

Extreme fire emissions dominate the Amazonian land sink decline in 2024

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Dear Editors,

The Amazon is home to the largest tropical forest on Earth, holding nearly half of tropical forest carbon stocks and thus playing a crucial role in the global carbon cycle. However, the carbon sink of the Amazon is threatened by climate extremes over the past two decades, driven by reduced photosynthesis and increased fire emissions. For example, atmospheric inversion studies suggest that the Amazonian heat-droughts in 2010, 2015, and 2023 led to net carbon releases of 0.48 ± 0.18 , 0.9 ± 0.29 , and 0.31 ± 0.19 PgC yr⁻¹, respectively.^{1–3} These climate extremes and associated legacy effects have even turned the Amazon from a net carbon sink into a net carbon source, raising concerns about the current Amazonian sink capacity.

Globally, the year 2024 is the first time that the global mean air temperature is 1.5 °C above that in the pre-industrial period (1850–1900). Associated with this exceptional warming, extreme climate events were observed over both land and ocean in 2024, including heatwaves, droughts and wildfires across many regions. For the Amazon, the year 2024 is the hottest year on record in the twenty-first century: the annual mean air temperature exceeded the multi-year average (2000–2024) by 1.2°C, while precipitation decreased by up to 16% (Figure 1A). Such extreme heat-drought and their associated high fire activity may significantly affect the Amazonian land sink. However, the state of the Amazonian land sink in 2024 is still poorly known.

Here, we use the Global Carbon Assimilation System, version 2 (GCASv2)⁴ to estimate the land CO₂ flux (net biosphere exchange, NBE) by assimilating the column-averaged CO₂ mole fraction (XCO₂) retrievals from Orbiting Carbon Observatory 2 (OCO-2), with a focus on the Amazon. In regions with sparse surface CO₂ measurements, such as tropical regions, satellite observations have better spatial coverage and can thus improve the estimates of NBE and its responses to climate extremes. For the GCASv2 atmospheric inversions, two different fire emissions^{5,6} and two different biosphere flux simulations^{7,8} are used as prior inputs to conduct four inversion experiments in this study, in order to obtain a more comprehensive NBE estimate. Moreover, two satellite-derived gross primary production (GPP) products^{9,10} are utilized to help separate NBE into its components: GPP, total ecosystem respiration (TER), and fire emissions. Our study aims to address the following key questions: (1) How did the land sink in the Amazon change in 2024 relative to 2020–2022? (2) Which carbon cycle process primarily drove this change? The reason for choosing 2020–2022 as the reference period is that the Amazonian land sinks did not fully recover from 2015/16 El Niño event before 2020.

Compared to 2020–2022, the NBE flux of the Amazon showed positive anomalies of 0.24 ± 0.16 PgC yr⁻¹ in 2024 (Figure 1D), with positive values indicating a decrease in land sink and vice versa. The magnitude of declined Amazonian land sink was lower than those during the 2010, 2015, and 2023 droughts.^{1–3} Widespread positive NBE anomalies were observed in the southeastern Amazon, especially for the Arc of deforestation in the states of Pará and Mato Grosso (Figure 1E). In contrast, the northwestern and central Amazon, such as lowland Peru, Colombia, and western Brazil, showed weak neutral or even negative NBE anomalies (Figure 1E). Positive NBE anomalies emerged early in the year, turned negative in June–July, and rebounded to positive thereafter (Figure 1C). The most substantial decline in land sink in the Amazon was observed in August–September. Overall, these results suggest a large reduction of the Amazonian land sink (0.24 ± 0.16 PgC yr⁻¹) in the extreme heat-drought year of 2024.

We further analyze the components of NBE: GPP, TER, and fire carbon emissions. The results show that the decrease in the Amazonian land sink in 2024 was primarily driven by the spike in fire carbon emissions (Figure 1D). Compared to 2020–2022, fire emissions in 2024 showed positive anomalies of 0.20 ± 0.08 PgC yr⁻¹, representing the largest emissions observed over the past two decades. Although GPP also showed large reductions of 0.33 ± 0.25 PgC yr⁻¹, it was largely offset by the concurrent decrease in TER (0.28 ± 0.31 PgC yr⁻¹) (Figure 1D). The majority of the intensified fire carbon emission anomalies in 2024 were concentrated in the Arc of deforestation (Figure 1H), which aligns with the patterns of declined land sinks in the Amazon. These anomalous fire activity and emissions were associated with the lowest total precipitation in several decades across most of South America, with central Brazil experiencing drought conditions unparalleled in over seven centuries. The largest fire emission anomalies occurred in August–September, contributing 70% of the total fire anomalies in 2024. Therefore, the large reductions in the Amazonian land sink were largely driven by the extreme fire emissions in 2024.

We find a spatially synchronized variation between GPP and TER, but the magnitude of GPP anomalies was different from that of TER anomalies (Figures 1 F–G). Generally, widespread negative anomalies of GPP and TER were observed in 2024, except for the central part of Amazon, where positive GPP and TER anomalies exhibited. In the northwestern Amazon without fire emissions, the decreases in GPP were offset more by large TER reductions, resulting in a marginal negative NBE anomalies in 2024. However, in the southern and southeastern Amazon, the GPP reductions were larger than TER reductions, combined with elevated fire carbon emissions, leading to

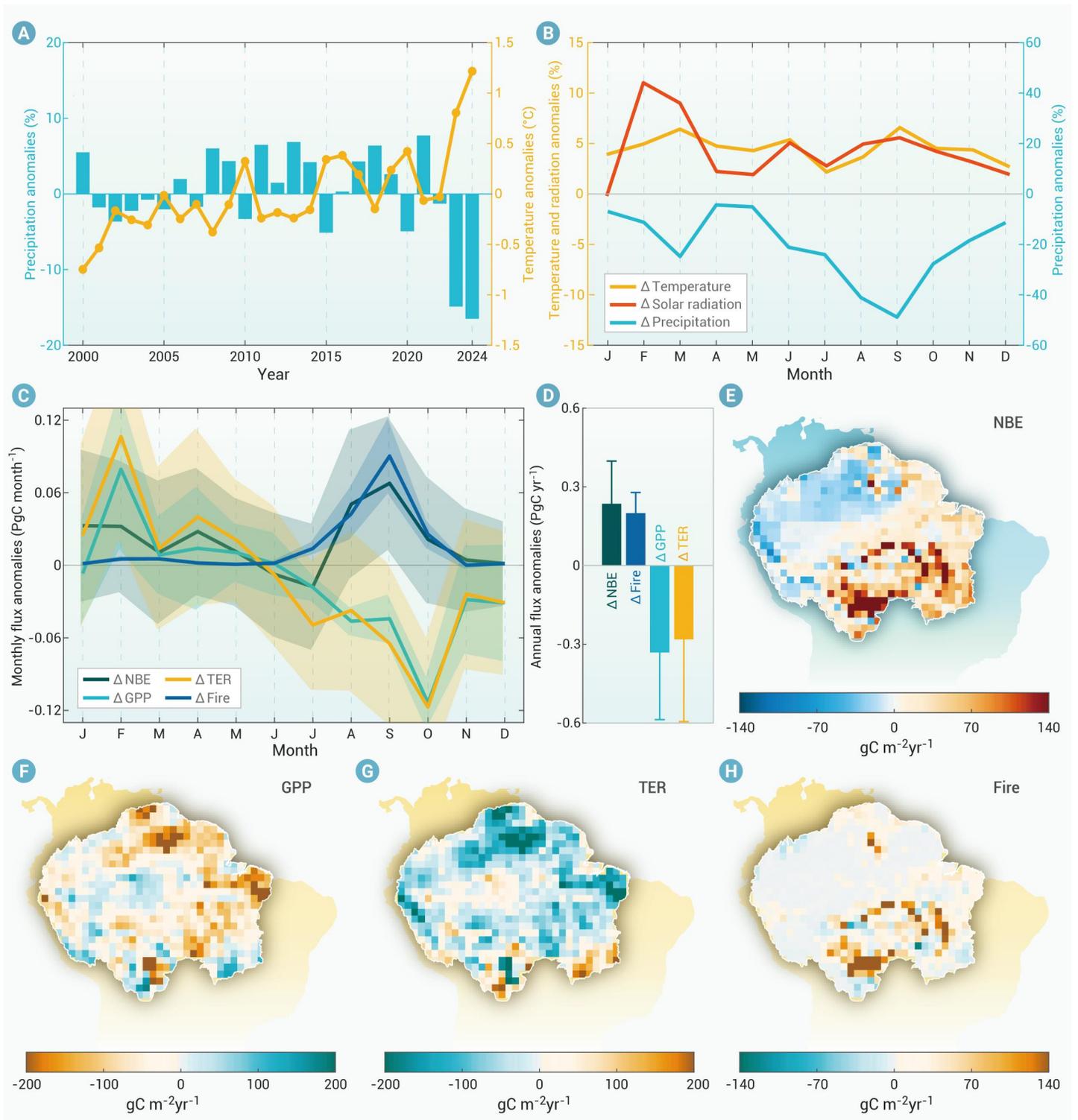


Figure 1. Anomalies of climate factors and NBE as well as its constituent fluxes in the Amazon for 2024 relative to 2020–2022 (A) Annual mean air temperature and precipitation anomalies relative to 2000–2024 average (unit: °C for air temperature, % for precipitation). (B) Monthly anomalies of air temperature, solar radiation, and precipitation in 2024 relative to 2020–2022 (unit: %). (C) Monthly anomalies of NBE, GPP, TER, and fire emissions (unit: PgC month⁻¹). (D) Annual anomalies of NBE, GPP, TER, and fire emissions (unit: PgC yr⁻¹). (E–H) Spatial patterns of (E) NBE, (F) GPP, (G) TER and (H) fire emission anomalies in 2024 (unit: gC m⁻² yr⁻¹). Shaded areas and error bars in (B–C) represent uncertainties of the estimates of these carbon fluxes. NBE was estimated from the GCASv2 atmospheric inversions; Fire emissions are the mean of GFED4.1s and GFAS products; GPP is the mean of GOSIF GPP and FluxSat GPP products. TER was separated from NBE by using GPP and fire emissions.

large reductions in the land sink. From January to May, the increase in TER exceeded that of GPP, resulting in a net reduction of the Amazonian land sink. Later (June and July), TER decreased more markedly than GPP, thereby enhancing the land sink. Hence, the monthly anomalies of the sink during the first half of 2024 were predominantly controlled by variations in TER. Starting in August, we find a steep decline in GPP, which is accompanied by a consistent decrease in TER, with the most significant negative anomalies in Octo-

ber. The GPP reductions were mostly offset by the decline in TER, while fire emissions increased dramatically, leading to the large Amazonian land sink decline during the dry season (August–October).

Intriguingly, although the Amazon experienced extreme heat and drought in 2024, it did not show dramatic declines in photosynthesis, which is contrary to the striking decline in Amazonian carbon uptake observed during the 2015/16 El Niño event.² The decline in GPP in the second half of the year was

partly offset the increase in the first part of the year, alleviating the overall decrease in GPP in 2024. The GPP increase in the first half of the year was due to the relatively higher temperature and stronger solar radiation (Figure 1B), which enhanced canopy photosynthesis in the Amazon during the wet season. Yet, negative GPP anomalies occurred in the second half of the year 2024, despite the La Niña event beginning in September. The declined GPP could be explained by the persistent and intensified heat-drought and high fire activity. The dynamics of the GPP anomalies matched well with the relative changes in precipitation during the second half of the year, with a legacy of one month (Figures 1B–C). Additionally, in northwestern Amazon without fire emissions, we find an enhanced land sink in 2024 relative to 2020–2022, which is due to larger TER reductions that more than offset the GPP decreases. The substantial decrease in TER during the 2024 heat-drought may be due to multiple mechanisms, including decreased autotrophic respiration associated with decreased GPP, and decreased soil respiration due to reduced supply of photosynthetic substrates as well as suppressed root and soil microbial activities and respiratory enzyme capacity.

In summary, the Amazonian land sink in 2024 decreased by 0.24 ± 0.16 PgC yr⁻¹ relative to 2020–2022. This reduction was largely driven by extreme fire emissions, accounting for 83% of NBE anomalies, while the decrease in GPP was largely offset by TER reductions. This study highlights the compound impact of the high temperature and severe drought and extreme fires in 2024 on the Amazonian land sink. Future studies should utilize multi-source observational data to further analyze the mechanism regarding the response of Amazonian land sink to the extreme compound event in 2024.

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AUTHOR CONTRIBUTIONS

F.J. and G.D. conceptualized and designed the study. F.J. and G.D. performed the analyses and wrote the paper. F.J. provided the atmospheric inversion estimates. W.J. and Y.Z. provided the prior biosphere flux used in the atmospheric inversion. J.X. and X.L., provided the GOSIF GPP data, and G.R.W. provided the GFEDv4.1s fire emission data. F.J., G.D., G.L., and Y.Z. prepared the figures. Y.Z., J.X., X.L., Z.Z. M.W., J.T., J.W., Y.Z., Y.X., K.Z., and J.M.C. offered thoughts on the data analysis and the writing of the manuscript. All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.