**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. To explore the role of climate factors on GPP, we use partial correlation model to investigate the relationship between the standardized anomalies of GPP and temperature, radiation, VPD and soil moisture. Besides, we extend the study period from 8 days before flash drought to 8 days after flash drought. We have revised 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:

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

where i represents GPP, j represents the target meteorological variables and $m_1, m_{2\dots} and\ m_n$ represent the control meteorological variables. $r_{ij(m_1,m_{2\dots}m_n)}$ is the partial correlation coefficient between i and j, where $m_1, m_{2\dots} and\ m_n$ are control variables, and $r_{ij(m_1,\dots m_{n-1})}$ , $r_{im_n(m_1,\dots m_{n-1})}$ and $r_{jm_n(m_1,\dots m_{n-1})}$ are partial correlation coefficients between i and j, i and $m_n$, j and $m_n$ respectively under control of $m_1, m_{2\dots} and\ m_{n-1}$." (L218-230)

"**3.5 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 including radiation, temperature and VPD and soil moisture percentiles during different stages of soil moisture flash droughts with GPP responses. 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 partial 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 soil moisture flash droughts. SGPPA is positively correlated with soil moisture and negatively with VPD for SAV both during recovery stages and 8 days after the soil moisture flash drought." (L422-440)

"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).” (L386-389)

“During 8 days after flash drought, the standardized anomalies of uWUE are still positive, whereas SGPPA and ET are both lower than the climatology for all ecosystems. The ecological negative effect of soil moisture flash drought would persist after the flash drought due to legacy effects of drought.” (L418-4421)

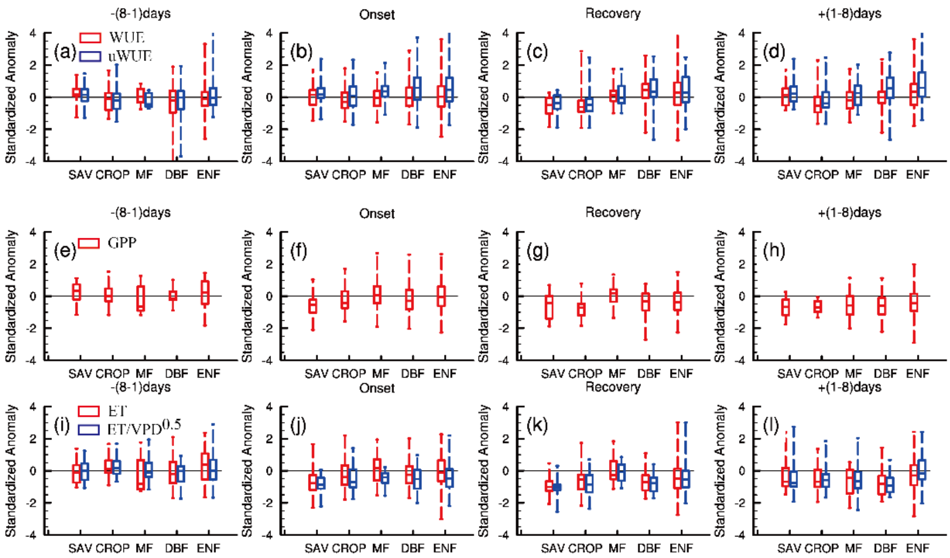


**Figure 7.** Standardized anomalies of water use efficiency (WUE), underlying WUE (uWUE), GPP, ET and $ET/\sqrt{VPD}$ during 8 days before flash drought onset, onset and recovery stages of flash drought events and 8 days after flash drought.

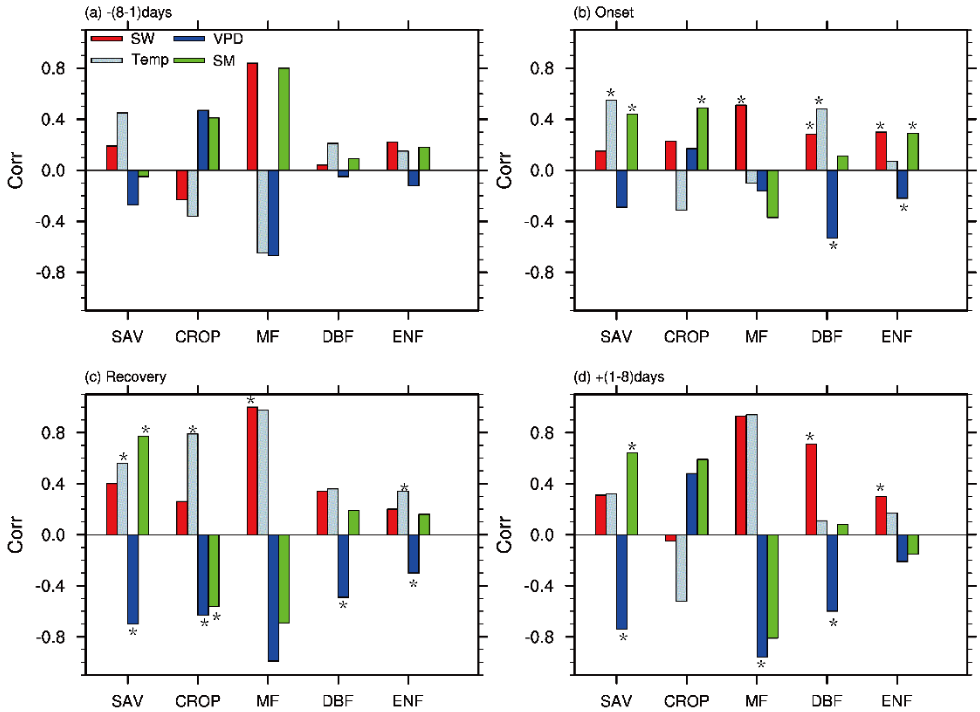


**Figure 8.** The partial correlation coefficients between GPP and soil moisture (SM), shortwave radiation (SW), temperature (temp) and vapor pressure deficit (VPD) for different vegetation types including savannas (SAV), rain-fed croplands (CROP), mixed forests (MF), deciduous broadleaf forests (DBF), 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 statistically significant at the 95% level.

*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. This study emphasizes the onset of ecological response to flash droughts and three flash drought events occurring at different ecosystems are selected to show the rapid response to flash droughts, not the lasting effects of flash drought on GPP. However, it is still an important issue to assess the impacts of flash droughts and we use lagged autocorrelation models to explore the lasting effects of flash droughts on vegetation (Barnes et al., 2016) through establishing the relationship between GPP and soil moisture conditions during 8 days after flash droughts, and GPP at the end of flash droughts as follows:

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

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 positive significantly 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. Thus, we added the discussion about the legacy effects of flash droughts connected with climate and vegetation conditions in the revised manuscript.

**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 |

"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 although the soil moisture flash drought ends. The legacy effects of flash droughts may be related to the vegetation and climate conditions (Barnes et al., 2016; Kannenberg et al., 2020).” (L480-484)

*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 revised the manuscript as follows:

“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 further exacerbating 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.” (L505-512)

*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 revised our manuscript as follows:

“GPP is derived from direct eddy covariance observations of NEP and terrestrial ecosystem respiration, and 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 S1). 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 quicker than the RTmin of soil moisture especially for DBF and ENF, which may be related to the increase of ecosystem respiration (Figure S1 i and j).” (L359-367)

“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)." (L458-461)

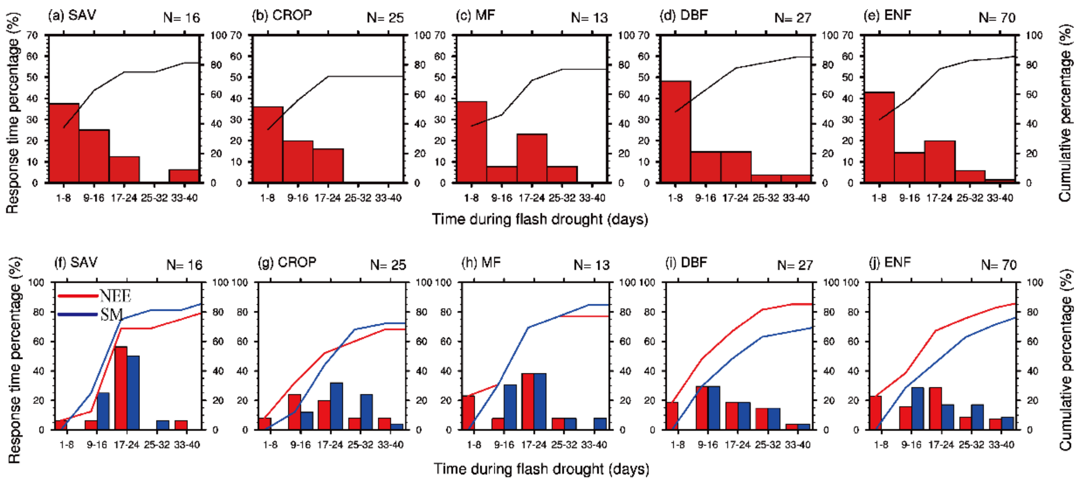


**Figure S1.** Percentage of the response time (days) of the first occurrence of negative net ecosystem productivity (NEP) anomaly (a-e), minimum NEP anomaly and minimum soil moisture percentile (f-j) during flash drought for different vegetation types. SAV: savanna, CROP: rainfed cropland, MF: mixed forest, DBF: deciduous broadleaf forest and ENF: evergreen needleleaf forest.

*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:** Thanks for your comments. Due to the limitation of soil moisture measurements, here we used soil moisture observations mainly at the depths of 5 to 10 cm in this study. 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 the response of GPP to flash droughts identified by ERA5 soil moisture at the depth of 1m (Figure R3). 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 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.

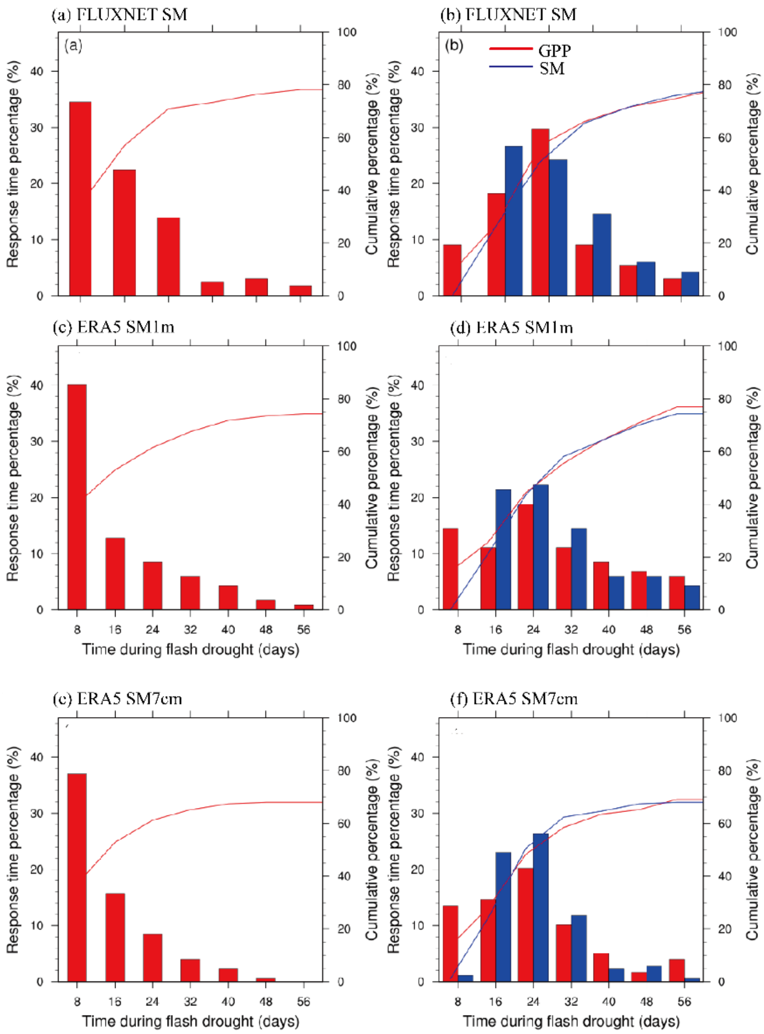


**Figure R3.** Response of carbon fluxes to flash droughts based on soil moisture from FLUXNET (a&b) and ERA5 at the depth of 7cm (c&d) and 1m (e&f). a, c and e are the percentages of the response time of the first occurrence of negative GPP anomaly and b, d, and f are the minimum values of GPP (red bars) and soil moisture (blue bars) during flash droughts.

*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:** Thanks for your comments. We selected the study sites based on the observation period with less than 5% missing values.

*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:** Thanks for your comments. We have examined the GPP response during 8 days after flash droughts in Response #1 and we have revised the manuscript as follows:

"The negative anomalies of GPP during soil moisture flash drought are considered as the onset of ecological response." (L176-178)

*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:** Thanks for your comments. The durations of flash droughts are averaged at site level and there was only one extreme flash drought event of 56 days at IT-Noe and US-Blo.

*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:

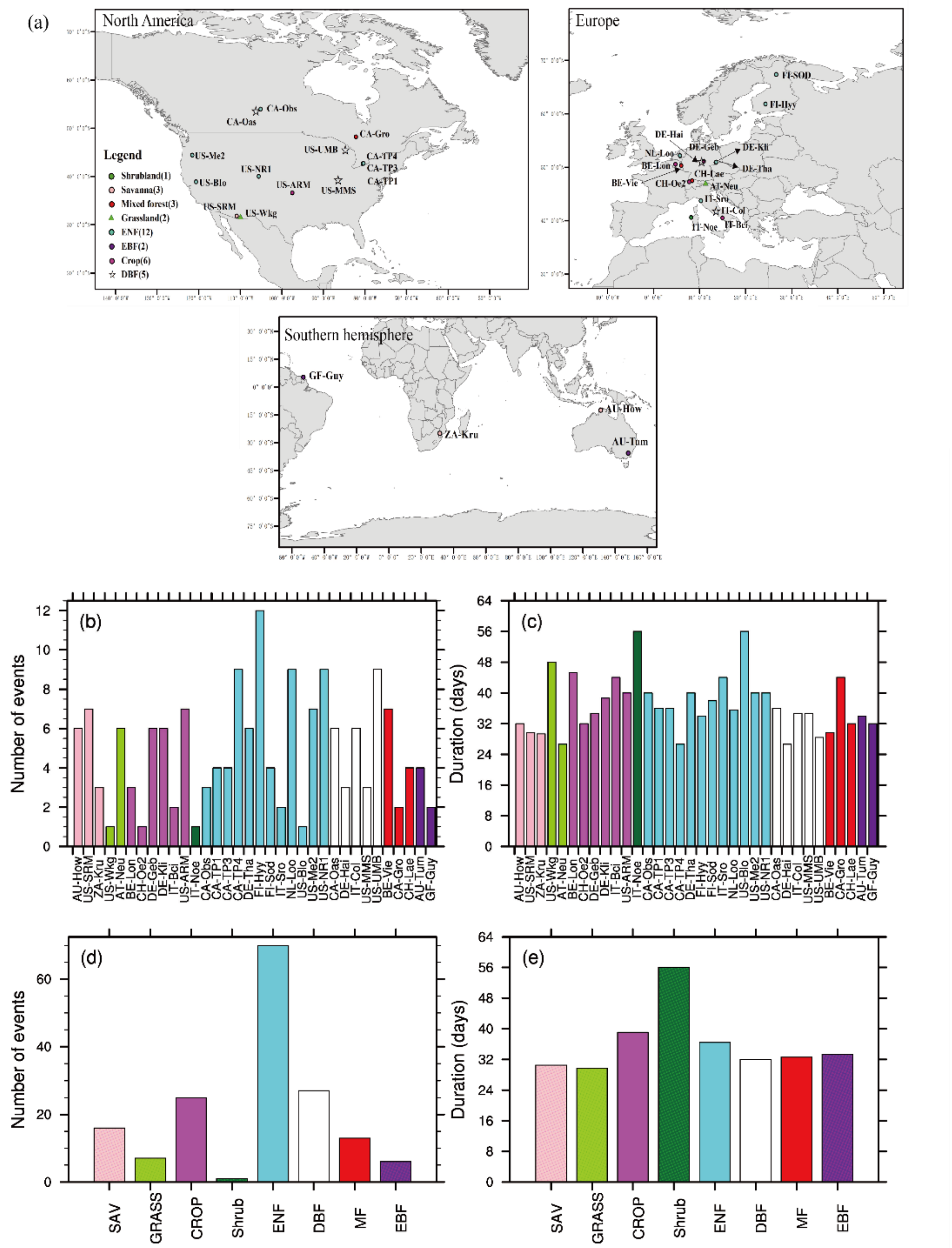


**Figure 2.** Flash drought characteristics. (a) Global map of 34 FLUXNET sites used in this study. (b&d) Total numbers (events) and (c&e) mean durations (days) of flash drought events for each site and vegetation type during their corresponding periods (see Table 1 for details). Different colors represent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

*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:** Thanks for your comments. 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 in the revised manuscript, which is also used in Koster et al., 2019.

*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:** It is not completely clear to us what the reviewer refers to here. The anomalies of ET and GPP are standardized to compare the ecological responses to flash droughts at different sites, and such analysis is quite usual like in Barriopedro et al., 2012 and Ciais et al., 2005.

"Intensification" and "onset" are quite similar to describe the development of flash droughts and the termination usually uses "onset" to describe the rapid decline in soil moisture in literature of flash droughts (Ford and Labosier, 2017; Otkin et al., 2016), thus here we use "onset" to be consistent with previous studies. Here we select three representative flash drought events from different ecosystems to reflect rapid response of GPP and ET to flash droughts. However, 81% of flash droughts would influence vegetation photosynthesis and not all flash drought events are necessary to analyze. As the reviewer suggested, we have now also introduced the locations, vegetation types and climates of the selected sites in the revised manuscript as follows:

"Here we select FI-Sod site (26.64°E, 67.36°N), US-SRM site (110.87°W, 31.82°N) and IT-Col site (13.59°E, 41.85°N) to show the response of vegetation to flash droughts for different ecosystems and different climate. FI-Sod is with the mean annual precipitation of 500 mm $yr^{-1}$ and the mean annual temperature of -1 ℃, and it is green all the year dominated by woody vegetation of ENF. The mean annual temperature and precipitation for US-SRM are 18 ℃ and 380 mm $yr^{-1}$, respectively. US-SRM is located at SAV covered by herbaceous and other understory systems. IT-Col is dominated by DBF with leaf-on and leaf-off periods and the mean annual temperature and precipitation are 6.3 ℃ and 1180 mm $yr^{-1}$." (L119-128)

*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. 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 refer to Response #1.

*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:** Thanks for your comments. Figure 5a/b only shows the cumulative response frequency within 1-40 days of flash droughts, which is slightly different the total response frequency. 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:** Thanks for your comments. We have revised the manuscript as follows:

"The result is consistent with 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)." (L346-351)

*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.

"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)." (L405-407)

"However, the positive anomalies of uWUE for DBF and ENF imply that the decline in GPP mainly results from the stomata closure." (L411-412)

*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 in Response #1 and #2. Besides, we have revised the manuscript as follows:

"Eventually, 81% of soil moisture flash drought events cause declines in GPP." (L483-484)

*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 may be related to the adaptation of vegetation to flash drought from physiological perspective, or the deeper roots that obtain more water." (L498-501)

*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.

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