Response to comments from reviewer #1

Dear editor:

Thank you very much for handling our manuscript. We really appreciate the reviewer's insightful comments and suggestions. Below, we address the comments from reviewer #1 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 #1

General comments:

Comment 1A: *In the manuscript "Spatially asynchronous changes in strength and stability of terrestrial net ecosystem productivity", Chen et al. studied the spatial variations of annual mean NEP and IAV_NEP using in-situ eddy covariance observations and gridded NEP datasets from FLUXCOM and CLM4.5. They proposed a new approach that decomposes NEP into beta, log(U/R) and log (CUP/CRP) and used some of them as "local indicators" to indicate the spatial variation of NEP and IAV_NEP. I am intrigued by this study and find it has the potential to provide some emergent constraints on NEP that we much need at local scales, though I feel some minor revisions are needed to clarify the motivation and the interpretations of the Results.*

Response: Thanks for the recognitions and valuable suggestions. The comments from the reviewer have inspired us to strengthen the importance of the local indicators. We have added one sentence in *Introduction Section* (Lines 83-86) to extend the motivation of this study:

> "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."

Specific comments:

Comment 2A: *"Spatially asynchronous" is a bit misleading phrase as it makes me wondering what is meant to be spatially asynchronous/synchronous for NEP, or is it simply used as a substitute for "spatial variation". I think the running title of the manuscript is more accurate which suggests that the authors studied "spatial variability" of NEP and NEP_IAV and found local indicators for them.*

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

Comment 3A: *The first part of the results (section 3.1) serves to prove that there are large spatial variations in NEP and IAV_NEP, and to further motivate a need to study "local indicators" for NEP and IAV_NEP. However, many literatures have reported large spatial variations of NEP and IAV_NEP already, and I feel this kind of reasoning is more suitable to be included in Introduction rather than Results. In addition, FLUXCOM NEP is used here but we know is might not be the best source to study IAV_NEP (Jung et al., 2020).*

Response: Thanks for this suggestion. We have deleted this part of results, and moved the related content to the *Introduction Section* (Lines 65-69):

> "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 4A: *The IAV_NEP and beta for shrublands and savannas are among the smallest compared to other PFTs (Figure 3). Is it at odds with previous global studies that suggest semi-arid ecosystems contributed the most to global IAV_NEP? (Ahlström et al., 2015).*

Response: Thanks for this suggestion. As the reviewer has mentioned, there are very few semi-arid ecosystems (e.g. 2 shrublands and 5 savannas in the presented study) in the FLUXNET sites, while they represent a large portion of land at the global scale and have been shown to substantially control the interannual variability of NEP. Therefore, we have added several sentences in *Discussion Section* (Lines 238-241) to illustrate this point:

"However, the relatively lower β in shrublands and savannas should be interpreted cautiously. There are very few semi-arid ecosystems in the FLUXNET sites, 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)."

Technical comments:

Comment 5A: *In the legend of Figure 1 please indicate the source of NEP data.*

Response: This section has been removed.

Comment 6A: *L74. Do you mean the "relative differences" between photosynthesis and respiration or between their covariances?*

Response: Thanks, we have rephrased this sentence as "Because photosynthesis and respiration are strongly correlated over space (Baldocchi et al., 2015; Biederman et al., 2016), their relative difference could determine the spatial variation of NEP."

Comment 7A: *L100. Rephrase. "to address the local indicators"?*

Response: Thanks, we have rephrased this sentence as "In this study, we decomposed annual NEP into U and R, and explored the local indicators for spatially varying NEP."

Comment 8A: *L102. Reference for FLUXNET2015 is Pastorello et al., 2017.*

Response: Thanks. This sentence has been revised.

Comment 9A: *L84 -86. Generally, I feel there is a need to clarify why there is a need to find a local indicator (which is also a new phrase)? Does it help in the attribution of spatial variation of NEP and IAV_NEP to different processes, or does it provide an independent constrain on NEP and IAV_NEP?*

Response: Thanks for this valuable suggestion. The suggestion proposed by the reviewer inspires us to reorganize the importance of our work. We have added several sentences in the *Introduction Section* (Lines 81-86) to state the necessary of exploring the local indicators:

"However, despite the previous efforts in a predictive understanding of the land-atmospheric C exchanges, the multi-model spread has not reduced 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."

Comment 10A: *L135. I understand the scale-mismatch between model and eddy-covariance sites is difficult to address, but is it possible that muted spatial variation of NEP and IAV_NEP from gridded products is partly related to the scale mismatch?*

Response: Thanks for this suggestion.

First, considering the scale mismatch between FLUXNET sites and the gridded products, we have removed the direct comparison of the spatial variation of mean annual NEP and IAV_{NEP} from different sources in *Section 3.3*. Instead, we mainly emphasize the important role of local indicators in indicating the spatially varying NEP.

Second, we have run the same analysis at the global scale based on the Jena Inversion product, the FLUXCOM product and the outputs of CLM4.5 model (Figure 1A). 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 the results of these new analyses into the *Results Section* (Lines 81-86) as Figure 6. The major revisions in the *Results Section 3.3* are cited 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."

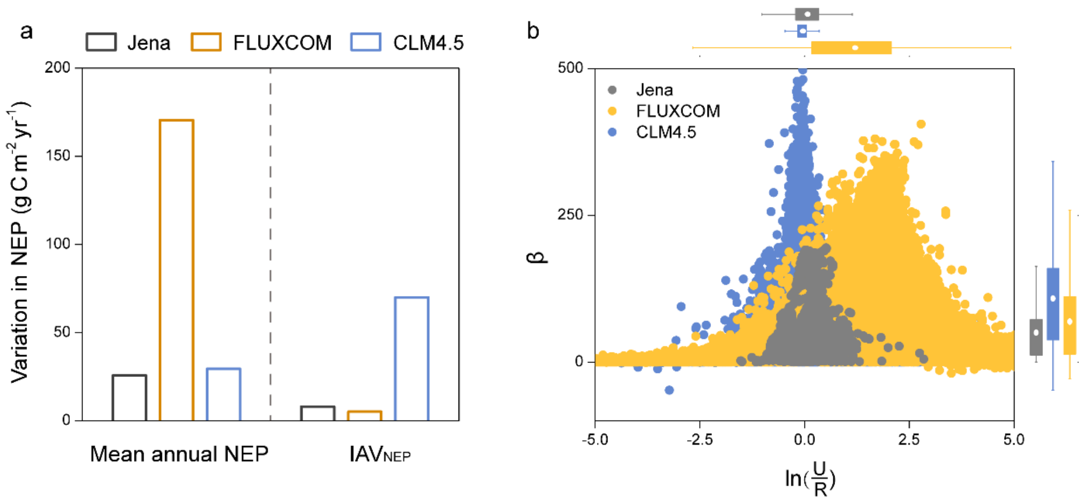

Figure 4B. Representations of the spatially varying NEP and its local indicators in FLUXCOM product and the Community Land Model (CLM4.5) at the global scale. **a**, The variation of mean annual NEP and IAV_{NEP} derives from Jena Inversion, FLUXCOM and CLM4.5. Variation in mean annual NEP: the spatial 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 11A: *L229. "difference" -> "variation".*

Response: Done as suggested.

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: Thank you 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 contents 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. the 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. the 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: Thanks for pointing out this issue. We have rephrased the relevant statement as "based on daily NEP observations from FLUXNET sites and the atmospheric inversion product" in this version (Line 38).

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: Done. We have rephrased this sentence as "is related to the strength of carbon exchange" (Line 60).

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: Done. 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)." (Lines 74-76).

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: In the former version, the first sentence illustrated the decomposition of NEP as the difference between photosynthesis and respiration, while the last sentence lead 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 on Lines 86-91 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). 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 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: Done. We have rephrased this section and strengthened our points by adding the following sentences (Lines 81-91):

> "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 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: 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: The authors really appreciate the reviewer for this great 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* (Lines 193-198) and Figure 2 (i.e., the following Fig. 1B) 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."

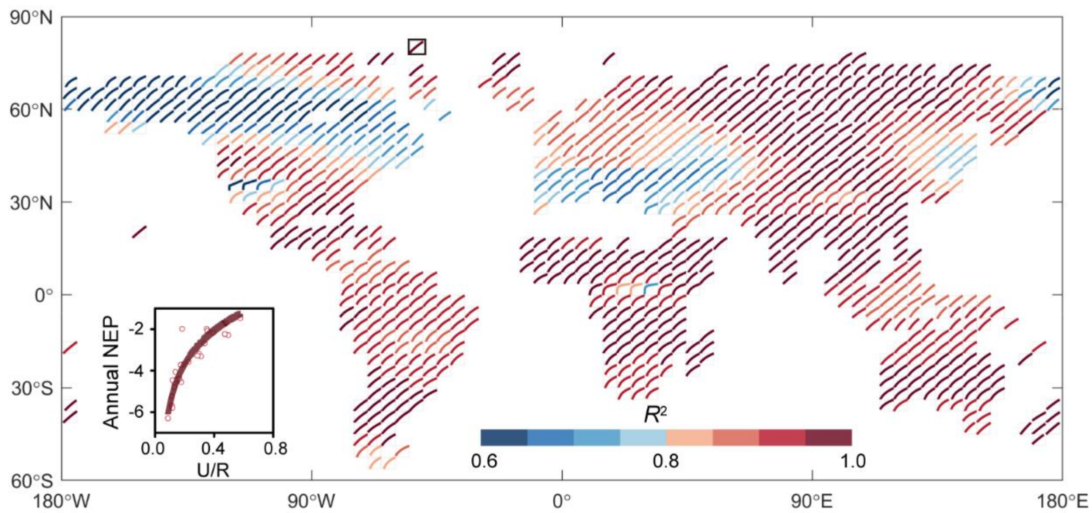

Figure 1B. Relationship between annual NEP and $\frac{U}{R}$ for Jena Inversion product (of the form $NEP = \beta \cdot \ln(\frac{U}{R})$). The black box indicates the location of the sample.

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: Done. We have rephrased the description of FLUXCOM product by adding the following sentences in *Method Section* (Lines 141-143):

> "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 138-141):

> "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 (1985-2010) 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 confusion. We have drawn a concept figure to show our method to decompose the NEP in our study (Fig. 2B). 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*.

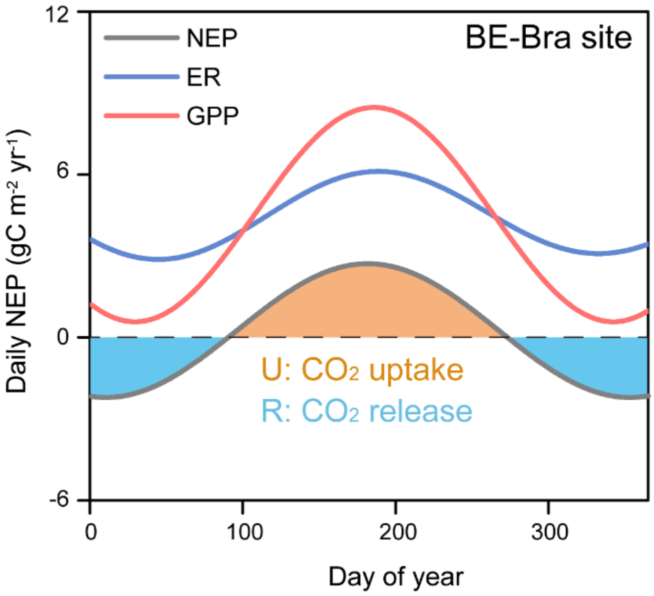

Figure 2B. Conceptual figure for the decomposition of annual NEP in this study. The example shows daily observations from BE-Bra site.

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} yr^{-1} and calculated from the mean daily CO_2 uptake ($\overline{U}$, gC m^{-2} d^{-1}) over the carbon uptake period (*CUP*, d yr^{-1}). In fact,, the equations (2)-(3) and (4)-(5) are mathematically equivalent. Based on the suggestions from the reviewer, and in order to avoid using the ambiguous units, we have removed the original 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: Done. 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* (Lines 81-91):

> "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.

In the *Method* Section, please find the added sentences on Lines 175-179 as:

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

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

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

In the *Results* Section, the added sentences could be found on Lines 206-210 as:

"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."

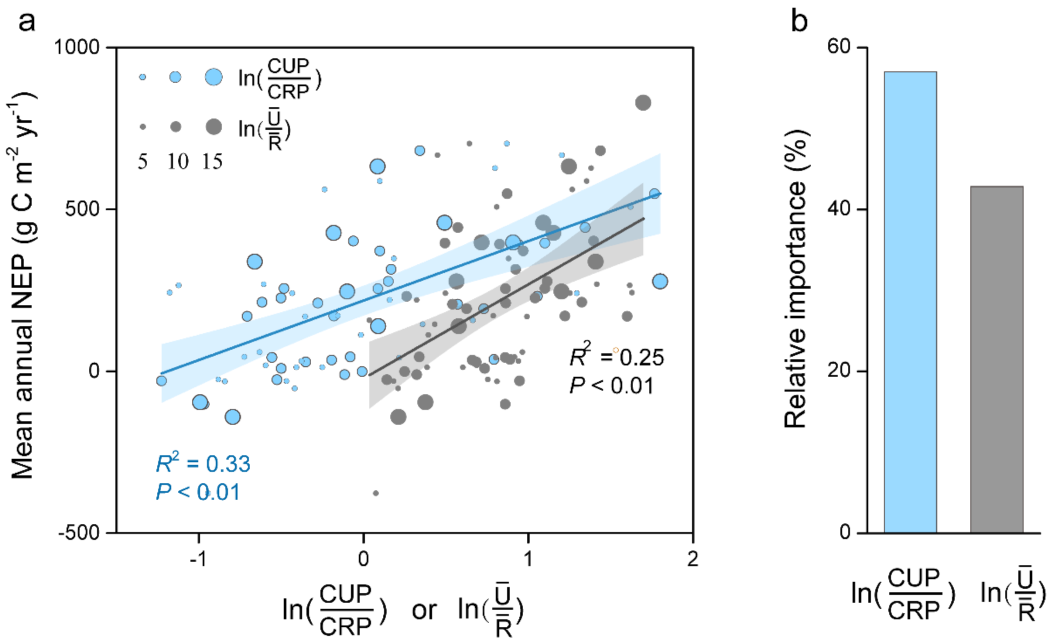

Figure 3B. The relative contributions of the local indicators in explaining the spatial patterns of mean annual NEP. a, The linear regression between mean annual NEP with $\frac{CUP}{CRP}$ (R^2 = 0.33, P < 0.01) and $\frac{\bar{U}}{\bar{R}}$ (R^2 = 0.25, P < 0.01) across sites. b, The relative contributions 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* (Lines 65-69):

"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. Because this section has been removed in this revised version, so we didn't further discuss the eddy-covariance data quality issues.

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 (Lines 190-192) 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: Yes, the previous analysis in Figure 5 was based on the extracted time series for FLUXNET sites. We agree with the reviewer that it would be interesting to also run the analysis at the global scale. In this revised version, we 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* (Lines 219-225) as Figure 6. The major revisions in *Results Section* are as below:

"In addition, the spatial variations of NEP and IAV_{NEP} were associated with the spatial resolution of the product (Marcolla et al., 2017). Considering the scale mismatch between FLUXNET sites and the gridded product, we run the same analysis at the global scale based on Jena Inversion product. At the global scale, the spatial variation of mean annual NEP can be also well indicated by ln (U/R) (Fig. 6). The larger C uptake in FLUXCOM resulted from its higher simulations for ln(U/R). Furthermore, the larger spatial variation of IAV_{NEP} in CLM4.5 could be inferred from the indicator β."

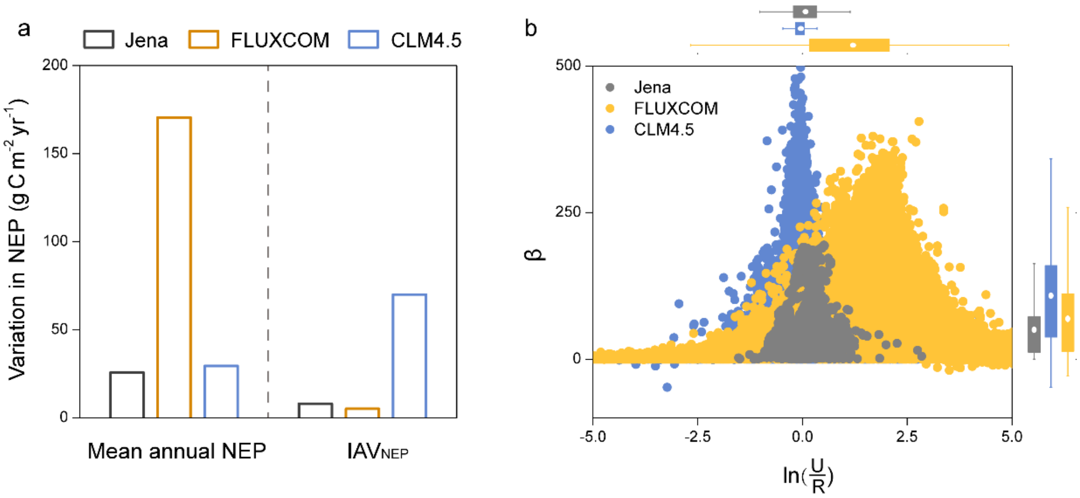

Figure 4B. Representations of the spatially varying NEP and its local indicators in FLUXCOM product and the Community Land Model (CLM4.5) at the global scale. **a,** The variation of mean annual NEP and IAV_{NEP} derives from Jena Inversion, FLUXCOM and CLM4.5. Variation in mean annual NEP: the spatial 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 pointing out the issue of scale mismatch. Considering the scale mismatch between FLUXNET sites and the gridded products, we have removed the direct comparison of the spatial variation of mean annual NEP and IAV_{NEP} from different sources in *Section 3.3*. Instead, we mainly emphasized the important role of local indicators in indicating the spatially varying NEP.

Also, 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'.
Response: Done as suggested.

L. 62 'dramatic'. Try to avoid emotional semantic in a scientific paper. Maybe 'substantial' instead?
Response: Done as suggested.

L. 77. replace Musavi, 2017 by Musavi et al., 2017
Response: Done as suggested.

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: Done. We have removed it.

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: 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." on line 158-159.

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

Research article

Title

Spatial variations in terrestrial net ecosystem productivity and its local indicators Spatially asynchronous changes in strength and stability of terrestrial net ecosystem productivity

Running title

Spatial variability in terrestrial NEP

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Key words

Net ecosystem productivity, spatial asynchronousvariation, CO_2 uptake and release, local indicators, model

Abstract

Multiple lines of evidence have demonstrated the persistence of global land carbon (C) sink during the past several decades. However, both annual net ecosystem productivity (NEP) and its inter-annual variation (IAV_{NEP}) keep varying over space. Thus, identifying local indicators for the spatially varying NEP and IAV_{NEP} is critical for locating the major and sustainable C sinks on the land. Here, ~~based on a machine-learning-derived database, we first showed that the variations of NEP and IAV_{NEP} are spatially asynchronous. Then, ~~based on daily NEP observations from ~~eddy covariance~~FLUXNET sites and the atmospheric inversion product, we found a robust logarithmic correlation between annual NEP and ratio of total CO_2 exchanges during net uptake (*U*) and release (*R*) periods (i.e., *U*/*R*). The cross-site variation of mean annual NEP ~~can~~ could be linearly indicated by ln(*U*/*R*), while the spatial distribution of IAV_{NEP} was well indicated by the slope (i.e., β) of the demonstrated logarithmic correlation. Among biomes, for example, forests and croplands had the largest *U*/*R* ratio (1.06 ± 0.83) and β (473 ± 112 g C m^{-2} yr^{-1}), indicating the highest NEP and IAV_{NEP} in forests and croplands, respectively. We further showed that these two simple indicators could directly infer the spatial variations in NEP and IAV_{NEP} in global gridded products~~the spatial variations of NEP and IAV_{NEP} were both underestimated by the machine-learning-based and process-based global models~~. Overall, this study ~~underscores the asynchronously changes in the strength and stability of land C sinks over space, and~~ provides two simple local indicators for ~~their~~ the intricate spatial variations in the strength and stability of land C sinks. These indicators could be helpful for locating the persistent terrestrial C sinks and provides valuable constraints for improving the simulation of land-atmospheric C exchanges.

1. Introduction

Terrestrial ecosystems reabsorb about one-quarter of anthropogenic CO_2 emission (Ciais et al., 2019) and are primarily responsible for the recent temporal fluctuations of the measured atmospheric CO_2 growth rate (Randerson, 2013; Le Quéré et al., 2018). ~~However~~In addition, evidence based on eddy-flux measurements (Baldocchi~~, Chu, & Reichstein~~ et al., 2018; Rödenbeck~~, Zaehle, Keeling, & Heimann,~~ et al., 2018), aircraft atmospheric budgets (Peylin et al., 2013), and process-based model simulations (Poulter et al., 2014; Ahlstrom et al., 2015) has shown a large spatial variability in net ecosystem productivity (NEP) on the land. The elusive variation of terrestrial NEP over space refers to both of the substantial~~dramatic~~ varying mean annual NEP and the divergent inter-annual variability (IAV) in NEP (i.e., IAV_{NEP}; usually quantified as the standard deviation of annual NEP) across space (Baldocchi~~, Chu, & Reichstein~~ et al., 2018; Marcolla~~, Rödenbeck, & Cescatti~~ et al., 2017). The mean annual NEP is related to the strength of carbon ~~sink~~ exchange of a specific ecosystem (Randerson~~, Chapin III, Harden, Neff, & Harmon~~ et al., 2002; Luo~~, &~~ and Weng, 2011; Jung et al., 2017), while IAV_{NEP} characterizes the stability of such carbon ~~sink~~ exchange (Musavi et al., 2017). Thus, whether and how NEP and IAV_{NEP} change ~~asynchronously~~ over the space is important for predicting the future locations of carbon sinks on the land (Yu et al., 2014; Niu et al., 2017).

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 product and the process-based global models (Jung et al., 2020; Fu et al., 2019). These discrepancies further revealed the necessary to identify local indicators for the spatially varying NEP and IAV_{NEP}, separately.

The NEP in terrestrial ecosystems is determined by two components, including vegetation photosynthesis and ecosystem respiration (Reichstein et al., 2005). Because ~~there is a strong covariance between~~ photosynthesis and respiration are strongly correlated over space (Baldocchi~~, Sturtevant, & Contributors~~ et al., 2015; Biederman et al., 2016), their relative difference could determine the spatial variation of NEP. Many previous analyses have attributed the IAV_{NEP} at the site level to the different sensitivities of ecosystem photosynthesis and respiration to environmental ~~fluctuations among years~~drivers (Gilmanov et al., 2005; Reichstein et al., 2005) ~~;~~and biotic controls ~~(Gilmanov et al., 2005; Reichstein et al., 2005;~~ (Besnard et al., 2018; Musavi et al., 2017). For example, some studies have reported that IAV_{NEP} is more associated with variations in photosynthesis than carbon release (Ahlstrom et al., 2015; Novick~~, Oishi, Ward, Siqueira, Juang, & Stoy~~ et al., 2015; Li et al., 2017), whereas others have indicated that respiration is more sensitive to anomalous climate variability (Valentini et al., 2000; von Buttlar et al., 2017). ~~Alternatively, the annual NEP of a given ecosystem can be defined numerically as the balance between the CO_2 uptake and release processes (Gray et al., 2014), which are more direct components for NEP (Fu et al., 2019).~~ However, despite the previous efforts in a predictive understanding of the land-atmospheric C exchanges, the multi-model spread has not reduced 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 ~~whether~~ ecosystem CO_2 uptake and release fluxes would ~~could be integrated into~~ control ~~some simple indicators for~~ the spatially varying NEP~~ and IAV_{NEP} in terrestrial ecosystems~~.

Conceptually, the total CO_2 uptake flux (*U*) is determined by the length of CO_2 uptake period (*CUP*) and the CO_2 uptake rate, while the total CO_2 release flux (*R*) depends on the length of CO_2 release period (*CRP*) and the CO_2 release rate (Fig. 2b). The variations of NEP thus should be innovatively attributed to these decomposed components. A strong spatial correlation between mean annual NEP and length of CO_2 uptake period has been reported in evergreen needle- and broad-leaved forests (Churkina~~, Schimel, Braswell, & Xiao~~ et al., 2005; Richardson~~, Keenan, Migliavacca, Ryu, Sonnentag, & Toomey~~ et al., 2013; Keenan et al., 2014), whereas atmospheric inversion data and vegetation photosynthesis model indicated a dominant role of the maximal carbon uptake rate (Fu~~, Dong, Zhou, Stoy, & Niu~~ et al., 2017; Zhou et al., 2017). However, the relative importance of these phenological and physiological indicators for the spatially varying NEP remains unclear.

In this study, ~~we first explored the changes in NEP and IAV_{NEP} at the global scale based on data from a widely used machine learning-derived product (i.e., FLUXCOM). To address the local indicators for spatially varying NEP,~~ we decomposed annual NEP into U and R, and explored the local indicators for spatially varying NEP. Based on the eddy-covariance fluxes from FLUXNET2015 Dataset (Pastorello et al., 2017) and the atmospheric inversion product (Rödenbeck et al., 2018), ~~Then,~~we ~~we~~ examined the relationship ~~of~~ between NEP and its direct components. ~~$NEP \propto \frac{U}{R}$ based on the observations at 72 eddy covariance towers which has >5 years measurements in the FLUXNET2015 Dataset (Jung et al., 2017). In~~ In addition, we used the observations to evaluate the spatial variations of NEP and IAV_{NEP} in the FLUXCOM ~~database~~ product and a process-based model (CLM4.5) (Oleson et al., 2013). The major aim of this study is to explore whether there are useful local indicators for the spatially varying NEP and IAV_{NEP} in terrestrial ecosystems.

2. Materials and Methods

2.1 Datasets

Daily NEP observations of eddy covariance sites ~~were~~ are obtained from the FLUXNET2015 Tier 1 dataset (http://fluxnet.fluxdata.org/data/fluxnet2015-dataset/). The FLUXNET2015 dataset provides half-hourly data of carbon, water and energy fluxes at over 210 sites that are standardized and gap-filled (Pastorello et al., 2017). However, time series of most sites are still too short for the analysis of inter-annual variation in NEP. So only the sites that provided the availability of eddy covariance flux measurements for at least 5 years are selected. This leads to a global dataset of 72 sites with different biomes across different climatic regions. Based on the biome classification from the International Geosphere-Biosphere Programme (IGBP) provided for the FLUXNET2015 sites, the selected sites include 35 forests (FOR), 15 grasslands (GRA), 11 croplands (CRO), 4 wetlands (WET), 2 shrublands (SHR) and 5 savannas (SAV) (Fig. S1 and Table S1). ~~The stand age information of forest sites is the average tree age of the stand, and~~

was obtained from the Biological Ancillary Disturbance and Metadata (BAMD) of the FLUXNET dataset (Musavi, et al., 2017).

The Jena CarboScope Inversion product compiles from high precision measurements of atmospheric CO_2 concentration with simulated atmospheric transport (Rödenbeck et al., 2018). Here, we used the daily land-atmosphere CO_2 fluxes from the s85_v4.1 version at a spatial resolution of 5°× 3.75°. Considering the relatively low spatial resolution of the Jena Inversion product, the daily fluxes were only used to calculate the local indicators for the spatially varying NEP at the global scale.

Daily NEP simulations from Community Land Model version 4.5 (CLM4.5) were also used to calculate the local indicators for the spatially varying NEP at the corresponding flux tower sites. We ran the CLM4.5 model from 1985 to 2010 at a spatial resolution of 1° with CRUNECP meteorological forcing. Here, NEP was derived as the difference between GPP and TER, and TER was calculated as the sum of simulated autotrophic and heterotrophic respiration. The daily outputs from CLM4.5 were used to calculate the local indicators for the spatially varying NEP both at the global scale and at the FLUXNET site level.

——The FLUXCOM dataset product presents an upscaling of carbon flux estimates from 224 flux tower sites based on multiple machine learning algorithms and meteorological drivers satellite data (Jung et al., 2017). 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.Meteorological measurements from CRUNCEPv6 and a serious of remotely sensed datasets were used as input. 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. For this study, we downloaded tThe FLUXCOM NEP product is downloaded from the Data Portal of the Max Planck Institute for Biochemistry (https://www.bgc-jena.mpg.de). Daily outputs from FLUXCOM for the period 19801985-2013 2010 at 0.5° spatial resolution were used to map the spatial variation in terrestrial NEP and calculate the local indicators for the spatially varying NEP both at the global scale and at the FLUXNET site level.~~at the same locations of the flux tower sites.~~

~~Daily NEP simulations from Community Land Model version 4.5 (CLM4.5) were also used to calculate the local indicators for the spatially varying NEP at the corresponding flux tower sites. We ran the CLM4.5 model from 1990 to 2010 with a spatial resolution of 1° to match the available FLUXCOM dataset. Here, NEP was derived as the difference between GPP and TER, and TER was calculated as the sum of simulated autotrophic and heterotrophic respiration. The daily outputs from CLM4.5 were used to calculate the local indicators for the spatially varying NEP at the same locations of the flux tower sites.~~

2.2 Decomposition of NEP and the calculations for its local indicators

The annual NEP of a given ecosystem can be defined numerically as the difference between the CO_2 uptake and release. As illustrated in Figure 2b:

$$NEP = U - R \qquad (1)$$

These components of NEP contain both photosynthesis and respiration flux, which directly indicate the net CO_2 exchange of an ecosystem. ~~where t~~The total CO_2 uptake flux (*U*) and the total CO_2 release flux (*R*) can be further decomposed as:

$$U = \overline{U} \times CUP \qquad (2)$$

$$R = \overline{R} \times CRP \qquad (3)$$

where the $\overline{U}$ (g C m^{-2} d^{-1}) is the mean daily CO_2 uptake over *CUP* (d yr^{-1}) and $\overline{R}$ (g C m^{-2} d^{-1}) represents the mean daily CO_2 release over *CRP* (d yr^{-1}). In addition, ~~The calculations of these direct indicators are as follows:~~

~~$$U = \sum_{i=1}^{m} NEP_i \; (NEP_i > 0;\; CUP = m) \qquad (4)$$~~

~~$$R = \sum_{i=1}^{n} NEP_i \; (NEP_i < 0;\; CRP = n) \qquad (5)$$~~

~~where NEP_i refers to the daily NEP (g C m^{-2} d^{-1}) in the *ith* day. Because many studies have reported that the vegetation CO_2 uptake during the growing season and the non-growing soil~~

~~respiration are tightly correlated (Luo, & Zhou, 2006; Xia, Chen, Piao, Ciais, Luo, & Wan, 2014; Zhao, Peichl, Öquist, & Nilsson, 2016),~~ we further tested the relationship between annual NEP and the ratio of $\frac{U}{R}$ (i.e., $NEP \propto \frac{U}{R}$). Ecologically, the ratio of $\frac{U}{R}$ reflects the relative strength of the ecosystem CO_2 uptake. ~~Then we found that annual NEP was closely related with the ratio of $\frac{U}{R}$ (Figure S2).~~ Therefore, NEP in any year of any given ecosystem can be expressed as:

$$NEP = \beta \cdot \ln\left(\frac{U}{R}\right) \qquad (~~6~~4)$$

where the parameter β represents the slope of the linear relationship of $NEP \propto \ln\left(\frac{U}{R}\right)$. Based on the definitions of U and R, the ratio $\frac{U}{R}$ can be further written as:

$$\frac{U}{R} = \frac{\overline{U}}{\overline{R}} \cdot \frac{CUP}{CRP} \qquad (~~7~~5)$$

~~These components of NEP contain both photosynthesis and respiration flux, which directly indicate the net CO_2 exchange of an ecosystem.~~ Ecologically, the ratio of $\frac{\overline{U}}{\overline{R}}$ reflects the relative physiological difference between ecosystem CO_2 uptake and release strength, while the ratio of $\frac{CUP}{CRP}$ is an indicator of net ecosystem CO_2 exchange phenology. Environmental changes may regulate these ecological processes and ultimately affect the ecosystem NEP. The slope β indicates the response sensitivity of NEP to the changes in phenology and physiological processes. All of β, $\frac{CUP}{CRP}$ and $\frac{\overline{U}}{\overline{R}}$ were then calculated from the selected eddy covariance sites and the corresponding pixels of these sites in models. These derived indicators from eddy covariance sites were then used to benchmark the results extracted from the same locations in models.

2.4 Calculation of the relative contributions

~~To~~ We further ~~identify~~ quantified the relative contributions of $\frac{\overline{U}}{\overline{R}}$ and $\frac{CUP}{CRP}$ in driving the ~~spatiotemporal~~ spatial variations in ~~the local indicator $\frac{U}{R}$~~ NEP~~, we linearized the equation (7) as~~:

$$\sout{\log\left(\frac{U}{R}\right)} \mathrm{NEP} = \int\left(\frac{\overline{U}}{\overline{R}}, \frac{CUP}{CRP} \sout{\log\left(\frac{\overline{U}}{\overline{R}}\right) + \log\left(\frac{CUP}{CRP}\right)}\right)$$

(~~8~~6)

~~Then w~~We used a relative importance analysis method to quantify the relative contributions of each ratio to the ~~spatiotemporal~~ spatial variations in NEP. ~~$\frac{U}{R}$.~~ The algorithm was performed with the "ralaimpo" package in R (R Development Core Team, 2011). The "relaimpo" package is based on variance decomposition for multiple linear regression models. We chose the most commonly used method named "Lindeman-Merenda-Gold (LMG)" (Grömping, 2007) from the methods provided by the "ralaimpo" package. This method allows us to quantify the contributions of explanatory variables in a multiple linear regression model. ~~In each site, we calculated the contributions of $\frac{\bar{U}}{\bar{R}}$ and $\frac{CUP}{CRP}$ in explaining inter-annual variation in $\frac{U}{R}$.~~ Across the 72 FLUXNET sites, we quantified the relative importance of $\frac{\bar{U}}{\bar{R}}$ and $\frac{CUP}{CRP}$ to cross-site changes in ~~–~~ NEP~~$\frac{U}{R}$~~.

3. Results

~~**3.1 Spatial variability in terrestrial NEP**~~

~~Based on the FLUXCOM product, a large spatial variation in terrestrial NEP and IAV_{NEP} existed over 1980-2013. The tropical forests were typically large carbon sinks accompanied by considerable interannual variability. On the contrary, the boreal tundra ecosystems were stable carbon sinks and the shrublands in the Southern Hemisphere were variable carbon sources (Fig. 1a). This remarkable spatial difference in terrestrial NEP was particularly obvious from eddy-flux measurements (Fig. S1), and the global average IAV of NEP (175 ± 111 g C m^{-2} yr^{-1}) was large relative to global annual mean NEP (216 ± 234 g C m^{-2} yr^{-1}). These spatial patterns were also supported by the model outputs (Jung et al., 2017) and atmospheric inversion product (Marcolla, Rödenbeck, & Cescatti, 2017).~~

~~More importantly, we found that the variations of NEP and IAV_{NEP} were spatially asynchronous. Along the latitudinal gradients, terrestrial NEP peaked at equatorial regions, whereas the highest IAV_{NEP} existed in semiarid regions near 37° S (Fig. 1b). The demonstrated spatial asynchrony further revealed the necessary to identify local indicators for the spatially varying NEP and IAV_{NEP}, separately.~~

3.~~2~~1 ~~Local indicators for spatially varying~~The relationship between NEP and its direct

components

To find local indicators for the spatially varying NEP in terrestrial ecosystems, we ~~first~~ tested the relationship between NEP and ~~the~~ its direct components (U and R) ~~$\frac{U}{R}$ ratio~~ across the 72 flux-tower sites. The~~n we found~~ results showed that annual NEP was closely related with the ratio of $\frac{U}{R}$ (Figure S2). ~~We~~ The ~~found robust~~ logarithmic correlations between annual NEP and $\frac{U}{R}$ were significant at all sites (Fig. ~~2a~~1a; Fig. S2), ~~with~~ and ~90% of R^2 falling within a range from 0.7 to 1 (Fig. ~~2c~~1c).

–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.~~Across the 72 flux-tower sites, the spatial changes in mean annual NEP were significantly correlated to $\ln\left(\frac{U}{R}\right)$ ($R^2 = 0.65$, $P < 0.01$) (Fig. 3a). This finding suggests that the mean annual ratio $\ln\left(\frac{U}{R}\right)$ is a good indicator for NEP and its spatial variation. By contrast, the spatial variation of IAV_{NEP} was well explained by the slope (i.e., β) of the temporal correlation between NEP and $\ln\left(\frac{U}{R}\right)$ at each site ($R^2 = 0.39$, $P < 0.01$; Fig. 3b) rather than $\ln\left(\frac{U}{R}\right)$ (Fig. S3). The wide range of ratio β reveals a large divergence of NEP sensitivity across biomes, ranging from 121 ± 118 g C m^{-2} yr^{-1} in shrubland to 473 ± 112 g C m^{-2} yr^{-1} in cropland.~~

~~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 $\frac{U}{R}$ variability. The linear regression and relative importance analysis showed a more important role of $\frac{CUP}{CRP}$ (81%) than $\frac{\bar{U}}{\bar{R}}$ (19%) in explaining the cross-site variation of $\frac{U}{R}$ (Fig. 4). Therefore, the spatial distribution of mean annual NEP was mostly driven by the phenological rather than physiological changes.~~

3.2 Local indicators for spatially varying NEP

Across the 72 flux-tower sites, the spatial changes in mean annual NEP were significantly correlated to $\ln(\frac{U}{R})$ ($R^2 = 0.65$, $P < 0.01$) (Fig. 3a). This finding suggested that the mean annual ratio $\ln(\frac{U}{R})$ is a good indicator for cross-site variation in NEP. By contrast, the spatial variation of IAV_{NEP} was moderately explained by the slope (i.e., β) of the temporal correlation between NEP and $\ln(\frac{U}{R})$ at each site ($R^2 = 0.39$, $P < 0.01$; Fig. 3b) rather than $\ln(\frac{U}{R})$ (Fig. S3). The wide range of ratio β reveals a large divergence of NEP sensitivity across biomes, ranging from 121 ± 118 g C m^{-2} yr^{-1} in shrubland to 473 ± 112 g C m^{-2} yr^{-1} in cropland.

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.

3.3 Simulated spatial variations in NEP by models

We further used these two simple indicators (i.e., $\frac{U}{R}$ and β) to evaluate the simulated spatial variations of NEP by the compiled global product~~machine-learning approach~~ (i.e., FLUXCOM) and a widely-used process-based model at the FLUXNET site level (i.e., CLM4.5). We found that ~~both of FLUXCOM and CLM4.5 underestimated the spatial variation of mean annual NEP and IAV_{NEP} (Fig. 5a). T~~the low spatial variation of mean annual NEP in FLUXCOM and CLM4.5 could be inferred from their more converging $\ln(\frac{U}{R})$ than flux-tower measurements (Fig. 5~~b~~). The underestimated variation of IAV_{NEP} in these modeling results was also clearly shown by the smaller β values (268.22, 126.00 and 145.08 for FLUXNET, FLUXCOM and CLM4.5, respectively) (Fig. 5b).

In addition, the spatial variations of NEP and IAV_{NEP} were associated with the spatial resolution of the product (Marcolla et al., 2017). Considering the scale mismatch between

FLUXNET sites and the gridded product, we run the same analysis at the global scale based on Jena Inversion product. At the global scale, the spatial variation of mean annual NEP can be also well indicated by $\ln(\frac{U}{R})$ (Fig. 6). The larger C uptake in FLUXCOM resulted from its higher simulations for $\ln(\frac{U}{R})$. Furthermore, the larger spatial variation of IAV_{NEP} in CLM4.5 could be inferred from the indicator β.

4. Discussion

4.1 New perspective for locating the major and sustainable land C sinks

Large spatial differences of mean annual NEP and IAV_{NEP} have been well-documented in previous studies (Jung et al., 2017; Marcolla~~, Rödenbeck, & Cescatti~~ et al., 2017; Fu et al., 2019). Here we provide a new perspective for quantifying the spatially varying NEP by tracing annual NEP into several local indicators. Therefore, these traceable indicators could provide useful constraints for predicting annual NEP, especially in areas without eddy-covariance towers.

Typically, the C sink capacity and its stability of a specific ecosystem are characterized separately (Keenan et al., 2014; Ahlstrom et al., 2015; Jung et al., 2017). Here we integrated NEP into two simple indicators that could directly locate the major and sustainable land C sink. Among biomes, forests and croplands had the largest $\ln(\frac{U}{R})$ and β, indicating the strongest and the most unstable C sink in forests and croplands, respectively.

However, the relatively lower β in shrublands and savannas should be interpreted cautiously. There are very few semi-arid ecosystems in the FLUXNET sites, 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). The highest β in croplands implies that the rapid global expansion of cropland may enlarge the IAV_{NEP} on the land. In fact, the cropland expansion has been confirmed as one important driver of the recent increasing global vegetation growth peak (Huang et al., 2018) and atmospheric CO_2 seasonal amplitude (Gary et al., 2014; Zeng et al., 2014).

4.2 Phenology-dominant spatial distribution of mean annual NEP

Recent studies have demonstrated that the spatiotemporal variations in terrestrial gross primary productivity are jointly controlled by plant phenology and physiology (Xia et al., 2015; Zhou et al., 2016). Here we demonstrated the dominant role of the phenology indicator $\frac{CUP}{CRP}$ in driving the spatial difference of ~~$\frac{U}{R}$ and therefore the~~ mean annual NEP. The reported low correlation ~~between $\frac{U}{R}$ and the physiological~~ between mean annual NEP and the physiological indicator $\frac{\bar{U}}{\bar{R}}$ could partly be attributed to the convergence of $\frac{\bar{U}}{\bar{R}}$ across FLUXNET sites (Fig. S4). The convergent $\frac{\bar{U}}{\bar{R}}$ across sites was first discovered by Churkina *et al*. (2005) as 2.73 ± 1.08 across 28 sites, which included DBF, EBF and crop/grass. In this study, we found the $\frac{\bar{U}}{\bar{R}}$ across the 72 sites is 2.71 ± 1.61, which validates the discovery by Churkina *et al*. However, the $\frac{\bar{U}}{\bar{R}}$ varied among biomes (2.86 ± 1.56 for forest, 2.16 ± 1.14 for grassland, 3.47 ± 1.98 for cropland, 2.89 ± 1.47 for wetland, 1.89 ± 1.10 for shrub, 1.83 ± 0.88 for savanna). This spatial convergence of $\frac{\bar{U}}{\bar{R}}$ at the ecosystem level provides important constraints for global models that simulate various physiological processes (Peng et al., 2015; Xia et al., 2017). These findings imply that the phenology changes will greatly affect the locations of the terrestrial carbon sink by modifying the length of carbon uptake period (Richardson~~, Keenan, Migliavacca, Ryu, Sonnentag, & Toomey~~ et al., 2013; Keenan et al., 2014).

4.3 The simulated ~~underestimated spatial variations of~~local indicators from gridded products ~~NEP in models~~

This study showed that the considerable spatial variations in mean annual NEP and IAV_{NEP} ~~were both underestimated by~~ from global gridded products ~~the machine-learning-based and process-based global models, which~~ could also be inferred from their local indicators. The low variations of $\frac{U}{R}$ ratio in ~~the two modeling approaches~~CLM4.5 could be largely due to their simple representations of the diverse terrestrial plant communities into a few plant functional types with parameterized properties (Cui et al., 2019; Sakschewski et al., 2015). In addition, the higher $\frac{U}{R}$ ratio from FLUXCOM product indicated its widely reported larger C uptake (Fig. 6) (Jung et al., 2020). Meanwhile, ~~The~~ the ignorance of fire, land-use change and other disturbances~~year-to-year vegetation dynamic~~ could lead to the smaller β by allowing for only limited variations of phenological and physiological ~~responses to environmental changes~~dynamics (Reichstein~~, Bahn, Mahecha, Kattge, & Baldocchi~~ et al., 2014; Kunstler et al., 2016). Although the magnitude of IAV_{NEP} depends on the spatial resolution (Marcolla~~, Rödenbeck, & Cescatti~~ et al., 2017), we recommend future model benchmarking analyses to use not only the global product compiled from machine-learning~~-based data product~~ method (Bonan et al., 2018) but also the site-level measurements or indicators (i.e., $\ln\left(\frac{U}{R}\right)$ and β).

4.4 Conclusions and further implications

In summary, this study highlights the changes in NEP and IAV_{NEP} over space on the land, and provides the $\frac{U}{R}$ ratio and β as two simple local indicators for their spatial variations. These indicators could be helpful for locating the persistent terrestrial C sinks in where the $\ln\left(\frac{U}{R}\right)$ ratio is high but the β is low. Their estimates based on observations are also valuable for benchmarking and improving the simulation of land-atmospheric C exchanges in Earth system models.

In addition, the findings in this study have some important implications for understanding the variation of NEP on the land. First, forest ecosystems have the largest annual NEP due to the largest $\ln\left(\frac{U}{R}\right)$ while croplands show the highest IAV_{NEP} because of the highest β. Second, the spatial convergence of $\frac{\bar{U}}{\bar{R}}$ suggests a tight linkage between plant growth and the non-growing season soil microbial activities (Xia~~, Chen, Piao, Ciais, Luo, & Wan~~ et al., 2014; Zhao~~, Peichl, Öquist, & Nilsson~~ et al., 2016). However, it remains unclear whether the inter-biome variation in $\frac{\bar{U}}{\bar{R}}$ is due to different plant-microbe interactions between biomes. Third, the within-site convergent but spatially varying β needs better understanding. Previous studies have shown that a rising standard deviation of ecosystem functions could indicate an impending ecological state transition (Carpenter~~, &~~ and Brock, 2006; Scheffer et al., 2009). Thus, a sudden shift of the β-value may be an important early-warning signal for the critical transition of IAV_{NEP} of an ecosystem. –

~~In addition~~Furthermore, considering the limited eddy-covariance sites with long-term observations, these findings need further validation once the longer time-series of measurements from more sites and vegetation types become available. Overall, this study highlights the asynchronous changes in NEP and IAV_{NEP} over space on the land, and provides the $\frac{U}{R}$ ratio and β as two simple local indicators for their spatial variations. These indicators could be helpful for locating the persistent terrestrial C sinks in where the $\ln(\frac{U}{R})$ ratio is high but the β is low. Their estimates based on observations are also valuable for benchmarking and improving the simulation of land-atmospheric C exchanges in Earth system models.

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Data availability statement. Eddy flux data are available at http://fluxnet.fluxdata.org/data/fluxnet2015-dataset/**;** the data supporting the findings of this study are available within the article and the Supplementary Information.

Author contribution. E. Cui and J. Xia devised and conducted the analysis. Y. Luo, S. Niu, Y. Wang and C. Bian provided critical feedback on the method and results. All authors contributed to discussion of results and writing the paper.

Competing interests. The authors declare that there is no conflict of interest.

FIGURES

~~**Figure 1** Locations of carbon sinks (mean annual NEP) and their stability (IAV_{NEP}) on the land. a, Spatial patterns of mean annual NEP and IAV_{NEP}. b, Latitudinal patterns of mean annual NEP and IAV_{NEP}.~~

Figure ~~2~~ 1 Relationship between annual NEP and $\frac{U}{R}$ for 72 FLUXNET sites (of the form $\mathrm{NEP} = \beta \cdot \ln\left(\frac{U}{R}\right)$). a, Dependence of annual NEP on the ratio between total CO_2 exchanges during net uptake (*U*) and release (*R*) periods (i.e., $\frac{U}{R}$). Each line represents one flux site with at least 5 years of observations. b, Conceptual figure for the decomposition framework introduced in this study. Annual NEP can be quantitatively decomposed into the following indicators: $NEP = U - R$. c, Distribution of the explanation of $\frac{U}{R}$ on temporal variability of NEP (R^2) for FLUXNET sites.

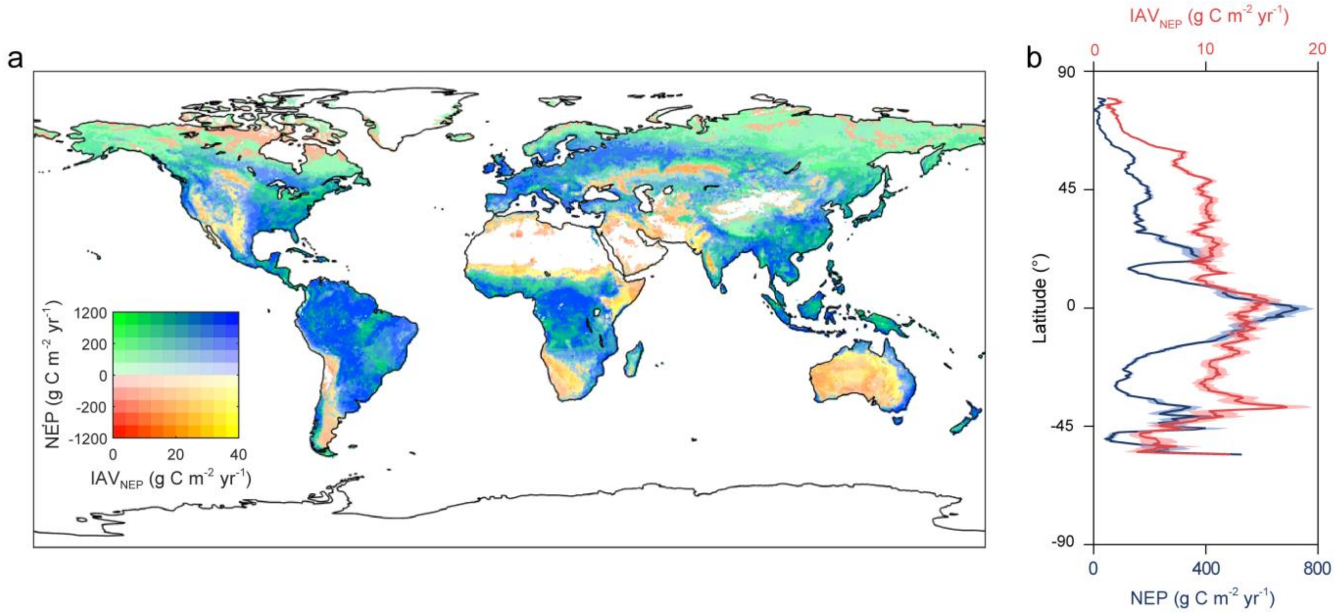
Figure 2 Relationship between annual NEP and $\frac{U}{R}$ for Jena Inversion product (of the form $\mathrm{NEP} = \beta \cdot \ln\left(\frac{U}{R}\right)$). The black box indicates the location of the sample.

Figure 3 Contributions of the two indicators in explaining the spatial patterns of mean annual NEP and IAV_{NEP}. a, The relationship between annual mean NEP and $\ln\left(\frac{U}{R}\right)$ across FLUXNET sites (R^2 = 0.65, P < 0.01). The insets show the variation of $\ln\left(\frac{U}{R}\right)$ for different terrestrial biomes. b, The explanation of β on IAV_{NEP} (R^2 = 0.39, P < 0.01). The insets show the distribution of parameter β for different terrestrial biomes. The number of site-years at each site is indicated with the size of the point.

Figure 4 The linear regression between $\frac{U}{R}$ with $\frac{CUP}{CRP}$ (R^2 = 0.71, P < 0.01) and $\frac{\bar{U}}{\bar{R}}$ (R^2 = 0.09, P < 0.01) across sites. The insets show the relative contributions of each indicator to the spatial variation of $\frac{U}{R}$. The number of site-years at each site is indicated with the size of the point.

Figure 5 Representations of the spatially varying NEP and its local indicators in FLUXCOM product and the Community Land Model (CLM4.5) at the FLUXNET site level. a, The variation of mean annual NEP and IAV_{NEP} derives from FLUXNET, FLUXCOM and CLM4.5. Variation in mean annual NEP: the standard deviation of mean annual NEP across sites; Variation in IAV_{NEP}: the standard deviation of IAV_{NEP} across sites. b, Representations of the local indicators for NEP in FLUXNET, FLUXCOM and CLM4.5. The corresponding distributions of $\ln\left(\frac{U}{R}\right)$ and β are shown at the top and right. Significance of the relationship between annual NEP and $\ln\left(\frac{U}{R}\right)$ for each site is indicated by the circle: closed circles: P<0.05; open circles: P>0.05. Note that the modeled results are from the pixels extracted from the same locations of the flux tower sites.

Figure 6 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 NEP; 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.



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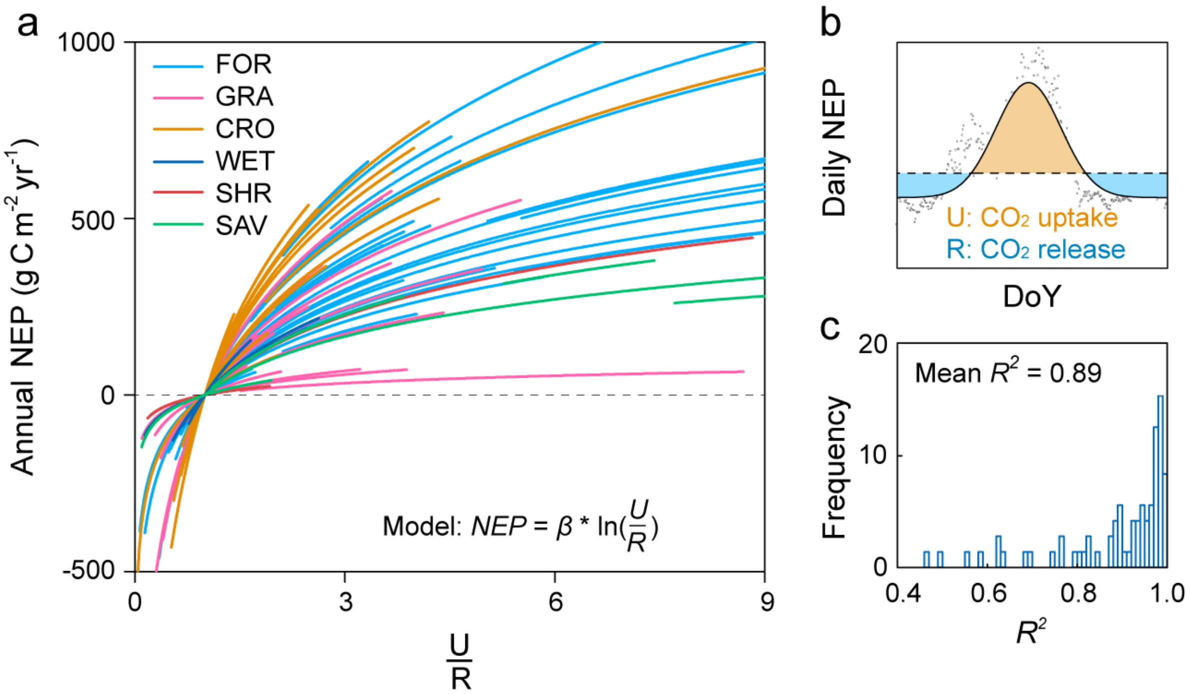

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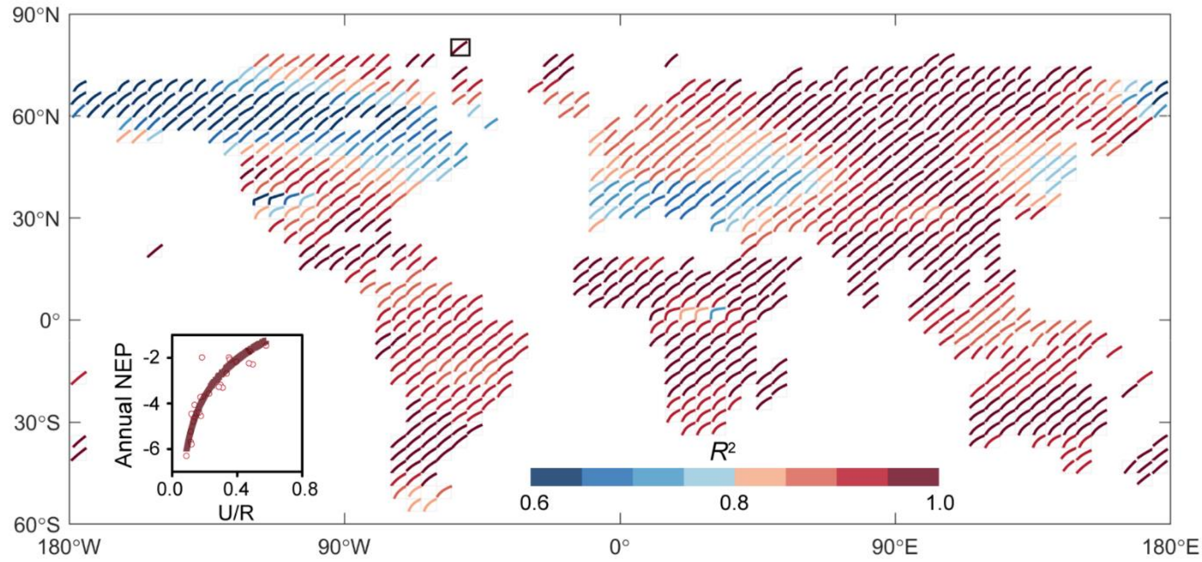

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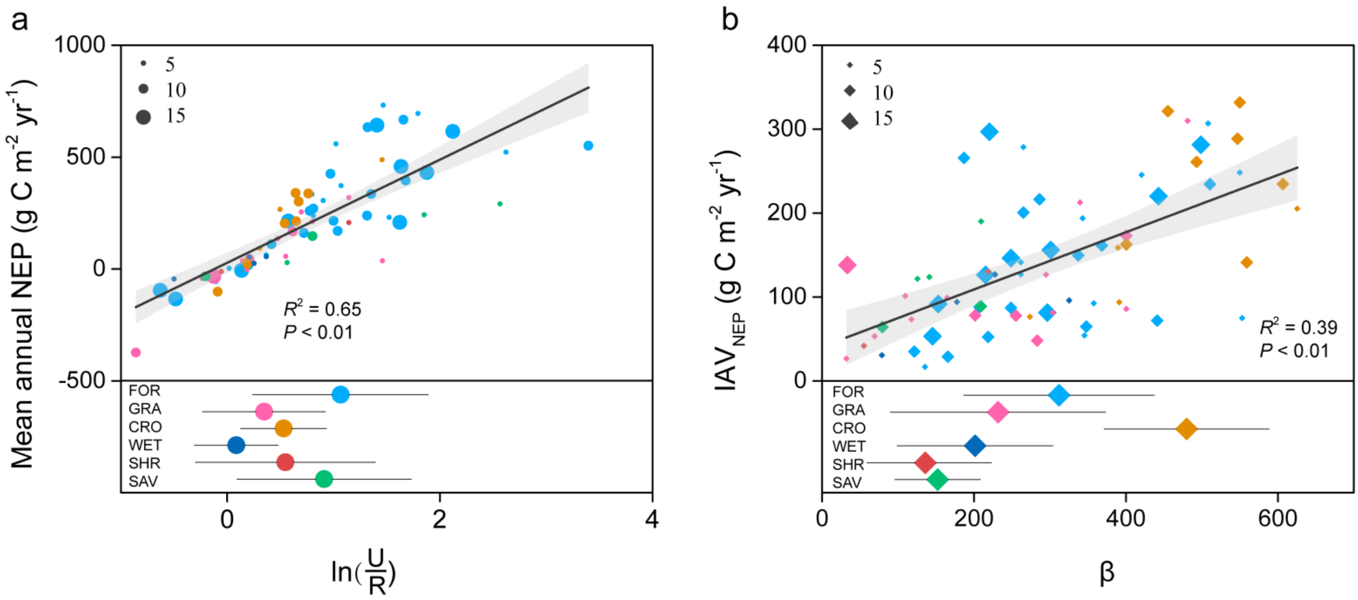

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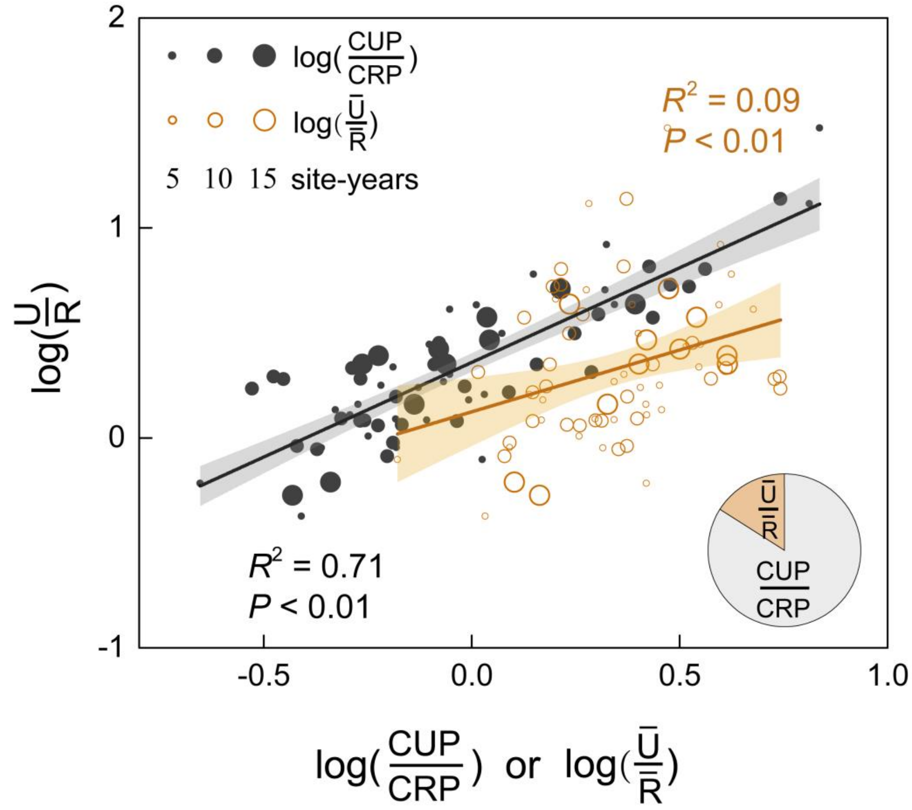

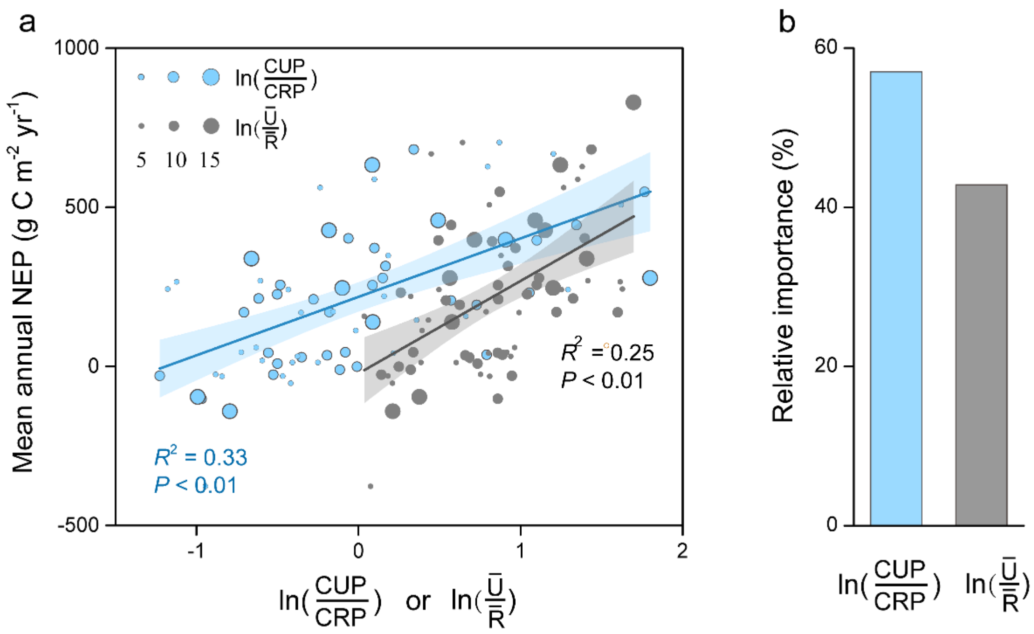

Figure 4 The relative contributions of the local indicators in explaining the spatial patterns of mean annual NEP. **a**, The linear regression between mean annual NEP with $\frac{CUP}{CRP}$ (R^2 = 0.33, P < 0.01) and $\frac{\bar{U}}{\bar{R}}$ (R^2 = 0.25, P < 0.01) across sites. **b**, The relative contributions of each indicator to the spatial variation of NEP. The number of site-years at each site is indicated with the size

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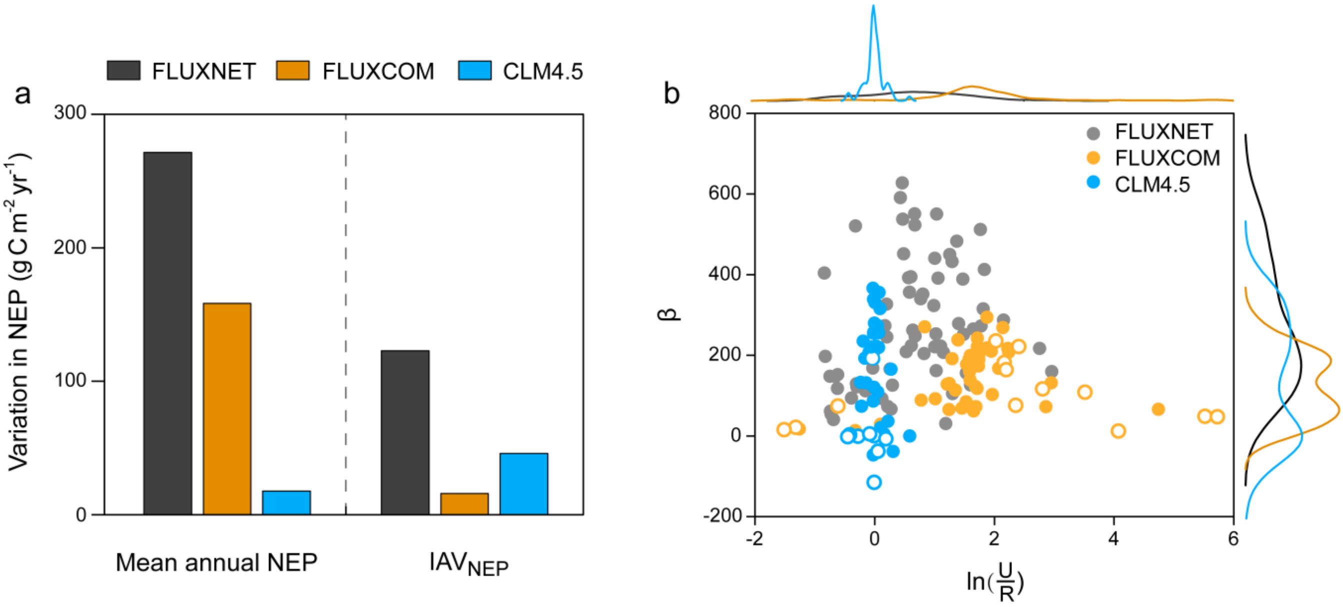

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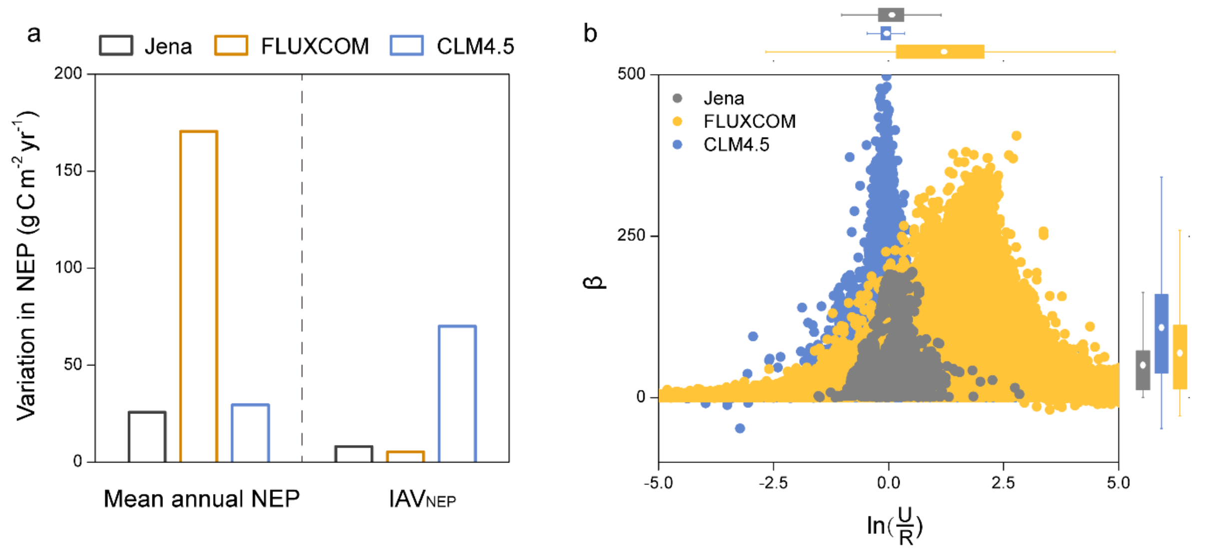

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