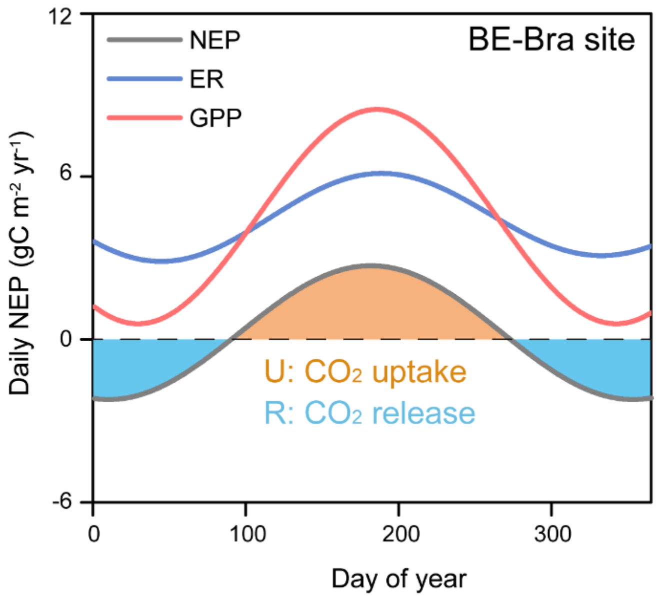

Figure 2B. Conceptual figure for the decomposition of annual NEP in this study. The example shows daily observations from BE-Bra site.

Comment 16B: L. 143 I am not sure if this equation is written correctly. Assuming that U is supposed to be expressed in gC m-2 d-1, the way the equation is written suggests that the U would be expressed in gC m-2 (assuming that CUP is a length expressed in the number of days), which is then inconsistent with equation 4. Or did I misunderstand how CUP is calculated?

Response: Thanks for reminding the confusion of the units. In this study, *U* is expressed in gC m^{-2} and calculated from the mean daily CO_2 uptake ($\overline{U}$, gC m^{-2} d^{-1}) over the carbon uptake period (*CUP*, d).

Actually, the results of equations (2)-(3) and equations (4)-(5) are mathematically equivalent. However, as suggested by the reviewer, the units of these two approaches are ambiguous. Therefore, considering the subsequent analysis, we have deleted equations (4) and (5).

Comment 17B: L. 144 The same applies to this equation.

Response: Thanks, we have deleted equations (4) and (5).

Comment 18B: L. 148-149 I think these equations are correct and good enough to explain how U and R are calculated, therefore I would discard equation (2) and (3) to avoid confusion. Again, U and R derived from equations 2 and 3 do not seem to match how U and R are calculated from eq 4 and 5.

Response: Thanks. We have discard equations (2) and (3) to avoid confusion

Comment 19B: L. 150-153 "Because many studies have [..] are tightly correlated" I would move this sentence to the introduction. I am also not sure that this is enough to justify the need to look at the relationship between annual NEP and the ratio U/R.

Response: Thanks for this suggestion, we have removed these sentences to the *Introduction Section* and added several sentences to state the motivation to explore the relationship between annual NEP and its components *U* and *R*:

> "However, despite the previous efforts in a predictive understanding of the land-atmospheric C exchanges, the multi-model spread has not changed over time (Arora et al., 2019). Therefore, it is imperative to explore the potential indicators for the spatially varying NEP, which could help attribute the spatial variation of NEP and IAV_{NEP} into different processes and provide valuable constraints for the global C cycle. Alternatively, the annual NEP of a given ecosystem can be also directly decomposed into CO_2 uptake flux and CO_2 release flux (Gray et al., 2014), which are more direct components for NEP (Fu et al., 2019). Many studies have reported that the vegetation CO_2 uptake during the growing season and the non-growing season soil respiration are tightly correlated (Luo et al., 2014; Zhao et al., 2016). It is still unclear how the ecosystem CO_2 uptake and release fluxes would control the spatially varying NEP."

Comment 20B: L. 160 This equation is correct if one assumes that equations 2 and 3 correct, and if I understood correctly their formulation, equations 2 and 3 are not (see comment above). Therefore, I do not believe that the ratio U/R can be partitioned as presented in equation 7. It seems that part of the paper is based on assuming that equations 2 and 3 are correct, therefore I have concerned related to the analysis relying on equations 2 and 3.

Response: Thanks for this comment. To be consistent with the equation (7), we have deleted the equations (4) and (5) and kept the equations (2) and (3) as the final decomposition approaches.

Comment 21B: L. 171 I think the analysis presented in section 4 is not correct for the issues I have raised related to equations 2 and 3 at least the way equation 8 is expressed. One could express U/R = f(U/R, CUP/CUR) though and run the variable importance analysis. Why not just do the variable importance analysis as NEP = f(U/R, CUP/CUR)? I find it cleaner although it might be a bit circular and spurious as U and R are derived from NEP.

Response: Thanks for this valuable suggestion. In the revised version, we have directly tested the effect of these two ratios on the spatial variation in NEP (Figure 3B). These new results have been added in the *Results* as Figure 4. The major revisions in *Method Section* and *Results Section* are as below:

Method Section: "We further quantified the relative contributions of $\frac{\bar{U}}{\bar{R}}$ and $\frac{CUP}{CRP}$ in driving the spatial variations in NEP:

$$\text{NEP} = \int(\frac{\bar{U}}{\bar{R}}, \frac{CUP}{CRP}) \quad (6)$$

We used a relative importance analysis method to quantify the relative contributions of each ratio to the spatial variations in NEP."

Results Section: "The decomposition of indicator $\frac{U}{R}$ into $\frac{\bar{U}}{\bar{R}}$ and $\frac{CUP}{CRP}$ allowed us to quantify the relative importance of these two ratios in driving NEP variability. The linear regression and relative importance analysis showed a more important role of $\frac{CUP}{CRP}$ (58%) than $\frac{\bar{U}}{\bar{R}}$ (42%) in explaining the cross-site variation of NEP (Fig. 4). Therefore, the spatial distribution of mean annual NEP was mostly driven by the phenological rather than physiological changes."

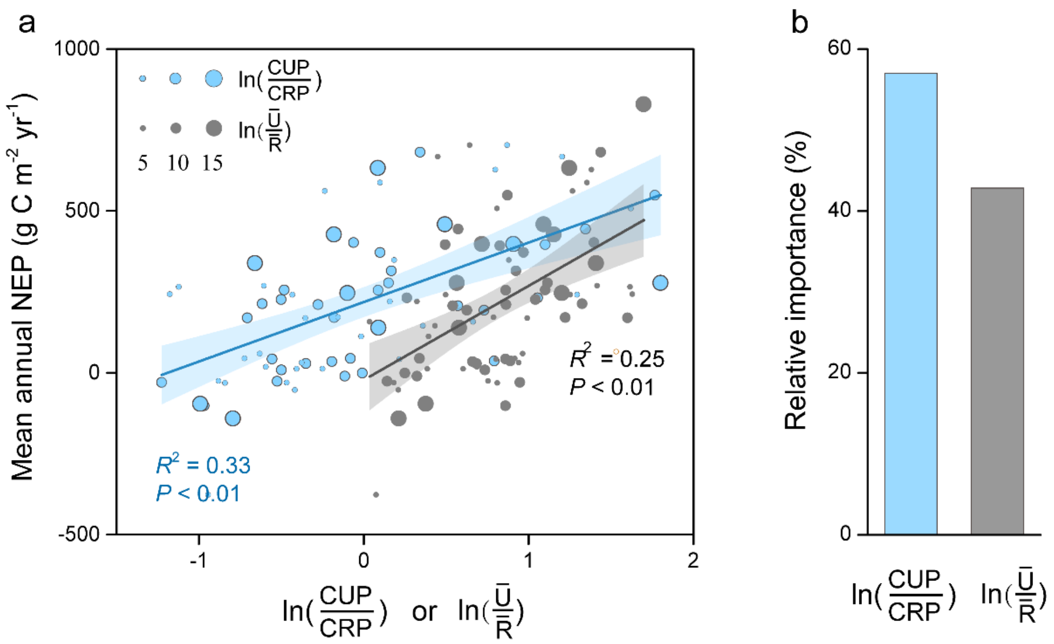

Figure 3B. The relative contributions of the local indicators in explaining the spatial patterns of mean annual NEP. a, The linear regression between mean annual NEP with $\frac{CUP}{CRP}$ (R^2 = 0.33, P < 0.01) and $\frac{\bar{U}}{\bar{R}}$ (R^2 = 0.25, P < 0.01) across sites. b, The relative contributions of each indicator to the spatial variation of NEP. The number of site-years at each site is indicated with the size of the point.

Comment 22B: L. 186 I do not find this section relevant in the context of the study. Besides, most of the presented results are already well documented in the literature (e.g. Jung at al. 2020).

Response: Thanks for this suggestion. We have deleted this section from *Results*, and moved the related content to the *Introduction Section*:

> "Large spatial difference in terrestrial NEP has been reported from eddy-flux measurements, model outputs and atmospheric inversion products. In addition, the global average IAV of NEP was large relative to global annual mean NEP (Baldocchi et al., 2018). More importantly, the spatial variations of NEP and IAV_{NEP} were typically underestimated by the compiled global dataset and the process-based global models (Jung et al., 2020; Fu et al., 2019)."

Comment 23B: L. 188 Be aware that the 'large carbon sinks' are very likely related to an artifact in the eddy-covariance datasets due to advection and storage issues. It might be relevant to discuss eddy-covariance data quality issues.

Response: Thanks for this suggestion, and this section has been removed.

Comment 24B: L. 204 Would that make sense to discard the sites for which the logarithmic function does not provide a correlation >0.9 for robustness?

Response: Thanks, we have rephrased this sentence as "The logarithmic correlations between annual NEP and $\frac{U}{R}$ were significant at all sites (Fig. 1a; Fig. S2), and ~90% of R^2 falling within a range from 0.7 to 1 (Fig. 1c)."

Comment 25B: L. 207-208 "This finding suggests that the mean annual ratio ln(U/R) is a good indicator for NEP and its spatial variation." Isn't it expected? I mean U and R are derived from NEP so you might expect that their ratio explains the annual variability of NEP, right?

Response: Thanks. We have rephrased the related sentences to make the statements clearer: (1) *Results Section 3.1*: "These two datasets both showed that the indicator $\frac{U}{R}$ could successfully capture the variability in annual NEP." (2) *Results Section 3.2*: "This finding suggested that the mean annual ratio $\ln\left(\frac{U}{R}\right)$ is a good indicator for cross-site variation in NEP."

Comment 26B: L. 218 Again, is this analysis being done on the extracted time series for each Fluxnet sites or globally? If the former, I do not really see the point of included results based on FLUXCOM or CLM4.5 for the purpose of the study. It would be interesting to run this analysis both at the global scale and at the Fluxnet level.

Response: Thanks for this valuable suggestion. We have done additional analyses at the global scale:

First, yes, the previous analysis in Figure 5 is based on the extracted time series for FLUXNET sites.

Second, as suggested by the reviewer, we also have run the same analysis at the global scale based on Jena Inversion product, FLUXCOM product and CLM4.5 model (Figure 4B). The results have strengthened our major conclusion that the spatial variation of mean annual NEP can be indicated by ln(U/R), while the spatial distribution of IAV_{NEP} is well indicated by the slope (i.e., β) of the demonstrated logarithmic correlation. We have added these new analyses in *Results Section* as Figure 6. The major revisions in *Results Section* are as below:

"However, the spatial variations of NEP and IAV_{NEP} were associated with the spatial resolution of the product (Marcolla et al., 2017). At the global scale, the spatial variation of mean annual NEP can be also well indicated by ln(U/R) (Fig. 6). The widely reported larger C uptake in FLUXCOM (Jung et al., 2020) resulted from its higher simulations for U/R. In addition, the larger spatial variation of IAV_{NEP} in CLM4.5 could be inferred from the indicator β."

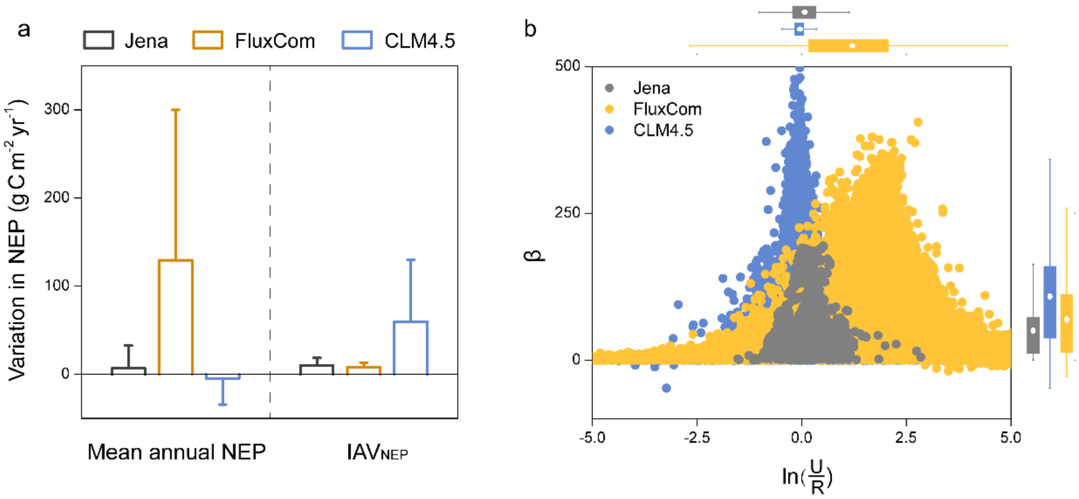

Figure 4B. Representations of the spatially varying NEP and its local indicators in FLUXCOM product and the Community Land Model (CLM4.5) at the global scale. **a**, The variation of mean annual NEP and IAV_{NEP} derives from Jena Inversion, FLUXCOM and CLM4.5. Variation in mean annual NEP: the spatial variation of mean annual NEPs; Variation in IAV_{NEP}: the spatial variation of standard deviation in IAV_{NEP}. **b**, Representations of the local indicators for NEP in Jena Inversion, FLUXCOM and CLM4.5.

Comment 27B: L. 219 I do not think that one can directly compare the results from FLUXNET data and the two global products (i.e. FLUXCOM and CLM4.5) simply because of the strong bias in representativeness in the FLUXNET datasets. For instance, there are very few semi-arid ecosystems (e.g. 2 shrublands and 5 savannas in the presented study) in the FLUXNET dataset, while they represent a large portion of land at the global scale and have been shown to substantially control the interannual variability of NEP (Ahlström et al., 2015). Or do you extract FLUXCOM and CLM4.5 time series for each FLUXNET site location? If so, it is anyway not a fair comparison due to spatial mismatch as the footprint of a tower is definitely lower than 1 degree (CLM4.5) or 0.5 degree (FLUXCOM) spatial resolution. As previously mentioned, I would rather run this analysis globally and not only at FLUXNET sites to have a real added value by using global products such as FLUXCOM and CLM4.5.

Response: Thanks for the comment on scale mismatch. As suggested by the reviewer, we have done the same analysis both at the global scale and at the FLUXNET site level. The results from FLUXNET sites are used to benchmark the simulations of FLUXCOM product and CLM4.5 model at the FLUXNET site level, and the results from Jena Inversion product are used to evaluate the simulations of FLUXCOM product and CLM4.5 model at the global scale. As shown in Figure 4B, the analyses at the global scale and at the FLUXNET site level both support our major conclusion that the spatial variation of mean annual NEP can be indicated by ln(U/R), while the spatial distribution of IAV_{NEP} is well indicated by the slope (i.e., β) of the demonstrated logarithmic correlation.

Technical corrections:
Comment 28B:

L.57 'However' does not sound appropriate. Maybe 'furthermore' or 'in addition'.
L. 62 'dramatic'. Try to avoid emotional semantic in a scientific paper. Maybe 'substantial' instead?
L. 77. replace Musavi, 2017 by Musavi et al., 2017
L. 104 'database' Replace database by product.

Response: Done as suggested.

L. 119-121 Stand age information is mentioned here but is they even being used further in the analysis? If not, please remove it.

Response: Removed.

L. 154-155 'Then we found that annual NEP [...] (Figure S2).' To me, this already belongs to the results section.

Response: Thanks, we have removed this sentence to the *Results Section*.

L. 154 'the ratio U/R'. It might be relevant for the reader to see a sentence explaining the meaning of the ratio U/R. This explanation in L. 162-163 comes a bit too late.

Response: Thanks, we have added the meaning of ratio U/R as "we further tested the relationship between annual NEP and the ratio of U/R. Ecologically, the ratio of U/R reflects the relative strength of the ecosystem CO_2 uptake.".

L. 151-152 'the non-growing soil respiration' Is that what you mean here? Maybe rephrase.

Response: Thanks, we have rephrased it as "the non-growing season soil respiration".

L. 208 I would not say 'was well explained' but rather that the correlation was moderate (i.e. 0.3 > r> 0.7)

Response: Thanks, we have rephrased it as "was moderately explained".

L. 347 In Fig. 1, it is not clear to me what products are we looking at. FLUXCOM, CLM 4.5 or both? It seems to be FLUXCOM (L. 99) but please specify in the figure's caption.

Response: As suggested by Comment 22B, we have deleted Figure 1 and the related results.

References:

Ahlström, Anders, et al. "The dominant role of semi-arid ecosystems in the trend and variability of the land CO_2 sink." Science 348.6237 (2015): 895-899.

Besnard, Simon, et al. "Quantifying the effect of forest age in annual net forest carbon balance." Environmental Research Letters 13.12 (2018): 124018.

Jung, Martin, et al. "Scaling carbon fluxes from eddy covariance sites to globe: Synthesis and evaluation of the FLUXCOM approach." Biogeosciences17.5 (2020): 1343-1365.

Marcolla, B., Rödenbeck, C., and Cescatti, A.: Patterns and controls of inter-annual variability in the terrestrial carbon budget. Biogeosciences, 14, 3815-3829, 2017.

Rödenbeck, Christian, et al. "How does the terrestrial carbon exchange respond to inter-annual climatic variations?: A quantification based on atmospheric CO_2 data." Biogeosciences (2018).