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Short Communication

Unprecedented decline in photosynthesis caused by summer 2022 record-breaking compound drought-heatwave over Yangtze River Basin

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The frequency and intensity of droughts and hot extremes have increased due to anthropogenic greenhouse gas emissions [1]. Drought and heat are major abiotic stresses on terrestrial ecosystems, which can greatly influence the regional carbon cycling [2–6]. Specifically, these weather extremes can inhibit gross primary productivity (GPP) [2,6,7], increase tree mortality [8], induce losses of above-ground biomass [9], and promote wildfires [10]. The severe drought and heat in 2003, for instance, reduced GPP over Europe by about 30%, which caused a strong anomalous carbon source to the atmosphere (about 0.5 Pg C a^{-1}), offsetting the net ecosystem carbon sequestration for the previous four years [2]. However, the impact of drought and heat on terrestrial carbon cycling can be different over different geographical regions and seasons, which is closely related to differences in the vegetation composition, phenological stage and preconditioning effects of past disturbance legacies [4]. An extensive and in-depth understanding of the impact of drought and heat worldwide is important in understanding the variations in global and regional carbon cycling.

An extreme compound drought–heatwave hit China in summer 2022, especially provinces in the Yangtze River Basin (YRB; defined in this study as 25°–33°N, 103°–123°E) [11], with long-lasting, large-scale, and high-impact characteristics. The impacts of this extreme weather event on people's daily life and health, as well as on various sectors of the national economy, have received much media attention. However, the extent to which this extreme compound drought–heatwave affected ecosystems (both natural vegetation and human-managed crops) and carbon fluxes is still unclear.

In this short communication, we assessed the impacts of this extreme compound drought–heatwave on vegetation structure and carbon fluxes over the YRB using the latest available multi-source datasets. The datasets in the main text include the surface air temperature, the calculated vapor pressure deficit (VPD), and soil wetness from the Japan Meteorological Agency 55-year (JRA-55) reanalysis dataset, the Moderate Resolution Imaging Spectroradiometer (MODIS) Normalized Difference Vegetation Index (NDVI, an indicator of vegetation greenness), and the FluxSat GPP product. Detailed descriptions of these datasets are given in the Supplementary materials (online). We also calculated the near-infrared reflectance of vegetation (NIR_v) based on the MODIS NDVI and surface reflectance in the near-infrared (NIR, 841–876 nm) part of spectrums according to the formula $NIR_v = (NDVI - 0.08) \cdot NIR$ [12]. NIR_v is strongly correlated with the solar-induced chlorophyll fluorescence, which has been used to estimate the globally gridded GPP magnitudes [12]. For consistency, we interpolated these datasets into a 0.5°×0.5° grid using the Climate Data Operator (CDO).

Control by an unusually strong western Pacific subtropical high (represented by the 588-dagpm contours in Fig. S1 online), especially in August, associated with the prevailing downdraft, favored the long-lasting heatwave over the YRB, resulting in a

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high-temperature anomaly of approximately 1.2 K in July–September (JAS) 2022 (Fig. 1a). This was the strongest positive temperature anomaly since 2000. In detail, the anomalously high temperatures (>1.2 K) were mainly located in the eastern Sichuan, Chongqing, Hunan, Hubei, Jiangxi, southern Anhui, and Zhejiang (Fig. 1c). The prevailing downdraft simultaneously caused less precipitation and a lower relative humidity (Fig. S2 online). Together with the increased saturated vapor pressure induced by the high temperatures, the VPD was significantly strengthened (Fig. 1a, d). Additionally, more evapotranspiration, potentially induced by the high temperatures associated with less precipitation, accelerated the depletion of soil water, leading to drought,

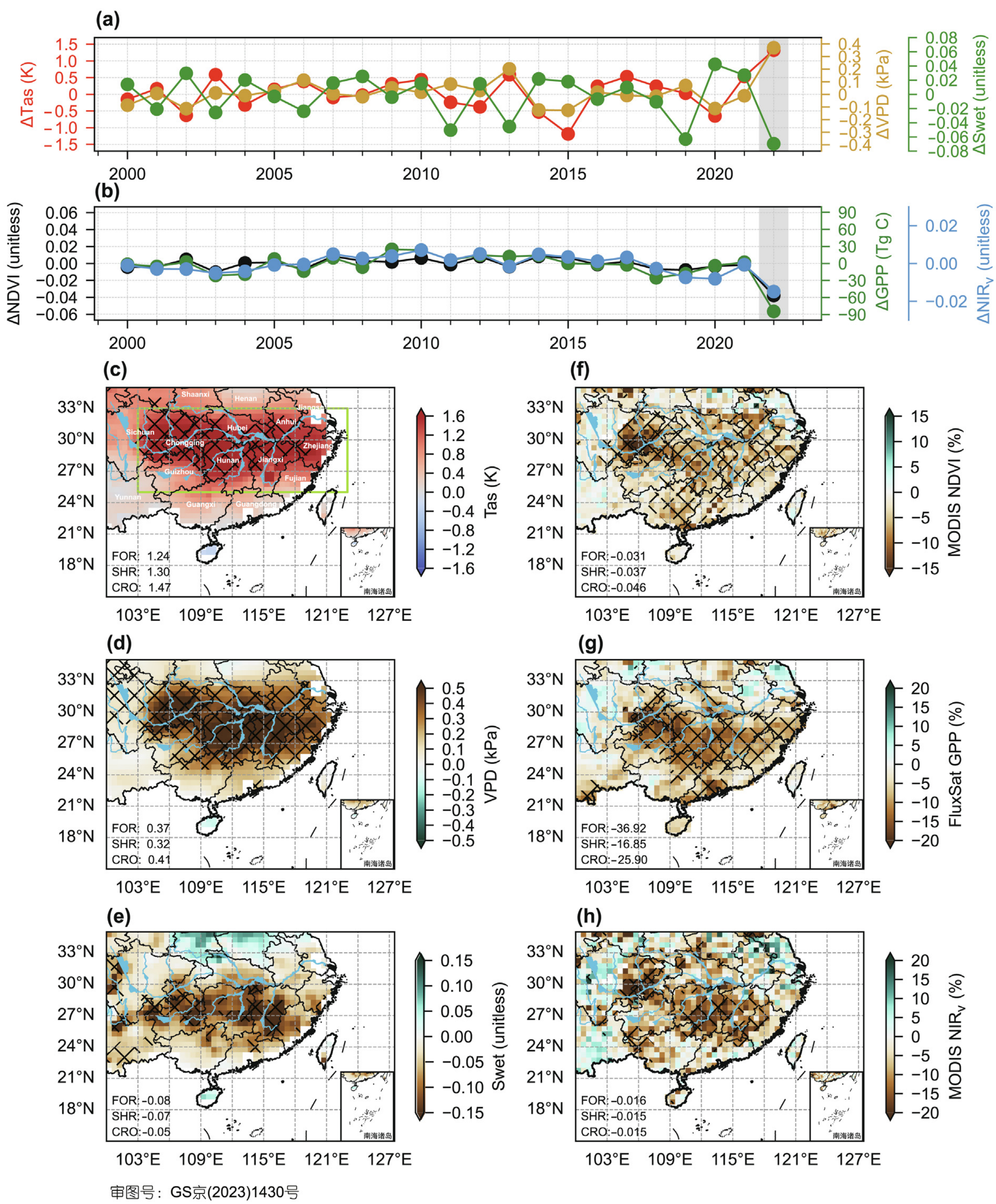

Fig. 1. Detrended anomalies in climate, vegetation greenness, and photosynthesis during July–September (JAS) 2022. Time series of the surface air temperature (Tas), vapor pressure deficit (VPD), and soil wetness (Swet) anomalies (a) and the normalized difference vegetation index (NDVI), gross primary productivity (GPP), and near-infrared reflectance of vegetation (NIR_v) (b) in JAS from 2000 to 2022 averaged in the region of 25°–33°N, 103°–123°E. Geographical distributions of the anomalies for the Tas (K) (c), VPD (kPa) (d), and Swet (unitless) (e) and the relative changes (%) for the NDVI (f), FluxSat GPP (g), and NIR_v (h). The hatched areas show anomalies in JAS 2022 that were larger than 2 standard deviations ($2-\sigma$) in JAS from 2000 to 2021. The yellowgreen box in (c) denotes the concerned region. The texts in (c–h) show the average changes in Tas, VPD, Swet, NDVI, and NIR_v and the total carbon flux for GPP (Tg C) over the forest (FOR), shrub (SHR), and crop (CRO) in JAS over Yangtze River Basin, respectively.

especially over Chongqing, Guizhou, Hunan, and Jiangxi (Fig. 1a, e). The VPD and soil wetness over the YRB in JAS 2022 showed the strongest increase of 0.37 kPa and a reduction of 0.07, respectively (Fig. 1a).

It is well known that anomalously high temperatures and atmospheric and soil dryness can largely affect terrestrial ecosystems. This extreme compound drought–heatwave event led to the worst declines of the NDVI by 0.04 (5.16%), the GPP by 84.50 Tg C (7.46%) and the NIR_v by 0.01 (7.43%) since 2000 (Fig. 1b). Spatially, the NDVI showed widespread suppressions over the YRB (Fig. 1f and Fig. S3a online), especially over Chongqing and eastern Sichuan with their negative anomalies more than 10% (Fig. 1f). The FluxSat GPP showed widespread reductions in photosynthesis over Chongqing, Guizhou, Hunan, Jiangxi, Fujian, and Zhejiang, with decreases basically stronger than 1 gC m^{-2} d^{-1} or close to 10% (Fig. 1g and Fig. S3b online). When used as a proxy for GPP, the NIR_v also showed anomalous reductions over eastern Sichuan, Chongqing, Hunan, Jiangxi, and Fujian (Fig. 1h and Fig. S3c online), which basically coincided with the anomalies in the FluxSat GPP, although its accuracy may be affected by the reflectance of the soil. Additionally, these negative anomalies of the NDVI, GPP, and NIR_v over most of the YRB exceeded 2 standard deviations ($2-\sigma$) of their variations in JAS from 2000 to 2021.

On the provincial scale, Chongqing consistently showed the strongest declines of the NDVI by 8.26%, the GPP by 12.46%, and the NIR_v by 11.02%, and Hunan had the second strongest declines of the NDVI by 5.40%, the GPP by 12.06%, and the NIR_v by 10.59% (Table S1 online). By contrast, the third strongest declines of the NDVI by 5.11% and the NIR_v by 9.02% occurred in Jiangxi, while the third strongest decline of the GPP by 9.43% occurred in Guizhou. More statistics are presented in Table S1 (online).

We aggregated the 1:1,000,000 Atlas of vegetation over the YRB and found that there were 3 main types of vegetation: forest (41.10%), shrub (18.35%), and crop (33.75%) (Fig. S4 online). The average NDVI anomalies were all negative for these vegetation types, with the lowest value of −0.046 for crop and second lowest of −0.037 for shrub (Fig. 1f). By contrast, forest contributed to the largest total GPP anomaly of −36.92 Tg C, accounting for about 43% of its total decrease over the entire region, followed by an anomaly of −25.90 Tg C for crop (Fig. 1g). The average NIR_v also had the lowest anomaly of −0.016 for forest, in agreement with the GPP, whereas the anomalies for shrub and crop were comparable at about −0.015 (Fig. 1h).

A comparison of the climate extremes in July, August, and September showed that the anomalously high temperatures, less precipitation, and higher VPD over the YRB were most severe in August (Fig. S5 online). The climate anomalies in July led to moderate responses in vegetation greenness and photosynthesis. The NDVI was reduced over Chongqing, Jiangxi, Fujian, Zhejiang, and southern Anhui (Fig. S6a online). By contrast, the FluxSat GPP showed reductions mainly over Guizhou, Hunan, Jiangxi, Fujian, and Zhejiang, but increases over Jiangsu, Anhui, and eastern Sichuan (Fig. S6d online). These differences in the NDVI and GPP anomalies may indicate that the changes in vegetation structure and photosynthesis were not strongly synchronized [13]. Widespread reductions consistently occurred in the NDVI, GPP, and NIR_v (Fig. S6b, e, h online) with the development of more severe heat and dryness in August (Fig. S5b, e, h, k online). In September, although the high temperatures had abated somewhat (Fig. S5c online) and the precipitation had increased over the YRB (Fig. S5f online), the atmospheric dryness and drought conditions persisted (Fig. S5i, l online). The lagged responses of the vegetation and the long-lasting atmospheric and soil dryness resulted in the most severe reductions in the NDVI, GPP, and NIR_v among these three months (Fig. S6 online).

Further, we used a simple decomposition analysis, as adopted in the previous study [14], to understand the contributions of the individual stresses of temperature, VPD, and soil wetness to these anomalies in the NDVI, GPP, and NIR_v over different vegetation types in the YRB (Supplementary materials Eqs. (S3) and (S4) online). The model showed a good performance overall, with the coefficient of determination (R^2) in the range of 0.52–0.90. Additionally, it is worth mentioning that the value of R^2 over crop was relatively smaller than that over forest or shrub (Fig. 2), which may be related to human management practices, such as irrigation in some areas. The VPD-induced reductions in the NDVI over forest and shrub dominated their total declines in JAS, whereas the reduction induced by high temperatures explained much of the decrease in the NDVI over crop (Fig. 2a). In terms of the GPP and NIR_v, a higher VPD resulted in the suppression of vegetation photosynthesis, confirming the results of a previous study [15], and consistently dominated their significant declines over forest,

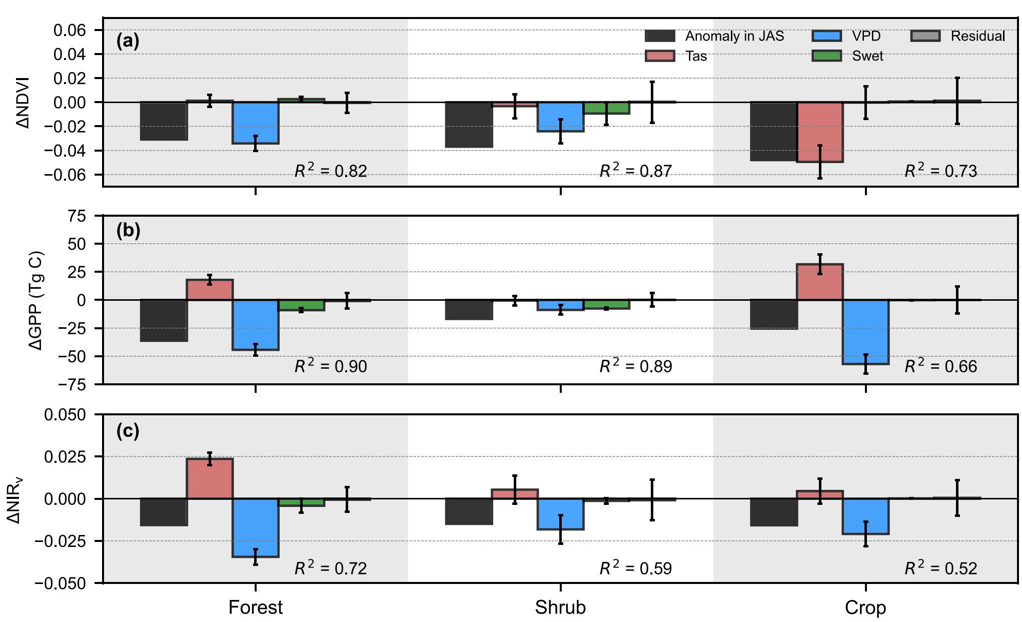

Fig. 2. Contributions of Tas, VPD, and Swet to NDVI (a), GPP (b), and NIR_v (c) anomalies over different vegetation types over the Yangtze River Basin. The term of "Residual" denotes the unexplained variation and the error bars represent the standard errors.

shrub, and crop in the YRB (Figs. 1 and 2). The soil dryness also led to the decreases in photosynthesis over forest and shrub, although the effects were weaker than those induced by the VPD (Fig. 2b, c). Compared with the atmospheric and soil dryness, higher temperatures seemed to promote photosynthesis.

In summary, the record-breaking compound drought–heatwave hit the China's YRB in summer 2022, resulting in the strongest anomalies of temperature, VPD, and soil wetness in JAS since 2000. These abiotic stresses together caused the widespread reductions in vegetation greenness and photosynthesis, especially over Chongqing and Hunan provinces with their declines of the NDVI, GPP, and NIR_v by approximately 5%–8%, 12%, and 11%, respectively. Over the entire YRB, this extreme compound event led to the worst declines of the average NDVI by 0.04 (5.16%), the total GPP by 84.50 Tg C (7.46%), and the NIR_v by 0.01 (7.43%) in JAS, respectively, since 2000. Separating the YRB into mainly three vegetation types (forest, shrub, and crop), we found that the average NDVI had the lowest anomaly of −0.046 over crop, whereas photosynthesis was mostly reduced over forest, with a total GPP anomaly of −36.92 Tg C and an average NIR_v anomaly of −0.016. Decomposition analysis revealed that except the decrease in the NDVI over crop mainly induced by higher temperatures, the decreases of NDVI over other vegetation types and photosynthesis over all vegetation types were dominated by the increased VPD. Surely, more studies are needed to further investigate how well vegetation greenness and photosynthesis recover after this extreme compound drought–heatwave.

Nevertheless, compared with the reduction in GPP over Europe by approximately 30% induced by the severe 2003 drought–heatwave [2], it seems that the ecosystems have the strong resistance in the YRB because of the total decreases in vegetation greenness and photosynthesis less than 10% induced by this record-breaking 2022 compound event. However, the declines have been worst in the past two decades. Importantly, with global warming, the intensity and frequency of compound climate extremes will keep increasing [1], thus potentially enhancing the vulnerability of the ecosystems in the YRB and seriously threatening its capacity of carbon sequestration. It is therefore important to continuously monitor the response of the ecosystems in the YRB to extreme compound climate events, which can better serve the national carbon neutrality.

Conflict of interest

The authors declare that they have no conflict of interest.

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Author contributions

Jun Wang conceived the research, prepared the figures, and wrote the manuscript. Ran Yan assisted the data analysis. All authors discussed the results and contributed significantly to the revisions of this manuscript.

Appendix A. Supplementary materials

Supplementary materials to this short communication can be found online at https://doi.org/10.1016/j.scib.2023.08.011.

Data availability

The climate dataset including surface air temperature, relative humidity, geopotential height, and soil wetness from JRA-55 is available at https://data.diasjp.net/dl/storages/filelist/dataset:204/lang:en. The precipitation from the Global Precipitation Measurement (GPM) mission is available at https://disc.gsfc.nasa.gov/datasets/. The MODIS NDVI is provided at https://lpdaac.usgs.gov/products/mod13c2v061/. The 1:1,000,000 Atlas of vegetation in China is available at https://www.resdc.cn/data.aspx?DATAID=122. The FluxSat GPP product is provided at https://avdc.gsfc.nasa.gov/pub/tmp/FluxSat_GPP/.

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