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Natural forests in China demonstrate higher resilience compared to planted forests

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Abstract:

Drought stress is increasingly constraining forest recovery under climate change. However, national-scale differences in drought resilience between natural and planted forests remain unclear. Here, we combined event-based drought characterization with lag-1 temporal autocorrelation (TAC) analysis of solar-induced chlorophyll fluorescence (SIF) and net ecosystem exchange (NEE). We assessed forest recovery dynamics across China from 2000 to 2022. Results show a widespread slowdown in forest recovery. Positive TAC trend slopes occurred in 60.94% of SIF pixels and 61.05% of NEE pixels. Drought intensity and duration were more consistently associated with increasing TAC than drought frequency. This indicates that forest recovery was constrained mainly by the severity and persistence of water deficit. Clear forest-type differences were observed. Planted forests had higher proportions of positive TAC slopes than natural forests for both SIF (69.35% vs. 56.17%) and NEE (65.33% vs. 58.19%). They also responded more strongly to drought-event gradients. Planted forests responded more strongly to drought-event gradients than natural forests. For SIF-derived TAC trend slopes, the responses to drought intensity and duration were 1.87- and 3.23-fold stronger in planted forests, respectively. For NEE-derived TAC trend slopes, the response to drought intensity was 1.24-fold stronger in planted forests, whereas the difference in response to drought duration was relatively small. These findings indicate that planted forests are more sensitive to drought-related recovery slowdown, especially in photosynthetic activity. Our study highlights the need to

integrate drought-event characteristics and forest type into resilience assessments and to improve planted forest management under future climate extremes.

Keywords: drought resilience; temporal autocorrelation; solar-induced chlorophyll fluorescence; net ecosystem exchange; forest type; China

1.Introduction

Forests play a key role in the global carbon cycle, hydrological processes, and climate regulation. They act as a major sink for atmospheric CO₂ and store more than half of terrestrial carbon (Pan et al., 2011; Friedlingstein et al., 2022; Mitchard, 2018). However, climate change has intensified drought stress, one of the most critical climatic constraints on forest ecosystems. In recent decades, drought events have become more frequent, intense, and persistent, with substantial impacts on forest structure and function (Chen and Sun, 2015; Li et al., 2020). Persistent or extreme drought can suppress photosynthesis and reduce carbon sequestration. It may also drive forest degradation and reduce ecosystem stability through cumulative water deficits (Gatti et al., 2021; Zhao et al., 2024). In this context, drought resilience has become a central issue in global change research because it is closely linked to regional ecological security, carbon-cycle stability, and climate feedbacks.

Over recent decades, China has implemented the world's largest afforestation program. Its planted forests now exceed 92 million hectares and account for more than one quarter of the global total (Cheng et al., 2023; Cheng et al., 2024a). These forests have substantially contributed to carbon sequestration and ecological restoration (Hua et al., 2022; Huang et al., 2024). However, their drought resilience remains uncertain. Planted forests often have rapid growth, relatively simple structure, and high stand density. These traits may increase water demand and drought sensitivity. Management practices and species selection may also modify their drought responses (Yu et al., 2019; McDowell et al., 2018; Fernández et al., 2009). Natural forests, in contrast, often have greater species diversity and structural complexity. These characteristics may support stronger resistance and recovery under drought (Sun et al., 2024). Despite these potential contrasts, the drought resilience of natural and planted forests has rarely been compared at the national scale (Bai et al., 2020). This limitation restricts a comprehensive assessment of drought-related ecological risks in China's planted forests.

As ecosystems approach critical transitions, their recovery from perturbations slows. This phenomenon is known as critical slowing down. It is commonly reflected by an increase in lag-1 temporal autocorrelation (TAC), which indicates stronger

system memory and weaker restorative feedbacks (Dakos et al., 2008; Scheffer et al., 2009; Dakos et al., 2012). Recent studies suggest that TAC is not only an early-warning signal of critical transitions, but also a general indicator of ecosystem resilience (Scheffer et al., 2012; Gao et al., 2016). It is robust, interpretable, and applicable across different ecological contexts (Carpenter and Brock, 2006; Kéfi et al., 2013; Dakos et al., 2012). Remote sensing has further advanced TAC-based diagnostics from theoretical analysis to large-scale monitoring. Satellite time-series studies have shown that TAC can capture declines in forest vitality and recovery dynamics, providing an empirical basis for resilience assessment (Lambert et al., 2015; Verbesselt et al., 2016). In the Amazon, increasing lag-1 autocorrelation has revealed a marked decline in forest resilience since the early 2000s, especially in drier and more human-impacted regions (Boulton et al., 2022; Van Passel et al., 2024). Broader-scale analyses have also reported widespread but spatially heterogeneous changes in ecosystem resilience under climate stress (Smith et al., 2022; Smith et al., 2023; Forzieri et al., 2022). Evidence from China further suggests that increasing aridity and interannual precipitation variability can weaken the resilience of restored forests, highlighting the value of TAC in water-limited ecosystems (Wang et al., 2025). Despite these advances, most existing TAC-based studies have focused on broad resilience trends or hydroclimatic gradients. Less attention has been given to how discrete drought-event characteristics, such as frequency, intensity, and duration, shape TAC-based resilience changes. Moreover, differences in drought resilience between natural and planted forests have rarely been examined within a TAC framework.

Within the TAC framework, SIF and NEE provide complementary information for capturing resilience changes in photosynthetic activity and carbon-exchange dynamics, respectively. SIF provides a physiologically relevant proxy for photosynthetic activity. It is less prone to saturation than reflectance-based indices, such as NDVI and EVI. It also depends less on canopy structure and is more sensitive to environmental stress, especially drought. These advantages enable earlier detection of functional ecosystem changes (Wen et al., 2025; Duveiller et al., 2020; Magney et al., 2019). Gridded NEE products provide estimates of net ecosystem carbon exchange. They reflect the balance between photosynthetic carbon uptake and ecosystem respiration. Compared with greenness-based indices, NEE offers a more process-relevant measure of ecosystem responses and carbon-cycle consequences under drought. It can also capture drought legacy effects on carbon fluxes (Bastos et al., 2020). Combining SIF and NEE links physiological processes with ecosystem-level functional outcomes. This provides a

coherent pathway for tracking drought impacts across scales. However, linking TAC-based resilience changes to drought requires an event-level perspective. Ecosystem responses are shaped not only by mean water deficits, but also by drought frequency, intensity, and duration. These event properties may leave legacy effects on vegetation recovery and carbon exchange after drought conditions have ended. Event-based drought characterization therefore provides a direct way to connect drought disturbances with changes in ecosystem recovery dynamics (Lloyd-Hughes, 2012). Here, we used an event-based drought inventory derived from SPAI and 3D-DBSCAN. It identifies spatiotemporally connected drought events and quantifies their frequency, intensity, and duration, providing a consistent basis for linking TAC variations to drought-event characteristics (Liu et al., 2024; Cammalleri and Toreti, 2023).

In this study, we integrated event-based drought characterization with temporal autocorrelation analysis to examine drought-driven changes in forest resilience across China. We first characterized the spatial patterns of drought-event properties across China's forest regions, including drought intensity, duration, and frequency. We then calculated TAC from SIF and NEE time series to represent resilience changes in photosynthetic activity and carbon-exchange dynamics, respectively. Finally, we linked TAC trends to drought-event characteristics and compared their responses between natural and planted forests. This framework allows us to assess how drought disturbances affect forest recovery dynamics and whether these effects differ between forest types. We addressed three questions. First, how have SIF- and NEE-derived TAC trends changed across China's forests? Second, how do drought intensity, duration, and frequency affect TAC trends? Third, do TAC responses to drought-event characteristics differ between natural and planted forests? By clarifying drought legacy effects and forest-type differences, this study provides a basis for improving planted forest management, reducing drought risk, and enhancing ecosystem resilience (United Nations, 2019).

2. Materials

2.1 Forest Classification

Forest-type maps were obtained from the Spatiotemporal Dynamics Dataset of Natural and Planted Forests in China (1990–2020) (Cheng et al., 2023; Cheng et al., 2024a; Cheng et al., 2024b). Natural forests were defined as native stands regenerated mainly through natural processes. Planted forests were defined as stands established by human planting or seeding. These definitions are consistent with those of the National Forestry and Grassland Administration and the Food and Agriculture Organization. The

dataset provides nationwide forest-type maps at a 30 m resolution. It was generated from multi-temporal Landsat imagery and field-validated samples using a machine-learning workflow on Google Earth Engine. We used these products directly as input layers for subsequent resilience analyses.

2.2 Precipitation Data

Precipitation data were obtained from CHIRPS (Funk et al., 2015), developed by the Climate Hazards Group at the University of California, Santa Barbara, and partner institutions. CHIRPS provides daily precipitation data at a 0.05° spatial resolution over near-global land areas. It integrates satellite infrared observations, in situ gauge records, and climatological fields. The dataset provides a continuous daily record from 1981 onward and supports trend analysis, drought monitoring, and long-term hydroclimatic studies. Compared with coarser-resolution products, CHIRPS provides finer spatial detail. It therefore enables more accurate regional and watershed-scale analyses. Its fusion of ground observations and satellite information, including cold cloud duration, improves precipitation estimation. CHIRPS is also readily available in Google Earth Engine, which supports efficient large-scale processing.

2.3 NEE Data

NEE data were obtained from the GloFlux global carbon-flux product (Yuan et al., 2025). This dataset integrates eddy-covariance observations, satellite-derived variables, and meteorological forcing data. Its training data include major flux networks and standard tower-based carbon-flux measurements, with quality control applied by the data provider. We used the published monthly NEE product for 2000–2023 at a 0.1° spatial resolution as the carbon-flux input for this study.

2.4 SIF Dataset

SIF data were obtained from the LHSIF product (Zou et al., 2025). This dataset integrates observations from multiple satellite sensors, including GOME, SCIAMACHY, GOME-2, and OCO-2. It provides a continuous global monthly record from 1995 to 2023 at a 0.05° spatial resolution. The product is based on far-red SIF retrievals and model–data fusion with key environmental predictors. It has been cross-validated against independent satellite products, model simulations, and flux-tower benchmarks. These validations support its use for monitoring large-scale photosynthetic dynamics. We used this monthly SIF dataset as the photosynthesis indicator in this study.

2.5 Drought Events

Drought events were characterized using the China Extreme Drought Event Set (ChinaExtreDroEventSet v1.0) (Liu et al., 2024; Liu et al., 2023a; Liu and Zhou, 2023b). This dataset is based on ERA5 precipitation data and identifies spatiotemporally coherent extreme droughts across China using an event-based SPAI and 3D-DBSCAN framework. Drought conditions are first detected from persistent negative SPAI anomalies and then grouped into independent events through three-dimensional clustering in space and time. We used the published event inventory directly for subsequent attribution analyses, including drought frequency, intensity, and duration. The dataset spans 1951–2022 at a 1° spatial resolution and includes 56 major extreme drought events across China.

3. Methods

3.1 Data preprocessing and spatial harmonization

SIF, NEE, forest-type, drought-event, and precipitation-background datasets were harmonized to a common 0.05° grid under the WGS84 coordinate system. Forest pixels were classified as natural forests or planted forests. To reduce the influence of land-cover transitions, only pixels consistently identified as forest for at least ten consecutive years were retained. Drought events were obtained from the published ChinaExtreDroEventSet, which was generated using an ERA5-based SPAI and 3D-DBSCAN framework. Based on this event inventory, drought frequency, mean duration, and mean intensity were derived and spatially matched to the 0.05° forest grid. CHIRPS-derived precipitation seasonality and interannual precipitation variability were extracted as background hydroclimatic covariates. Forest resilience was quantified using TAC derived from SIF and NEE time series across rolling windows of 12, 36, and 60 months. Relationships among drought-event metrics, hydroclimatic covariates, and TAC-based resilience changes were then assessed using pixel-level regression and marginal-effect analyses. The overall analytical workflow is shown in Fig. 1.

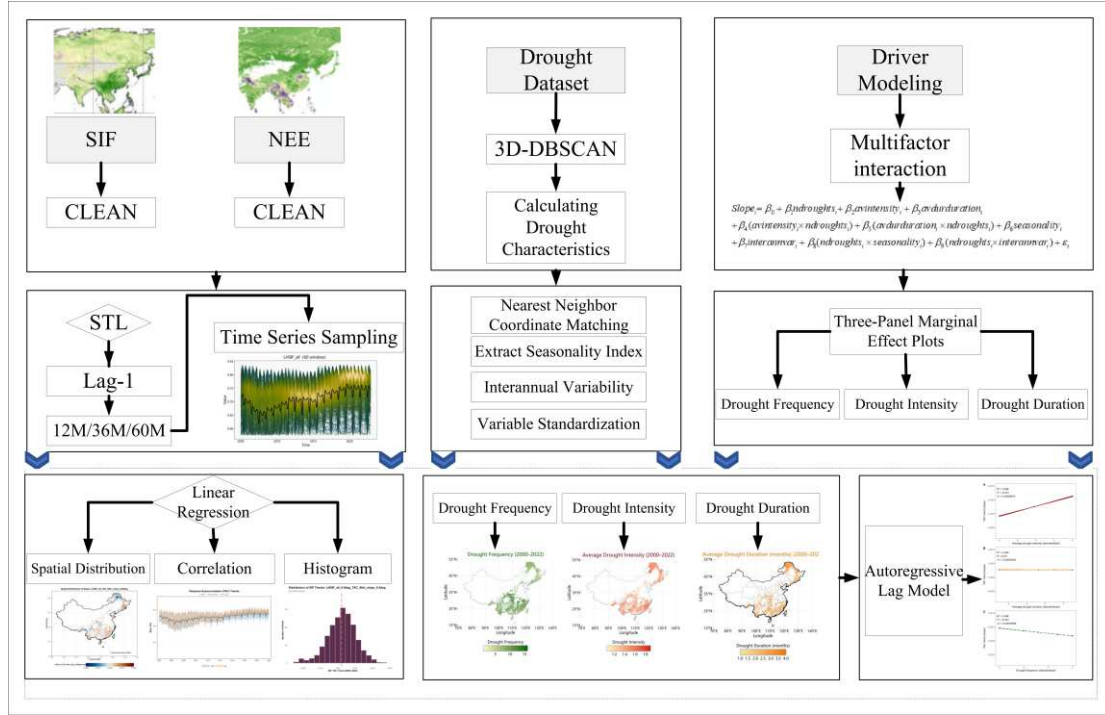


Fig. 1. Workflow for assessing drought-driven changes in forest resilience using SIF- and NEE-derived temporal autocorrelation. Monthly SIF and NEE datasets were first cleaned and processed to extract vegetation functional time series. Seasonal-trend decomposition using LOESS was then applied, and lag-1 temporal autocorrelation was calculated within 12-, 36-, and 60-month rolling windows. Linear regression was used to estimate TAC trend slopes and generate spatial distributions, temporal correlations, and frequency histograms. In parallel, drought events were characterized from the drought dataset using the 3D-DBSCAN framework, and drought frequency, intensity, and duration were calculated. Drought metrics were matched to TAC pixels through nearest-neighbor coordinate matching, together with precipitation seasonality and interannual variability. Standardized variables were then incorporated into multifactor interaction models. Finally, marginal-effect plots were generated to evaluate the responses of TAC trends to drought frequency, drought intensity, and drought duration.

3.2 TAC-based resilience estimation

To quantify changes in forest recovery dynamics, we calculated temporal autocorrelation from monthly SIF and NEE time series at the pixel level. TAC reflects ecosystem memory. Higher TAC indicates slower recovery from perturbations and lower resilience.

For each forest pixel, the original SIF and NEE time series were decomposed using seasonal-trend decomposition based on LOESS (STL):

$$Y_t = T_t + S_t + R_t \quad (1)$$

where Y_t is the original time series, T_t is the long-term trend component, S_t is the seasonal component, and R_t is the residual component. The residual series was used for TAC calculation after removing long-term trends and seasonality.

Lag-1 TAC was calculated within rolling windows of 12, 36, and 60 months:

$$TAC_t = \frac{\sum_{j=1}^{w-1} (R_j - \bar{R})(R_{j+1} - \bar{R})}{\sum_{j=1}^w (R_j - \bar{R})^2} \quad (2)$$

where TAC_t is the lag-1 autocorrelation for the rolling window ending at time t , w is the window length, R_j and R_{j+1} are adjacent STL residuals within the window, and $\bar{R}$ is the mean residual value within that window. This calculation is equivalent to estimating the lag-1 ACF of the STL residuals within each rolling window.

The temporal trend in TAC was estimated using ordinary least squares:

$$TAC_t = \alpha + \beta t + \varepsilon_t \quad (3)$$

where α is the intercept, t represents the rolling-window time step, β represents the TAC trend slope, and ε_t is the residual error term. A positive β indicates increasing TAC, slower recovery, and declining resilience. A negative β indicates decreasing TAC, faster recovery, and increasing resilience.

3.3 Event-based drought metrics

Drought-event characteristics were derived from the ChinaExtreDroEventSet v1.0. This dataset identifies spatiotemporally coherent drought events across China using SPAI and a 3D-DBSCAN clustering framework. For each forest pixel, three event-based drought metrics were calculated over the study period: drought frequency, mean duration, and mean intensity.

Drought frequency was defined as the cumulative number of independent drought events affecting pixel i during 2000–2022:

$$F_i = N_i \quad (4)$$

where F_i is drought frequency and N_i is the total number of drought events recorded at pixel i over the study period.

Mean drought duration was calculated as:

$$D_i = \frac{1}{N_i} \sum_{k=1}^{N_i} d_{ik} \quad (5)$$

where D_i is mean drought duration and d_{ik} is the duration of the k -th drought event at pixel i .

Mean drought intensity was calculated as:

$$I_i = \frac{1}{N_i} \sum_{k=1}^{N_i} |SPA I_{ik}^{min}| \quad (6)$$

where I_i is mean drought intensity and $SPA I_{ik}^{min}$ is the minimum SPAI value during the k -th drought event at pixel i . The absolute value was used so that larger values indicate stronger drought intensity.

3.4 Regression modelling and marginal-effect analysis

To assess the effects of drought-event characteristics on forest resilience, TAC trend slopes were linked to drought metrics and hydroclimatic covariates at the pixel level. For each TAC slope location, the nearest drought pixel was identified using geographic-coordinate-based nearest-neighbor matching.

Drought frequency, mean duration, and mean intensity were then assigned to the corresponding TAC slope location. Precipitation seasonality and interannual precipitation variability were extracted from gridded climate layers and used as background hydroclimatic covariates.

The TAC trend slope was used as the response variable. Separate models were fitted for SIF-derived and NEE-derived TAC slopes, and for all forests, natural forests, and planted forests. The regression model was specified as:

$$\beta_i = \gamma_0 + \gamma_1 F_i + \gamma_2 I_i + \gamma_3 D_i + \gamma_4 S_i + \gamma_5 V_i + \gamma_6 (I_i \times F_i) + \gamma_7 (D_i \times F_i) + \gamma_8 (F_i \times S_i) + \gamma_9 (F_i \times V_i) + \varepsilon_i \quad (7)$$

where β_i is the TAC trend slope at pixel i . F_i , I_i , and D_i represent drought frequency, mean drought intensity, and mean drought duration, respectively. S_i represents precipitation seasonality, and V_i represents interannual precipitation variability. γ_0 is the intercept, and $\gamma_1 - \gamma_9$ are regression coefficients for the corresponding main effects and interaction terms. ε_i is the residual error term, representing unexplained variation in TAC trends at pixel i . The interaction terms were included to examine whether the effects of drought intensity and duration varied with drought frequency, and whether the effect of drought frequency depended on background hydroclimatic conditions.

All explanatory variables were standardized to zero mean and unit variance before model fitting. The TAC trend slope was not standardized, allowing the response variable to retain its original units. Models were fitted using ordinary least squares. Model performance was evaluated using regression coefficients, standard errors, significance levels, and R^2 .

Marginal-effect curves were generated for drought intensity, drought duration, and drought frequency, with other predictors held at their mean values. For each curve, an

approximate marginal slope K was calculated as the change in fitted TAC trend divided by the corresponding change in the standardized drought variable. This K value was used to compare TAC sensitivity to drought gradients across forest types and indicators.

4. Results

4.1 Spatial patterns of drought-event characteristics

Figure 2 shows clear spatial heterogeneity in drought-event characteristics across China's forest regions. Mean drought duration was generally higher in southern and northeastern China (Fig. 2a). Longer durations mainly occurred in Guizhou, Chongqing, Hunan, and parts of the Yunnan–Guizhou Plateau. High values were also observed in northeastern Inner Mongolia and northwestern Heilongjiang, where droughts commonly lasted more than three months. In contrast, shorter durations were mainly found in northern China.

Drought frequency showed a distinct spatial pattern (Fig. 2b). High-frequency drought events were concentrated in southern China, the Yangtze River Basin, and parts of central and eastern China. Lower frequencies were mainly observed in northeastern and northwestern China. Overall, drought frequency was higher in southern and central China than in northern China.

Drought intensity also varied strongly across regions (Fig. 2c). High-intensity droughts were mainly observed in northeastern Inner Mongolia, northwestern Heilongjiang, and parts of southern China, including Fujian and the Yunnan–Guizhou Plateau. Moderate intensity occurred across the Yangtze River Basin, whereas lower intensity was more common in northern China. Together, these patterns show that drought duration, frequency, and intensity had distinct but overlapping spatial structures. Southern China and parts of northeastern China experienced relatively stronger drought-event pressure.

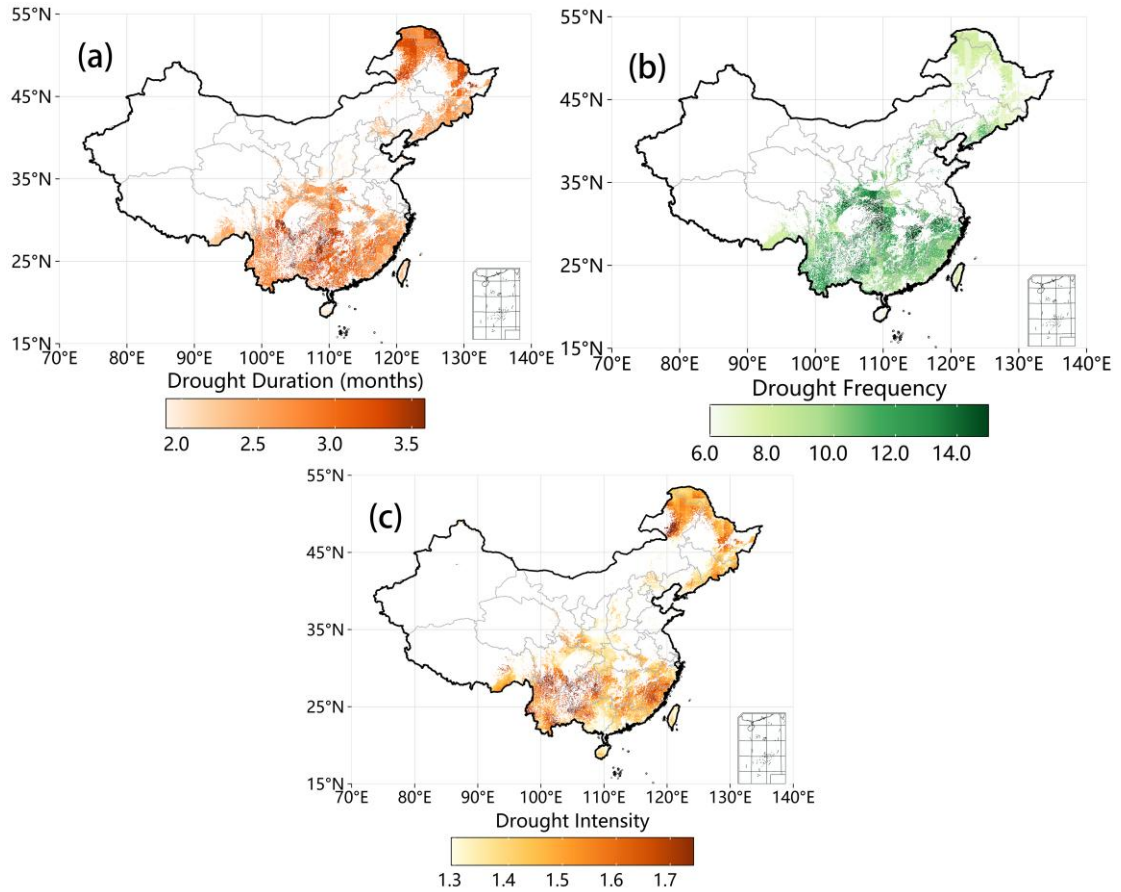


Fig.2. Spatial patterns of drought-event characteristics across China's forest regions during 2000–2022. (a) Mean drought duration (months); (b) drought frequency, expressed as the cumulative number of drought events during the study period; and (c) mean drought intensity.

4.2 Temporal changes in SIF- and NEE-derived TAC across forest types

To assess temporal changes in forest recovery dynamics, we analyzed SIF- and NEE-derived TAC time series using a 60-month rolling window. Higher TAC indicates stronger temporal memory, slower recovery from perturbations, and lower resilience.

The SIF-derived TAC time series showed a gradual increase from 2010 to 2022 (Fig. 3a). TAC increased in both natural and planted forests, but values were generally slightly higher in planted forests during most of the study period. In planted forests, mean TAC increased from approximately 0.70 in the early period to about 0.78–0.80 after 2018. Natural forests showed a similar but slightly weaker increase. This pattern indicates a progressive slowdown in photosynthetic recovery, with a more pronounced signal in planted forests.

The pixel-level SIF-derived TAC trajectories further support this temporal pattern (Fig. 3b). Although individual pixels showed large variability, the median trajectory increased after 2010. The high-density range also shifted toward higher TAC values.

This indicates that the increase was not limited to a few isolated pixels but reflected a broader change across forested regions.

NEE-derived TAC showed a more moderate temporal increase than SIF-derived TAC (Fig. 3c). Mean TAC values remained similar between natural and planted forests during most of the study period. However, after 2014, planted forests consistently showed slightly higher TAC than natural forests. This suggests that the NEE-derived signal was weaker and more stable overall, but still indicated a modest post-2014 slowdown in carbon-exchange recovery in planted forests.

Pixel-level NEE-derived TAC trajectories also showed substantial spatial variability (Fig. 3d). The median trajectory increased slightly over time, while high-density values remained concentrated in the upper TAC range. Together, the SIF- and NEE-derived results indicate a slowdown in forest recovery dynamics during the study period. This slowdown was more evident in SIF than in NEE, and planted forests generally showed stronger TAC increases than natural forests.

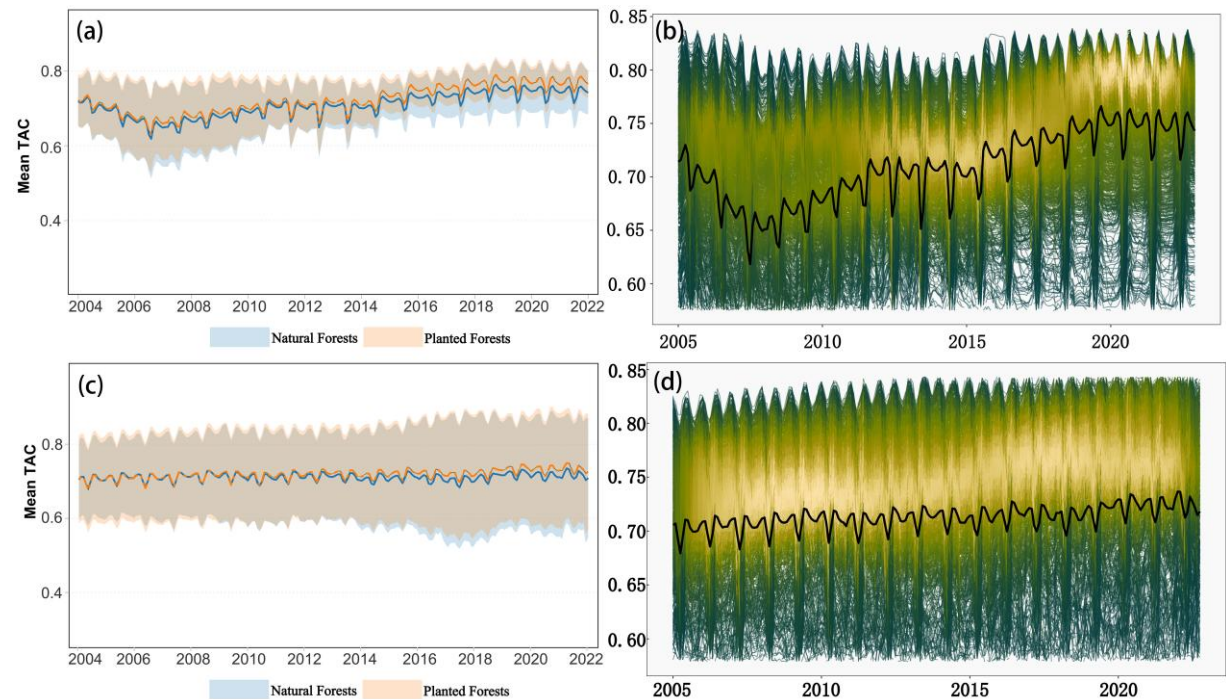


Fig. 3. Temporal changes in SIF- and NEE-derived TAC across forest types. (a, c) Mean TAC time series for natural and planted forests based on SIF and NEE, respectively. Shaded areas indicate mean ± 1 standard deviation. (b, d) Pixel-level TAC trajectories based on SIF and NEE, respectively. Black lines indicate median time series. TAC was calculated using a 60-month rolling window.

4.3 Spatial patterns of SIF- and NEE-derived TAC trends

To further examine where these temporal increases occurred, we mapped pixel-level TAC trend slopes across forest types. Figure 4 shows the spatial patterns and

frequency distributions of SIF- and NEE-derived TAC trend slopes. Across all forests, positive TAC slopes accounted for 60.94% of SIF pixels and 61.05% of NEE pixels (Figs. 4e and 4f). This indicates that more than half of China's forest pixels showed increasing TAC during the study period. Positive slopes were widely distributed in southern and central China, as well as parts of northeastern China, although clear spatial heterogeneity was observed.

Forest-type differences were evident. In natural forests, positive TAC slopes accounted for 56.17% of SIF pixels and 58.19% of NEE pixels (Figs. 4a and 4c). Positive trends were mainly distributed in parts of northeastern and southeastern China, whereas negative or weak trends occurred in northern and southwestern China. In planted forests, the proportions of positive TAC slopes were higher, reaching 69.35% for SIF and 65.33% for NEE (Figs. 4b and 4d). These proportions exceeded those in natural forests by 13.18 percentage points for SIF and 7.14 percentage points for NEE. Positive trends were also more widespread in planted forests, particularly in southern, central, and northeastern China.

The frequency histograms further support these spatial patterns. In natural forests, TAC slope distributions were centered near zero, with relatively balanced positive and negative values. In contrast, planted forests showed a stronger shift toward positive TAC slopes. This pattern was consistent for both SIF and NEE, although the shift was more pronounced for SIF. Overall, the spatial maps and histograms indicate a broader increase in TAC in planted forests than in natural forests, suggesting a stronger slowdown in recovery dynamics during the study period.

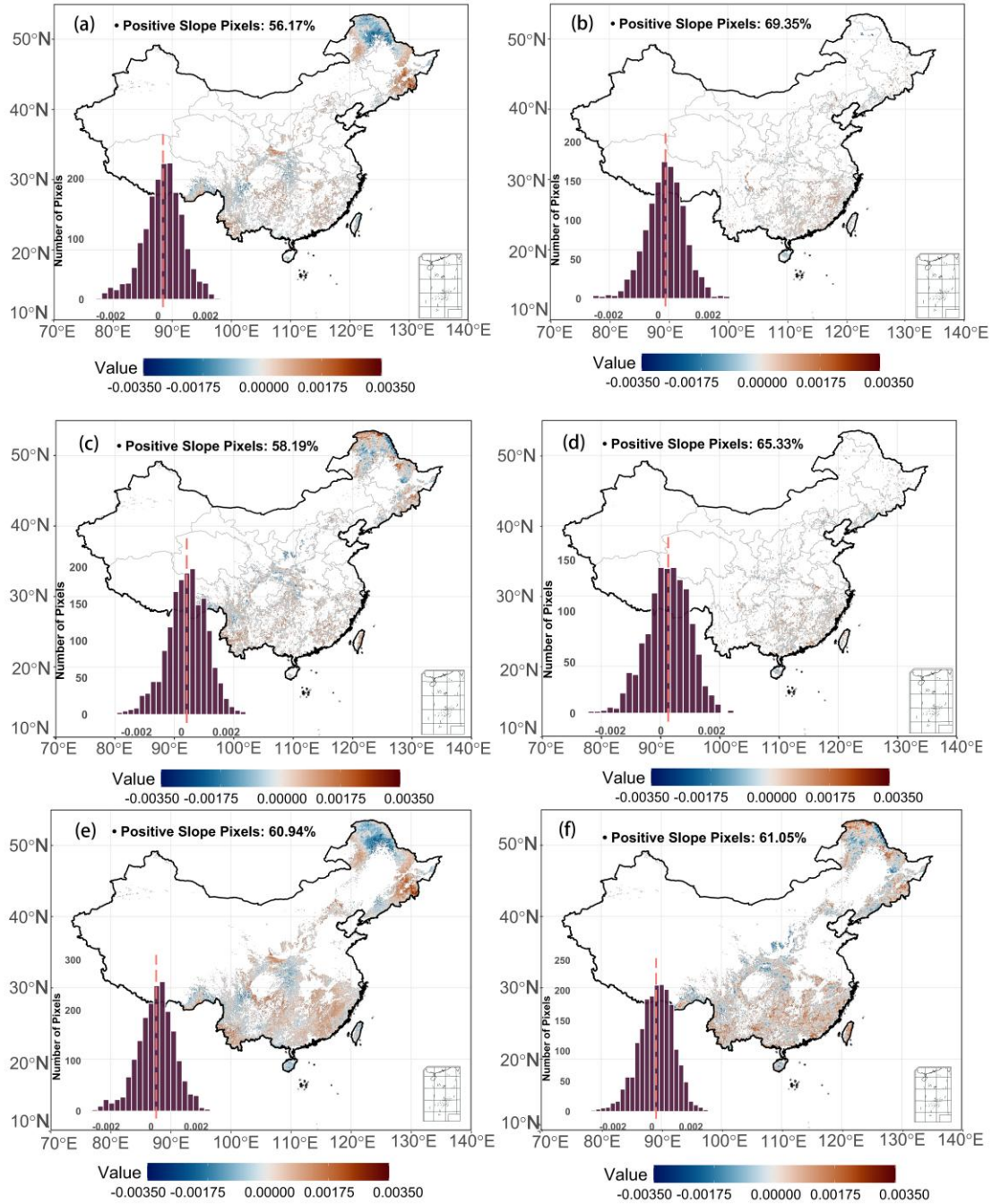


Fig. 4. Spatial patterns and frequency distributions of SIF- and NEE-derived TAC trend slopes across forest types in China. (a, b) SIF-derived TAC trend slopes for natural and planted forests, respectively. (c, d) NEE-derived TAC trend slopes for natural and planted forests, respectively. (e, f) SIF- and NEE-derived TAC trend slopes for all forests, respectively. The percentages above each panel indicate the proportion of pixels with positive TAC slopes. Colors indicate slope magnitude, with blue representing negative slopes and brown representing positive slopes. Insets show pixel-level frequency distributions of TAC trend slopes, and red dashed lines indicate the median values. TAC slopes were calculated using a 60-month rolling window.

4.4 Responses of TAC trend slopes to drought-event gradients

4.4.1 Responses of SIF-derived TAC trend slopes to drought-event gradients

SIF-derived TAC trends showed clear forest-type differences along drought-event gradients (Fig. 5). In natural forests, TAC trends increased with drought intensity, with a marginal slope of $K = 0.00007048$ (Fig. 5a). However, responses to drought duration and drought frequency were negative, with $K = -0.00001494$ and $K = -0.00012207$, respectively (Figs. 5c and 5e). These results suggest weak or mixed SIF-derived TAC responses to drought-event gradients in natural forests.

In planted forests, SIF-derived TAC trends showed consistently positive responses to all three drought metrics. TAC trends increased with drought intensity ($K = 0.00013165$; Fig. 5b), drought duration ($K = 0.00004827$; Fig. 5d), and drought frequency ($K = 0.00005172$; Fig. 5f). The response to drought intensity was approximately 1.87 times stronger in planted forests than in natural forests. For drought duration and drought frequency, the response shifted from weak negative slopes in natural forests to positive slopes in planted forests.

Together, these results indicate stronger SIF-derived TAC increases in planted forests than in natural forests along drought-event gradients. This pattern suggests a more pronounced slowdown in photosynthetic recovery in planted forests under increasing drought intensity, duration, and frequency.

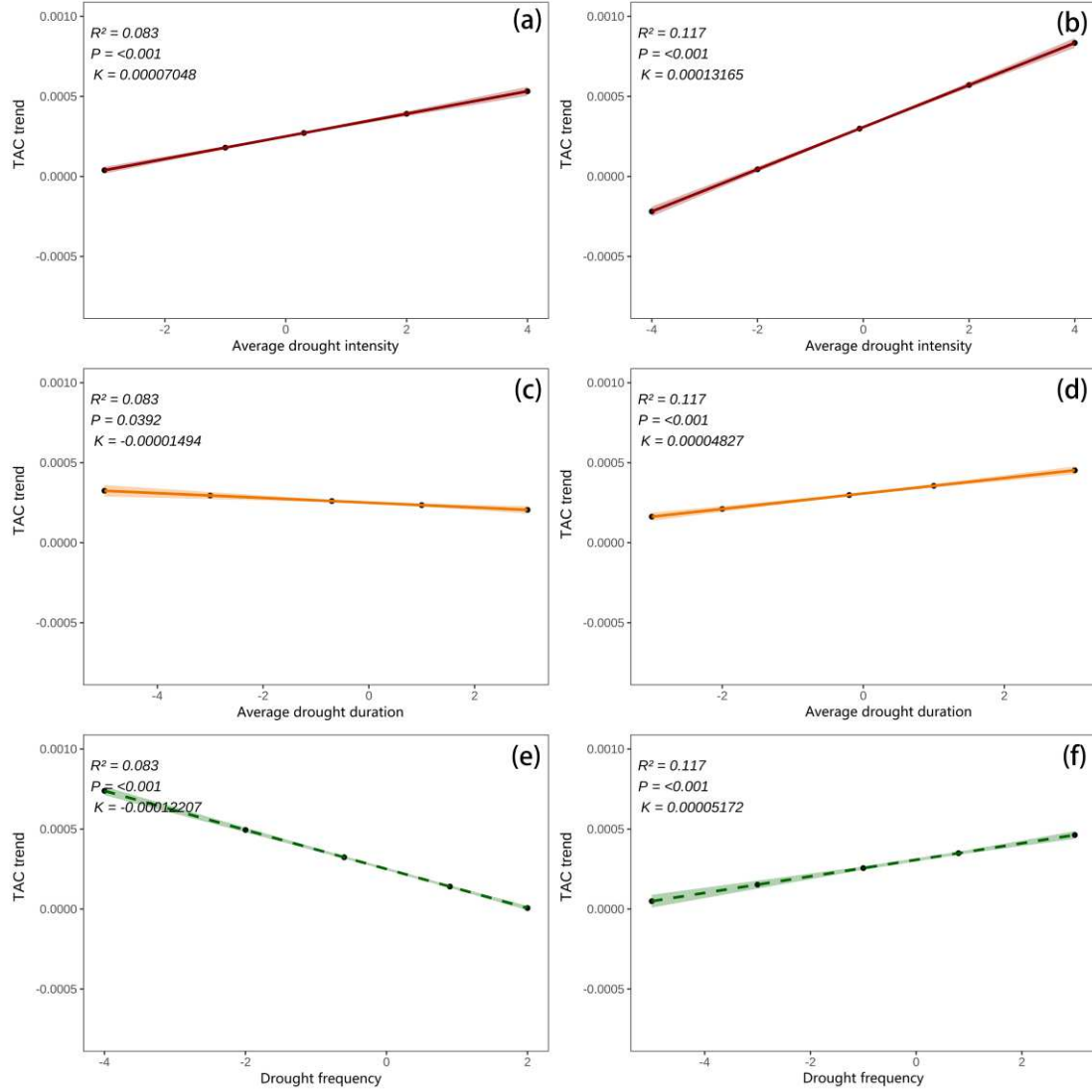


Fig. 5. Marginal effects of drought-event characteristics on SIF-derived TAC trends in natural and planted forests. (a, c, e) Natural forests; (b, d, f) planted forests. Panels (a, b), (c, d), and (e, f) show the responses of SIF-derived TAC trends to mean drought intensity, mean drought duration, and drought frequency, respectively. Lines indicate fitted marginal effects from pixel-level regression models, and shaded areas indicate standard errors. The x -axes represent standardized drought variables, and the y -axes represent SIF-derived TAC trend slopes. Each panel reports R^2 , P -values, and the marginal slope K .

4.4.2 Responses of NEE-derived TAC trend slopes to drought-event gradients

NEE-derived TAC trends showed similar but weaker forest-type differences along drought-event gradients (Fig. 6). In natural forests, TAC trends increased with drought intensity and drought duration, with marginal slopes of $K=0.00003910$ and $K=0.00009419$, respectively (Figs. 6a and 6c). In planted forests, the corresponding slopes were slightly higher, reaching $K=0.00004858$ for drought intensity and

K=0.00009812 for drought duration (Figs. 6b and 6d). The response to drought intensity was approximately 1.24 times stronger in planted forests than in natural forests, whereas the response to drought duration was about 4.2% higher. Responses to drought frequency were also evaluated, but forest-type differences were weaker than those observed for drought intensity and duration (Figs. 6e and 6f).

Compared with the SIF-derived results, forest-type differences in NEE-derived TAC trends were more moderate. This suggests that carbon-exchange recovery, as reflected by NEE, showed weaker forest-type differences than photosynthetic recovery reflected by SIF. Nevertheless, the consistently higher marginal slopes in planted forests indicate stronger increases in NEE-derived TAC under increasing drought intensity and duration.

Together with the SIF-derived results, these NEE-derived patterns suggest a broader slowdown in recovery dynamics in planted forests than in natural forests. However, the magnitude of this contrast differed between photosynthetic and carbon-exchange indicators.

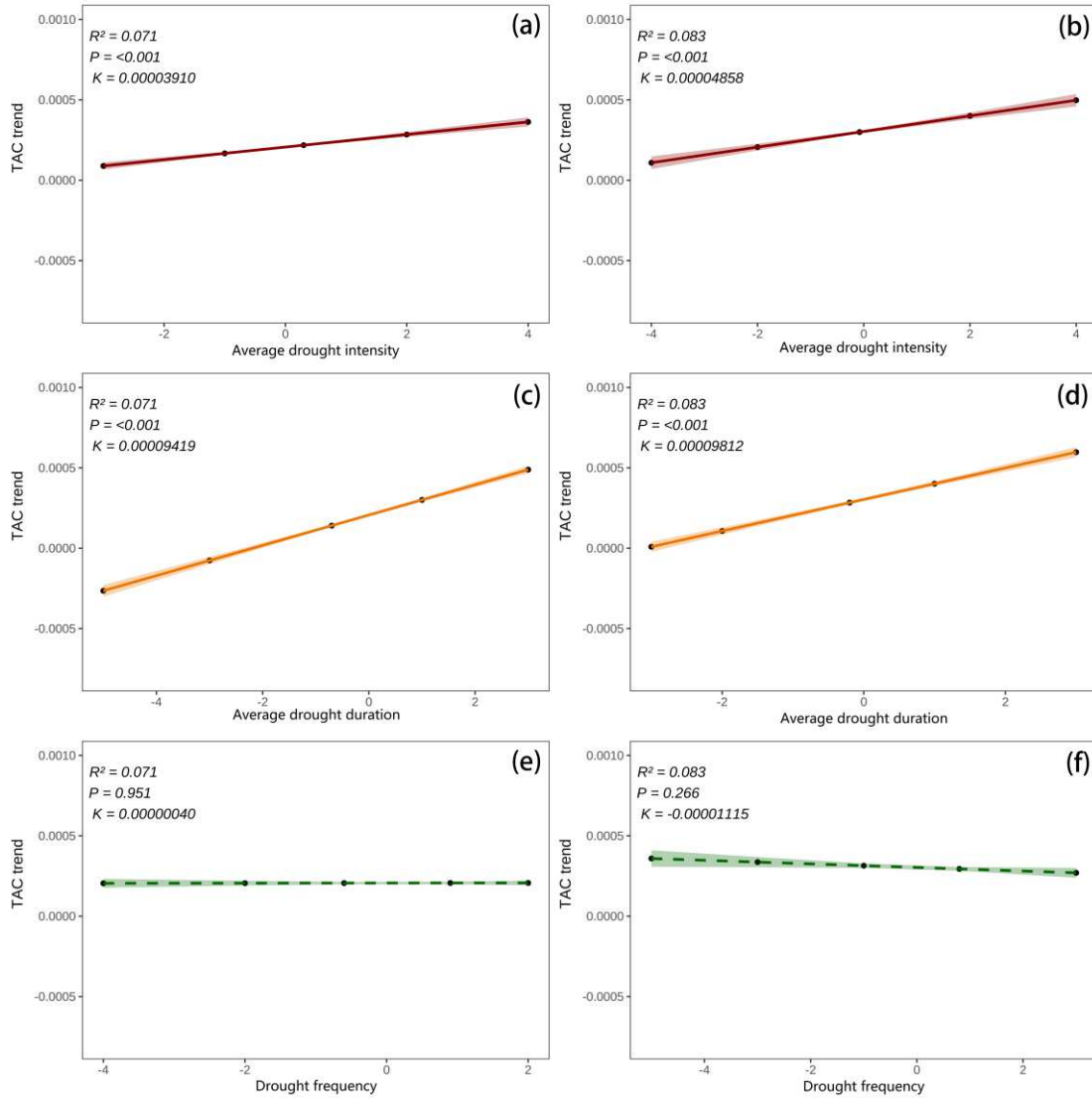


Fig. 6. Marginal effects of drought-event characteristics on NEE-derived TAC trends across forest types. (a, c, e) Natural forests; (b, d, f) planted forests. Panels show the effects of mean drought intensity (a, b), mean drought duration (c, d), and drought frequency (e, f). Lines represent fitted marginal effects from pixel-level regression models, with shaded areas indicating standard errors. The x -axes show standardized drought variables, and the y -axes show NEE-derived TAC trend slopes. R^2 , P -values, and marginal slopes K are shown in each panel.

4.4.3 Responses of SIF- and NEE-derived TAC trend slopes across all forests

Across all forests, SIF- and NEE-derived TAC trends showed consistent positive responses to drought intensity and drought duration (Fig. 7). For SIF, the marginal slopes were $K=0.00002302$ for drought intensity and $K=0.00003527$ for drought duration (Figs. 7a and 7c). For NEE, the corresponding slopes were higher, with $K=0.00005267$ for drought intensity and $K=0.00010166$ for drought duration (Figs. 7b and 7d).

Responses to drought frequency were less consistent. SIF-derived TAC trends decreased with drought frequency ($K=-0.00006525$; Fig. 7e), whereas NEE-derived TAC trends showed almost no response ($K=-0.00000225$; $P=0.652$; Fig. 7f). This indicates that drought intensity and duration were more closely associated with increasing TAC trends than drought frequency at the national scale.

Together, the all-forest results show that China's forests exhibited increasing TAC along gradients of drought intensity and duration. This pattern suggests a broad slowdown in forest recovery dynamics during the study period. Combined with the forest-type results, these findings suggest that planted forests contributed disproportionately to the overall positive TAC response, especially under stronger and longer drought conditions.

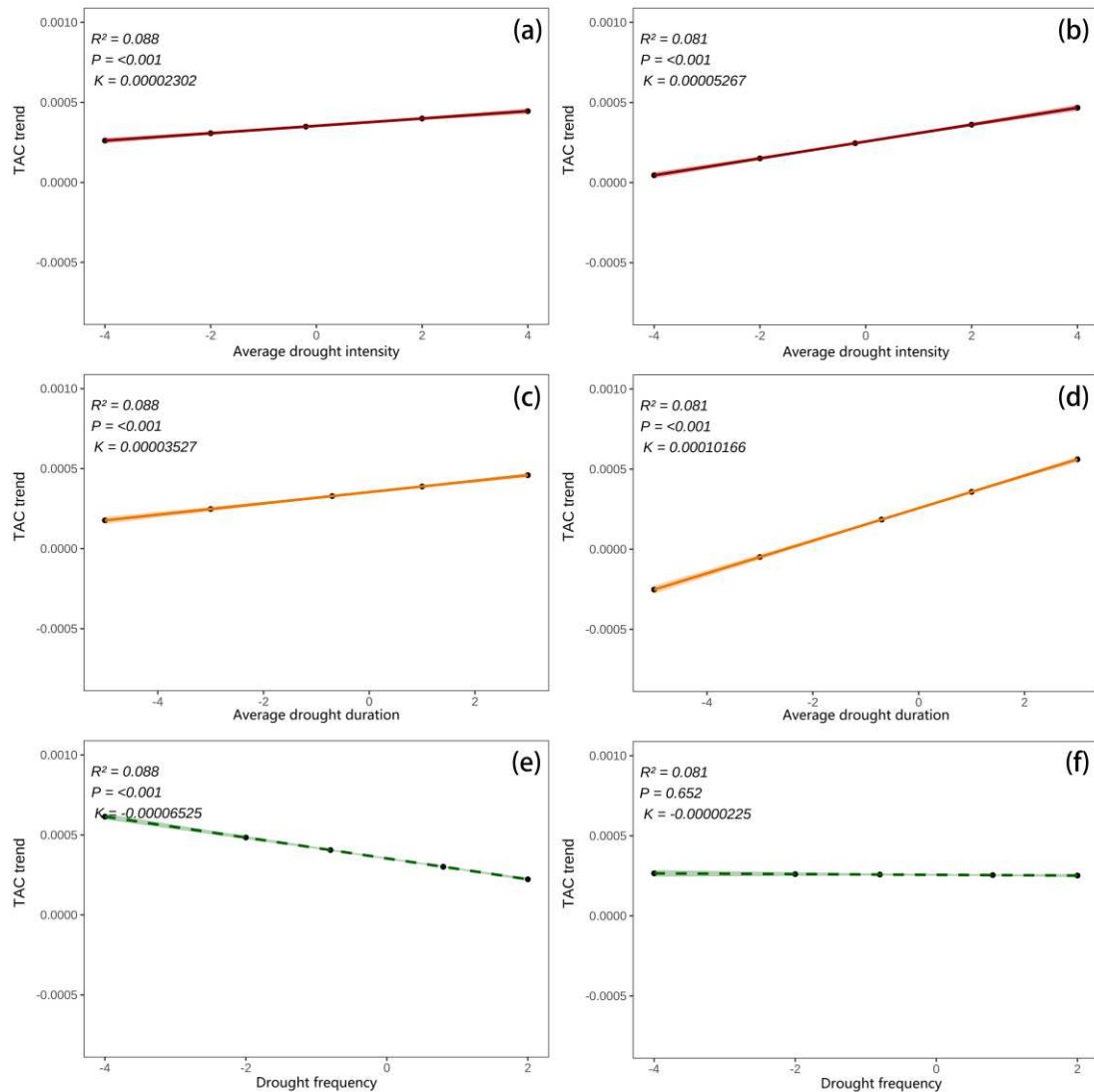


Fig. 7. Marginal effects of drought-event characteristics on SIF- and NEE-derived TAC trends across all forests in China. (a, c, e) SIF-derived TAC trends; (b, d, f) NEE-derived TAC trends. Panels show the effects of mean drought intensity (a, b), mean drought

duration (c, d), and drought frequency (e, f). Lines represent fitted marginal effects from pixel-level regression models, with shaded areas indicating standard errors. The x -axes show standardized drought variables, and the y -axes show TAC trend slopes. R^2 , P -values, and marginal slopes K are shown in each panel.

5. Discussion

Our results provide clear evidence that China's forests experienced a widespread slowdown in recovery dynamics during 2000–2022. Both SIF- and NEE-derived TAC trend slopes were predominantly positive, with increasing TAC observed in 60.94% of SIF pixels and 61.05% of NEE pixels. Because higher TAC reflects stronger temporal memory and slower recovery from perturbations, this pattern indicates a broad decline in forest resilience under drought stress (Scheffer et al., 2009; Dakos et al., 2012). Positive TAC slopes were widely distributed in southern and central China and parts of northeastern China, although clear spatial heterogeneity remained. This suggests that recovery slowdown was not confined to isolated drought-prone regions, but represented a national-scale signal across China's forest ecosystems. These findings are consistent with critical slowing down theory and with recent remote-sensing studies showing declining forest resilience under increasing water limitation and climate variability (Boulton et al., 2022; Forzieri et al., 2022; Smith et al., 2022; Wang et al., 2025). By linking TAC trends to event-based drought characteristics, our study further shows that this resilience decline was closely associated with the severity and persistence of drought events (Frank et al., 2015; Müller and Bahn, 2022; Van Passel et al., 2024).

Among the three drought-event characteristics, mean drought intensity and mean drought duration were more consistently associated with increasing TAC than drought frequency. Across all forests, both SIF- and NEE-derived TAC trends increased along gradients of drought intensity and duration, whereas their responses to drought frequency were weak or inconsistent. This pattern suggests that forest recovery dynamics were constrained less by the number of drought events alone than by the severity and persistence of water deficit. Stronger drought intensity can induce acute physiological stress through stomatal closure, photosynthetic suppression, hydraulic limitation, and carbon imbalance (Novick et al., 2024). Longer drought duration can prolong water deficit, delay post-drought recovery, and generate legacy effects even after climatic conditions improve (Frank et al., 2015; Gessler et al., 2020; Hoover et al., 2021; Müller and Bahn, 2022). Similar event-based evidence from the Amazon shows that drought intensity and duration can exert stronger destabilizing effects on TAC trends than drought frequency alone (Van Passel et al., 2024). These findings highlight

the importance of distinguishing drought-event properties when assessing forest resilience under climate change.

Forest type further modulated the drought-related slowdown in recovery dynamics. Planted forests showed a higher proportion of positive TAC trend slopes than natural forests, indicating a broader shift toward slower recovery. This contrast was also evident along drought-event gradients. In particular, SIF-derived TAC trends in planted forests showed stronger positive responses to increasing drought intensity and duration. This pattern is consistent with recent evidence that planted forests in China have higher drought risk and lower drought resilience than natural forests, especially under severe drought conditions (Ma et al., 2025). It also agrees with previous findings that natural forests in China can maintain higher carbon sequestration with lower water consumption than planted forests, suggesting a better balance between carbon gain and water use (Yu et al., 2019). At a broader restoration scale, global syntheses have shown that native and more diverse restoration approaches often provide greater biodiversity and ecosystem-service benefits than plantation-based restoration, although plantations can contribute substantially to wood production and carbon gains (Hua et al., 2022; Parr et al., 2024). Together, these studies support our interpretation that planted forests are a more drought-sensitive component of China's forest ecosystems. Several structural and physiological factors may explain this difference. Planted forests often have simpler species composition, more uniform age structure, higher stand density, and lower canopy complexity. These traits can increase competition for soil water, amplify water demand, and weaken stand-level buffering capacity during and after drought events (Yu et al., 2019; Hua et al., 2022; Cheng et al., 2024a; Ma et al., 2025). In contrast, natural forests generally have greater species diversity, stronger structural heterogeneity, and more complex rooting and canopy structures. These features may help maintain functional stability and support post-drought recovery (Guo and Ren, 2014; Isbell et al., 2015; Karim et al., 2023; Sun et al., 2024). However, this result should not be interpreted as evidence that planted forests are inherently non-resilient. Their drought responses can be strongly shaped by tree age, species selection, stand density, and management practices (Li et al., 2025; Ma et al., 2025). Therefore, the stronger TAC increase observed in planted forests more likely reflects higher vulnerability under current structural and management conditions.

The different responses of SIF- and NEE-derived TAC trends provide further insight into how drought affects forest recovery processes. Forest-type differences were more pronounced for SIF-derived TAC trends than for NEE-derived TAC trends,

suggesting that drought-related recovery slowdown was more evident in photosynthetic activity. SIF is closely linked to canopy photosynthesis and can respond rapidly to water stress through changes in stomatal regulation, light-use efficiency, and photosynthetic downregulation (Magney et al., 2019; Duveiller et al., 2020; Wen et al., 2025). By contrast, NEE represents net ecosystem carbon exchange and integrates photosynthetic carbon uptake with ecosystem respiration. Its response can therefore be influenced by temperature, soil moisture, respiration dynamics, and post-drought carbon release (Bastos et al., 2020). Thus, the weaker forest-type contrast in NEE-derived TAC trends does not contradict the SIF results. Rather, it suggests that drought-induced recovery slowdown is more readily detected at the photosynthetic level, whereas its translation into carbon-exchange dynamics may be buffered or delayed by respiratory and environmental processes.

These findings have important implications for forest management and resilience-oriented restoration in China. Planted forests remain important for carbon sequestration, ecological restoration, and regional environmental improvement. However, our results suggest that their long-term stability under intensifying drought cannot be ensured by forest expansion alone. In drought-prone regions, management should move beyond a primary focus on forest area and rapid carbon gain, and place greater emphasis on structural complexity, species diversity, and water-use adaptation. Mixed-species planting, appropriate thinning, density control, and drought-tolerant species selection may help reduce water competition and enhance post-drought recovery (Yu et al., 2019; Hua et al., 2022; Ma et al., 2025). At the same time, planted forests should not be regarded as inherently lacking resilience, because their drought responses can be modified by forest age, species composition, stand structure, and management practices (Li et al., 2025; Ma et al., 2025). Several limitations should also be acknowledged. Our analysis was based on gridded SIF and NEE products, which are suitable for detecting large-scale functional changes but cannot fully capture tree mortality, radial growth, belowground processes, or local management history. In addition, the spatial mismatch between drought-event data and forest functional indicators may introduce uncertainty in pixel-level attribution. Future studies should integrate satellite observations with forest inventories, tree-ring records, flux-tower measurements, and detailed management information. Such integration would help clarify the mechanisms by which drought affects forest recovery and support the development of planted forests that are both productive and resilient under future climate extremes.

6.Conclusion

This study integrated event-based drought characterization with SIF- and NEE-derived TAC analysis to assess drought-related changes in forest resilience across China during 2000–2022. China’s forests showed a widespread slowdown in recovery dynamics, with more than 60% of forest pixels exhibiting positive TAC trend slopes. Drought intensity and duration were more consistently associated with increasing TAC than drought frequency, indicating that forest recovery was constrained mainly by the severity and persistence of water deficit rather than by the number of drought events alone. Clear forest-type differences were also observed. Planted forests had higher proportions of positive TAC slopes and stronger responses to drought-event gradients than natural forests, especially for SIF-derived TAC trends. This suggests greater sensitivity of photosynthetic recovery to drought stress in planted forests. NEE-derived TAC trends showed a more moderate but consistent response, indicating that drought-induced recovery slowdown also affected carbon-exchange dynamics. Overall, these findings highlight the importance of considering both drought-event characteristics and forest type when assessing forest resilience. Future afforestation and forest management should move beyond increasing forest area alone and place greater emphasis on structural complexity, species diversity, stand-density regulation, and water-use adaptation to sustain forest ecosystem functions under intensifying climate extremes.

Author Contributions

Sun Yingkai: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft. Sun Xiaofang: Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing. Wang Meng: Methodology, Validation, Writing – review & editing. Liu Fengshan: Supervision, Validation, Writing – review & editing. All authors read and approved the final manuscript.

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Conflict of Interest Statement

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the first author, Sun Yingkai, upon reasonable request at sun_yk@qfnu.edu.cn.

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