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July 30, 2020

Re: hess-2020-185

Dear Dr. Hildebrandt,

Regarding your decision letter on our manuscript entitled "Rapid reduction in ecosystem productivity caused by flash drought based on decade-long FLUXNET observations" (hess-2020-185), we have now carefully considered your and reviewers' comments and incorporated them into the manuscript to the extent possible. The main changes include revising the flash drought definition by dropping the 60-day duration limit to consider all flash drought cases (although it does not affect the conclusions in this study), analyzing the responses of GPP and ET during different stages of flash droughts, investigating the climate controls on GPP using partial correlation analysis, extending the discussion, and providing point-by-point responses. We hope that you find the revised manuscript and the response acceptable to *Hydrology and Earth System Sciences*. The detailed responses to the comments are attached.

We appreciate the effort you spent to process the manuscript and look forward to hearing from you soon.

Sincerely yours,

Xing Yuan

Response to the comments from Reviewer #1

We are grateful to the reviewer for the constructive and careful review. We have incorporated the comments to the extent possible. The reviewer's comments are italicized and our responses immediately follow.

General Comments:

1) Terminology-Because the definition for flash drought recovery focuses on changes in soil moisture, this framework introduces some confusion when also used to examine changes in GPP given the lag between the onset of soil moisture drought and its impact on vegetation health. For example, it is counterintuitive to refer to periods of "recovery" as those that also have substantial reductions in GPP. I think the framework used in this study is okay, but that different terminology needs to be used when referring to these periods because the "recovery" is only with respect to soil moisture conditions. The new terminology will need to be used in the abstract, and throughout the paper. It would also help to remind the reader at various stages of the paper that "flash drought" refers to "soil moisture flash drought"

Response: Yes, given the definition of flash drought in this study is based on soil moisture deficit and decline rate, the "recovery" means the recovery of soil moisture drought instead of ecological drought. There is a lagged effect of ecosystem to soil moisture drought, so the GPP recovery usually lags behind the soil moisture recovery. According to the suggestion, we have revised "flash drought" as "soil moisture flash drought" throughout the paper.

2) Definition-I think it's fine that you chose to add a maximum length threshold (lines128-131) to the flash drought definition if you also want to solely focus on sub-seasonal drought events. However, this choice, and its impact on the resultant analysis, needs to be clearly noted in the revised text. For example, limiting flash drought duration to no more than two months means that situations where a period of rapid intensification preceded development of a longer-term drought will be excluded from the climatology because the soil moisture will not rise to greater than the 20th *percentile within the chosen period of time. In fact, many of the most notable flash drought events discussed in the introduction (such as the 2012 U.S. flash drought) would presumably not be classified as flash drought with this methodology because the period of rapid intensification itself lasted for two or more months after that. In reality, the method used in this study only examines a subset of flash droughts, where not only must they exhibit a period of rapid intensification over 1-2 months, but then the drought conditions themselves must also be completely eliminated within another month. So, there are sub-seasonal events in their entirety. This is alluded to at lines 193-195. To reiterate, I think the methodology itself is okay, but that is needs to be clearly stated at various points of the text (abstract, methods, results, discussion, conclusions) that the goal is to look "only" at flash drought events that develop and decay over a single season, and that the method will exclude flash droughts that subsequently develop into long-term drought.*

Response: Thanks for your comments. In the last version of the manuscript, we only focused on the first two months of the flash drought if it did not recover. So we actually did not remove those flash droughts with long durations, but the maximum length threshold may affect the analysis during the recovery stage and after the flash drought. To avoid the confusion, we have now removed the maximum length threshold to consider the whole evolution of flash drought events even if it lasts for more than two months. In the revised manuscript, there are 151 flash drought events, and 20 of them have durations that are longer than two months. However, the main conclusions remain the same. The changes related to the removal to maximum length threshold are as follows:

"The number of soil moisture flash drought ranges from 13 to 70 events among different vegetation types. There are 12 ENF sites in this study, and the number of soil moisture flash droughts for ENF (70) is the most among all the vegetation types. The duration for flash drought events ranges from 24 days to several months. In some extreme cases, the flash droughts would develop into long-term droughts without enough rainfall to alleviate drought conditions. Mean durations of soil moisture flash droughts for different vegetation types range from around 30 days to 50 days (Figure

2c).” (L232-241)

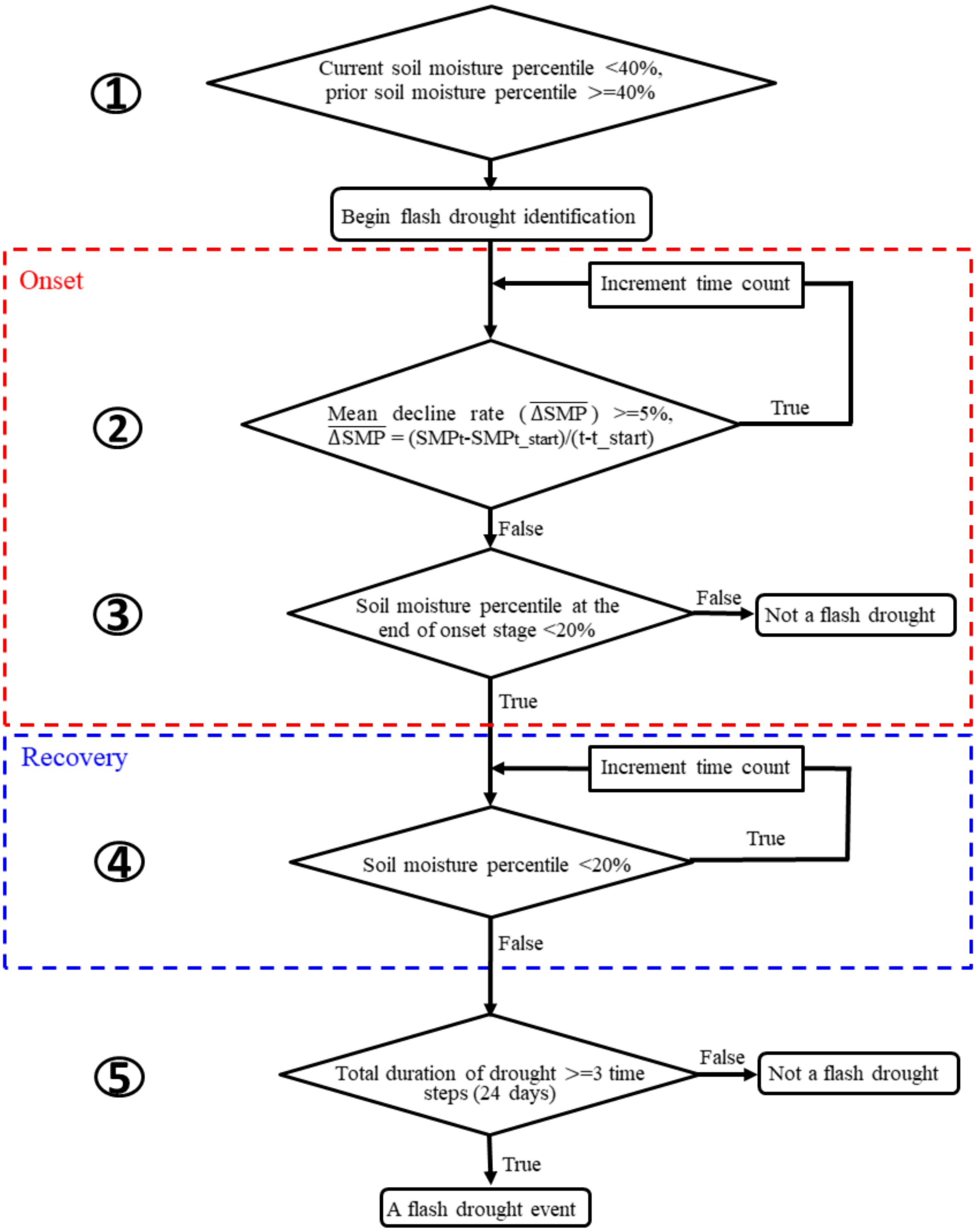

Figure 1. A flowchart of flash drought identification by considering soil moisture decline rate and drought persistency.

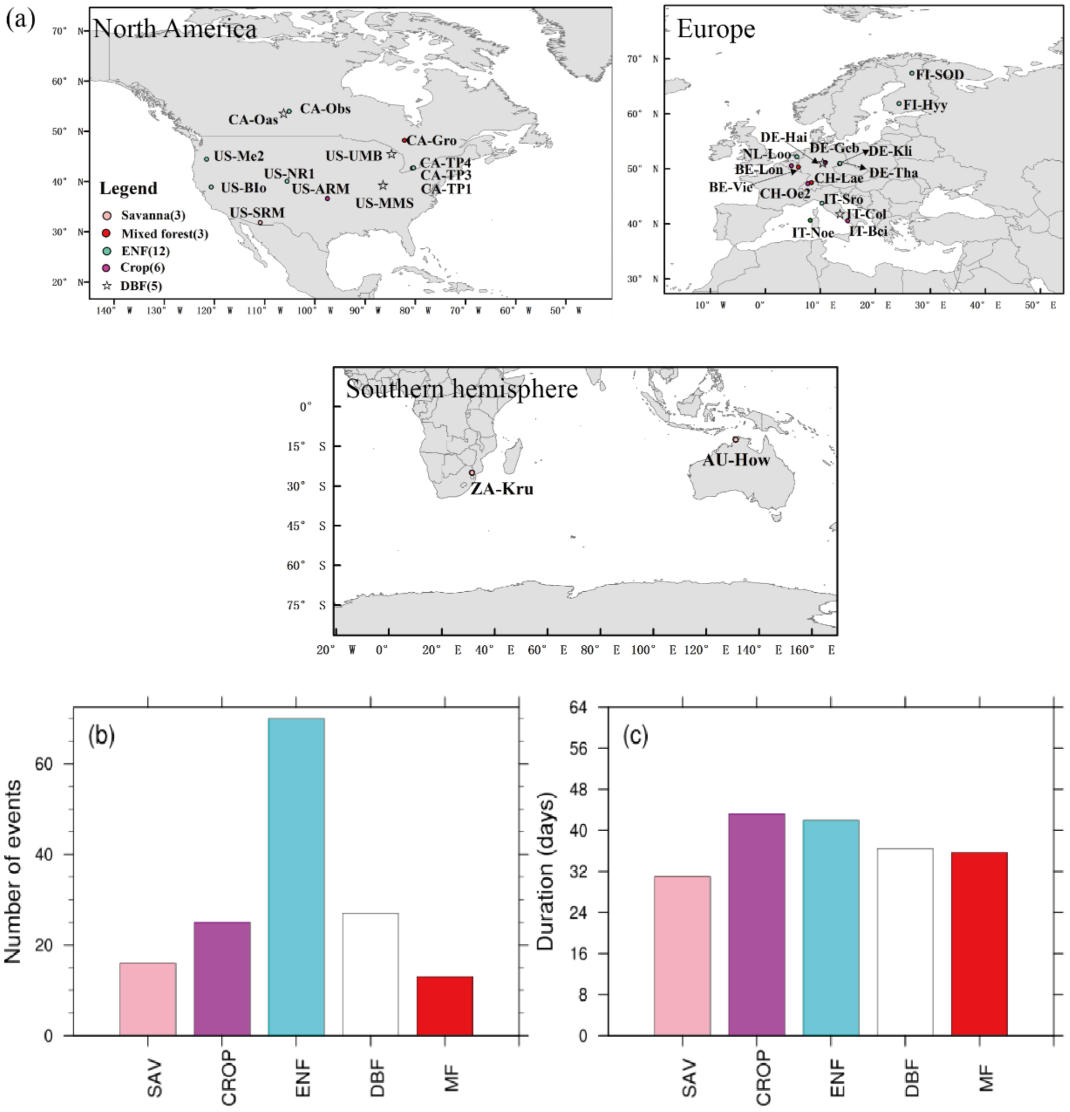

Figure 2. (a) Global maps of 29 FLUXNET sites used in this study. (b) Total numbers (events) and (c) mean durations (days) of soil moisture flash drought events for each vegetation type during their corresponding periods (see Table 1 for details). Different colors represent different vegetation types.

3) Section 3.3-This section needs to be substantially revised. Given that the focus elsewhere in the paper has been to evaluate the results based on the vegetation type, it is confusing why this section primarily focuses on analyzing the results accumulated over all vegetation types in Fig.5., before then very briefly discussing vegetation specific results in Fig.6. It would be much more insightful, and consistent with the rest of the paper, if you were to instead expand the existing briefly analysis for each of the *vegetation types into something more substantial. This would result in the removal of Fig.5 that focuses on all of the stations in aggregate and redoing the bottom panels in Fig.5 so that they can be added to Fig.6 for each individual vegetation type. This will then allow you to continue to examine the time series for each vegetation type as has been done elsewhere in the paper.*

Response: Thanks for your constructive comments. We have reorganized the results and shown them for each vegetation type, and removed those results accumulated over all vegetation types. We have revised the manuscript as follows:

"Different types of vegetation including herbaceous plants and woody plants all react to soil moisture flash drought in the early stage (Figures 4a-e). Among them, SAV shows the fastest reaction to water stress (Figures 4a and 4f), and the RT is within 8 days for 63% events, suggesting that SAV responds concurrently with soil moisture flash drought onset. Ultimately, 88% events for SAV show reduced vegetation photosynthesis. The result is consistent with previous studies regarding the strong response of semi-arid ecosystems to water availability (Gerken et al., 2019; Vicente-Serrano et al., 2013; Zeng et al., 2018), and the decline in GPP for SAV is related to isohydric behaviors during soil moisture drought and higher VPD, through closing stomata to decrease water loss as transpiration and carbon assimilation (Novick et al., 2016; Roman et al., 2015). For ENF, only 27% of soil moisture flash droughts cause the negative SGPPA during the first 8 days. When RT is within 40 days, the cumulative frequencies range from 74% to 88% among different vegetation types. The response frequency of RTmin and the response time of minimum soil moisture percentiles are quite similar, although there are discrepancies among the patterns of the response frequency for different vegetation types. The response frequency of RTmin for SAV increases sharply during 17-24 days of soil moisture flash droughts (Figure 4f). GPP is derived from direct eddy covariance observations of NEP and nighttime terrestrial ecosystem respiration, and temperature-fitted terrestrial ecosystem respiration during daytime. The response of NEP to flash droughts shows the compound effects of vegetation photosynthesis and ecosystem respiration. In terms of RT, the response of NEP is slower than GPP for SAV, but is quicker for DBF and ENF (Figure 5). The discrepancies between NEP and SM in terms of RTmin are more obvious than those between GPP and SM, and the RTmin of NEP is much shorter than the RTmin of soil moisture especially for DBF and ENF, which may be related to the increase of ecosystem respiration (Figures 5 i and j).

Figure 6 shows the temporal changes of SGPPA and soil moisture percentiles during 8 days before soil moisture flash droughts and during the first 24 days of the droughts. During 8 days before flash droughts, there is nearly no obvious decline for SGPPA, while SAV, DBF and ENF shows small increase in GPP. The decline in SGPPA is more significant during the first 9-24 days of soil moisture flash droughts for different vegetation types, and SGPPA for SAV and CROP show quicker decline even during the first 8 days of soil moisture flash droughts. The decline rates in soil moisture are mainly concentrated within the first 16 days of flash droughts. There are various lag times for the response of GPP to the decline in soil moisture among different vegetation." (L337-375)

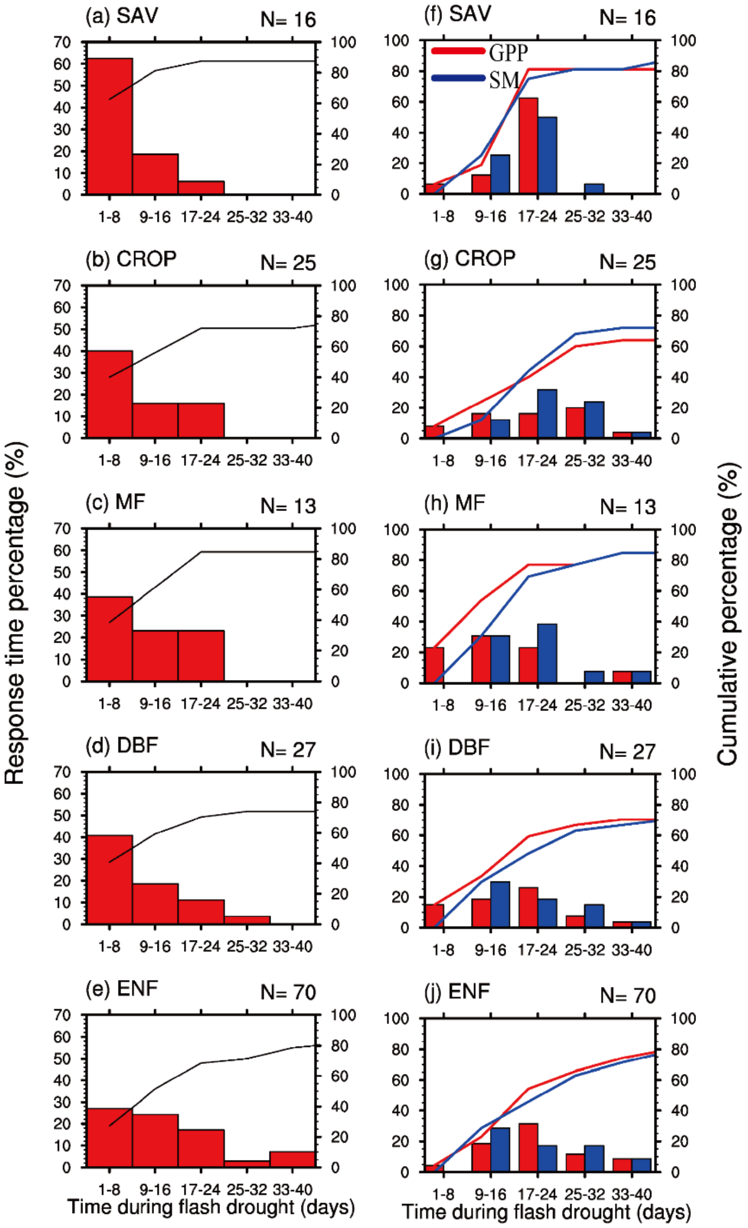

Figure 4. Percentage of the response time (days) of the first occurrence of negative GPP anomaly (a-e), minimum GPP anomaly and minimum soil moisture percentile (f-j) during soil moisture flash drought for different vegetation types. SAV: savanna, CROP: rainfed cropland, MF: mixed forest, DBF: deciduous broadleaf forest and ENF: evergreen needleleaf forest.

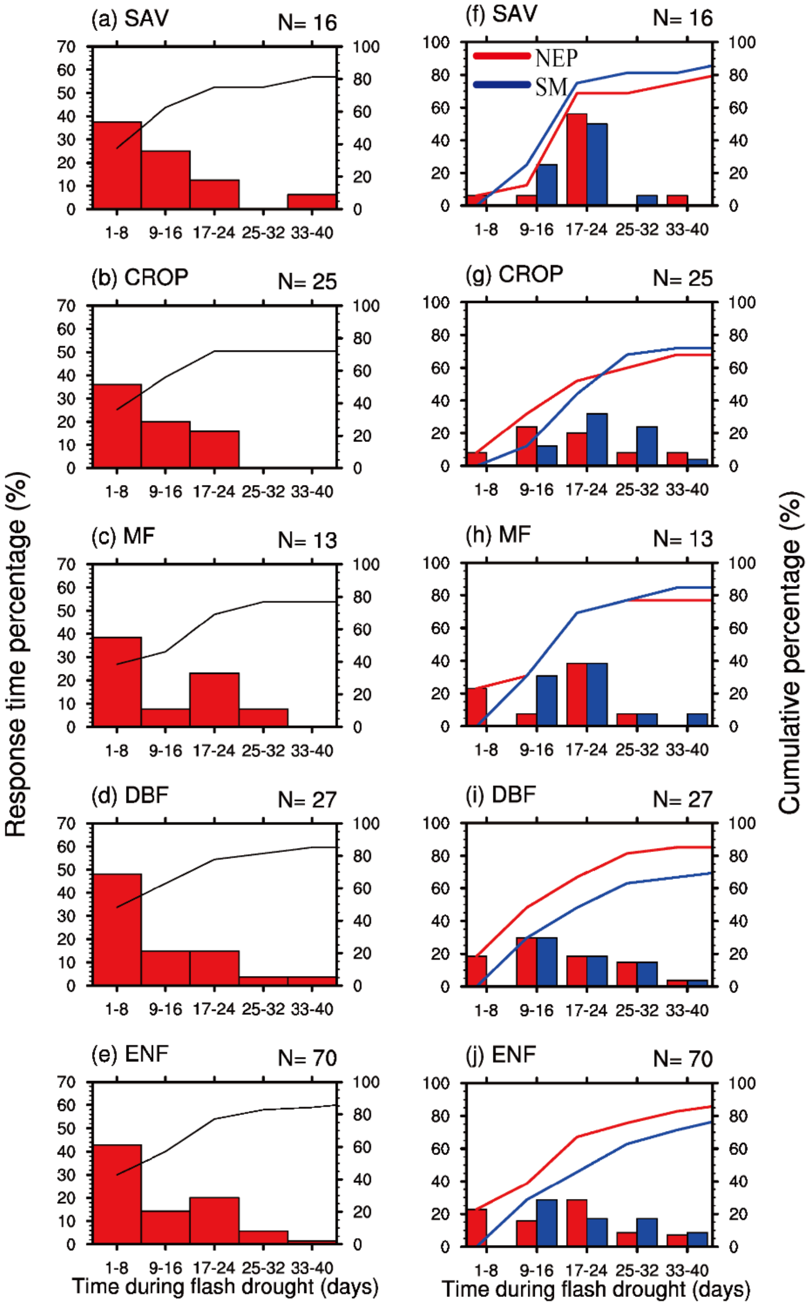

Figure 5. The same as Figure 4, but for net ecosystem productivity (NEP).

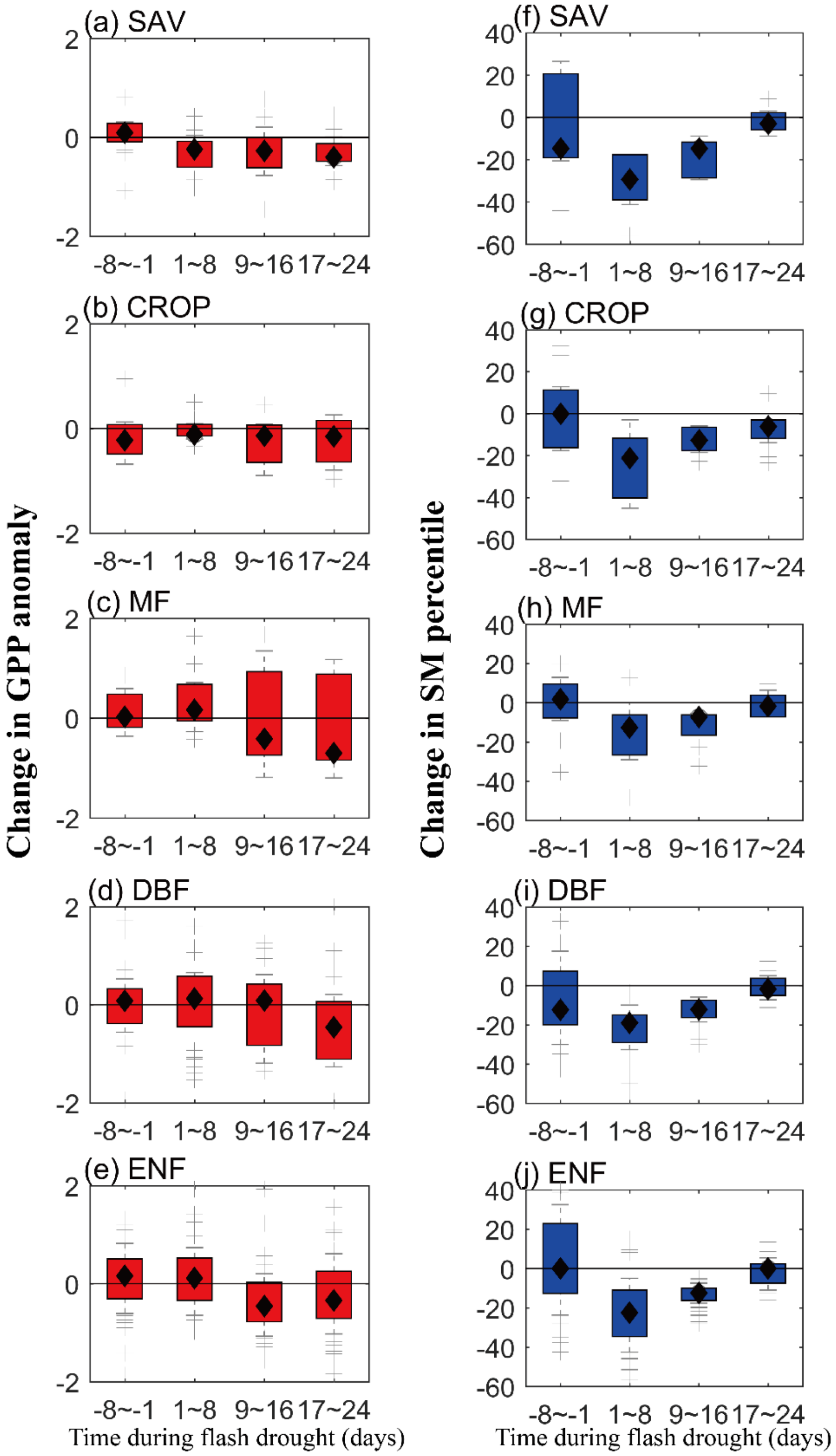

Figure 6. The temporal change rates of standardized GPP anomalies (a-e) and soil moisture percentiles (f-j) for different vegetation types. SAV: savanna, CROP: rainfed cropland, MF: mixed forest, DBF: deciduous broadleaf forest and ENF: evergreen needleleaf forest.

Specific Comments:

4) Line 37-Insert "future" before "land carbon uptake" in this sentence.

5) Line 58-Please add the Svoboda et al. (2002) reference for the U.S. Drought Monitor.

Response: Revised as suggested. (L38; L60)

6) Line 59-This drought also impacted parts of southern Canada.

Response: We have revised it as:

"He et al. (2019) assessed the impacts of the 2017 northern USA flash drought (which also impacted parts of southern Canada) on vegetation productivity based on GOME-2 solar-induced fluorescence (SIF) and satellite-based evapotranspiration." (L61-64)

7) Line 78-Few studies, or no studies have investigated this parameter? If there are previous studies, please cite them here.

Response: We have revised as "…few studies have investigated WUE during flash droughts that usually occur at sub-seasonal time scale (Xie et al., 2016; Zhang et al., 2019)." (L83-85)

8) Introduction-It would also be good to cite the Otkin et al. (2018; WCAS) paper because they examined the impact of a flash drought on vegetation health across the north-central U.S.

Response: We have revised as:

"Besides, the 2016 flash drought over U.S. northern plains also decreased agricultural production (Otkin et al., 2018b)." (L67-68)

9) Line 99-Please add some additional information about the soil moisture sensors, such as their type, their accuracy, and how they are sited. It would also be good to know what the soil type is for each of the stations.

Response: We have added additional information as follows:

"Soil moisture observations are usually averaged over multiple sensors including time domain reflectometer (TDR), frequency domain reflectometer (FDR), and water content reflectometer etc. However, the older devices may be replaced with newer devices at certain sites, which may decrease the stability of long-term soil moisture observations and the average observation error of soil moisture is ±2%." (L106-111)

10) Line 103-106 -How were these vegetation classifications determined? I think it would also be good to briefly discuss the phenological characteristics of these classifications.

Response: We have clarified the classification as follows:

"The vegetation classification is according to International Geosphere-Biosphere Program (IGBP; Belward et al., 1999), where MF is dominated by neither deciduous nor evergreen tree types with tree cover larger than 60%, and the land tree cover is 10-30% for SAV." (L121-124)

11) Line 106- Please make this sentence explicit rather than simply stating "etc". Also, this would be a good spot to point the readers to the top panel in Fig.2 to see the locations of these stations.

Response: We have revised the manuscript as follows:

"Here we only select the FLUXNET observations including 12 evergreen needleleaf forest sites (ENF), 5 deciduous broadleaf forests (DBF), 6 crop sites (CROP; 5 rain-fed sites and 1 irrigated site), 3 mixed forests (MF), and 3 savannas (SAV). The sites for grasslands, evergreen broadleaf forests, and shrublands are excluded because there are less than 10 soil moisture flash drought events." (L116-121)

We have also revised Figure 2. Please see our response above.

12) Lines 106-108-Please provide some justification for why these three particular sites were chosen for the case study analyses. It would also be helpful to mention here where these three stations are located, and a brief overview of their climate *characteristics. For example, are there stations located in regions that are known to frequently experience flash droughts?*

Response: We have removed the case analyses in the revised manuscript because they cannot represent the situations for different vegetation types. Instead, we have now focused on the composite analysis of soil moisture flash droughts for each vegetation type.

13) Line 116-Does the first day of the flash drought occur at the beginning, middle, or end of the 8-day period used to compute the mean conditions? Please clarify.

Response: We have clarified it as follows:

"1) Soil moisture flash drought starts at the middle day of the 8-day period when the 8-day mean soil moisture is less than the 40th percentile, and the 8-day mean soil moisture prior to the starting time should be higher than 40th percentile to ensure the transition from a non-drought condition." (L136-140)

14) Figure 1-The label between steps 2 and 3 should be "true". The box for step five should also be expanded to include "and <2 months". Please correct these errors.

Response: We have now removed the maximum duration threshold and updated the figure. Please see our response above.

15) Line 119-It would be good to note here that these differences are also being computed at 8-day increments to match the cadence of the 8-day mean periods.

Response: Thanks for your comments. We have revised the manuscript as follows:

"2) The mean decreasing rate of 8-day mean soil moisture percentile should be no less than 5% per 8 days to address the rapid drought intensification." (L140-141)

16) Lines 123-125-"Recovery" is imprecise here because a decrease of 4% from one period to the next does not represent recovery; instead, it simply means that the deterioration is not fast enough to meet the threshold for a flash drought used in this study. Please change this term to "stabilization", or something similar, because that *will permit some degradation to still occur. Note that this only refers to the soil moisture status "stabilizing", thus, the inconsistency with respect to the vegetation parameters (see Major Comment#1) still remains and will also need to be properly addressed.*

Response: Thanks for your comments. The end of the onset stage of flash drought occurs when the **mean decline rate (from the beginning of flash drought)** is smaller than 5% in percentiles per 8 days, which would avoid such phenomenon that the soil moisture percentiles are still declining after the onset stage as much as possible. We compared the soil moisture percentiles during recovery stages and at the ending point of onset stages, and found that the soil moisture still declines at the rate of 2~3% in percentiles per 8 days only for 3% of flash drought events (Figure R1). Therefore, the soil moisture percentiles during the identified recovery stages increase as compared with the ending point of onset stages for most cases.

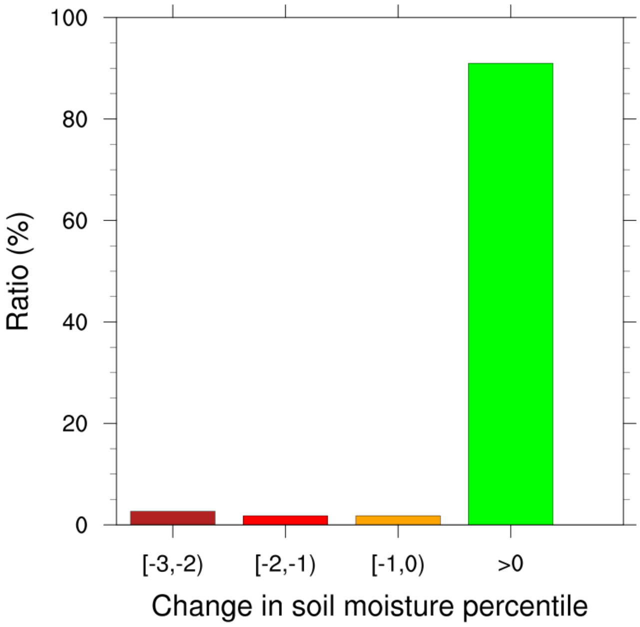

Figure R1. The frequency of soil moisture percentile changes between recovery stages and the ending point of onset stages.

17) Line 132-Please change the start of this sentence to "At least decade long"

Response: Revised as suggested. (L154)

18) Line 132-140-It would be good to reiterate here that the percentiles themselves are still only computed over an 8-day period, but that the use of the surrounding 8-day periods are used to increase the sample size. These surrounding time periods though are certainly not completely independent, so please also comment on how much this approach does or does not increase the effective sample size when computing the percentiles

Response: Thanks for your comments. Figure R2 shows the probability density function of soil moisture at different time based on the climatology solely from the target time of all observation years (a_clim) and the climatology consisting of the target time and 8 days before and after the target time of all observation years (b_clim). The b_clim is smoother than a_clim, indicating that the extended samples would decrease the uncertainty caused by certain extreme values. We have revised the manuscript as follows:

"Besides, the target 8-day soil moisture percentiles are only based on the target 8-day soil moisture in the context of the expanded samples." (L157-159)

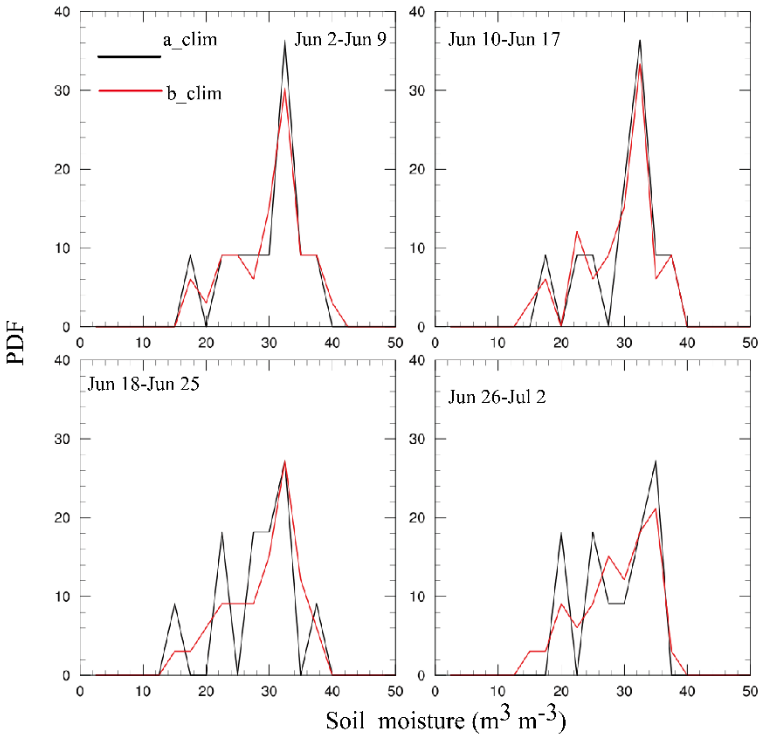

Figure R2. The probability density function of soil moisture at Jun 2-9, Jun 10-Jul 17, Jun 18-Jun 25, Jun 26-Jul 2 based on the climatology solely from the target time during all observation years (black lines; a_clim) and the climatology from not only the target time but also 8 days before and after the target time from all observation years (red lines; b_clim).

19) Lines 150-Please add the Crausbay et al. (2017) paper in BAMS that discusses ecological drought.

Response: Revised as suggested. (L174)

20) Line 154-You highlight an example with 19 years of data: however, most of the stations only have around 10 years of data. This is a short period for computing standard deviations. Please comment on how the short period of record will impact the anomalies and their subsequent use in this study.

Response: Thanks for your comments. Here the standardized deviation of GPP are also based on at least 30-sample climatology, which is same as that of soil moisture percentiles as we mentioned above. We have revised the manuscript as follows:

"For instance, all Apr 1-8 during 1996-2014 would have a μ_{GPP} and a σ_{GPP} based on a climatology same as soil moisture percentile calculation, which consists of March 24-31, Apr 1-8, and Apr 9-16 in all years, and Apr 9-16 would have another μ_{GPP} and another σ_{GPP}, and so on" (L179-182)

21) Lines 154-157-The example provided in this sentence implies that ecological drought always happens one period after the flash drought first develops. Is that the true intention here? If not, please clarify this sentence. I would expect there to be more than a one period lag because in many situations, the vegetation roots will extend much deeper than the 10-cm topsoil layer used in this study to identify flash droughts, thereby allowing them to remain healthy despite a rapidly drying topsoil layer. This needs to be highlighted in this section – a flash drought in the top soil layer may not correspond to an ecological drought because of the depth of the roots.

Response: Thanks for your comments. We have revised the manuscript as follows:

"Considering flash drought is identified through surface soil moisture due to the availability of FLUXNET data, vegetation with deeper roots may obtain water in deep soil and remain healthy during flash drought. The roots vary among different vegetation types and forests are assumed to have deeper roots than grasslands, which may influence the response to soil moisture flash droughts.” (L189-193)

22) Lines 150-162-It would be helpful if each of these indices were assigned separate names to be used in the results section.

23) Line 187-Please add “or equal to” before 24 days

Response: Revised as suggested.

24) Line 190-The station level average lengths are not helpful because many of the stations only have one or two events. It would be better to show the average length over all of the stations, or for all of the stations within a particular ecosystem type. Please do this in the revised text.

Response: We have now shown all results based on different vegetation types instead of at station level. The manuscript has been revised as follows:

“Figure 2a shows the distribution of the 29 sites with different vegetation types, which are mainly distributed over North America and Europe. The number of soil moisture flash drought ranges from 13 to 70 events among different vegetation types. There are 12 ENF sites in this study, and the number of soil moisture flash droughts for ENF (70) is the most among all the vegetation types. The duration for flash drought events ranges from 24 days to several months. In some extreme cases, the flash droughts would develop into long-term droughts without enough rainfall to alleviate drought conditions. Mean durations of soil moisture flash droughts for different vegetation types range from around 30 days to 50 days (Figure 2c).” (L231-241)

25) Lines 192-193-Is this sentence meant to imply that some stations may have multiple flash droughts because a single event is broken into two because of a rainfall event that temporally improves things? If so, please describe it as such, otherwise it is not clear what this sentence adds to the paper.

Response: This sentence has been deleted as it is not relevant to the results.

26) Line 192-What is meant by "variability of soil moisture"? Please describe this more clearly. Also, this really means variability of precipitation since it is the ultimate cause of the variability in soil moisture.

Response: The relationship between frequency of flash droughts and variability of soil moisture is not significant, so we have now deleted this sentence.

27) Figure 2-The panels on this figure are difficult to read. For example, the spatial heterogeneity briefly mentioned in the text is impossible to see in the top panel because most of the stations are crammed into central Europe or North America, and it is impossible to relate the results shown in the bottom panels to the map shown in the top panel. I suggest breaking this panel into separate panels for North America, Europe, and the other four stations individually, while still taking the same amount of space as the current panel. This will allow you to zoom into all of these regions and therefore more clearly show the spatial heterogeneity.

Response: We have revised Figure 2 as suggested. Please see our response above.

28) Lines 204-206-This sentence is imprecise. A decrease in ET will indeed limit the loss of soil moisture; however, it does not represent an alleviation of drought conditions. For one thing, soil moisture will still be decreasing in the absence of rainfall, albeit at a slower rate. Secondly, decreasing ET actually means that agricultural or ecological drought conditions are worsening. Please clarify this statement to account for these considerations.

Response: We have revised the sentence as follows:

"ET starts to decrease during the recovery stage due to the limitation of water availability, and the decreasing ET also reflects the enhanced water stress for vegetation during the recovery stage." (L413-415)

29) Lines 210-211-Please add some information describing where these stations are *located, and why these events were chosen for closer analysis.*

30) Figure 4-Please change the top and bottom rows so that precipitation and temperature anomalies can be both positive and negative, otherwise, the analysis is incomplete since only one part of the anomaly time series can be shown.

31) Line 220-This statement is too strong because it is based on a single case study.

32) Line 228-Is there a reference that supports this statement? The variability in the time series for this station is very similar to the other two time series shown on Fig.4.

33) Lines 230-231-This statement is not supported by the bottom row of Fig. 4 where the ET anomalies for this savanna station are actually less severe than those for the forested site. Please fix this in the revised text.

34) Lines 212, 224, and 236-It would help if you pointed the reader toward the appropriate panels on Fig. 4 in the introductions to each of these paragraphs.

Response: We have removed the case analyses in the revised manuscript and focused on the composite analysis of flash droughts for each vegetation type. Please see our response above.

35) Figure 5-Please move the legend on panel a to panel b since that is where both these lines are shown.

Response: We have reorganized the manuscript according to your comment 3.

36) Line 252-It would be good to clarify that is "flash drought as determined by soil moisture reductions"

Response: Revised as suggested.

37) Line 279-Why "down to its normal conditions"? I assume this is a mistake since you've already shown in previous section that GPP anomalies become negative during a flash drought.

Response: In this study, negative GPP anomalies did not occur during all flash drought events and GPP responded to 81% of flash droughts. We have clarified as follows:

“Here, we select 81% of soil moisture flash drought events with GPP declining down to its normal conditions to analyze the interactions between carbon and water fluxes, while GPP during the remaining 19% of soil moisture flash drought events may stay stable and is less influenced by drought conditions.” (L382-385)

38) Line 284-The ratio is reversed compared to that shown at line 172.

Response: Here uWUE ($\mathrm{GPP} \times \sqrt{VPD}/ET$) is partitioned into GPP and $ET/\sqrt{VPD}$, which is more direct when compared the response of vegetation photosynthesis and stomatal conductance to soil moisture flash droughts, respectively.

39) Line 288-Again, this terminology is confusing-how can “recovery” be accompanied by “significant reductions” in GPP and ET. Those reductions show that vegetation conditions have deteriorated, not improved. This is also repeated at lines 319-320. This terminology needs to be changed to reflect that the “recovery” is only respect to soil moisture.

Response: We highlight the recovery is referred to soil moisture flash droughts (L401).

40) Line 315-Please change “intensify” to “reduction”.

Response: Revised as suggested.

Response to the comments from Reviewer #2

We are grateful to the reviewer for the constructive and careful review. The constructive suggestions have helped improved our manuscript. The reviewer's comments are italicized and our responses immediately follow.

The authors present first evaluation of GPP from FLUXNET in response to flash drought. This is an important topic and this submission is timely as well as novel. At the same time, I feel that a more detailed analysis is warranted before publication.

General comments:

1) I generally think that analyzing the relationships between flash drought and GPP is very important. I am wondering though, whether this paper leaves out a large part of the story by focusing narrowly on the 30-60 days of flash drought. Similarly, there is very little analysis that looks into the underlying mechanisms of GPP besides the WUE analysis. I am wondering how temperature, global radiation, SM, and VPD, which all affect GPP behave. For example one would expect drought to be associated with elevated temperatures. In this context, the authors stress the GPP reduction associated with drought, but several other papers have shown that GPP reduction during drought can be associated with compensation effects before and after the drought. By only focusing strictly on the drought these are being missed.

Response: Thanks for your comments. In the revised manuscript, we have now dropped the maximum length threshold of 60 days for the definition of flash drought, although the main conclusions remain unchanged. To explore the role of climate factors on GPP, we have now used partial correlation to investigate the relationship between the standardized anomalies of GPP and temperature, radiation, VPD and soil moisture. Besides, we have extended the study period from 8 days before flash drought to 8 days after flash drought. There is little change of GPP during 8 days before flash droughts, and the decreasing in GPP is more obvious during the recovery stage of flash droughts and 8 days after. The deficits in soil moisture play an important role in decreasing GPP during onset stages of flash droughts, whereas VPD is more significant to GPP during recovery stages. We have revised the manuscript as follows:

“2.2.4 The role of meteorological conditions on GPP

Considering the compound impacts of temperature, radiation, VPD and soil moisture on vegetation photosynthesis, the partial correlation is used to investigate the relationship between GPP and each climate factor, with the other 3 climate factors as control variables as follows:

$$r_{ij(m_1,m_2\ldots m_n)} = \frac{r_{ij(m_1,\ldots m_{n-1})} - r_{im_n(m_1,\ldots m_{n-1})} r_{jm_n(m_1,\ldots m_{n-1})}}{\sqrt{(1 - r^2_{in(m_1,\ldots m_{n-1})})(1 - r^2_{jn(m_1,\ldots m_{n-1})})}} \quad (1)$$

where i represents GPP, j represents the target meteorological variables and $m_1, m_{2\ldots} and\ m_n$ represent the control meteorological variables. $r_{ij(m_1,m_2\ldots m_n)}$ is the partial correlation coefficient between i and j, and $r_{ij(m_1,\ldots m_{n-1})}$, $r_{im_n(m_1,\ldots m_{n-1})}$ and $r_{jm_n(m_1,\ldots m_{n-1})}$ are partial correlation coefficients between i and j, i and m_n, j and m_n respectively under control of $m_1, m_{2\ldots} and\ m_{n-1}$.” (L215-226)

“3.4 The role of climate factors on GPP during soil moisture flash drought

Figure 8 shows the partial correlation coefficients between standardized anomalies of GPP and meteorological variables and soil moisture percentiles during different stages of soil moisture flash droughts. The correlation between climate factors and GPP is not statistically significant during 8 days before soil moisture flash droughts. During onset stages of soil moisture flash droughts, the partial correlation coefficients between SGPPA and soil moisture percentiles are 0.44, 0.49 and 0.29, respectively for SAV, CROP, and ENF ($p<0.05$). Besides, shortwave radiation is positively correlated with SGPPA for MF, DBF, and EBF (Figure 8b) during onset stages and the positive anomalies of shortwave radiation could partially offset the loss of vegetation photosynthesis due to the deficits in soil moisture. SGPP is also positively correlated with temperature during onset stages for SAV and DBF. The partial correlation coefficients between SGPPA and VPD are -0.53 and -0.22 respectively for DBF and ENF, and the higher VPD would further decrease GPP during onset stages. The influence of VPD on GPP is much more significant during recovery stages and 8 days after. SGPPA is positively correlated with soil moisture and negatively with VPD for SAV both during recovery stages and 8 days after.” (L423-439)

“During 8 days before soil moisture flash drought, WUE and uWUE are generally close to the climatology (Figure 7a) and there are no significant changes in GPP, ET, and $ET/\sqrt{VPD}$ (Figures 7e and 7i). However, the median value of SGPPA for SAV is positive (Figure 7e).” (L385-389)

“During 8 days after flash drought, the standardized anomalies of uWUE are still positive for forests, whereas SGPPA and ET are both lower than the climatology for all ecosystems. The ecological negative effect would persist after the soil moisture flash drought.” (L419-422)

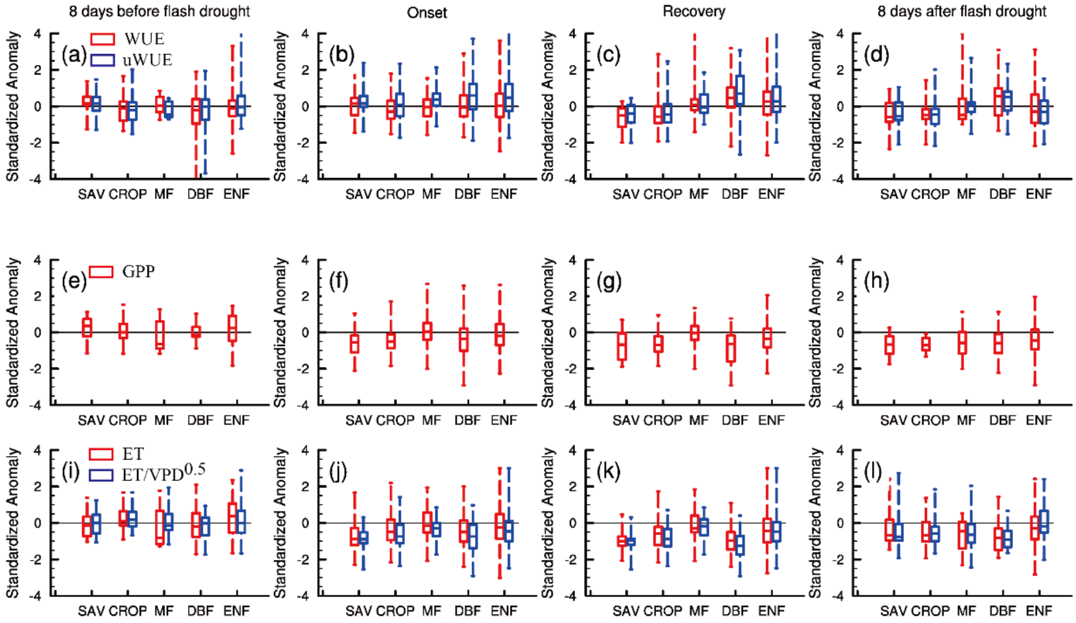

Figure 7. Standardized anomalies of water use efficiency (WUE), underlying WUE (uWUE), GPP, ET and $ET/\sqrt{VPD}$ during 8 days before flash drought onset, onset and recovery stages of flash drought events, and 8 days after flash drought.

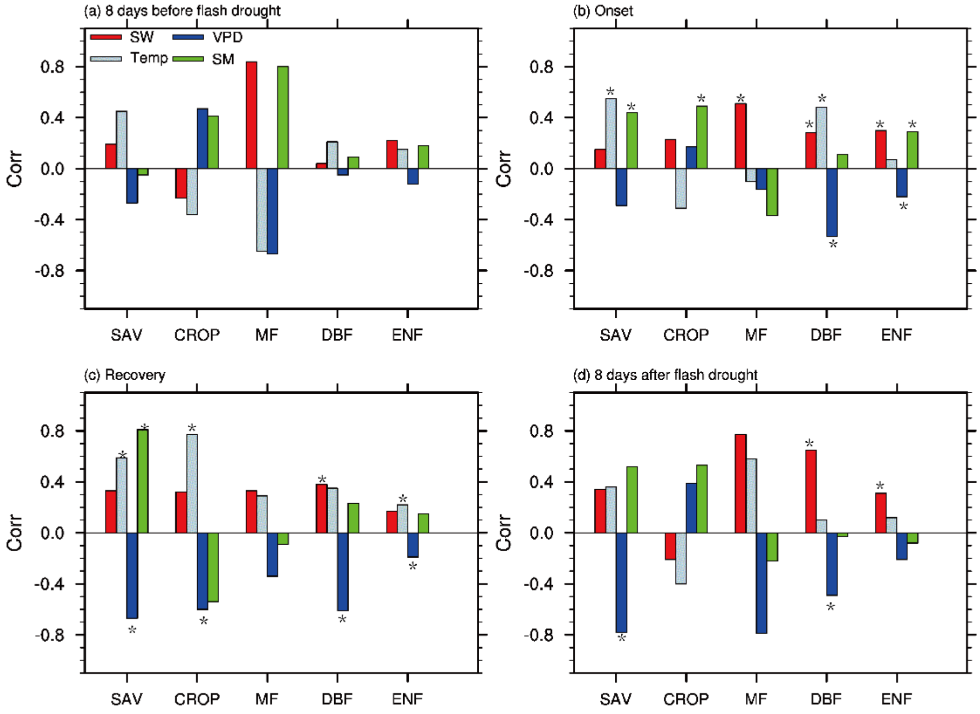

Figure 8. The partial correlation coefficients between GPP and soil moisture (SM), shortwave radiation (SW), temperature (Temp) and vapor pressure deficit (VPD) for different vegetation types including savannas (SAV), rain-fed croplands (CROP), mixed forests (MF), deciduous broadleaf forests (DBF), and evergreen needleleaf forests (ENF) during 8 days before soil moisture flash drought, onset and recovery stages and 8 days after soil moisture flash drought. * indicates the correlation is statistically significant at the 95% level. (L934-941)

2) Similarly, the authors bin data based on onset (which should probably rather be called intensification) and recovery time as well as 8-day intervals. They present 3 examples of flash droughts in Figure 4, but it is unclear to me to what extent these are being representative and whether it makes sense to lump all drought events together like this. For example, the FI-Sod event shows fast recovery in SM, GPP, and ET (i.e. is terminated by a strong rain event), while US-SRM and IT-Col show basically no recovery of GPP and only ET recovery for IT-Col, which indicates that there is no real recovery taking place. Based on this, I would not expect to find generalizable *behavior during this period. I am not sure how to resolve this in detail, but I think that a deeper dive into data and individual events is merited.*

Response: Thanks for your comments. We have removed the case analysis in the revised manuscript because they cannot represent different vegetation types. Instead, we have now focused on the composite analysis for each vegetation type throughout the manuscript. This study focuses on the ecological response during the onset and recovery stages of flash droughts. However, it is still an important issue to assess the ecological impacts after flash droughts. Therefore, we use lagged autocorrelation models to investigate the relationship between GPP and soil moisture conditions during 8 days after flash droughts, and GPP at the end of flash droughts as follows:

$$GPP_{t+1} = b_0 + b_1 SM_{t+1} + b_2 GPP_t \qquad (1)$$

where GPP_{t+1} and SM_{t+1} are the standardized anomalies of GPP and soil moisture percentiles during 8 days after flash droughts, and GPP_t is the GPP at the end of flash droughts. b_0, b_1 and b_2 are empirically derived coefficients. Table R1 shows the regression coefficients of b1 and b2. The regression coefficients for soil moisture during 8 days after flash droughts is significantly positive for SAV, DBF, and ENF, and the regression coefficients for GPP at the end of flash droughts are also positive for SAV and CROP (Table R1). These indicate that the antecedent vegetation conditions and soil moisture after flash droughts would influence the GPP at different ecosystems.

Table R1. The regression coefficients of b1 and b2 for soil moisture during 8 days after flash droughts and the GPP at the end of flash droughts, respectively. * indicates statistically significant at the 95% level.

	SAV	CROP	MF	DBF	ENF
b1	0.009*	-0.006	-0.006	0.007*	0.001*
b2	0.82*	0.52*	0.11	0.61	0.56

Thus, we have added the discussion about the legacy effects of flash droughts connected with climate and vegetation conditions in the revised manuscript as follows:

"During 8 days after the soil moisture flash drought, the anomalies of GPP and ET are still negative, indicating that the vegetation does not recover immediately after the soil moisture flash drought. The legacy effects of flash droughts may be related to the vegetation and climate conditions (Barnes et al., 2016; Kannenberg et al., 2020)." (L479-483 in the revised manuscript)

3) The discussion is falling a bit short with respect to differences between plant functional type classes. Some discussion around differences between grasslands and forests as outlined in specific comments may help here.

Response: Thanks for your comments. We have compared the response of NEP and GPP and discussed the correlation between soil moisture and GPP for different vegetation types in the revised manuscript as follows:

"Due to the influence of ecosystem respiration, the responses of NEP for DBF and ENF to flash droughts are much quicker than GPP, implying that the sensitivity of ecosystem respiration is less than that of vegetation photosynthesis (Granier et al., 2007)." (L457-460)

"Due to the limitation of FLUXNET soil moisture measurements, here we used soil moisture observations mainly at the depths of 5 to 10 cm. We also analyzed the response of GPP to flash drought identified by 0.25-degree ERA5 soil moisture reanalysis data at the depths of 7cm and 1m. The response of GPP to flash droughts identified by FLUXNET surface soil moisture are quite similar to those identified by ERA5 soil moisture at the depth of 1m (not shown). There are less GPP responses to flash droughts identified by ERA5 surface soil moisture. Although we select the ERA5 grid cell that is closest to the FLUXNET site and use the ERA5 soil moisture data over the same period as the FLUXNET data, we should acknowledge that the gridded ERA5 data might not be able to represent the soil moisture conditions as well as flash droughts at in-situ scale due to strong heterogeneity of land surface. Therefore, the in-situ surface soil moisture from FLUXNET is useful to identify flash droughts compared with reanalysis soil moisture, although the in-situ root-zone soil moisture would be better.” (L490-504)

“The correlation between soil moisture and GPP is more significant for SAV, CROP, and ENF during onset stages of flash droughts, which is consistent with the strong response to water availability of SAV and CROP (Gerken et al., 2019). SAV is more isohydric than forests and would reduce stomatal conductance immediately to prohibit water loss that further exacerbates drought (Novick et al., 2016; Roman et al., 2015). However, almost all vegetation types show high sensitivity to VPD during the recovery stage of flash droughts.” (L519-525)

4)Given that FLUXNET measures NEE rather than GPP and GPP is partitioned, some discussion on this partitioning may be warranted and NEE should probably also be shown.

Response: Thanks for your positive comments. We have clarified the measurement of NEP and revised our manuscript as follows:

“GPP is derived from direct eddy covariance observations of NEP and nighttime terrestrial ecosystem respiration, and temperature-fitted terrestrial ecosystem respiration during daytime. The response of NEP to flash droughts shows the compound effects of vegetation photosynthesis and ecosystem respiration. In terms of RT, the response of NEP is slower than GPP for SAV, but is quicker for DBF and ENF (Figure 5). The discrepancies between NEP and SM in terms of RTmin are more obvious than those between GPP and SM, and the RTmin of NEP is much shorter than the RTmin of soil moisture especially for DBF and ENF, which may be related to the increase of ecosystem respiration (Figures 5 i and j).” (L355-364)

“Due to the influence of ecosystem respiration, the responses of NEP for DBF and ENF to flash droughts are much quicker than GPP, implying that the sensitivity of ecosystem respiration is less than that of vegetation photosynthesis (Granier et al., 2007).” (L457-460)

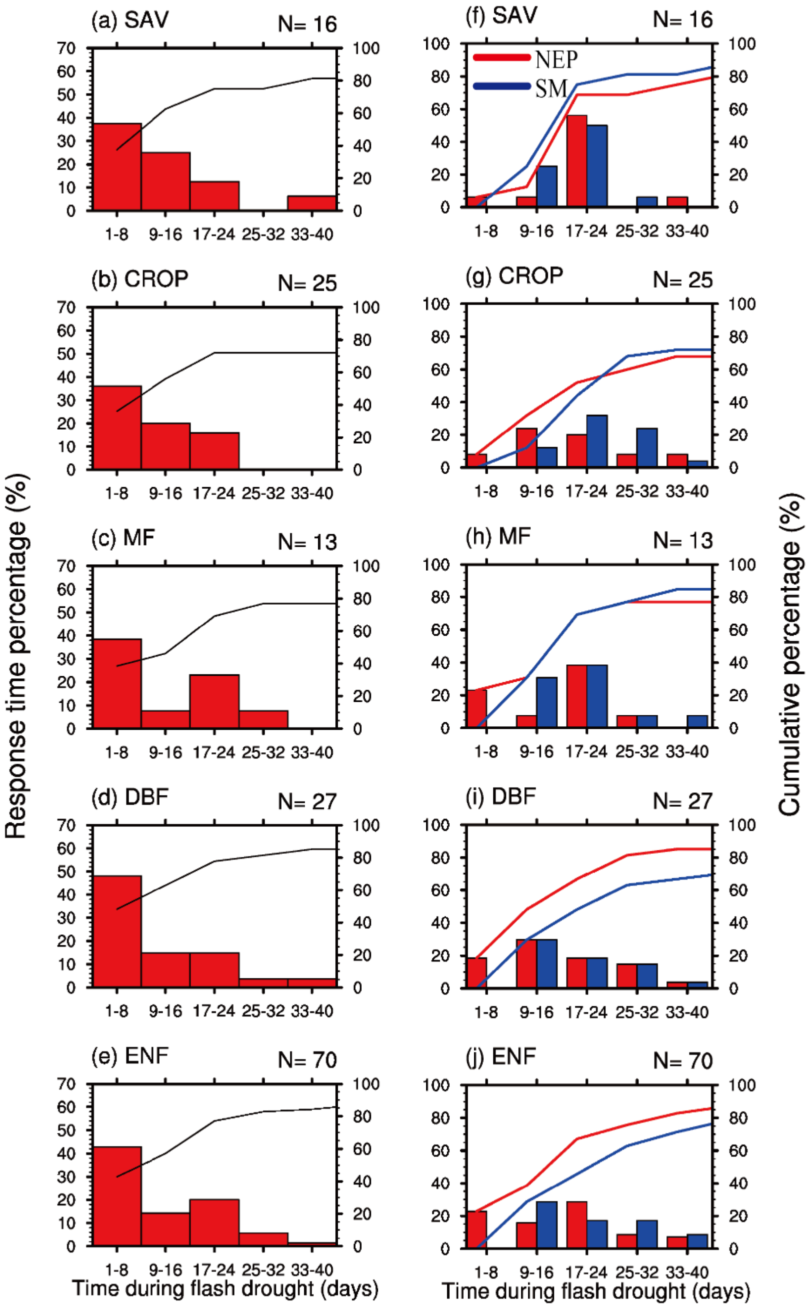

Figure 5. The same as Figure 4, but for net ecosystem productivity (NEP).

Specific Comments:

L99: It might be a good idea to also look into other sources of soil moisture here, as there is little standardization across FLUXNET with respect to sensor depth etc.

Response: Here we used 0.25-degree ERA5 soil moisture reanalysis data at the depths of 7cm and 1m to analyze the response of GPP to soil moisture flash droughts and added this into discussion in the response to your comment 3.

L101: We select 34 sites from FLUXNET where,…>are these all sites that fit the definition from this sentence or was there further subsetting done?

Response: We have clarified as follows:

"Here we only select the FLUXNET observations including 12 evergreen needleleaf forest sites (ENF), 5 deciduous broadleaf forests (DBF), 6 crop sites (CROP; 5 rain-fed sites and 1 irrigated site), 3 mixed forests (MF), and 3 savannas (SAV). The sites for grasslands, evergreen broadleaf forests, and shrublands are excluded because there are less than 10 soil moisture flash drought events." (L116-121)

L147: "The negative anomalies of GPP during flash drought are considered as the signal of ecological deterioration."> This sounds not correct to me. Water stress will reduce GPP, which is a given, but I don't think it necessarily follows that this has a lasting consequence as implies here. It would be interesting to see to what extent do these ecosystems compensate. I.e. is there a lasting effect from a flash drought even in the annual carbon balance.

Response: We agree with the reviewer that a GPP decline below its normal condition (long-term mean) does not necessarily indicate an ecological deterioration, where we actually regard it as the onset of ecological response. We have examined the GPP response during 8 days after flash droughts (please see our response to your first comment) and we have revised this sentence as follows:

"The negative anomalies of GPP during soil moisture flash drought are considered as the onset of ecological response." (L171-173)

L165: “influence of water and energy conditions”> “ water and energy availability?”

Response: Revised as suggested.

L189-190: “and the mean durations were from around 30 days to 60 days among FLUXNET sites”> I am a bit confused by that given that I was under the impression that droughts longer than 2 months days were excluded from the analysis. How can then mean drought length be 60 days, if that is also about the maximum possible length?

Response: In the revised manuscript, we have now removed the threshold of maximum duration of flash droughts and the average duration is calculated for each vegetation type not for each site.

Figure 2 is problematic: I would zoom into Europe. It is also not possible to link the sites from a) to b) and c) without consulting Table 1. As a side note: the 4 Canadian ENF sites are more or less directly adjacent to each other, with 3 of them showing almost the same behavior. It may be better to only keep two of them (CA-TP4 is different (Why?))

Response: Thanks for your comments. There are 4 Canadian ENF sites including CA-Obs, CA-TP1, CA-TP3, and CA-TP4 in this study. Although the vegetation type and climate conditions are quite similar for CA-TP1, CA-TP3, and CA-TP4, the ages of trees are different, which may influence soil moisture conditions and the ecological response to soil moisture flash droughts. We have revised Figure 2 as follows:

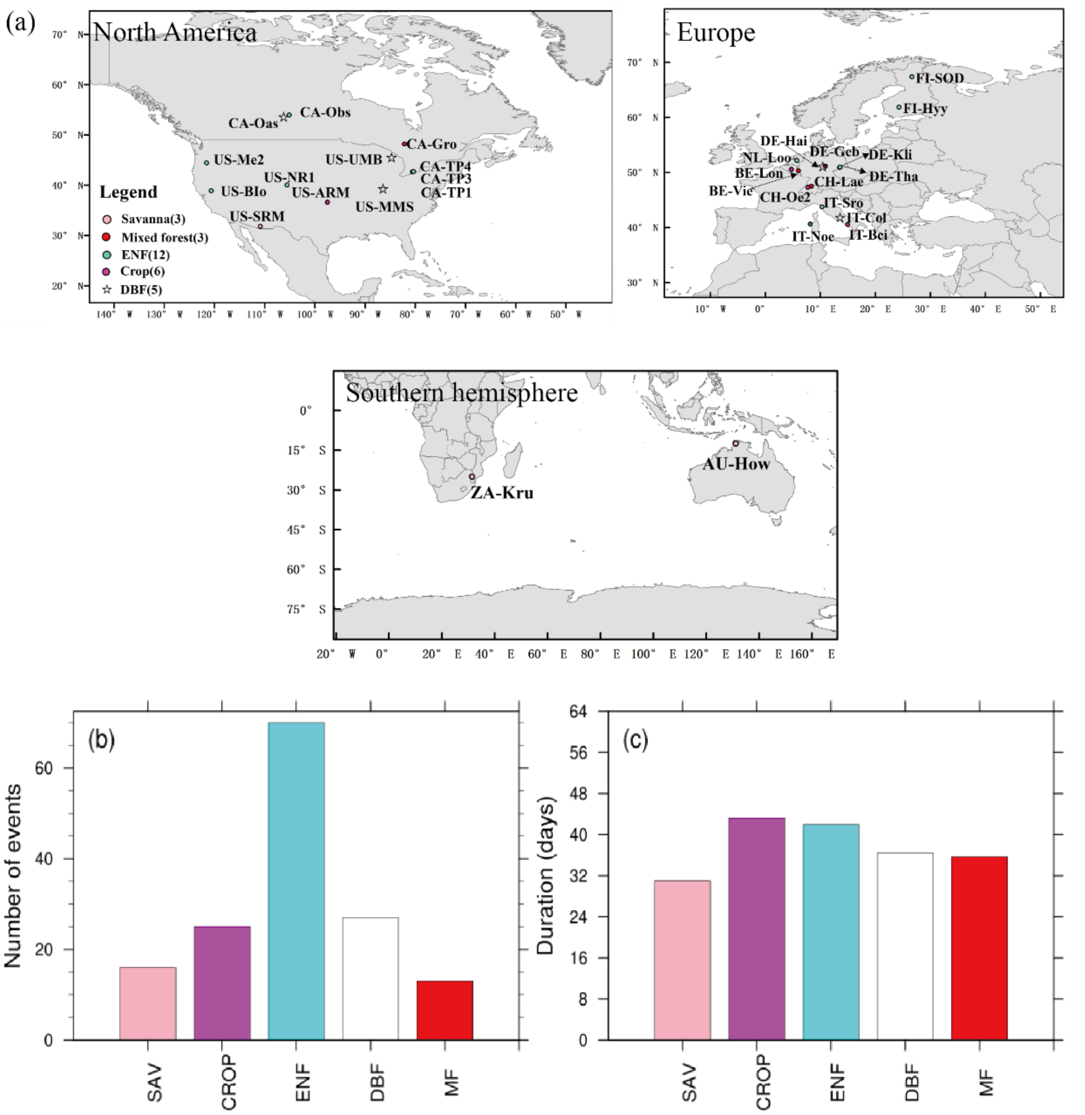

Figure 2. (a) Global maps of 29 FLUXNET sites used in this study. (b) Total numbers (events) and (c) mean durations (days) of soil moisture flash drought events for each vegetation type during their corresponding periods (see Table 1 for details). Different colors represent different vegetation types.

Figure 3 and associated text: I am a bit confused about onset and recovery. Are these singe 8 day periods or do they refer to several periods. I am not sure whether this is necessarily a good way of showing this data and what is really learned here, since everything is lumped together and there is an implied time-axis, which is not *consistent in itself. The temporal evolution of these events is also already well established in the literature.*

Response: To clarify different stages in the Figure 3, we have revised manuscript as follows:

"Here the onset and recovery stages of flash droughts refer to certain periods characterized by the soil moisture decline rates. The standardized anomalies of temperature, precipitation, VPD, and shortwave and soil moisture percentiles are composited to show the meteorological conditions during different stages of flash droughts." (L250-254)

Figure 4: It looks as if these sites were chosen as representative for each class, but this should be made explicit in the text. I don't particularly like the fact that anomalies are being plotted at the site level. We need to calculate ET, GPP, and SM anomalies to compare sites and establish drought, but here there is no need and it makes it harder to understand the underlying dynamics. I also think that if these sites are chosen, one should plot all drought events (all six or so per site) and not only specifically chosen year. Also, based on this figure, I feel that onset should be renamed as intensification.

Response: Thanks for your comment. We have removed the case analysis in the revised manuscript because they cannot represent different vegetation types. Instead, we have now focused on the composite analysis for each vegetation type throughout the manuscript. "Intensification" and "onset" are quite similar to describe the development of flash droughts. Corresponding with "recovery", "onset" would be a better name than "intensification" (Yuan et al., 2019).

Figure 5: a) It appears if there is a quick response of GPP at the beginning of the flash drought, which one would expect simply by having high VPD, which will lead to stomata closure, but SM seems to be much less affected. It would be nice to learn whether this is really unusual or whether this GPP responses related to soil moisture reduction (drought) or VPD forcing. For example Gerken et al. 2018

(https://www.hydrolearth-syst-sci-discuss.net/hess-2018-211/) showed that potential evapotranspiration (~VPD) happened before the onset 2017 Norther Great Plains flash drought. It would be interesting to see whether GPP reduction also occurs before drought onset. To what extent are panels c and d necessary.

Response: Thanks for your positive comments. We analyzed the standardized GPP anomalies during 8 days before flash drought and there is no obvious decline in GPP except for MF (Figure 6e). Besides, the decline in soil moisture plays a dominant role in affecting GPP during onset stages of flash droughts and the influence of higher VPD is more significant during recovery stages. Please see our response to your first comment.

L251: "that negative GPP anomalies occur during 81%"-> if this refers to the rad line in Figure 5a/b, then this number seems inconsistent with the figure, where it is more like 78%.

Response: In the last version of manuscript, Figures 5a and 5b only showed the cumulative response frequency within 1-40 days of flash droughts, whereas the total response frequency is 81% during the whole flash droughts. In the revised manuscript, we have deleted Figure 5 and focused on ecological responses to flash droughts for different ecosystems.

L270: "The result is consistent with the high vulnerability of vegetation in semiarid regions" > I would caution against this interpretation. Semi-arid ecosystems are highly adapted to changes in water availability and show fast response to changes in water availability (e.g. Gerken et al. 2019, 10.1038/s41612-019-0094-4). Without additional analysis, this should not be taken as a sign of degradation or vulnerability; especially since the final cumulative values are practically the same as for forests (MF, BF, ENF). Some discussion about isohydricity, VPD may also be helpful in this context (e.g. Novick et al, 2016, 10.1038/nclimate3114, Roman et al, 2015; 10.1007/s00442015-3380-9)

Response: Although the final cumulative values are similar to those for forests, GPP for Savanna does show faster response to flash drought as illustrated in Figure 4 in the revised manuscript. However, we agree with the reviewer that the statement of "high vulnerability of vegetation in semiarid regions" is not relevant. We have revised the manuscript as follows:

"The result is consistent previous studies regarding the strong response of semi-arid ecosystems to water availability (Gerken et al., 2019; Vicente-Serrano et al., 2013; Zeng et al., 2018) and the decline in GPP for SAV is more related to isohydric behaviors during soil moisture drought and higher VPD, through closing stomata to decrease water loss as transpiration and carbon assimilation (Novick et al., 2016; Roman et al., 2015)." (L342-348)

L285: "Increasing VPD and deficits in soil moisture would decrease canopy conductance" -> The fact that uWUE stays invariant shows that GPP reductions are due to canopy conductance. During recovery SAV and CROP, which are both dominated by grasses are likely brown, while forests are still green and quickly respond. This again likes directly to different biophysical responses of forests and grasslands and isohydricity effects. These should be discussed.

Response: Thanks for your constructive comments. We have incorporated them into the revised manuscript as follows:

"The decrease in uWUE for SAV and CROP during recovery stages indicates that SAV and CROP are likely brown due to carbon starvation caused by the significant decrease in stomatal conductance (McDowell et al., 2008)." (L405-408)

"However, the positive anomalies of uWUE for DBF and ENF during the recovery stage imply that the decline in GPP mainly results from the stomata closure." (L411-413)

L315: "Eventually, 81% of flash drought events cause negative ecological impacts on GPP." > I am not sure that a reduction in GPP is necessarily an negative impact. This depends greatly on the annual carbon balance. For example Wolf et al, 2016

(PNAS) showed that there is GPP compensation (i.e. warmer temperatures before drought causes higher initial GPP). Without looking into potential compensation effects, I feel that this statement is too harsh.

Response: Thanks for your comments. We explored the response of GPP during 8 days before and after flash droughts and their relationship with soil moisture conditions and antecedent vegetation conditions, and found that there is no obvious anomaly in GPP during 8 days before flash droughts but GPP does not recover immediately as the end of flash droughts, and the legacy effects of soil moisture flash droughts on vegetation may be related to soil moisture conditions after flash droughts and the intensity of GPP response (please see our responses to your first two comments). Besides, we have revised the statement as follows:

"Eventually, 81% of soil moisture flash drought events cause declines in GPP." (L460-461)

L346: "The positive anomalies of WUE and uWUE for forests show the adaptation of vegetation to flash drought from physiological perspective." > Not sure that this is true. Forests have also access to more water in the soil due to deeper roots and have invested much more in biomass. Grasslands just become dry and then recover. I think that these are different strategies rather than one being more prepared than the other.

Response: Thanks for your comments. We have revised the manuscript as follows:

"The positive anomalies of WUE and uWUE for forests suggest that their deeper roots can obtain more water than grasslands during flash drought." (L512-515)

Technical (not complete): L36: (e.g. droughtS, heat waveS)

L40: in some -> during (some is also not needed because of can)

L269: impaired -> reduced

Response: Revised as suggested. (L37; L41; L343)

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Rapid reduction in ecosystem productivity caused by flash drought based on decade-long FLUXNET observations

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Abstract. Flash drought is characterized by its rapid onset and arouses wide concerns due to its devastating impacts on the environment and society without sufficient early warnings. The increasing frequency of soil moisture flash drought in a warming climate highlights the importance of understanding its impact on terrestrial ecosystems. Previous studies investigated the vegetation dynamics during several extreme cases of flash drought, but there is no quantitative assessment on how fast the carbon fluxes respond to flash drought based on decade-long records with different climates and vegetation conditions. Here we identify soil moisture flash drought events by considering decline rate of soil moisture and the drought persistency, and detect the response of ecosystem carbon and water fluxes to soil moisture flash drought during its onset and recovery stages based on observations at ~~34~~ 29 FLUXNET stations from ~~grasslands~~ croplands to forests. Corresponding to the sharp decline in soil moisture and higher VPD, gross primary productivity (GPP) drops below its normal conditions in the first 16 days and reduces to its minimum within 24 days for more than 50% of the 1~~6~~51 identified flash drought events, and savannas show highest sensitivity to flash drought. Water use efficiency increases for forests but decreases for cropland and savanna during the recovery stage of flash droughts. These results demonstrate the rapid responses of vegetation productivity and ~~physiological adaptation~~resistance ~~for~~of forest ecosystems to flash drought.

Keywords: Flash drought; GPP; Soil moisture; Water use efficiency; FLUXNET

1. Introduction

Terrestrial ecosystems play a key role in the global carbon cycle and absorb about 30% of anthropogenic carbon dioxide emissions during the past five decades (Le Quéré et al., 2018). With more climate extremes (e.g. droughts, heat waves) in a warming climate, the rate of future land carbon uptake is highly uncertain regardless of the fertilization effect of rising atmospheric carbon dioxide (Green et al., 2019; Reichstein et al., 2013; Xu et al., 2019). Terrestrial ecosystems can even turn to carbon source ~~in some~~during extreme drought events (Ciais et al., 2005). Record-breaking drought events have caused enormous reduction of the ecosystem gross primary productivity (GPP), such as the European 2003 drought (Ciais et al., 2005; Reichstein et al., 2007), USA 2012 drought (Wolf et al., 2016), China 2013 drought (Xie et al., 2016; Yuan et al., 2016), Southern Africa 2015/16 drought (Yuan et al., 2017) and Australia Millennium drought (Banerjee et al., 2013). The 2012 summertime drought in USA was classified as flash drought with rapid intensification and insufficient early warning, which caused 26% reduction in crop yield (Hoerling et al., 2014; Otkin et al., 2016). Flash drought has aroused wide concerns for its unusually rapid development and detrimental effects (Basara et al., 2019; Christian et al., 2019; Ford & Labosier, 2017; Nguyen et al., 2019; Otkin et al., 2018a; Otkin et al., 2018b; Wang and Yuan, 2018; Yuan et al., 2015; Yuan et al., 2017; Yuan et al., 2019b). Despite the increasing occurrence and clear ecological impacts of flash droughts, our understanding of their impacts on carbon uptake in terrestrial ecosystems remains incomplete.

Recent studies assessed the impact of flash drought on vegetation including the 2012 central USA flash drought and the 2016 and 2017 northern USA flash drought. For instance, Otkin et al. (2016) used the evaporative stress index (ESI) to detect the onset of the 2012 central USA flash drought, and found the decline in ESI preceded the drought according to the United States Drought Monitor (Svoboda et al., 2002). He et al. (2019) assessed the impacts of the 2017 northern USA flash drought (which also impacted parts of southern Canada) on vegetation productivity based on GOME-2 solar-induced fluorescence (SIF) and satellite-based evapotranspiration in the US Northern plains. Otkin et al. (2019) examined the evolution of vegetation conditions using LAI from MODIS during the 2015 flash drought over the South-Central United States and found that the LAI decreased after the decline of soil moisture. Besides, the 2016 flash drought over U.S. northern plains also decreased agricultural production (Otkin et al., 2018b). However, previous impact studies only focused on a few extreme flash drought cases without explicit definition of flash drought events. As the baseline climate is changing (Yuan et al., 2019b), it is necessary to systematically investigate the response of terrestrial carbon and water fluxes to flash drought events based on long-term records rather than one or two extreme cases.

In fact, there are numerous studies on the influence of drought on ecosystem productivity (Ciais et al., 2005; Stocker et al., 2018; Stocker et al., 2019). It is found that understanding the coupling of water-carbon fluxes during drought is the key to revealing the adaptation and response mechanisms of vegetation to water stress

(Boese et al., 2019; Nelson et al., 2018). Water use efficiency (WUE) is the metric for understanding the trade-off between carbon assimilation and water loss through transpiration (Beer et al., 2009; Cowan and Farquhar, 1977; Zhou et al., 2014, 2015), and it is influenced by environmental factors including atmospheric dryness and soil moisture limitations (Boese et al., 2019). Although WUE has been widely studied for seasonal to decadal droughts, few studies have investigated WUE during flash droughts that usually occur at sub-seasonal time scale (Xie et al., 2016; Zhang et al., 2019).

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In this paper, we address the ecological impact of soil moisture flash droughts through analyzing FLUXNET decade-long observations of CO_2 and water fluxes. The specific goals are to (1) examine the response of carbon and water fluxes to soil moisture flash droughts from the onset to the recovery stages, and (2) investigate how WUE changes during soil moisture flash drought for different ecosystems. The methodology proposed by Yuan et al. (2019b) enables the analysis of the flash drought with characteristics of duration, frequency, and intensity in the historical observations. All the flash drought events occurred at the FLUXNET stations are selected to investigate the response of carbon fluxes and WUE. More than 10-year records of soil moisture, carbon and water fluxes are available (Baldocchi et al., 2002), which makes it possible to assess the response of vegetation to flash droughts by considering different climates and ecosystem conditions.

2. Data and Methods

2.1 Data

FLUXNET2015 provides daily hydrometeorological variables including precipitation, temperature, saturation vapor pressure deficit (VPD), soil moisture (sm), shortwave radiation (SW), evapotranspiration (ET) inferred from latent heat, and carbon fluxes including GPP and net ecosystem productivity (NEP). We use GPP data based on night-time partitioning method (GPP_NT_VUT_REF). Considering most sites only measure the surface soil moisture, here we use daily soil moisture measurements mainly at the depth of 5-10 cm averaged from half-hourly data. Soil moisture observations are usually averaged over multiple sensors including time domain reflectometer (TDR), frequency domain reflectometer (FDR), and water content reflectometer etc. However, the older devices may be replaced with newer devices at certain sites, which may decrease the stability of long-term soil moisture observations and the average observation error of soil moisture is ±2%. All daily hydrometeorological variables and carbon fluxes are summed to 8-day time scale to study the flash drought impact. ~~We select~~There are 34 sites from FLUXNET 2015 dataset (Table 1) consisting of 8 vegetation types, where the periods of observations are no less than 10 years ranging from 1996 to 2014, and the rates of missing data are lower than 5%. Here we only select ~~T~~the FLUXNET observations includ~~e~~ing 12 evergreen needleleaf forest sites (ENF), 5 deciduous broadleaf forests (DBF)~~ and~~, 6 crop sites (CROP; 5 rain-fed sites and 1 irrigated site), 3 mixed forests (MF), and 3 savannas (SAV).~~ etc~~ The sites for grasslands, evergreen broadleaf forests, and shrublands are excluded because there are less than 10 soil moisture flash drought events. The vegetation classification is according to International

Geosphere-Biosphere Program (IGBP; Belward et al., 1999), where MF is dominated by neither deciduous nor evergreen tree type with tree cover larger than 60% and the land tree cover is 10-30% for SAV. The detailed information is listed in Table 1. ~~Here we select three flash drought cases at different ecosystems including ENF (FI-Sod site), savanna (SAV; US-SRM site) and DBF (IT-Col site) to show the response of vegetation to flash droughts.~~

2.2 Methods

2.2.1 Definition of soil moisture flash drought events

The definition of soil moisture flash drought should account for both its rapid intensification and the drought conditions (Otkin et al., 2018a; Yuan et al., 2019b). Here we used soil moisture percentile to identify soil moisture flash drought according to Yuan et al. (2019b) and Ford et al. (2017). Figure 1 shows the procedure for soil moisture flash drought identification, including five criteria to identify the rapid onset and recovery stages of soil moisture flash drought. 1) Soil moisture ~~F~~flash drought starts at the middle day of the 8-day period when the 8-day mean soil moisture is less than the 40th percentile, and the 8-day mean soil moisture prior to the starting time should be higher than 40th percentile to ensure the transition from a non-drought condition. 2) The mean decreasing rate of 8-day mean soil moisture percentile should be no less than 5% per 8 days to address the rapid drought intensification. 3) The 8-day mean soil moisture after the rapid decline should be less than 20% in percentile, and the period from the beginning to the end of the rapid decline is regarded as the onset stage of soil moisture flash drought (those within red dashed line in Figure 1). 4) If the mean decreasing rate is less than 5% in percentile or the soil moisture percentile starts to increase, the soil moisture flash drought enters into the “recovery” stage, and the soil moisture flash drought event (as well as the recovery stage) ends when soil moisture recovers to above 20th percentile (those within blue dashed line in Figure 1). The recovery stage is also crucial to assess the impact of soil moisture flash drought (Yuan et al., 2019b). 5) The minimum duration of a flash drought event is 24 days to exclude those dry spells that last for a too short period to cause any impacts~~, and the maximum duration is limited to 2 months to separate flash droughts from traditional droughts (e.g., seasonal droughts)~~.~~.~~

At least ~~D~~decade-long observations of 8-day mean soil moisture are used to calculate soil moisture percentile with a moving window of 8-day before and 8-day after the target 8-day, resulting in at least 30 samples for deriving the cumulative distribution function of soil moisture before calculating percentiles. Besides, the target 8-day soil moisture percentiles are only based on the target 8-day soil moisture in the context of the expanded samples. For example, the soil moisture percentile of June 22nd in 1998 is calculated by firstly ranking June 14th, June 22nd, and June 30th soil moisture in all historical years (N samples) from lowest to highest, identifying the rank of soil moisture of June 22nd, 1998 (e.g., M), and obtaining the percentile as M/N*100. We focus on growing seasons during April-September for sites in the North Hemisphere and October-March for sites in the South Hemisphere.

2.2.2 Response time of GPP to soil moisture flash drought

Drought has a large influence on ecosystem productivity through altering the plant photosynthesis and ecosystem respiration (Beer et al., 2010; Green et al., 2019; Heimann & Reichstein, 2008; Stocker et al., 2018). GPP dominates the global terrestrial carbon sink and it would decrease due to stomatal closure and non-stomatal limitations like reduced carboxylation rate and reduced active leaf area index (de la Motte et al., 2019) under water stress. The negative anomalies of GPP during soil moisture flash drought are considered as the ~~signal~~onset of ecological ~~deterioration~~response. Here, we use two response time indices to investigate the relationship between soil moisture flash drought and ecological drought (Crausbay et al., 2017; Niu et al., 2018; Song et al., 2018; Vicente-Serrano et al., 2013): 1) the response time of the first occurrence (RT) of negative standardized GPP anomaly (SGPPA=$\frac{GPP-\mu_{GPP}}{\sigma_{GPP}}$, where μ_{GPP} and σ_{GPP} are mean and standard deviation of the time series of GPP at the same dates as the target 8-days for all years, which can remove the influence of seasonality. For instance, all Apr 1-8 during 1996-2014 would have a μ_{GPP} and a σ_{GPP} based on a climatology same as soil moisture percentile calculation which consists of March 24-31, Apr 1-8, and Apr 9-16 in all years, and Apr 9-16 would have another μ_{GPP} and another σ_{GPP}, and so on), which is the lag time between the start of flash drought and the time when SGPPA becomes negative during flash drought period; and 2) the response time of occurrence of minimum SGPPA (RTmin), which is the lag time between the start of flash drought and the time when SGPPA decreases to its minimum values during the flash drought period. If the response time is 8 days for the first occurrence of negative SGPPA, it means that the response of GPP starts at the beginning of flash drought (the first time step of flash drought). Considering flash drought is identified through surface soil moisture due to the availability of FLUXNET data, vegetation with deeper roots may obtain water in deep soil and remain healthy during flash drought. The roots vary among different vegetation types and forests are assumed to have deeper roots than grasslands, which may influence the response to soil moisture flash droughts.

2.2.3 Water use efficiency

Carbon assimilation and transpiration are coupled by stomates under the influence of water and energy ~~conditions~~availability (Boese et al., 2019; Huang et al., 2016; Nelson et al., 2018). Plants face a tradeoff at the level of the stomata to fix carbon through photosynthesis at the cost of water losses through transpiration. WUE quantifies the trade-off, which is defined as the assimilated amount of carbon per unit of water loss. At the ecosystem scale, WUE is the ratio of GPP over ET (Cowan and Farquhar, 1977). Drought would cause stomatal closure and non-stomatal adjustments in biochemical functions thus altering the coupling between GPP and ET. Underlying WUE (uWUE) is calculated as $\mathrm{GPP} \times \sqrt{VPD}/ET$ considering the nonlinear relationship between GPP, VPD and ET (Zhou et al., 2014). uWUE is supposed to reflect the relationship of photosynthesis-transpiration via stomatal conductance at the ecosystem level by considering the effect of VPD on WUE (Beer et al., 2009; Boese et al., 2019; Zhou et al., 2014, 2015). WUE varies under the influence of VPD on canopy conductance (Beer et al., 2009; Tang et al., 2006), whereas uWUE is considered to remove this effect and be more directly linked with the relationship between environmental conditions (e.g., soil moisture) and plant conditions (e.g., carboxylation rate; Lu et al., 2018). The standardized anomalies of WUE and uWUE are calculated the same as SGPPA, where different sites have different mean values and standard deviations for different target 8-days to remove the spatial and temporal inhomogeneity.

2.2.4 The relations between meteorological conditions and GPP

Considering the compound impacts of temperature, radiation, VPD and soil moisture on vegetation photosynthesis, the partial correlation is used to investigate the relationship between GPP and each climate factor, with the other 3 climate factors as control variables as follows:

$$r_{ij(m_1,m_2\ldots m_n)} = \frac{r_{ij(m_1,\ldots m_{n-1})} - r_{im_n(m_1,\ldots m_{n-1})} r_{jm_n(m_1,\ldots m_{n-1})}}{\sqrt{(1-r_{in(m_1,\ldots m_{n-1})}^2)(1-r_{jn(m_1,\ldots m_{n-1})}^2)}} \qquad (1)$$

where *i* represents GPP, *j* represents the target meteorological variables and $m_1, m_{2\ldots}$ and m_n represent the control meteorological variables. $r_{ij(m_1,m_2\ldots m_n)}$ is the partial correlation coefficient between *i* and *j*, and $r_{ij(m_1,\ldots m_{n-1})}$, $r_{im_n(m_1,\ldots m_{n-1})}$ and $r_{jm_n(m_1,\ldots m_{n-1})}$ are partial correlation coefficients between *i* and *j*, *i* and m_n, *j* and m_n respectively under control of $m_1, m_{2\ldots}$ and m_{n-1}.

3. Results

3.1 Identification of flash drought events at FLUXNET stations

Based on FLUXNET data, we have identified 1~~6~~51 soil moisture flash drought events with durations longer than or equal to 24 days using soil moisture observations of ~~428~~ 371 site years. Figure 2a shows the distribution of the ~~34~~ 29 sites with different vegetation types, which are mainly distributed over North America and Europe. The number of soil moisture flash drought range~~ed~~s from 13 to 70~~12~~ events among ~~FLUXNET sites~~different vegetation types~~, and the mean durations were from around 30 days to 60 days among FLUXNET sites (Figures 2b and 2c)~~. There are 12 ENF sites in this study, and the number of soil moisture flash droughts for ENF (70) is the most among all the vegetation types.~~–~~ The duration for flash drought events ranges from 24 days to several months. In some extreme cases, the flash droughts would develop into long-term droughts without enough rainfall to alleviate drought conditions. Mean durations of soil moisture flash droughts for different vegetation types range from around 30 days to 50 days (Figure 2c). ~~The frequency of flash drought shows great spatial heterogeneity which may be associated with variability of soil moisture. If enough rainfall comes after the flash drought, the soil moisture could recover to above 20% percentile. Without enough rainfall for recovery, flash drought would ultimately develop into longer and more severe drought (Wang and Yuan, 2018).~~

Figure 3 shows the meteorological conditions during different stages of soil moisture flash drought including the standardized anomalies of temperature, precipitation, VPD, and ~~and ET~~ shortwave radiation and soil moisture percentiles.~~during different stages of flash drought.~~ Here the onset and recovery stages of flash droughts refer to certain periods characterized by the soil moisture decline rates. The standardized anomalies of temperature, precipitation, VPD, and shortwave and soil moisture percentiles are composited to show the meteorological conditions during different stages of flash droughts. There is a slight reduction in precipitation~~ and increase in ET~~ during 8 days prior to soil moisture flash drought (Figure 3b~~&d~~). During the onset of soil moisture flash drought, soil moisture percentiles decline rapidly from nearly 50% during 8 days before flash drought to 18% during onset stages (Figure 3e). Th~~th~~e rapid drying of soil moisture is always associated with a large precipitation deficits, ~~and~~ anomalously high temperature and shortwave radiation and large VPD indicate increased atmospheric dryness (Ford et al., 2017; Koster et al., 2019; Wang et al., 2016), which persist until the recovery stage except for shortwave radiation. ~~ET is close to normal conditions thus enhancing the drying rate of soil moisture with less precipitation supply during the onset stage (Figure 3b&d). However, ET starts to decrease during the recovery stage because of the limitation from water availability, which alleviates the drought condition.~~ The soil moisture percentiles are averaged during the onset and recovery stages and the soil moisture percentiles during recovery stages are slightly lower than those during onset stages (Figure 3e) considering the soil moisture is not quite dry during the early period of onset stages. Sufficient precipitation occurs during the 8 days after soil moisture flash droughts to relieve the drought condition and soil moisture percentiles increase from 12% during recovery stages to 36% during 8 days after flash droughts.

~~3.2 Evolutions of carbon and water fluxes during flash drought events~~

~~Figure 4 shows the evolutions of soil moisture percentile, standardized GPP and ET anomalies during the flash droughts occurred in 2003 at FI-Sod site (Ciais et al., 2005), 2004 at US-SRM site and 2007 at IT-Col site.~~

~~FI-Sod is covered by northern boreal Scots pine with mean annual temperature of -1℃(Thum et al., 2007). 2003 summer drought over Europe accompanied by heat wave caused enormous carbon losses with 30% reduction in GPP (Ciais et al., 2005), and the drought outweighed heat wave for influencing the ecosystem (Reichstein et al., 2007). The 2003 flash drought at FI-Sod occurred in the late of June and ended in the early July although the soil moisture condition was still below the climatology (Figure 4a). During the 24-day flash drought, GPP and ET respond quickly to the rapid soil moisture drying and recover to their normal conditions as soon as the drought relieves (Figures 4b and 4c), which shows the resilience of evergreen needleleaf forest to short-term drought. Negative ET anomaly (Figure 4c) precedes the onset of soil moisture drought, indicating that the flash drought is mainly caused by rainfall deficit (Figure 4a).~~

~~US-SRM site is in dry land savanna. Savanna covers 20% of the global land area (Sankaran et al., 2005), and influences the terrestrial carbon sink significantly (Ahlstrom et al., 2015). Soil moisture plays a crucial role in regulating carbon and water fluxes in savanna regions (Scott et al., 2009; Williams & Albertson, 2004; Wolf et al., 2016), and there is a large variability of soil moisture at US-SRM. Soil moisture percentile declined from 33% to 5% in 8 days and stayed below 20% for 8 days (Figure 4d). The rapid decline in soil moisture is mainly from rainfall deficits because the evapotranspiration process is limited by soil water in semiarid savanna region. GPP and ET both decrease with the decline in soil moisture (Figures 4e and 4f), and the negative anomalies persist even after the flash drought. As there is not enough~~

~~rainfall to alleviate soil moisture drought, the vegetation damage continues (Figure 4e).~~

~~The flash drought lasted for 56 days in 2007 at IT-Col site and propagated into a long-term drought due to the persistence of precipitation deficits. IT-Col is in deciduous broadleaf forest with relatively humid climate (Van Dijk~~c~~ & Dolman, 2004). There is a lag time of 8 days between the responses of GPP and ET to flash drought (Figures 4h and 4i), which is because that the positive evapotranspiration anomaly at the onset of flash drought (30th in June) is driven by higher temperature and VPD. GPP and ET are below the climatology during flash drought, indicating the degradation in vegetation under water stress. The whole reduction of ET during flash drought is relatively small compared with GPP, indicating the decoupling between water and carbon fluxes.~~

~~In short, both GPP and ET fluxes reduce rapidly in responding to the sharp decline in soil moisture, although the reduction depends on environmental conditions and vegetation characteristics (Vicente-Serrano et al., 2013).~~

3.~~3~~2 Climatological statistics of the response time of GPP to flash drought

By analyzing all the 1~~6~~51 soil moisture flash drought events across ~~34~~29 FLUXNET sites, we find that negative GPP anomalies occur during 81% of the soil moisture flash drought events. Figure 4 shows the probability distributions of the response time of GPP to soil moisture flash drought as determined by soil moisture reductions for the first occurrence of negative SGPPA, the minimum negative value of SGPPA and the minimum soil moisture percentiles for different vegetation types, respectively. To reduce the uncertainty due to small sample sizes, only the results for vegetation types (SAV, CROP, MF, DBF, ENF) with more than 10 flash drought events are shown. ~~Figures 5a and 5b show the probability distributions of the response time of GPP to flash drought for the first occurrence of negative SGPPA and the minimum negative value of SGPPA, respectively.~~ For soil moisture flash droughts from all vegetation types, ~~T~~the first occurrences of negative SGPPA are concentrated during the first 24 days, and ~~for 57% flash droughts,~~ GPP starts to respond to soil moisture flash drought within 16 days for 57% flash droughts (Figures ~~5~~4a-e). The occurrences of minimum value of SGPPA rise sharply at the beginning of soil moisture flash drought, and reach the peak during 17-24 days, and then slow down (Figures ~~5~~4f-j~~b~~), which is similar to the decline in soil moisture. Although the first occurrences of negative SGPPA mainly occur in the onset stage, GPP would continue to decrease in the recovery stages for 60% of soil moisture flash drought events. ~~The time for soil moisture reaching its minimum is concentrated during 9-16 days since the occurrence of flash drought, preceding the minimum GPP by about 8 days. Large decreases in soil moisture percentiles are during the first 16 days of flash drought (Figure 5c), while large decrease in GPP occurs during 9-24 days (Figure 5d).~~

Different types of vegetation including herbaceous plants and woody plants all react to soil moisture flash drought in the early stage (Figures~~s~~ ~~6~~4a-e). Among them, ~~savanna~~ SAV shows the fastest reaction to water stress (Figures 4~~6~~a and ~~&6~~4f), ~~with~~and the RT is within 8 days for 63% events~~.~~, ~~showing~~ suggesting that ~~vegetation~~ SAV respon~~se~~ds concurrently with soil moisture flash drought onset. ~~and u~~Ultimately, 88% events for SAV show~~ing~~ ~~impaired~~ reduced vegetation photosynthesis. The result is consistent with previous studies regarding the strong response of semi-arid ecosystems to water availability (Gerken et al., 2019; Vicente-Serrano et al., 2013; Zeng et al., 2018), and the decline in GPP for SAV is related to isohydric behaviors during soil moisture drought and higher VPD, through closing stomata to decrease water loss as transpiration and carbon assimilation (Novick et al., 2016; Roman et al., 2015). ~~the high vulnerability of vegetation in semiarid regions (Vicente-Serrano et al., 2013; Zeng et al., 2018).~~ For ENF, only 27% of soil moisture flash droughts cause the negative SGPPA during the first 8 days. When RT is within 40 days, the cumulative frequencies range from 74% to 88% among different vegetation types. The response frequency of RTmin and the response time of minimum soil moisture percentiles are quite similar, although there are discrepancies among the patterns of the response frequency for different vegetation types. The response frequency of RTmin for SAV increases sharply during 17-24 days of soil moisture flash droughts (Figure 4f). GPP is derived from direct eddy covariance observations of NEP and nighttime terrestrial ecosystem respiration, and temperature-fitted terrestrial ecosystem respiration during daytime. The response of NEP to flash droughts shows the compound effects of vegetation photosynthesis and ecosystem respiration. In terms of RT, the response of NEP is slower than GPP for SAV, but is quicker for DBF and ENF (Figure 5). The discrepancies between NEP and SM in terms of RTmin are more obvious than those between GPP and SM, and the RTmin of NEP is much shorter than the RTmin of soil moisture especially for DBF and ENF, which may be related to the increase of ecosystem respiration (Figures 5 i and j).

Figure 6 shows the temporal changes of SGPPA and soil moisture percentiles during 8 days before soil moisture flash droughts and during the first 24 days of the droughts. During 8 days before flash droughts, there is nearly no obvious decline for SGPPA, while SAV, DBF and ENF shows small increase in GPP. The decline in SGPPA is more significant during the first 9-24 days of soil moisture flash droughts for different vegetation types, and SGPPA for SAV and CROP show quicker decline even during the first 8 days of soil moisture flash droughts. The decline rates in soil moisture are mainly concentrated within the first 16 days of flash droughts~~show differences among different vegetation types during flash drought, which are related to soil texture, vegetation cover and climates~~. There are various lag times for the response of GPP to the decline in soil moisture among different vegetation.

3.~~4~~3 ~~WUE~~The coupling between carbon and water fluxes under soil moisture stress

Figure 7 shows the standardized anomalies of WUE and uWUE and their components for different ecosystems during 8 days before and after soil moisture flash droughts and the onset and recovery stages~~ of flash drought~~. ~~Evergreen broadleaf forest (EBF) and grassland (GRA) were excluded due to insufficient flash drought cases. ~~Here, we select 81% of soil moisture flash drought events with GPP declining down to its normal conditions to analyze the interactions between carbon and water fluxes, while GPP during the remaining 19% of soil moisture flash drought events may stay stable and is less influenced by drought conditions. During 8 days before soil moisture flash drought, WUE and uWUE are generally close to the climatology (Figure 7a) and there are no significant changes in GPP, ET, and $ET/\sqrt{VPD}$ (Figures 7e and 7i). However, the median value of SGPPA for SAV is positive (Figure 7e). WUE is stable during the onset stage~~ except for croplands and mixed forests (MF)~~, whereas uWUE increases for all ecosystems except for CROP (Figure 7b~~a~~). For ~~croplands~~CROP, both GPP and ET decrease, and the decline in WUE is related with a greater reduction in GPP relative to ET (Figure 7~~e~~f a~~&~~nd 7~~e~~j). The positive anomalies of uWUE are correlated with decrease in $ET/\sqrt{VPD}$ mainly induced by the high VPD. Increasing VPD and deficits in soil moisture would decrease canopy conductance (Grossiord et al., 2020) but not GPP for MF and ENF. During the onset stage, GPP and ET reduce only for SAV~~savannas~~, and CROP~~croplands~~, and DBF, and the magnitudes of GPP and ET reduction are highest for SAV~~savannas~~. ET is close to normal conditions for MF, DBF, and ENF, thus enhancing the drying rate of soil moisture with less precipitation supply during the onset stage. But ~~for~~during recovery stage of soil moisture flash drought, GPP and ET show significant reductions except for MF (Figures 7g and 7k), and the responses of WUE and uWUE are different between herbaceous plants (SAV~~savannas~~ and ~~croplands~~CROP) and forests (MF, DBF, and ENF), where WUE and uWUE decrease significantly for ~~savannas~~ SAV and ~~croplands~~ CROP but increase slightly for forests (Figure 7c~~b~~). The decrease in uWUE for SAV and CROP during recovery stages indicates that SAV and CROP are likely brown due to carbon starvation caused by the significant decrease in stomatal conductance (McDowell et al., 2008). The decrease in

GPP during recovery stage is not only related to the reduction in canopy conductance, but also the decrease in uWUE under drought for SAV~~savannas~~ and CROP~~croplands~~ which is possibly influenced by suppressed state of enzyme and reduced mesophyll conductance (Flexas et al., 2012). However, the positive anomalies of uWUE for DBF and ENF during the recover stage imply that the decline in GPP mainly results from the stomata closure. ET starts to decrease during the recovery stage due to the limitation of water availability, and the decreasing ET also reflects the enhanced water stress for vegetation during the recovery stage. The average soil moisture conditions are 1~~1~~2% in percentile for recovery stage but 18% for onset stage. So, drier soil moisture in the recovery stage exacerbates ecological response. Figure 7~~b~~c also shows the higher WUE and uWUE for forests, which indicates their higher resistance to flash drought than herbaceous plants during recovery stage. During 8 days after flash drought, the standardized anomalies of uWUE are still positive for forests, whereas SGPPA and ET are both lower than the climatology for all ecosystems. The ecological negative effect would persist after the soil moisture flash drought.

3.4 The impact of climate factors on GPP during soil moisture flash drought

Figure 8 shows the partial correlation coefficients between standardized anomalies of GPP and meteorological variables and soil moisture percentiles during different stages of soil moisture flash droughts. The correlation between climate factors and GPP is not statistically significant during 8 days before soil moisture flash droughts. During onset stages of soil moisture flash droughts, the partial correlation coefficients between SGPPA and soil moisture percentiles are 0.44, 0.49 and 0.29, respectively for SAV, CROP, and ENF ($p<0.05$). Besides, shortwave radiation is positively correlated with SGPPA for MF, DBF, and EBF (Figure 8b) during onset stages and the positive anomalies of shortwave radiation could partially offset the loss of vegetation photosynthesis due to the deficits in soil moisture. SGPP is also positively correlated with temperature during onset stages for SAV and DBF. The partial correlation coefficients between SGPPA and VPD are -0.53 and -0.22 respectively for DBF and ENF, and the higher VPD would further decrease GPP during onset stages. The influence of VPD on GPP is much more significant during recovery stages and 8 days after. SGPPA is positively correlated with soil moisture and negatively with VPD for SAV both during recovery stages and 8 days after.

4. Discussion

Previous studies detected the vegetation response for a few extreme drought cases without a specific definition of flash drought from a climatological perspective (Otkin et al., 2016; He et al., 2019). Moreover, less attention has been paid to the coupling between carbon and water fluxes during soil moisture flash drought events. This study investigates the response of carbon and water fluxes to soil moisture flash drought based on decade-long FLUXNET observations during different stages of flash droughts. The responses vary across different phases of flash drought, and different ecosystems have different responses, which provide implications for eco-hydrological modeling and prediction. Besides, the influence of different climate factors including VPD and soil moisture also differs during different stages of soil moisture flash droughts.

4.1 The responses of carbon and water fluxes to flash droughts

Based on 1~~6~~51 soil moisture flash drought events identified using soil moisture from decade-long FLUXNET observations, the response of GPP to flash drought is found to be quite rapid. For more than half of the 1~~6~~51 soil moisture flash drought events, the GPP drops below its normal conditions during the first 16 days and reaches its maximum ~~intensity~~ reduction within 24 days. Due to the influence of ecosystem respiration, the responses of NEP for DBF and ENF to flash droughts are much quicker than GPP, implying that the sensitivity of ecosystem respiration is less than that of vegetation photosynthesis (Granier et al., 2007). Eventually, 81% of soil moisture flash drought events cause ~~negative ecological impacts on~~ declines in GPP. During the drought period, plants would close their stomata to minimize water loss through decreasing canopy conductance, which in turn leads to a reduction in carbon uptake. High VPD further reduces canopy conductance during soil moisture flash drought. The suppression of GPP and ET is more obvious for flash drought recovery stage determined by soil moisture than the onset stage. The discrepancy of GPP responses between different phases of soil moisture flash drought may result from 1) soil moisture conditions which are drier during the recovery stage, and 2) the damaged physiological functioning for specific vegetation types. The anomalies of uWUE for ecosystems are always positive or unchanged during soil moisture flash drought except for croplands and savannas during recovery stage. The decrease in canopy conductance would limit photosynthetic rate, however, the increase of uWUE may indicate~~s~~ adaptative regulations of ecosystem physiology which is consistent with Beer et al. (2009). uWUE is higher than WUE during onset stage of soil moisture flash drought, which is due to the decreased conductance under increased VPD. However, there is no obvious difference between WUE and uWUE during recovery stage, which indicates that photosynthesis is less sensitive to stomatal conductance and may be more correlated with limitations of biochemical capacity (Flexas et al., 2012; Grossiord et al., 2020). During 8 days after the soil moisture flash drought, the anomalies of GPP and ET are still negative, indicating that the vegetation does not recover immediately after the soil moisture flash drought. The legacy effects of flash droughts may be related to the vegetation and climate conditions (Barnes et al., 2016; Kannenberg et al., 2020).

This study is based on the sites that are mainly distributed over North America and Europe. It is necessary to investigate the impact of flash drought on vegetation over other regions with different climates and vegetation conditions. In addition, this study used in-situ surface soil moisture at FLUXNET stations to detect vegetation response due to the lack of soil moisture observations at deep soil layers. There would be more significant ecological responses to flash drought identified through using root-zone soil moisture because of its close link with vegetation dynamics. Due to the limitation of FLUXNET soil moisture measurements, here we used soil moisture observations mainly at the depths of 5 to 10 cm. We also analyzed the response of GPP to flash drought identified by 0.25-degree ERA5 soil moisture reanalysis data at the depths of 7cm and 1m. The response of GPP to flash droughts identified by FLUXNET surface soil moisture are quite similar to those identified by ERA5 soil moisture at the depth of 1m (not shown). There are less GPP responses to flash droughts identified by ERA5 surface soil moisture. Although we select the ERA5 grid cell that is closest to the FLUXNET site and use the ERA5 soil moisture data over the same period as the FLUXNET data, we should acknowledge that the gridded ERA5 data might not be able to represent the soil moisture conditions as well as flash droughts at in-situ scale due to strong heterogeneity of land surface. Therefore, the in-situ surface soil moisture from FLUXNET is useful to identify flash droughts compared with reanalysis soil moisture, although the in-situ root-zone soil moisture would be better.

4.2 Variation in ecological responses across vegetation types

The responses of GPP, ET and WUE to soil moisture flash drought vary among different vegetation types. The decline in GPP and ET only occurs across croplands and savannas during onset stage. For most forests, the deterioration of photosynthesis and ET appears during the recovery stage with higher WUE and uWUE. For CROP~~croplands~~ and SAV~~savannas~~, both WUE and uWUE decrease during the recovery stage and they may be brown due to reduced photosynthesis. The positive anomalies of WUE and uWUE for forests ~~show~~suggest that~~ the adaptation of vegetation to flash drought from physiological perspective~~ their deeper roots can obtain more water than grasslands during flash drought. Xie et al. (2016) pointed out that WUE and uWUE for a subtropical forest increased during the 2013 summer drought in southern China. The increased WUE in forest sites and unchanged WUE in grasslands were also found in other studies for spring drought (Wolf et al., 2013). In general, herbaceous plants are more sensitive to flash drought than forests, especially for savannas. The correlation between soil moisture and GPP is more significant for SAV, CROP, and ENF during onset stages of flash droughts, which is consistent with the strong response to water availability of SAV and CROP (Gerken et al., 2019). SAV is more isohydric than forests and would reduce stomatal conductance immediately to prohibit water loss that further exacerbates drought (Novick et al., 2016; Roman et al., 2015). However, almost all vegetation types show high sensitivity to VPD during the recovery stage of flash droughts.

4.3 Potential implications for ecosystem modelling

The study reveals the profound impact of soil moisture flash droughts on ecosystem through analyzing eddy covariance observations. It is found that the responses of carbon and water exchanges are quite distinguishing for forests and herbaceous plants. For the ecosystem modeling, the response of stomatal conductance under soil moisture stress has been addressed in previous studies (Wilson et al., 2000), but there still exists deficiency to capture the impacts of water stress on carbon uptake (Keenan et al., 2009), which is partly due to the different responses across species. Incorporating physiological adaptations to drought in ecosystem modeling especially for forests would improve the simulation of the impact of drought on the terrestrial ecosystems.

5. Conclusion

This study presents how carbon and water fluxes respond to soil moisture flash drought during 8 days before flash droughts, onset and recovery stages, and 8 days after flash droughts through analyzing decade-long observations from FLUXNET. Ecosystems show high sensitivity of GPP to soil moisture flash drought especially for savannas, and GPP starts to respond to soil moisture flash droughts within 16 days for more than half of the flash drought events under the influence of the deficit in soil moisture and higher VPD. However, the responses of WUE and uWUE vary across vegetation types. Positive WUE and uWUE anomalies for forests during the recovery stage indicate the ~~physiological adaptation~~resistance to soil moisture flash drought through non-stomatal regulations, whereas WUE and uWUE decrease for croplands and savannas during the recovery stage. For now, the main concern about the ecological impact of soil moisture flash drought is concentrated on the period of flash drought and the legacy effects of flash drought are not involved. It still needs more efforts to study the subsequent effects of soil moisture flash droughts which would contribute to assessing the accumulated ecological impacts of flash drought. Nevertheless, this study highlights the rapid response of vegetation productivity to soil moisture dynamics at sub-seasonal timescale, and different responses of water use efficiency across ecosystems during the recovery stage of soil moisture flash droughts, which complements previous studies on the sensitivity of vegetation to extreme drought at longer time scale. Understanding the response of carbon fluxes and the coupling between carbon and water fluxes to drought, especially considering the effects of climate change and human interventions (Yuan et al., 2020), might help assessing the resistance and resilience of vegetation to drought.

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Data availability statement

Carbon fluxes and hydrometeorological variables from FLUXNET2015 are available through https://fluxnet.fluxdata.org/data/fluxnet2015-dataset/.

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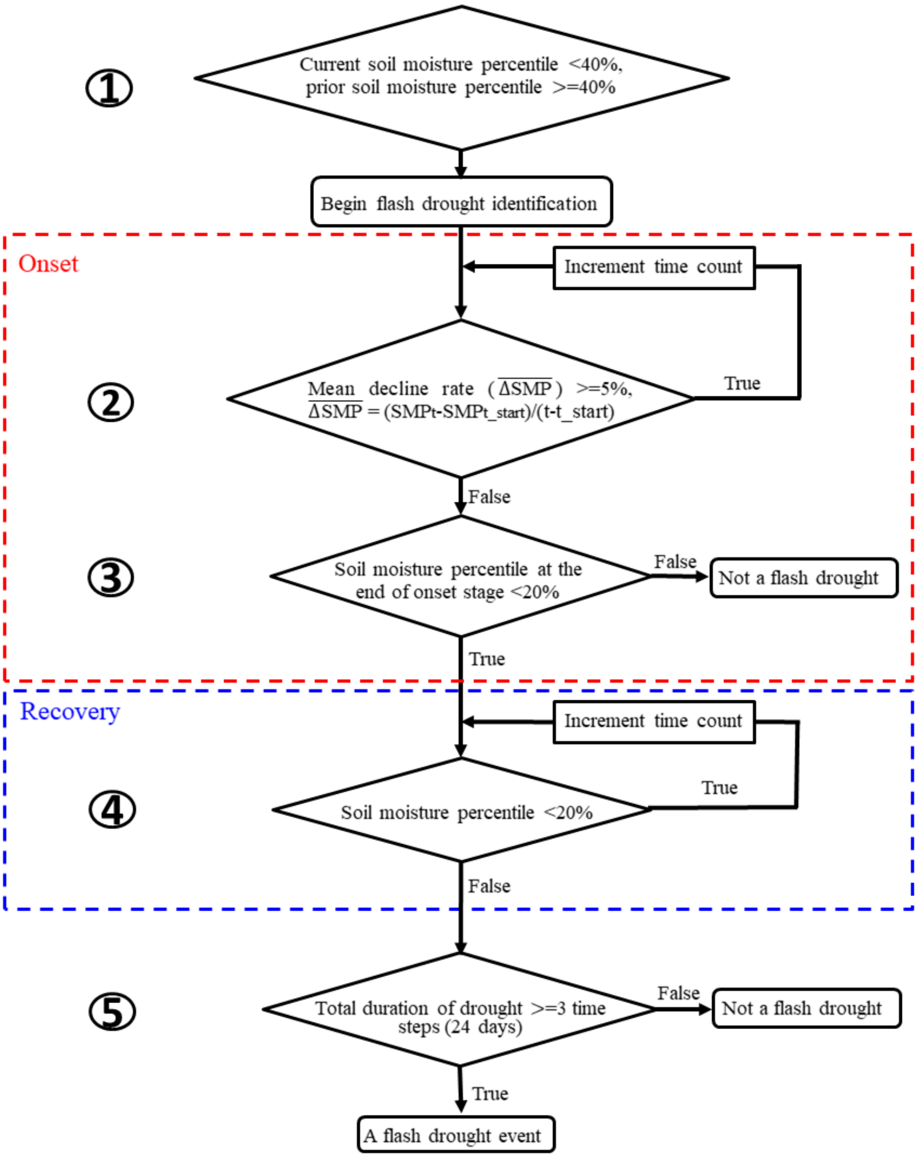

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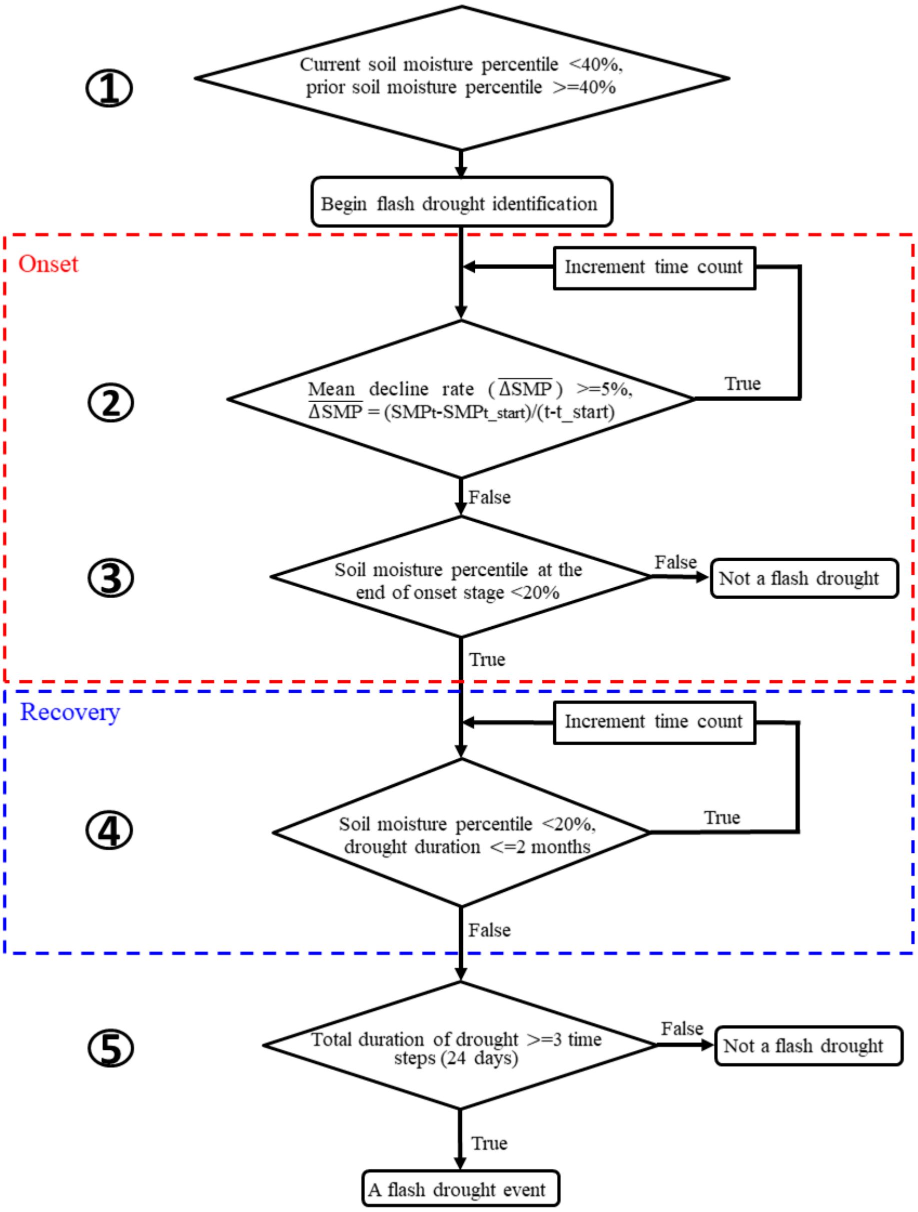

Figure 1. A flowchart of flash drought identification by considering soil moisture decline rate and drought persistency.

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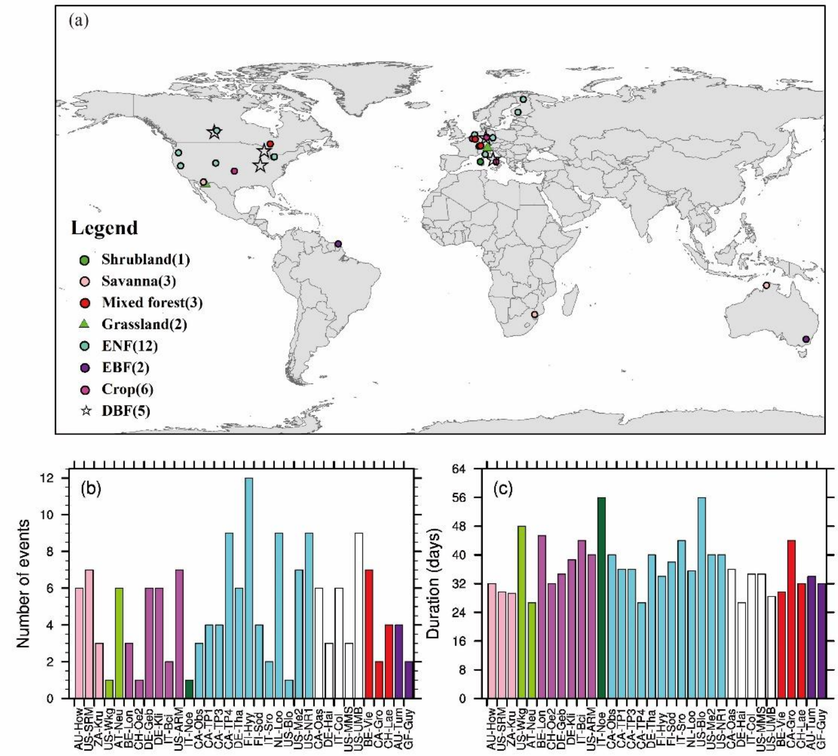

(a)
Legend
Shrubland(1)
Savanna(3)
Mixed forest(3)
Grassland(2)
ENF(12)
EBF(2)
Crop(6)
DBF(5)
(b)
Number of events
0
2
4
6
8
10
12
(c)
Duration (days)
0
8
16
24
32
40
48
56
64
AU-How
US-SRM
ZA-Kru
US-Wkg
AT-Neu
BE-Lon
CH-Oe2
DE-Geb
DE-Kli
IT-Bci
US-ARM
IT-Noe
CA-Obs
CA-TP1
CA-TP3
CA-TP4
DE-Tha
FI-Hyy
FI-Sod
IT-Sro
NL-Loo
US-Blo
US-Me2
US-NR1
CA-Oas
DE-Hai
IT-Col
US-MMS
US-UMB
BE-Vie
CA-Gro
CH-Lae
AU-Tum
GF-Guy

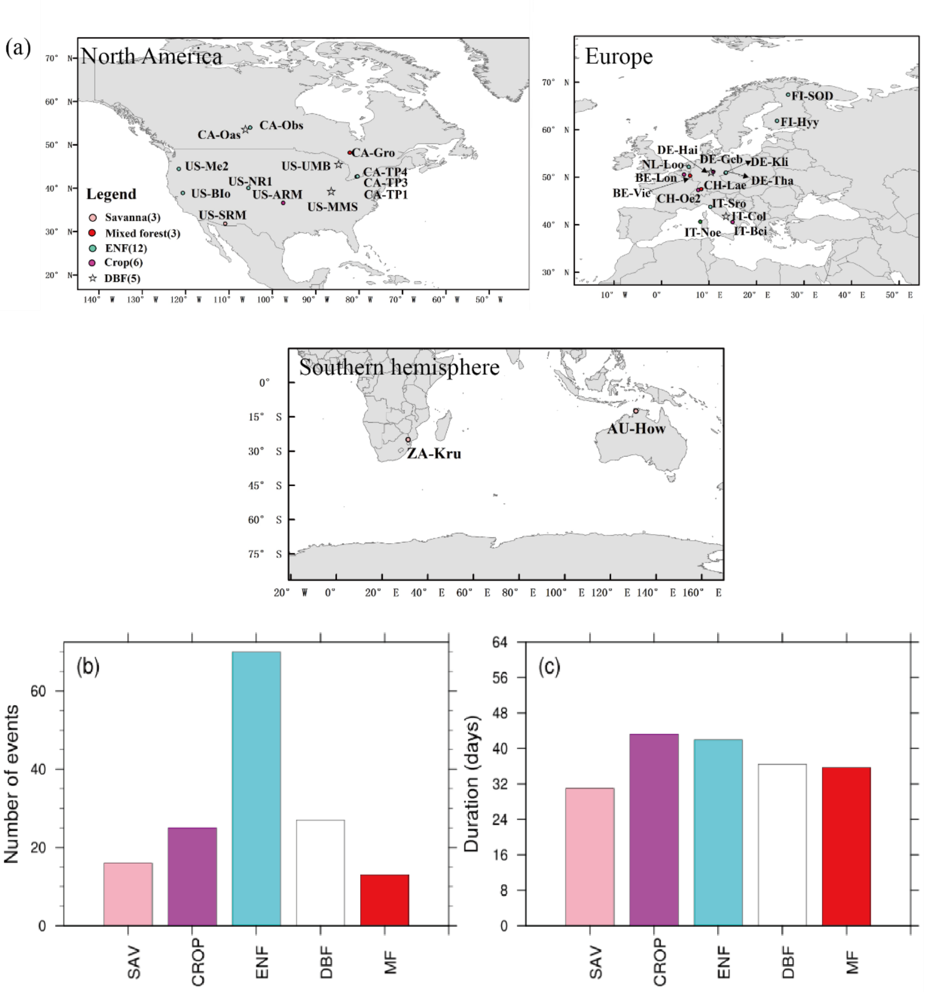
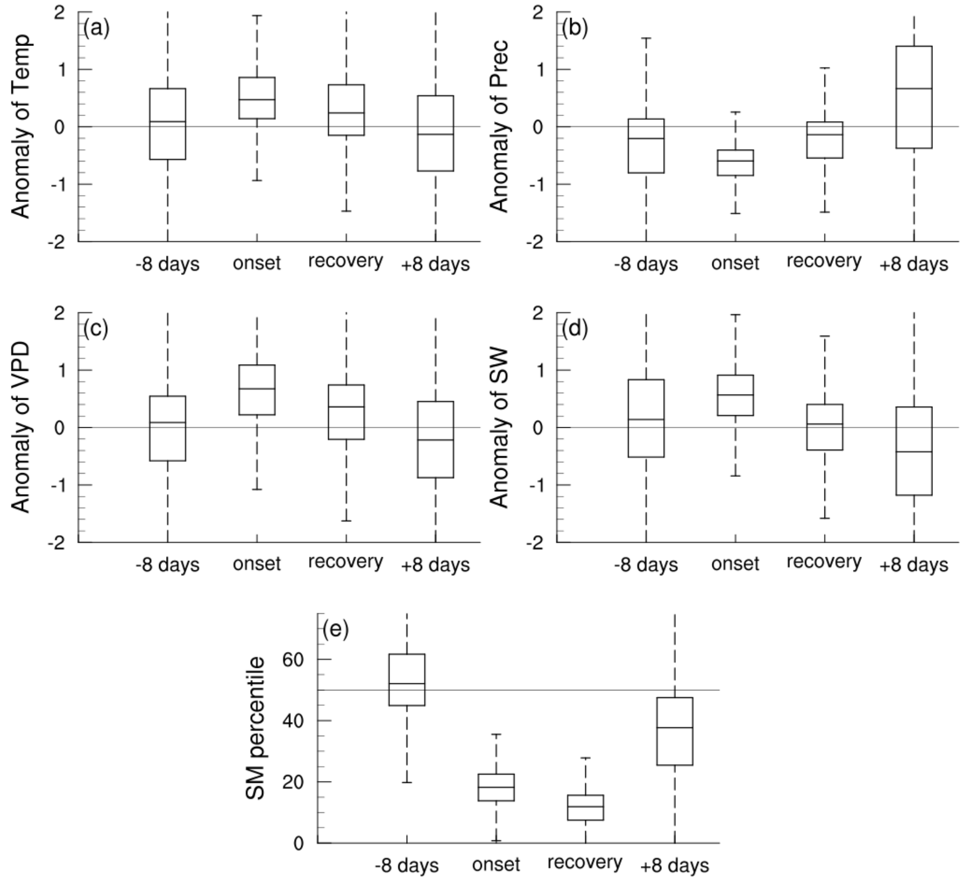


Figure 2. ~~Flash drought characteristics. (a)~~ Global map of 29~~34~~ FLUXNET sites used in this study (a) and flash drought characteristics (b&c). (b) ~~(b)~~ Total numbers (events) and (~~e~~c) mean durations (days) of flash drought events for ~~each site~~ each vegetation type during their corresponding periods (see Table 1 for details). Different colors represent different vegetation types.


(a)
Anomaly of Temp
2
1
0
-1
-2
-8 days
onset
recovery
+8 days
(b)
Anomaly of Prec
(c)
Anomaly of VPD
(d)
Anomaly of SW
(e)
SM percentile
60
40
20
0

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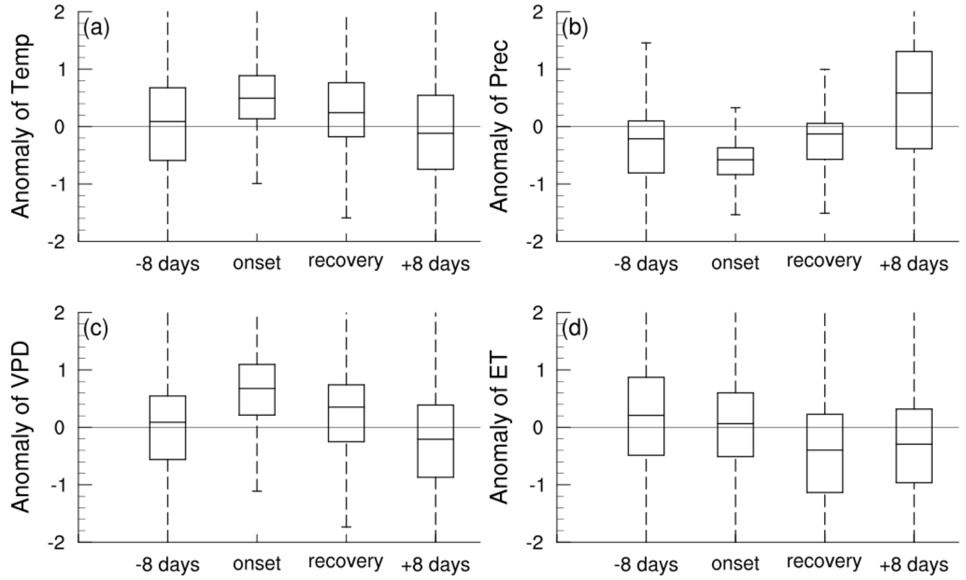
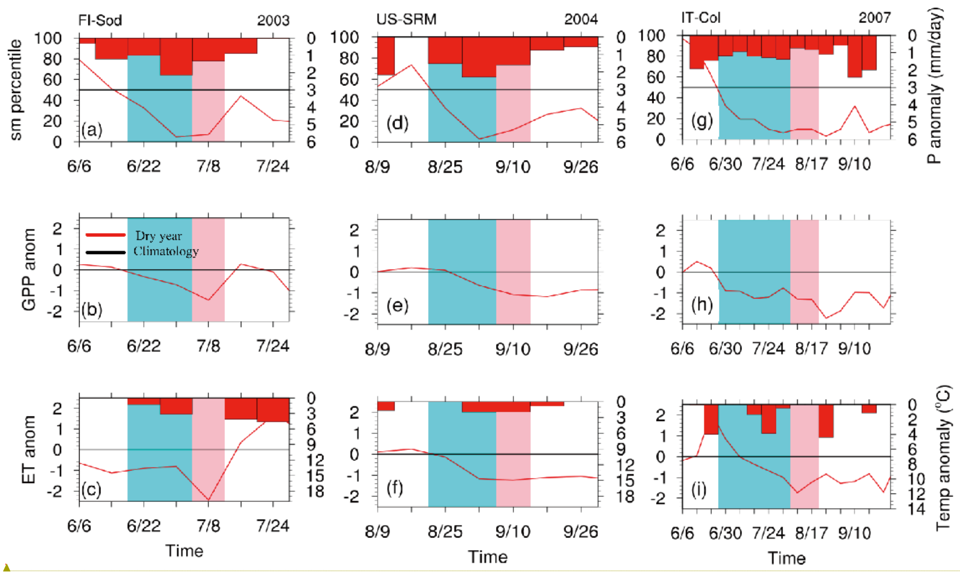

(a)
Anomaly of Temp
2
1
0
-1
-2
-8 days
onset
recovery
+8 days
(b)
Anomaly of Prec
(c)
Anomaly of VPD
(d)
Anomaly of ET

Figure 3. Standardized 8-day anomalies of (a) temperature, (b) precipitation, (c) VPD, ~~and~~ (d) ~~ET~~short wave radiation (SW), and (e) soil moisture (SM) percentiles during 8 days prior to flash drought onset, onset and recovery stages of flash drought, and 8 days after flash drought.



~~**Figure 4.** Time series of soil moisture percentile (top panels), standardized gross primary productivity (GPP) anomaly (middle panels) and standardized evapotranspiration (ET) anomaly (bottom panels) for the 2003 drought at FI-Sod station, 2004 drought at US-SRM station and 2007 drought at IT-Col station. Red lines are the time series in the target year, and black lines are the climatology (long-term mean values). The red bars are precipitation deficits in top panels and temperature anomalies in bottom panels, where data with positive precipitation anomaly or negative temperature anomaly are not shown. The blue and pink shaded areas are the onset and recovery stages of flash drought events, respectively.~~

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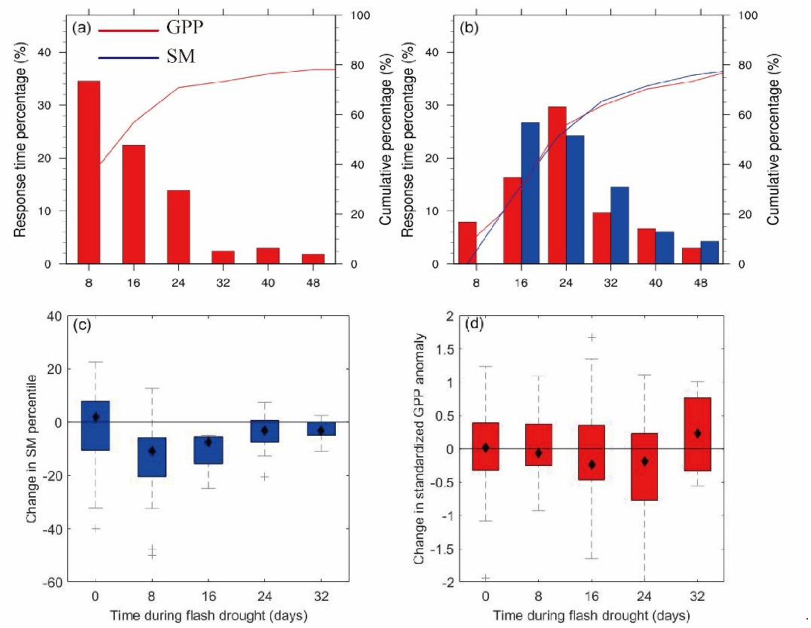
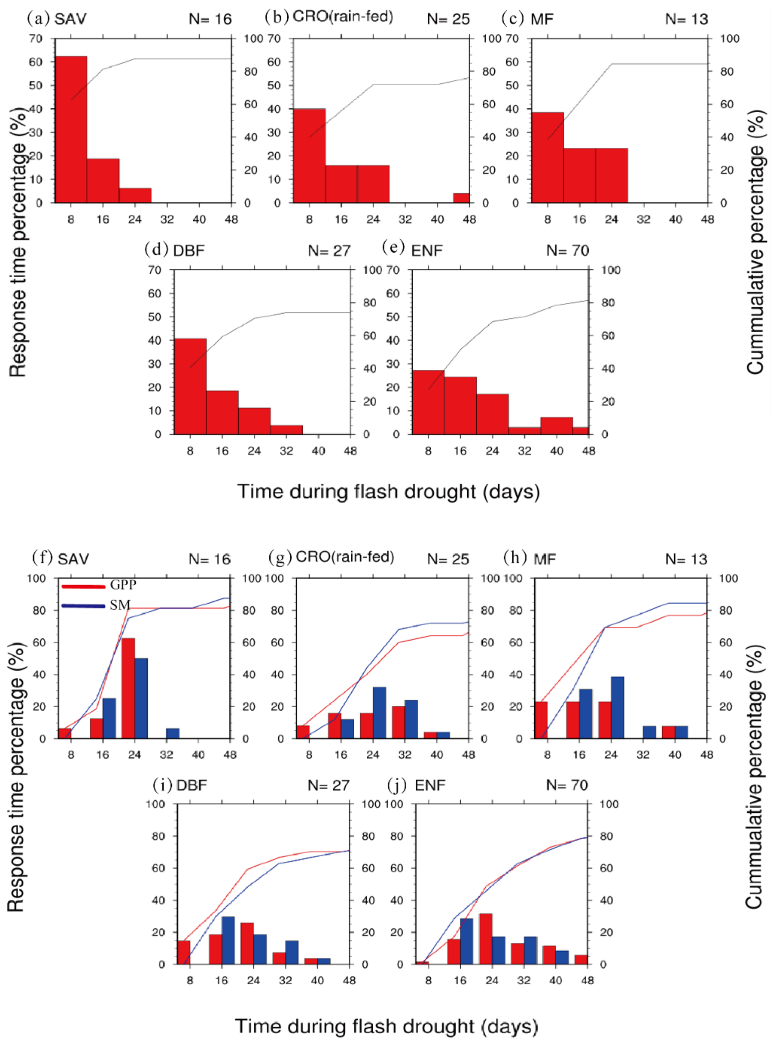


~~**Figure 5.** Response of carbon fluxes to flash droughts. (a) Percentage of the response time of the first occurrence of negative GPP anomaly and (b) the minimum values of GPP (red bars) and soil moisture (blue bars) during flash droughts. The temporal change rates of (c) soil moisture percentiles and (d) standardized GPP anomalies before and during flash droughts.~~



(a) SAV N= 16
(b) CRO(rain-fed) N= 25
(c) MF N= 13
(d) DBF N= 27
(e) ENF N= 70
Response time percentage (%)
Cummualative percentage (%)
Time during flash drought (days)
8 16 24 32 40 48
(f) SAV N= 16
GPP
SM
(g) CRO(rain-fed) N= 25
(h) MF N= 13
(i) DBF N= 27
(j) ENF N= 70
Response time percentage (%)
Cummualative percentage (%)
Time during flash drought (days)

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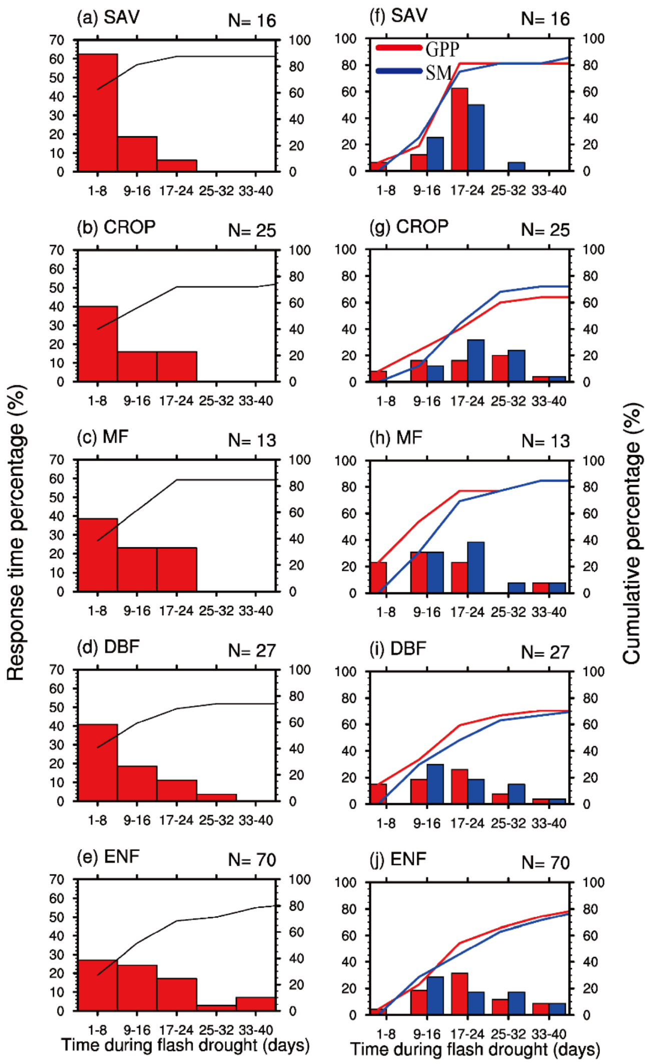

Figure ~~6~~4. Percentage of the response time (days) of the first occurrence of negative GPP anomaly (a-e), minimum GPP anomaly and minimum soil moisture percentile (f-j) during soil moisture flash drought for different vegetation types. SAV: savanna, CROP: rainfed cropland, MF: mixed forest, DBF: deciduous broadleaf forest and ENF: evergreen needleleaf forest.

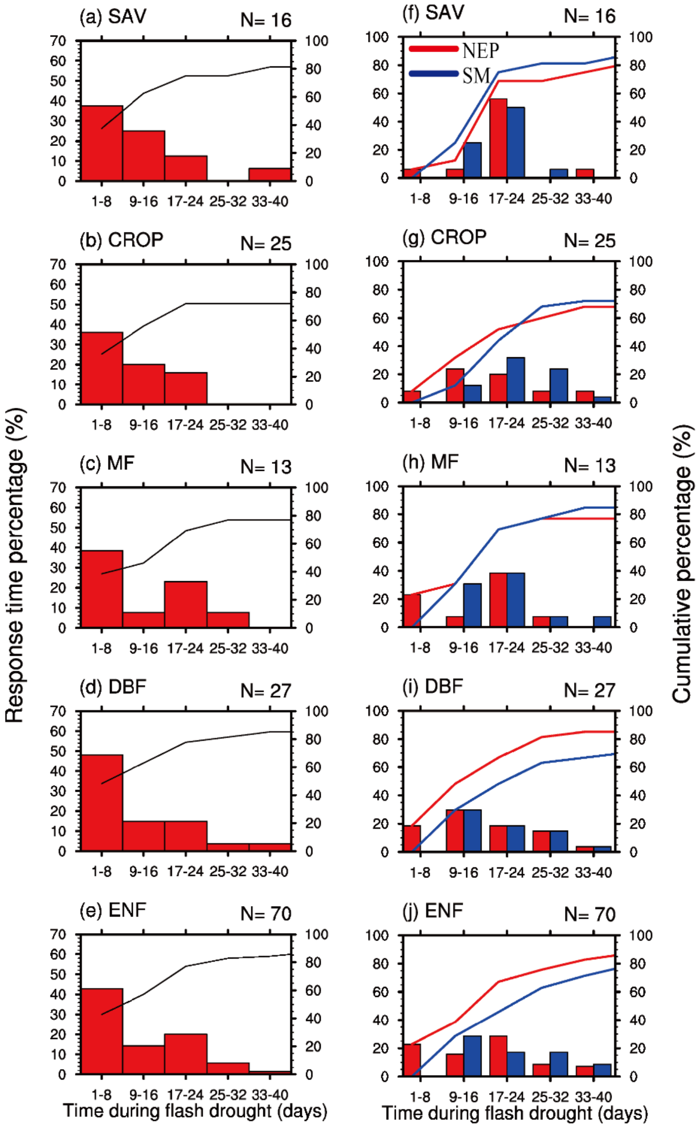

Figure 5. The same as Figure 4, but for net ecosystem productivity (NEP).

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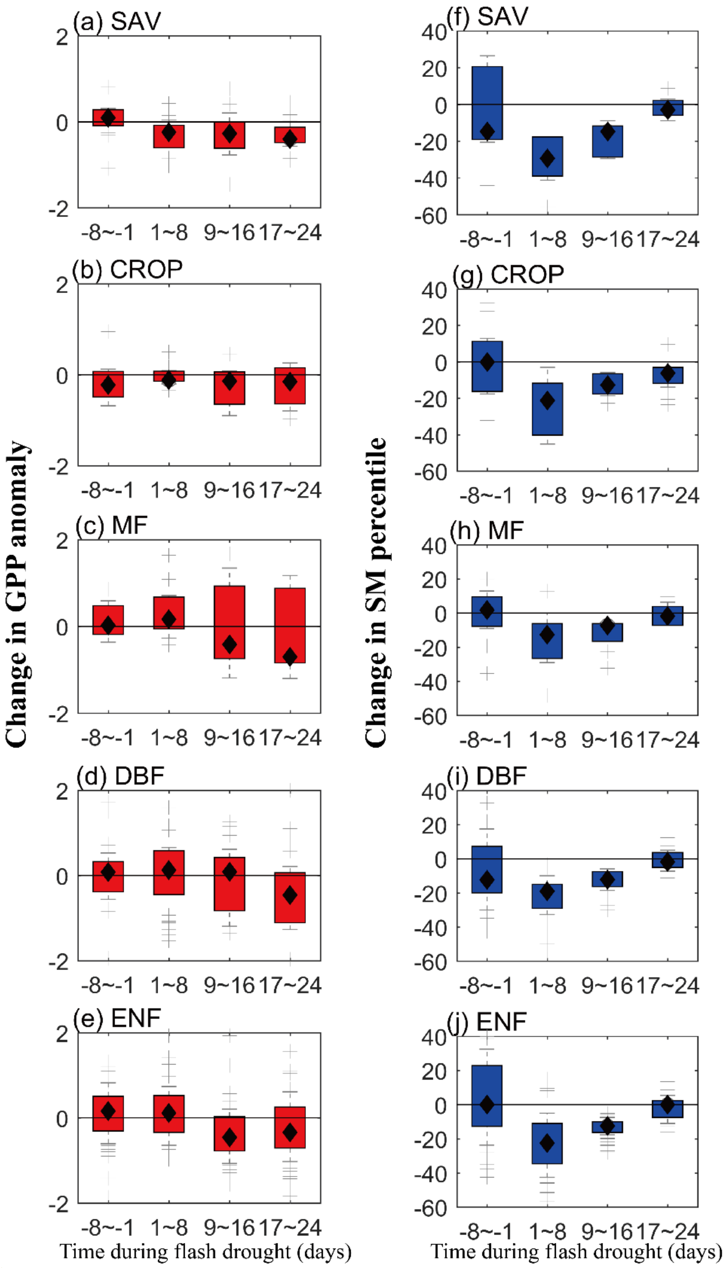
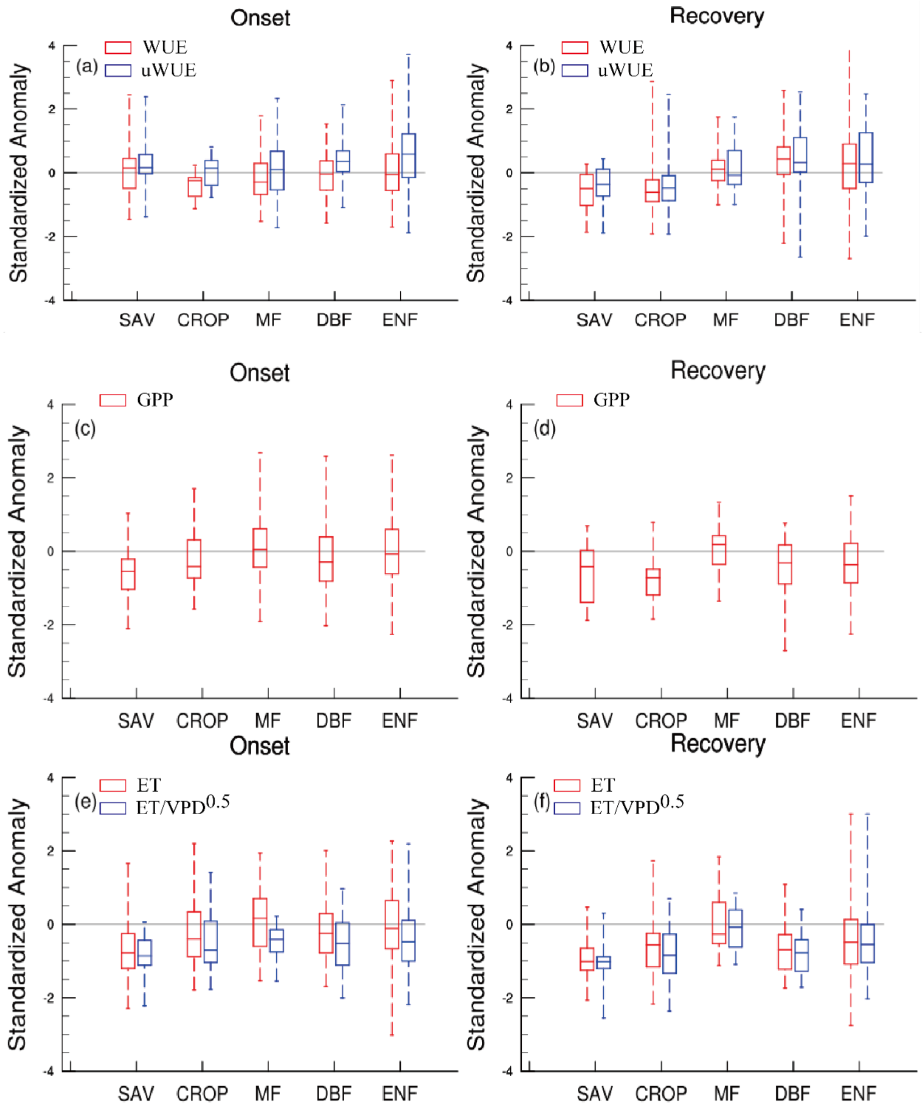


Figure 6. The temporal change rates of standardized GPP anomalies (a-e) and soil moisture percentiles (f-j) for different vegetation types. SAV: savanna, CROP: rainfed cropland, MF: mixed forest, DBF: deciduous broadleaf forest and ENF: evergreen needleleaf forest.


Onset
Recovery
(a)
(b)
WUE
uWUE
(c)
(d)
GPP
(e)
(f)
ET
ET/VPD$^{0.5}$
Standardized Anomaly
4
2
0
-2
-4
SAV
CROP
MF
DBF
ENF

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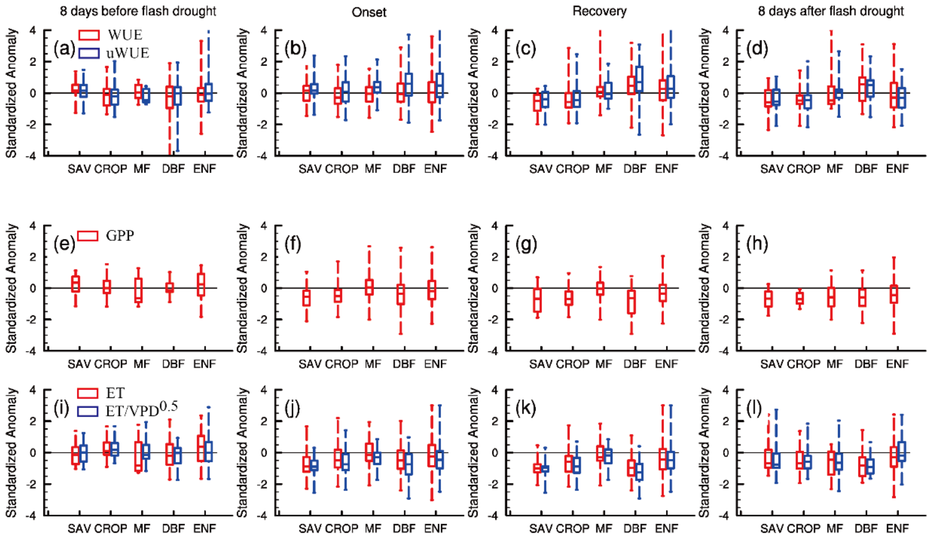

Figure 7. Standardized anomalies of water use efficiency (WUE), underlying WUE (uWUE), GPP, ET and $ET/\sqrt{VPD}$ during 8 days before flash drought onset, onset and recovery stages of flash drought events, and 8 days after flash drought. ~~SAV: savanna; CROP: cropland; MF: mixed forest; DBF: deciduous broadleaf forest; ENF: evergreen needleleaf forest.~~

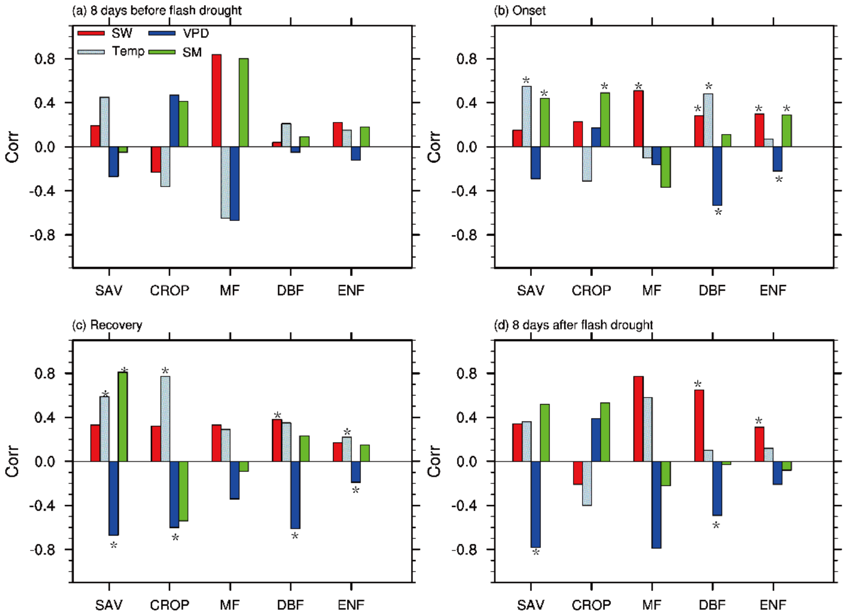

Figure 8. The partial correlation coefficients between GPP and soil moisture (SM), shortwave radiation (SW), temperature (Temp) and vapor pressure deficit (VPD) for different vegetation types including savannas (SAV), rain-fed croplands (CROP), mixed forests (MF), deciduous broadleaf forests (DBF), and evergreen needleleaf forests (ENF) during 8 days before soil moisture flash drought, onset and recovery stages and 8 days after soil moisture flash drought. * indicates the correlation is statistically significant at the 95% level.

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Table 1. Locations, vegetation types and data periods of Flux Tower Sites used in this study. WSA: woody savanna; CROP: cropland; EBF: evergreen broadleaf forests; MF: mixed forest; DBF: deciduous broadleaf forest; ENF: evergreen needleleaf forest; GRA: grassland; SAV: savanna.

station	lat	lon	IGBP	period
~~AT-Neu~~	~~41.12~~	~~11.32~~	~~GRA~~	~~2002-2012~~
AU-How	-12.49	131.15	WSA	2002-2014
~~AU-Tum~~	~~-35.66~~	~~148.15~~	~~EBF~~	~~2002-2014~~
BE-Lon	50.55	4.75	CROP-rainfed	2004-2014
BE-Vie	50.31	6.00	MF	1997-2014
CA-Gro	48.22	-82.16	MF	2004-2013
CA-Oas	53.63	-106.20	DBF	1996-2010
CA-Obs	53.99	-105.12	ENF	1999-2010
CA-TP1	42.66	-80.56	ENF	2002-2014
CA-TP3	42.71	-80.35	ENF	2002-2014
CA-TP4	42.71	-80.36	ENF	2002-2014
CH-Lae	47.48	8.37	MF	2005-2014
CH-Oe2	47.29	7.73	CROP-rainfed	2004-2014
DE-Geb	51.10	10.91	CROP-rainfed	2001-2014
DE-Hai	51.08	10.45	DBF	2000-2012
DE-Kli	50.89	13.52	CROP-rainfed	2005-2014
DE-Tha	50.96	13.57	ENF	1997-2014
FI-Hyy	61.85	24.29	ENF	1997-2014
FI-Sod	67.36	26.64	ENF	2001-2014
~~GF-Guy~~	~~5.28~~	~~-52.92~~	~~EBF~~	~~2004-2014~~
IT-Bci	40.52	14.96	CROP-irrigated	2005-2014
IT-Col	41.85	13.59	DBF	2005-2014
~~IT-Noe~~	~~40.61~~	~~8.15~~	~~SH~~	~~2004-2014~~
IT-Sro	43.73	10.28	ENF	2000-2012
NL-Loo	52.17	5.74	ENF	1999-2013
US-ARM	36.61	-97.49	CROP-rainfed	2003-2013
US-Blo	38.90	-120.63	ENF	1998-2007
US-Me2	44.45	-121.56	ENF	2002-2014
US-MMS	39.32	-86.41	DBF	1999-2014
US-NR1	40.03	-105.55	ENF	2002-2014
US-SRM	31.82	-110.87	WSA	2004-2014
US-UMB	45.56	-84.71	DBF	2002-2014
~~US-Wkg~~	~~31.74~~	~~-109.94~~	~~GRA~~	~~2005-2014~~
ZA-Kru	-25.02	31.50	SAV	2000-2010