Flash droughts threaten global managed forests

Jianzhuang Pang [1, 2], Hang Xu [1, 2, *], Yang Xu [1, 2], Yifan Zhang [1, 2], Xiaoyun Wu [1, 2], Kexin Li [1, 2], Zhiqiang Zhang [1, 2, *]

[1] Jixian National Forest Ecosystem Observation and Research Station, CNERN, Beijing Forestry University, Beijing 100083, P.R. China

[2] Key Laboratory of Soil and Water Conservation and Desertification Combating, State Forestry and Grassland Administration, China, Beijing 100083, China Jining Water Conservancy Development Center, Jining, 272000, China

*Correspondence

Assoc. Prof. Hang Xu, School of Soil and Water Conservation, Beijing Forestry University, Beijing, China. Email: hangxu@bjfu.edu.cn

Prof. Zhiqiang Zhang, School of Soil and Water Conservation, Beijing Forestry University, Beijing, China. Tel: 0086-10-62338828 Email: zhqzhang@bjfu.edu.cn

Supplementary Information:

- **Text 1**
- **Figures 1 to 7**

Supplementary Text 1. The SHapley Additive exPlanations method

To calculate the impact of regulating factor *i* on ΔNDVI, we first constructed a subset S that excludes factor *i*. The XGBoost model was driven separately by the subset S and the complete set of factors (S∪{*i*}). The difference in model outputs between these two sets was denoted as $SHAP_i$, which could be computed using the following formula:

$$SHAP_i = \sum_{S \subseteq F \setminus \{i\}} \frac{|N_S|!(|N_F| - |N_S| - 1)!}{|N_F|!} \left[f_x(S \cup \{i\}) - f_x(S) \right] \quad (1)$$

where $|N_F|$ and $|N_S|$ represented the number of factors in the full set S∪{*i*} and the subset S, respectively; $f_x()$ was the XGBoost model for ΔNDVI.

The interaction effect between factor *i* and factor *j* could be calculated as follows:

$$SHAP_{i,j} = \sum_{S \subseteq F \setminus \{i,j\}} \frac{|N_S|!(|N_F| - |N_S| - 2)!}{(2|N_F| - 1)!} \nabla_{i,j}(f, x, S) \quad (2)$$

when $i \neq j$, and

$$\nabla_{i,j}(f, x, S) = f_x(S \cup \{i, j\}) - f_x(S \cup \{i\}) - f_x(S \cup \{j\}) + f_x(S) \quad (3)$$

The interaction effect between feature *i* and feature *j* was split equally between each factors so that $SHAP_{i,j} = SHAP_{j,i}$. The remaining effects after removing all interaction effects from $SHAP_i$ were the individual effects of input factors to ΔNDVI.

Supplementary Figure 1

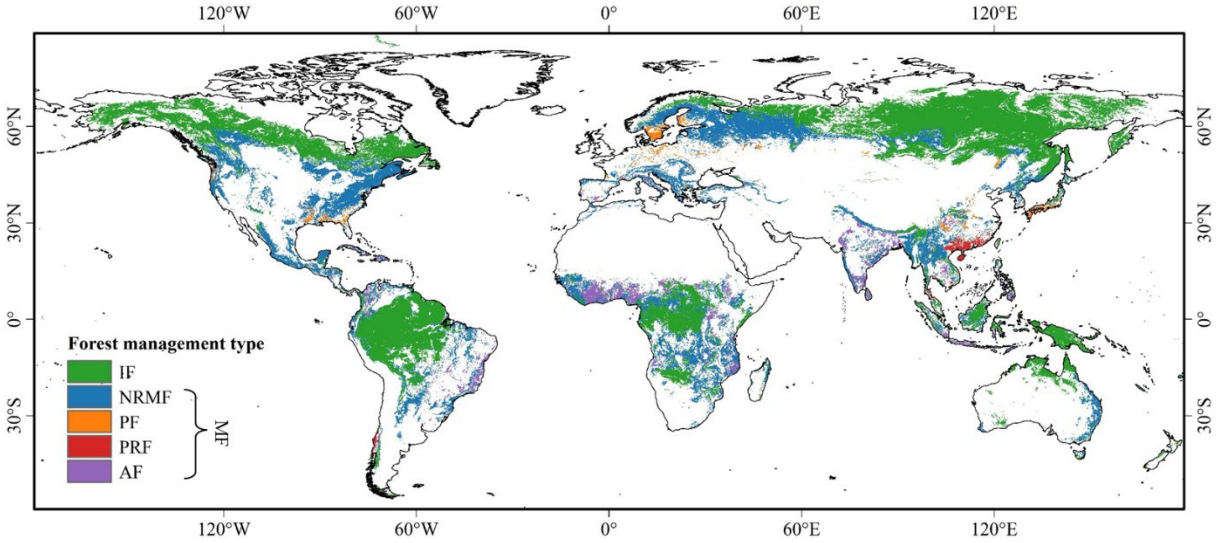

Figure 1. Forest management types. IF – forests without any signs of management, including primary forests and naturally regenerating forests; MF – forests with clear signs of management, including NRMF, PF, PRF, and AF; NRMF – naturally regenerating forests with signs of management, such as logging or clear-cutting; PF – planted forests; PRF – intensively managed forest plantations for timber with a short rotation period (maximum 15 years); AF – agroforestry, including fruit trees or sparse trees on agricultural fields.

Supplementary Figure 2

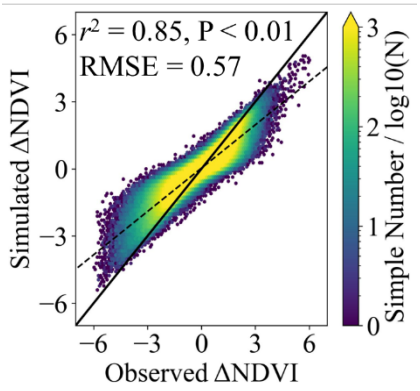

Figure 2. Evaluation of the XGBoost model's performance. The sample size used for modeling is 3,706,691. The solid black line represents the 1:1 line, while the dashed line represents the fit line between observed ΔNDVI and simulated ΔNDVI.

Supplementary Figure 3

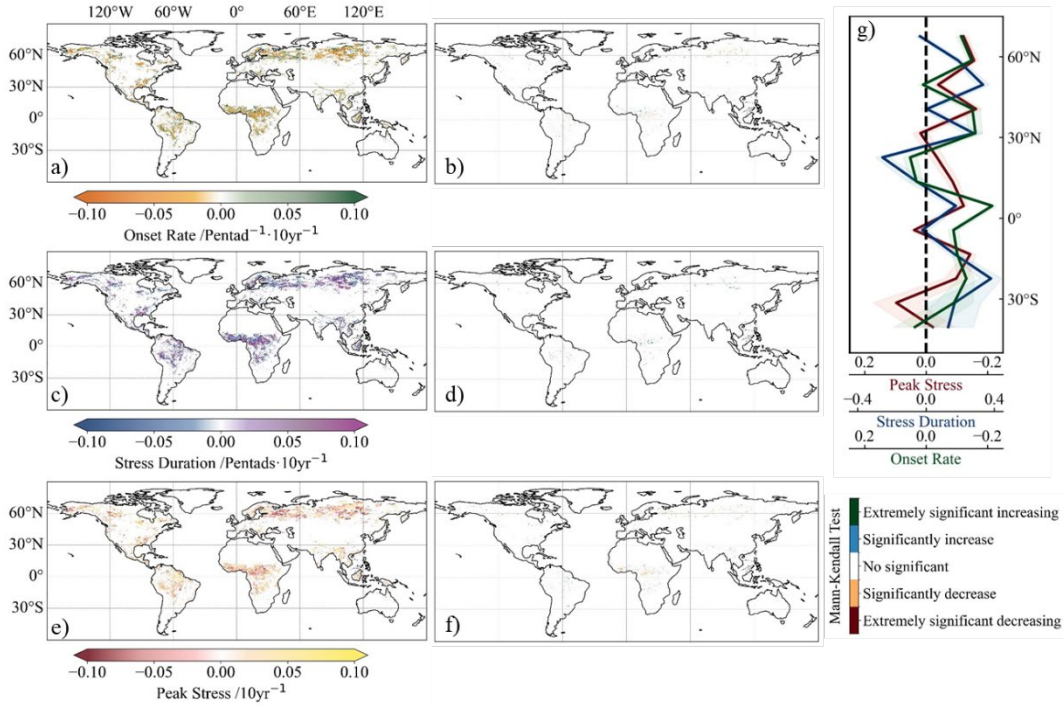

Figure 3. Spatial distribution of temporal trends in FD event characteristics. Sen's slope for a) onset rate, c) stress duration, and e) peak stress; Mann-Kendall test results for b) onset rate, d) stress duration, and f) peak stress; and g) latitude averages (solid lines) with standard errors (shaded areas) for FD characteristics.

Supplementary Figure 4

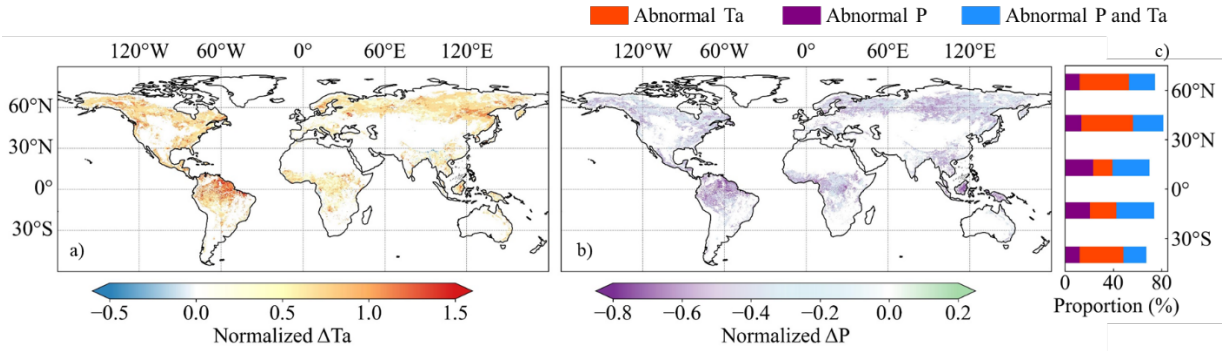

Figure 4. Spatial distribution of a) temperature anomalies, b) precipitation anomalies, and c) the consistency between precipitation and temperature anomalies during FD events. Where "Abnormal Ta" represents $\Delta Ta > 0.5\sigma$ and $\Delta P \geq -0.5\sigma$, "Abnormal P" represents $\Delta Ta \leq 0.5\sigma$ and $\Delta P < -0.5\sigma$, and "Abnormal P and Ta' represents $\Delta Ta > 0.5\sigma$ and $\Delta P < -0.5\sigma$ within the same grid.

Supplementary Figure 5

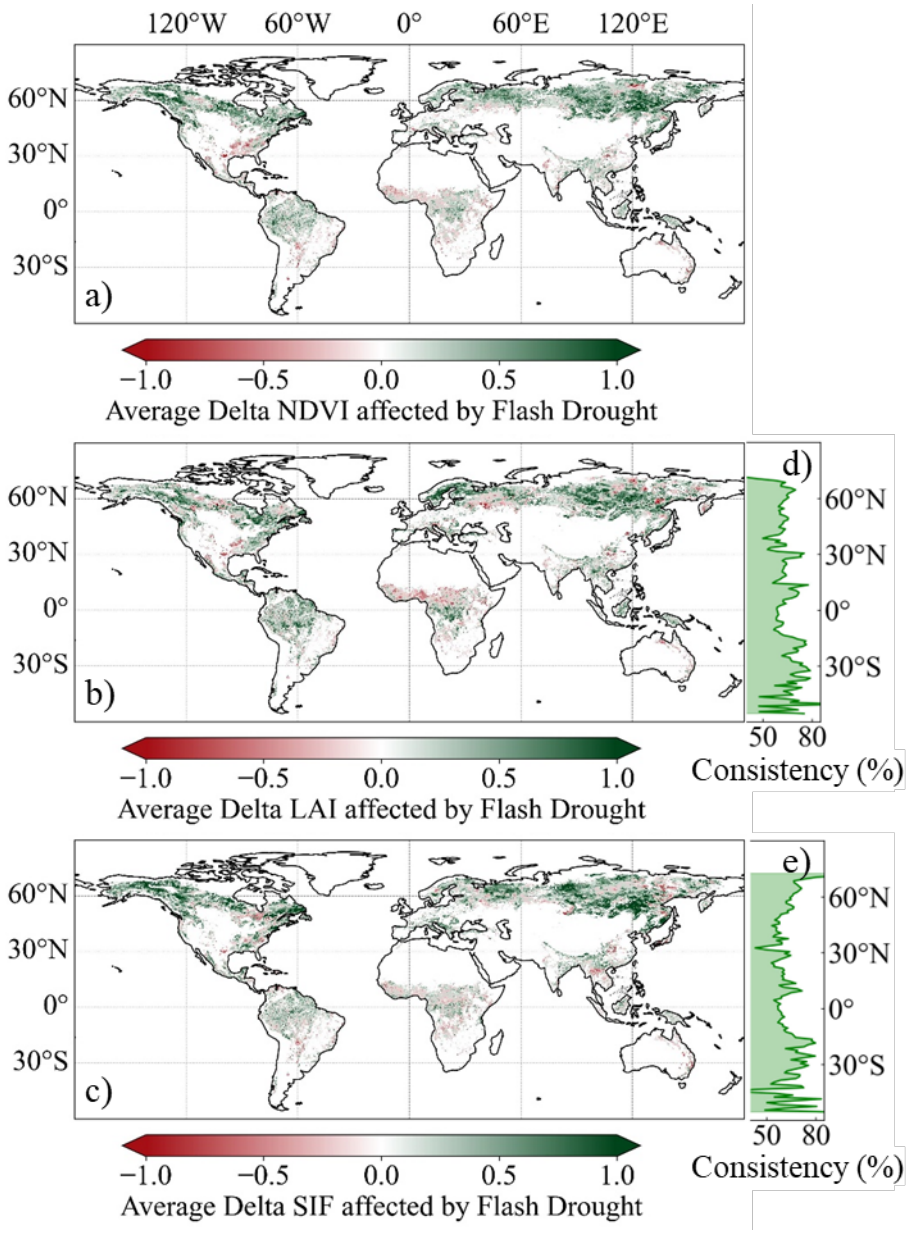

Figure 5. Spatial patterns of mean anomalies for a) Normalized Difference Vegetation Index (NDVI), b) Leaf Area Index (LAI), and c) Solar-Induced Chlorophyll Fluorescence (SIF), and the consistency of changes for d) LAI and e) SIF with NDVI during flash drought. "Consistency" represents that both indicators increasing or decreasing together at same grids.

Supplementary Figure 6

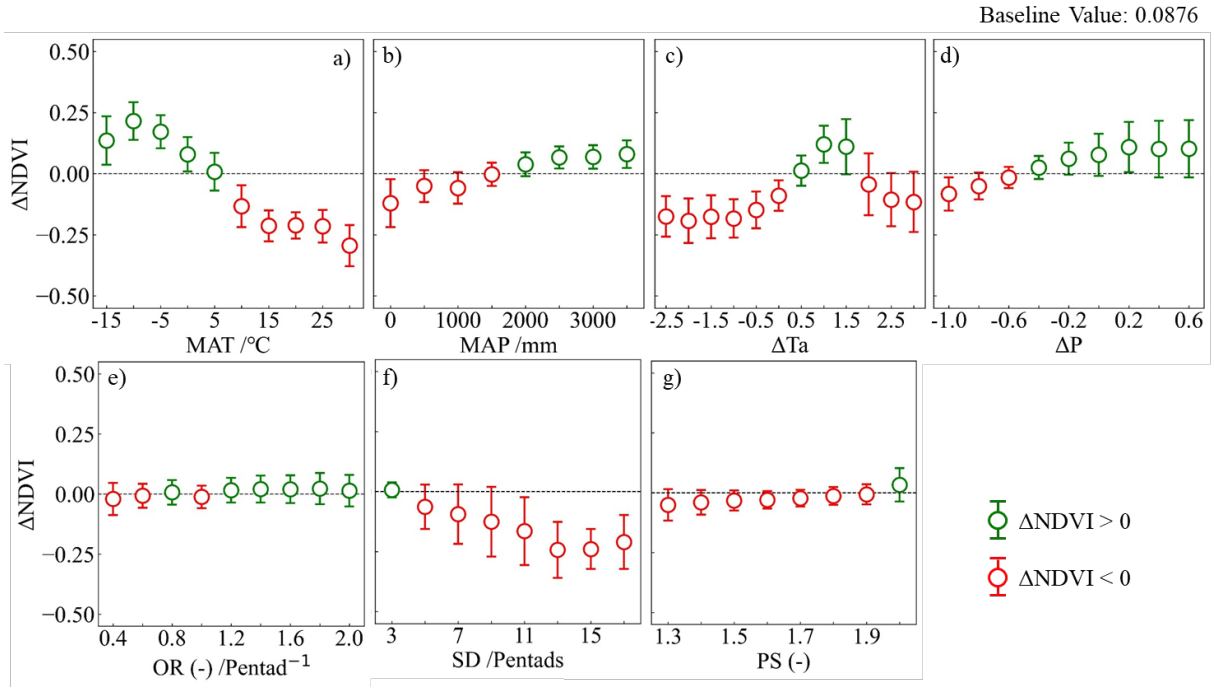

Figure 6. The impact of regulating factors on forest response. a) mean annual temperature, b) mean annual precipitation, c) temperature anomalies, d) precipitation anomalies, e) onset rate (negative), f) stress duration, and g) peak stress (negative). The green and red colors represent the ΔNDVI is significantly greater or less than 0 based on the t-test.

Supplementary Figure 7

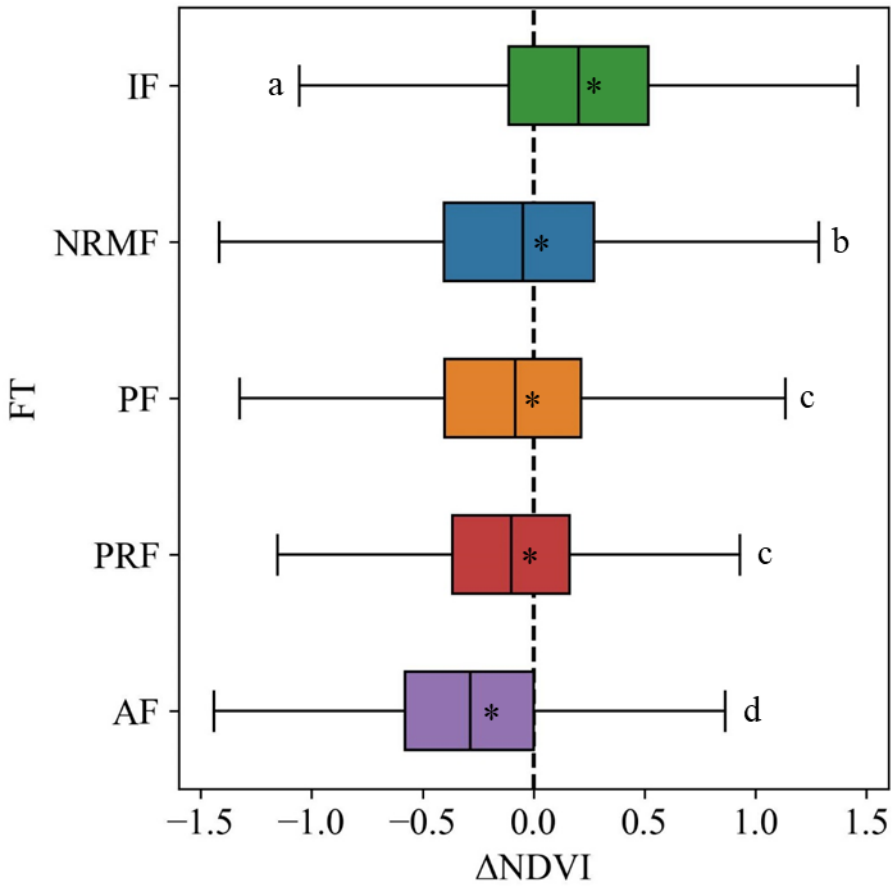

Figure 7. The anomalies of the Normalized Difference Vegetation Index (ΔNDVI) responses to FD events in different forest management types. The dashed line represents ΔNDVI = 0, and '*' indicates a mean ΔNDVI significantly lower or higher than 0 based on t-test; a ~ d represent significance groupings based on Tukey's test.