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Higher Sensitivity of Planted Forests' Productivity Than Natural Forests to Droughts in China

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Key Points:

- Planted forests (PFs) were more sensitive to droughts than natural forests (NFs)
- PFs tended to recover more rapidly after drought disturbance than NFs
- The differences in the sensitivity to droughts may reflect intrinsic differences between PFs and NFs ecosystems

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

Planted forests (PFs) account for about one-third of the total area of forests in China and make important contributions to carbon sequestration and ecosystem services. Droughts pose a major threat to all forest ecosystems and yet, despite the importance of PFs, there is limited information about their sensitivity to drought and how it compares with that of natural forests (NFs). In this study, satellite-based vegetation indices were used to investigate and compare the sensitivity of PFs and NFs to drought. We found that PFs' productivity was more sensitive to droughts than NFs, demonstrating a stronger correspondence to interannual variations in drought and a larger decline in productivity under drought conditions than NFs. However, PFs tended to recover more rapidly after drought disturbance than NFs. The observed differences in the sensitivity to droughts may reflect intrinsic differences between PF and NF ecosystems. We also found that the difference between the response of PFs and NFs to drought became less notable as the climate aridity increased, indicating influences from external environmental conditions. The findings from this study highlight the importance of increasing the resistance of PFs to climate change by various management strategies, giving special attention to water availability issues.

Plain Language Summary

China's afforestation practices have aroused wide concerns in recent years. Planted forests (PFs) differ from natural forests (NFs) in many aspects, such as age, species richness, plant density, and so on. Many studies have explored the sensitivity of forests to climate change, while few of them have specifically focused on the PFs. In this study, the sensitivities of PFs and NFs to drought have been comprehensively examined and compared over China. We found that PFs demonstrated a higher sensitivity to droughts than NFs, which resulted from the structural and functional differences between PFs and NFs ecosystems. Knowledge from this study is crucial for the understanding of changes of PFs in the context of climate change.

1. Introduction

Planted forests (PFs) are an important component of the forest ecosystem in China, and the total planted areas reached 69 million hectares, accounting for 33.4% of the total forested area by 2013 (SFAPRC, 2013). This huge area of PFs may be the result of restoration practices launched since 1970 to combat sandstorms, soil erosion, and ecological degradation (Lu et al., 2018; D. Y. Yu et al., 2011). As an important complement to natural ecosystem, PFs have played a critical role in enhancing ecosystem services (Fang et al., 2001; Li et al., 2018, 2019; Y. Pan et al., 2011; Peng et al., 2014; Sun et al., 2006; Tang et al., 2018; Xiao, 2014; Zhou et al., 2013), absorbing atmosphere CO_2 (Liu et al., 2014), and mitigating climate change (Fashing et al., 2012; Sloan & Sayer,, 2015).

Some studies have attempted to explore the structural differences between PFs and natural forests (NFs) (Domec et al., 2015; Q. Guo & Hai, 2015; Suo et al., 2009). It had been suggested that NFs tend to have higher species richness, more complex community structure, deeper roots, and older stands than PFs (Q. Guo & Hai, 2015). In addition, Z. Yu et al. (2019) found that the NFs consumed less water but sequestered more carbon than PFs in China. Q. Guo and Hai (2015) suggested that PFs had much higher carbon sequestration rates than NFs in China. Generally, due to the lack of in situ observations, the structural differences between NFs and PFs are still poorly understood. The vague mechanism limited our estimation on the drought sensitivity difference between NFs and PFs.

Increasing droughts under climate change have acutely impacted forests in various ways (Anderegg et al., 2012; Reichstein et al., 2013; van der Molen et al., 2011). Severe droughts can convert forest ecosystems from sinks to sources of carbon by inhibiting photosynthesis and thereby productivity, causing tree death because of hydraulic failure or carbon starvation, triggering fires and diseases (Doughty et al., 2015; Goulden & Bales,, 2019; Kolb et al., 2016; Yuan et al., 2014), and ultimately changing global carbon, water, and energy cycles. While numerous researchers have explored the sensitivity of forests to drought disturbances (Bennett et al., 2015; Brodrick et al., 2019; Clark et al., 2016), most focused on NF ecosystems. Although some researchers have already explored the differences in response to drought between PFs and NFs in a local scale, inconsistent results were concluded (Domec et al., 2015; Sánchez-Salguero et al., 2013; L. Wang et al., 2014; Zhou et al., 2013). For example, PFs are susceptible to water deficits because of their poor stomatal control even under high vapor pressure deficits (Elena Fernandez et al., 2009). In contrast, other researchers suggested that because they tend to be managed more intensively, for example, by human selection, plowing, and the use of fertilizers, PFs are more resistant to drought than NFs (L. Hui et al., 2016). Therefore, it is still unclear whether PFs are more or less sensitive to drought than NFs.

Using vegetation greenness derived from satellite observations as a proxy of plant productivity, this study investigated and compared the sensitivities of PFs' and NFs' productivity throughout China to drought conditions based on a range of drought indices. Here, the sensitivity of forests' productivity to drought was determined by the coefficient of the regression of the drought indices during the growing season on the vegetation greenness indices. The different responses of NFs and PFs to drought were indicated by (a) the correlations between the vegetation greenness indices and drought indices during the growing season and (b) the vegetation greenness anomalies of natural and PFs under drought disturbances.

2. Materials and Methods

2.1. Data Sources

The data sets used in this study are shown in Table S1 in Supporting Information S2. The vegetation productivity was represented by satellite vegetation greenness indices including the Normalized Difference Vegetation Index (NDVI) and the Enhanced Vegetation Index (EVI). The global monthly NDVI and EVI were obtained at a spatial resolution of 0.05° for the period 2004–2016 from the MOD13C2 product derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Terra platform (Solano et al., 2010).

The map of PFs used in this study was taken from the Seventh National Forest Resource Inventory (2004–2008) released by China's State Forestry Administration. This inventory was launched in 2004, so the PF map essentially reflected the PFs conditions around 2004. This map was digitized and spatially adjusted before spatial analysis. The NFs were identified from the MODIS land-cover product (MCD12Q1) at a resolution of 1 km, obtained from NASA's Earth Observing System Data and Information System. We selected the MODIS land-cover map in 2004 to match with the time of the PF map.

In this study, we used monthly precipitation (P) at a resolution of 0.5° from 1961 onward, provided by the National Meteorological Information Center of the Chinese Meteorological Administration. The accuracy of the monthly meteorological data had been examined before it was released. The Self-Calibrating Palmer Drought Severity Index (scPDSI) (Wells et al., 2004) is a popular drought index that is based on the water balance theory. This index can be used to compare drought conditions in different geographical regions (Schrier et al., 2013). We obtained a monthly scPDSI data set at a resolution of 0.5° from 1901 onward from the Climatic Research Unit (CRU; UK). The scPDSI data set was produced from the CRU TS 3.26 climate series.

We obtained data for global 0.25° daily root-zone soil moisture (SM) from 1980 to the present from the Global Land Evaporation Amsterdam Model (GLEAM) Version 3.3 (Martens et al., 2017). These data were estimated using a multilayer running water balance and were corrected using satellite-derived observations of surface SM. This product gives reasonably accurate estimates that can be compared with in situ

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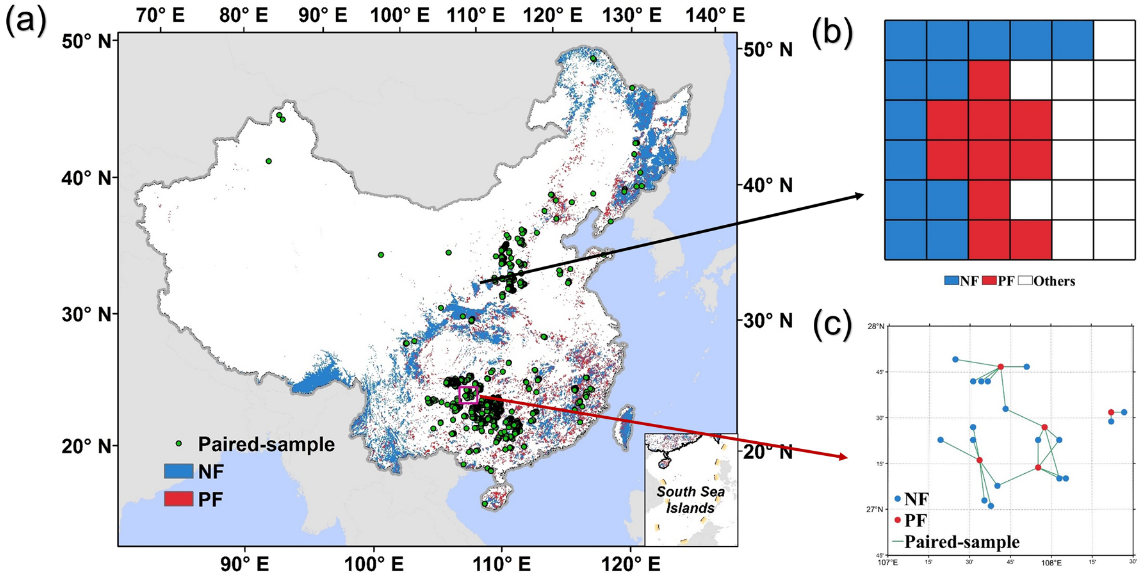

Figure 1. Spatial distribution of forests in China, and the examples of a sampling window and the paired forest stands. (a) Spatial distribution of natural forest (NF) (blue) and planted forest (PF) (red) in China; (b) an example of a 0.3° × 0.3° sampling window (the blue and red grids indicate PF grid and NF grid, respectively), and (c) an example of paired forest stands (the blue and red dots indicate PF stand and NF stand, respectively).

observations and is widely used in regional and global studies (Forzieri et al., 2017; Greve et al., 2014; Schumacher et al., 2019). Furthermore, another daily SM product retrieved from satellite observations, the ESA CCI SM with a spatial resolution of 0.25°, was also collected. The daily SM values were averaged to obtain monthly series.

In addition, we examined a database that comprised of extensive information about forest stands (10 × 10 m) (Q. Guo & Hai, 2015; D. Hui et al., 2012), including productivity, biomass, density, tree species, and age to determine the differences in the structure of NFs and PFs across China. This database was updated to 2013 and comprised of 6,153 records of forest stands, of which 1,716 were PFs and 4,437 NFs. Most of these data came from the inventories of the Forestry Ministry of China and the data obtained from published reports. The aboveground biomass of trees was measured by destructive harvesting and weighing within a given area. After that, all roots of sample trees by different diameter classes were excavated and the total belowground biomass was calculated. The annual net increments of stem, branch, and root were obtained by the proportion of tree biomass and their growth rate. The leaf productivity was derived from leaf biomass by dividing the leaf age of different trees. More detail about this database could be found in the studies of Ni et al. (2001), D. Hui et al. (2012), and Q. Guo and Hai (2015).

2.2. Mapping the Distribution of Planted and NFs

The distribution of NFs in China was determined by overlaying the PFs map with a map of forest cover extracted from the 2004 MODIS land-cover map (Figure 1a). Those forests which were not PFs were recognized as NFs. To ensure we were comparing NFs and PFs from the same climate conditions, a 0.3° × 0.3° moving window was applied over forest areas. This meant that, for the grid size of the land-cover map (0.05°), each window included 36 land-cover grids (Figure 1b). Only windows that had at least 5% (2 land-cover grids here) cover of both NFs and PFs were selected for analysis. To minimize the potential effect of elevation on climate and vegetation, we considered only those windows in which the elevation difference between PFs and NFs was less than 300 m. After refining the data set, 1,006 windows remained that met the standards. Meteorological data, SM, and scPDSI were aggregated to 0.3° resolution to match the window resolution, and to reflect the local climatic conditions. The vegetation index, NDVI, and EVI in each window were grouped into NFs and PFs. These indexes were then averaged to reflect the vegetation status of NFs and PFs.

2.3. Drought Indices

Three drought indices were used here to monitor droughts, including precipitation anomalies (PA), scPDSI, and SM anomalies (SMA). The monthly anomalies of P and SM were determined by the difference between monthly series of P or SM and multiyear (2004–2016) average value of current month P or SM, respectively. The monthly scPDSI from 2004 to 2016 was directly extracted from the global scPDSI product. Two monthly SMA series corresponding multiyear means during 2004–2016 were calculated based on GLEAM SM and ESA CCI SM data sets, respectively.

2.4. Tests of Sensitivity of Forests' Productivity to Drought

The linear regression coefficients of the NF/PF growing season greenness were calculated to indicate the differences between the sensitivities of NFs and PFs to drought conditions. In this study, we selected sampled windows in which the correlations between the NDVI and drought indices were significant at the 0.1 confidence level. Specifically, we examined the linear regression coefficient of growing season NDVI and the correlations between the growing season NDVI and three drought indices, namely PA, scPDSI, and SMA. We extended the time series of the vegetation index by using the monthly NDVI for the growing season (May–September) (Hua et al., 2017) for the period 2004–2016. To highlight the interannual variations, the seasonal variability and long-term trends in the variables of this study were removed before linear fitting analysis by subtracting the multiyear climate mean value, respectively. To allow for the potential effect of the delayed response of vegetation greenness on climate anomalies, the monthly NDVI anomalies were linear fitted to drought indices with lags of 0–3 months according to the principle of maximum correlation coefficient.

2.5. The Response of Forests' Productivity to Drought

The correlation coefficients between the NF/PF growing season greenness and drought indices were calculated to indicate the differences in the response of NFs and PFs to drought conditions. The different responses of PFs and NFs to droughts were also examined using an event-based analysis. For each window, we first defined a series of drought events, and then examined the deviation of the corresponding vegetation greenness to multiyear means. Here, a drought event was defined as a period that lasted for at least 3 months and had PA < 0, scPDSI < -1, or SMA < 0. Only drought events within the growing seasons of 2004–2016 were considered (Table S3 in Supporting Information S2). For each drought event, the abnormity of a given vegetation greenness of PFs and NFs in the same window was averaged, and the immediate vegetation response to the drought event was defined as the ratio of max negative abnormity of NDVI during this drought and the average of the growing season NDVI.

In addition, to explore the capacity of PFs and NFs to recover from drought, their recovery rates after drought were also tracked, examined, and compared. When analyzing the drought recovery time, only the drought events that had caused a negative anomaly of the vegetation greenness were considered. To ensure the continuity of recovery events, year-round anomalies in the vegetation proxy were considered rather than anomalies for the growing season only. The recovery time was tracked and started when the NDVI reached its minimum and ended when the post-drought NDVI returned to its pre-drought level (Schwalm et al., 2017). The pre-drought NDVI level value was defined as the pre-drought mean monthly NDVI across the same number of months as the relevant drought event.

3. Results

3.1. The Differences in Structures Between Natural and PFs

Using data from field investigations, the structures of NFs and PFs, including productivity, biomass, planting density, species richness, and tree age, were explored as shown in Figure 2. Across 1,539 paired samples in China, PFs were younger and planted much more densely than NFs, while the tree total and leaf productivity, tree total and root biomass were significantly higher in NFs than in PFs.

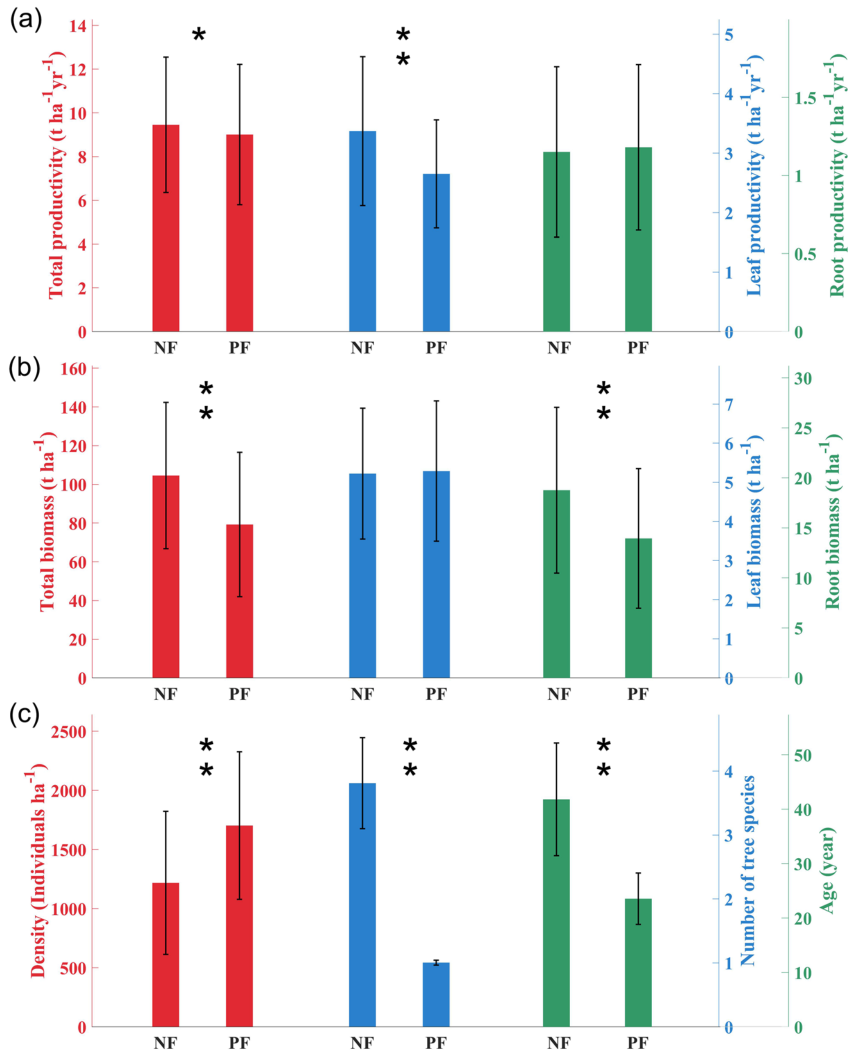

Figure 2. Differences in structure between natural forests (NFs) and planted forests (PFs). (a) The total leaf and root productivity and (b) the total leaf and root biomass of NFs and PFs; (c) the density and number of tree species in NFs and PFs and age of NFs and PFs across 1,539 paired samples in China. The asterisk indicates the significant level (*: $p < 0.05$, **: $p < 0.01$).

3.2. The Sensitivity of PFs and NFs to Temporal Variations of Drought Indices

The linear regression coefficients of the NF/PF growing season greenness were calculated to indicate the sensitivities of NFs and PFs to drought. As shown in Figure S1 in Supporting Information S1, the climatological NDVI in NFs is significantly higher than PFs. Information about how many sampled windows had significant correlations between NDVI and the three drought indicators was summarized in Table S2 in Supporting Information S2. The NDVI was more strongly correlated with the SMA than with the scPDSI or PA. Of all 1,006 sample windows, the NDVI and SMA (from GLEAM) were significantly correlated in 58.74%, while scPDSI versus NDVI correlation and PA versus NDVI correlation were significantly correlated in 38.97% and 30.82% windows, respectively. The linear regression coefficients of $NDVI_{PF}$ were generally higher than that of $NDVI_{NF}$. For example, the linear regression coefficients of the $NDVI_{PF}$ in the regression with SMA ($r = 0.37 \pm 0.18$) were significantly higher than that of the $NDVI_{NF}$ with SMA ($r = 0.31 \pm 0.17$; t-test, $p < 0.01$; $F = 42.61$). Figures 3a–3c show the difference between the linear regression coefficients of PFs and NFs in the NDVI-drought indices regression model. Apart from a few windows scattered over the south of China, the consistency of $NDVI_{PF}$ and drought indices was higher than that of $NDVI_{NF}$ and drought indices. We averaged the linear regression coefficients for all the sampled windows and found that the linear

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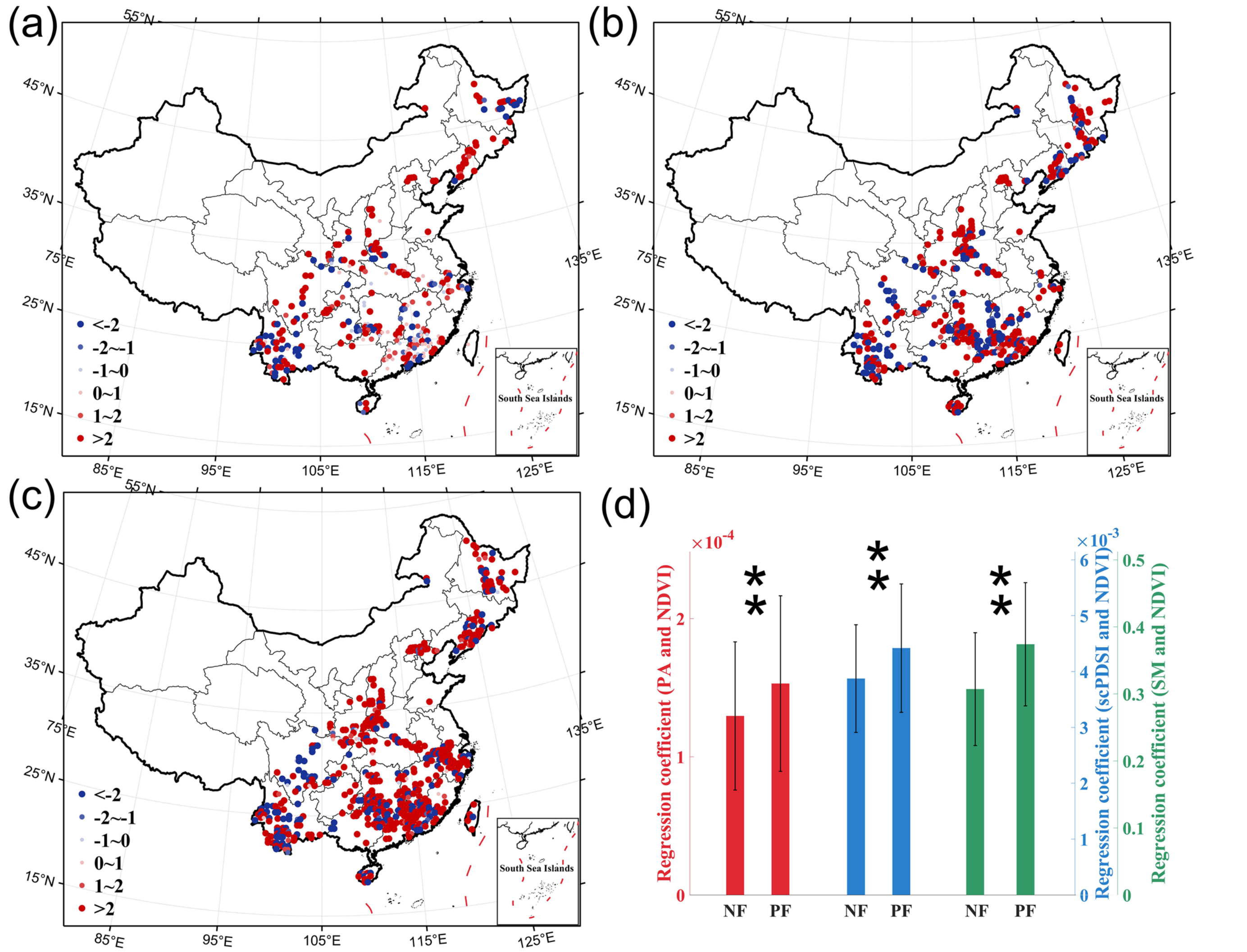

Figure 3. Differences in the linear regression coefficient of the Normalized Difference Vegetation Index (NDVI). (a–c) The spatial distribution of the difference in the linear regression coefficients of $NDVI_{NF}$ and $NDVI_{PF}$ with precipitation anomalies (PA), Self-Calibrating Palmer Drought Severity Index (scPDSI), and soil moisture anomalies (SMA), respectively. The units in (a–c) were 10^{-5}, 10^{-4}, and 10^{-2}, respectively; (d) averaged linear regression coefficient of the $NDVI_{NF}$/$NDVI_{PF}$ and PA, scPDSI, and SMA, across China, 2004–2016, respectively. For each sample window, the growing season monthly NDVI anomalies of natural forests (NFs) or planted forests (PFs) were linear fitted with the monthly PA, scPDSI, or SMA across China, 2004–2016, respectively, and the averaged linear regression coefficient was selected to indicate the sensitivity of forests to temporal variations of drought indices. The asterisk indicates the significant level (*: $p < 0.05$, **: $p < 0.01$). Only sample windows in which the correlation was significant ($p < 0.1$) are shown.

regression coefficients of the $NDVI_{PF}$ in the three regression models with the three drought indices were all significantly higher than those of the $NDVI_{NF}$ (Figure 3d). Additionally, the higher sensitivity of PFs than NFs to droughts were found across the region with variable climatological NDVI (Figure S2 in Supporting Information S1).

3.3. The Response of NFs and PFs to Drought

The response of NFs and PFs to drought was first indicated by the correlations between the NF/PF growing season greenness and drought indices (Figure S3 in Supporting Information S1). The $NDVI_{PF}$ was generally more strongly correlated with the drought indices than the $NDVI_{NF}$. We further explored the different sensitivities of NFs and PFs to drought by comparing the corresponding deviations in greenness during drought events. The NDVI of PFs and NFs were used to indicate the response of forests to drought. Overall, 81.76% of precipitation (Pre) negative events, 90.96% of scPDSI negative anomalies events, and 89.99% of

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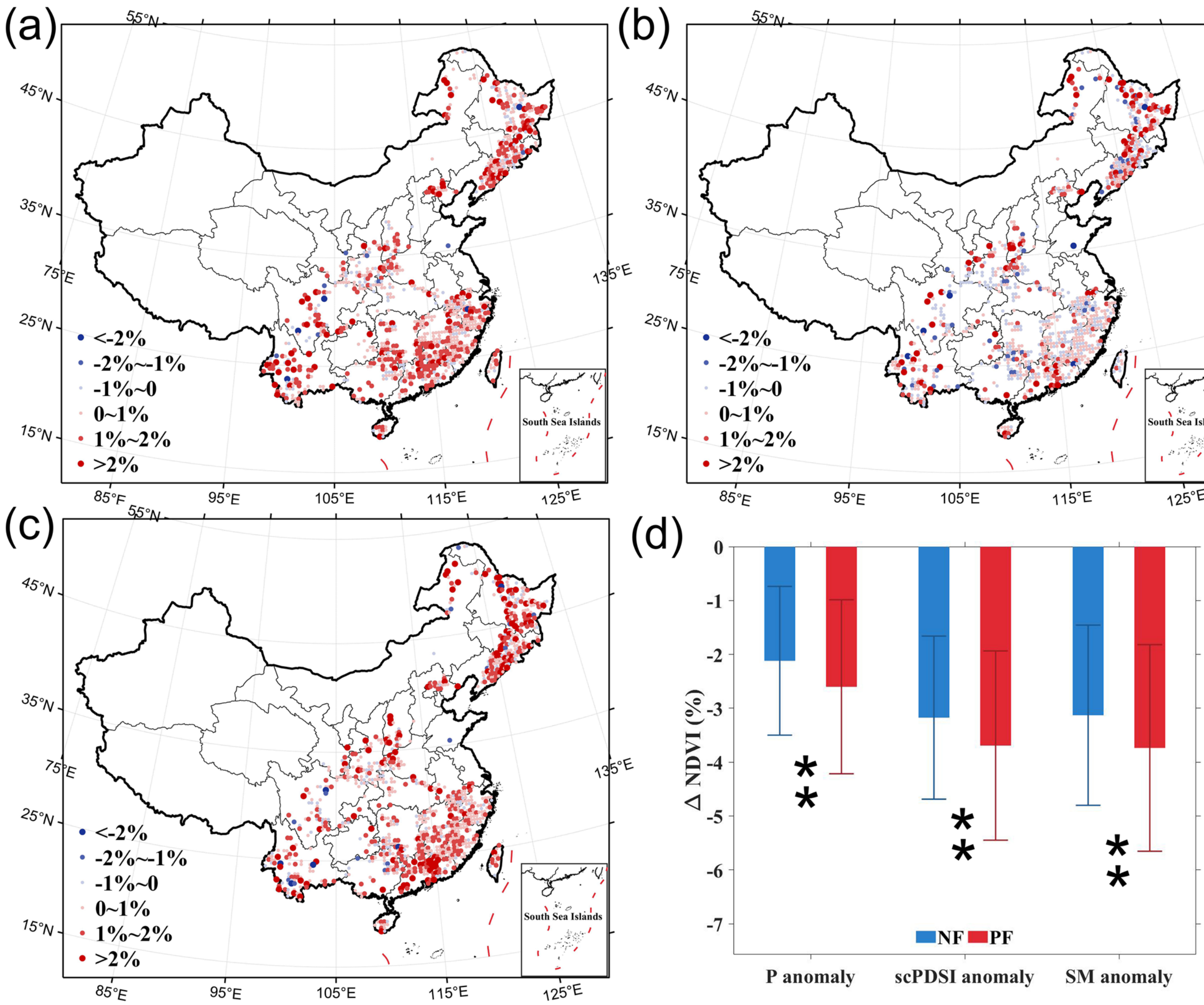

Figure 4. Deviations in Normalized Difference Vegetation Index (NDVI) during drought events. (a–c) Differences in the NDVI anomalies (%) between natural forests (NFs) and planted forests (PFs) under drought events indicated by (a) precipitation (P), (b) Self-Calibrating Palmer Drought Severity Index (scPDSI), and (c) soil moisture (SM) anomalies, respectively. (d) average NDVI anomalies of NFs and PFs under drought conditions across China. Drought events were defined as periods that lasted for 3 consecutive months when PA < 0, scPDSI < -1, and SMA < 0. The asterisk indicates the significant level (*: $p < 0.05$, **: $p < 0.01$).

SM negative anomalies events caused the reduction of vegetation indicated by the decline of $NDVI_{NF}$ or $NDVI_{PF}$ during the study periods, respectively. Figures 4a–4c show the spatial pattern of the differences in the NDVI anomalies between PFs and NFs under drought conditions indicated by PA, scPDSI, and SMA. In general, PFs suffered from a larger reduction in vegetation greenness than NFs during all three types of drought events. For example, the $3.74 \pm 1.92\%$ reduction in PFs was significantly larger than the 3.13 ± 1.67 reduction in NFs in the scPDSI negative anomalies (t-test, $p < 0.01$; $F = 71.88$). Spatially, the difference was greater in northeastern and southeastern China than in the other regions. Universally, the PFs are more severely hit by drought events across the region with variable climatological NDVI (Figure S4 in Supporting Information S1). Additionally, we explored the response of NFs and PFs to a drought event in southeastern China in 2004 (Figure S5 in Supporting Information S1). The $NDVI_{PF}$ declines more quickly than $NDVI_{NF}$ during severe drought across southeastern China in 2004. Above results indicated that PFs demonstrated a stronger correspondence to interannual variations in drought and a sharper decline in productivity under drought conditions than NFs.

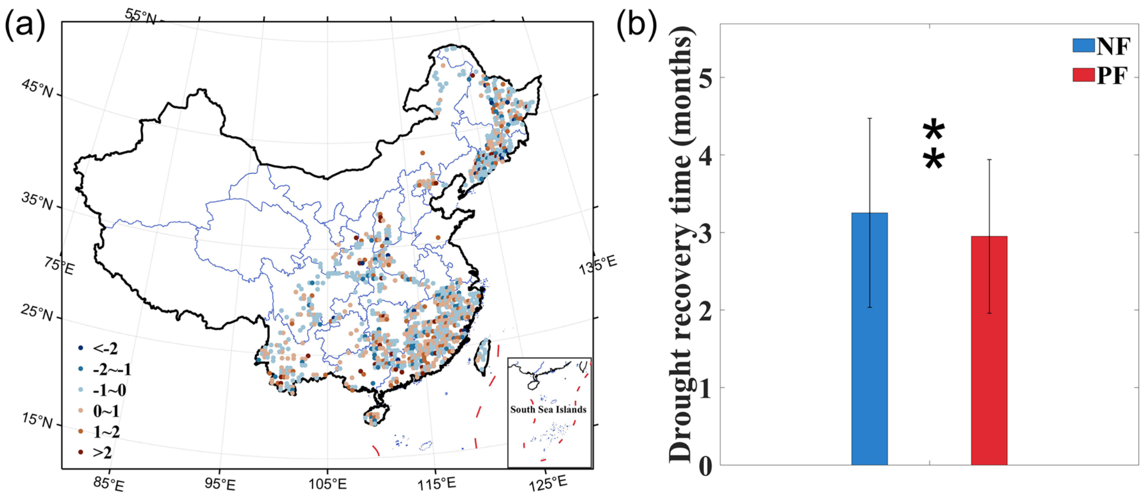

Figure 5. The drought recovery time of natural forests (NFs) and planted forests (PFs). Drought events here are defined as scPDSI < −1 lasting more than 3 months. (a) The spatial patterns of the difference between the drought recovery times of NFs and PFs (Drought recovery time of NFs−Drought recovery time of PFs). (b) The average time taken for NFs and PFs to recover from droughts. A total of 5,292 recoveries were observed during the study period. The difference between the drought recovery time of NFs and PFs was significant (3.25 ± 2.44 months vs. 2.95 ± 1.98 months; $F = 10.31$; t-test, $p < 0.01$).

3.4. The Recovery Time of NFs and PFs After Drought Events

The drought recovery time was a critical metric of the capacity of plants to recover from the impacts of a drought (Schwalm et al., 2017). Based on drought events indicated by the scPDSI, a total of 5,292 NDVI negative anomalies under drought events occurred across China during 2004–2016. The recovery times of the $NDVI_{NF}$ and $NDVI_{PF}$ were shown in Figure S6 in Supporting Information S1. Figure 5 showed the difference in the recovery time of vegetation greenness between NFs and PFs. The growing season $NDVI_{NF}$ generally took longer to recover than the $NDVI_{PF}$ (3.25 ± 2.44 months vs. 2.95 ± 1.98 months; $F = 10.31$; t-test, $p < 0.01$). Spatially, this difference was most obvious in northeastern and southeastern China (Figure 5a).

4. Discussion and Conclusion

4.1. The Robustness of Results From This Study

In this study, using in situ observations, we comprehensively explored the structural differences between PFs and NFs. We found that PFs tend to have higher density, lower productivity and biomass, and are younger than NFs. These conclusions were also consistent with Z. Yu et al. (2019)'s finding that NFs sequestered more carbon than PFs in China. However, Q. Guo and Hai (2015) used the same database for net primary productivity and found that the productivity of PFs was much higher than that of NFs in China. This difference may be explained by the different analysis methods used. Furthermore, PFs were generally younger than NFs. Considering the effect of the different tree ages on our research, we repeated the analysis in Section 3.1 and Figure 2 with additional limitation that the age of NFs for analysis is less than 80 (Q. Guo & Hai, 2015). Similar results were concluded and shown in Figure S7 in Supporting Information S1. Additionally, the significant positive correlation between vegetation index (NDVI or EVI) and total productivity of forests indicated that these two vegetation indices are good indicators to primary productivity of NFs and PFs (Figure S8 in Supporting Information S1).

More importantly, we found that the vegetation greenness of PFs was more sensitive to drought than that of NFs in China, indicated by larger linear regression coefficient, stronger correlations with drought indices, and larger negative anomalies under drought stress. It suggested that PFs may be more susceptible or less resistant to drought than NFs. The PFs have stronger correlation with drought indices than NFs, which was also the case when the vegetation status was indicated by EVI (Figure S9 in Supporting Information S1). Considering that the scPDSI and GLEAM SM were both calculated from a water balance model using rainfall as an input, scPDSI and GLEAM SM are expected to be highly correlated. The remote-sensing-based ESA CCI SM was further used for analysis. As shown in Figure S10 in Supporting Information S1, the

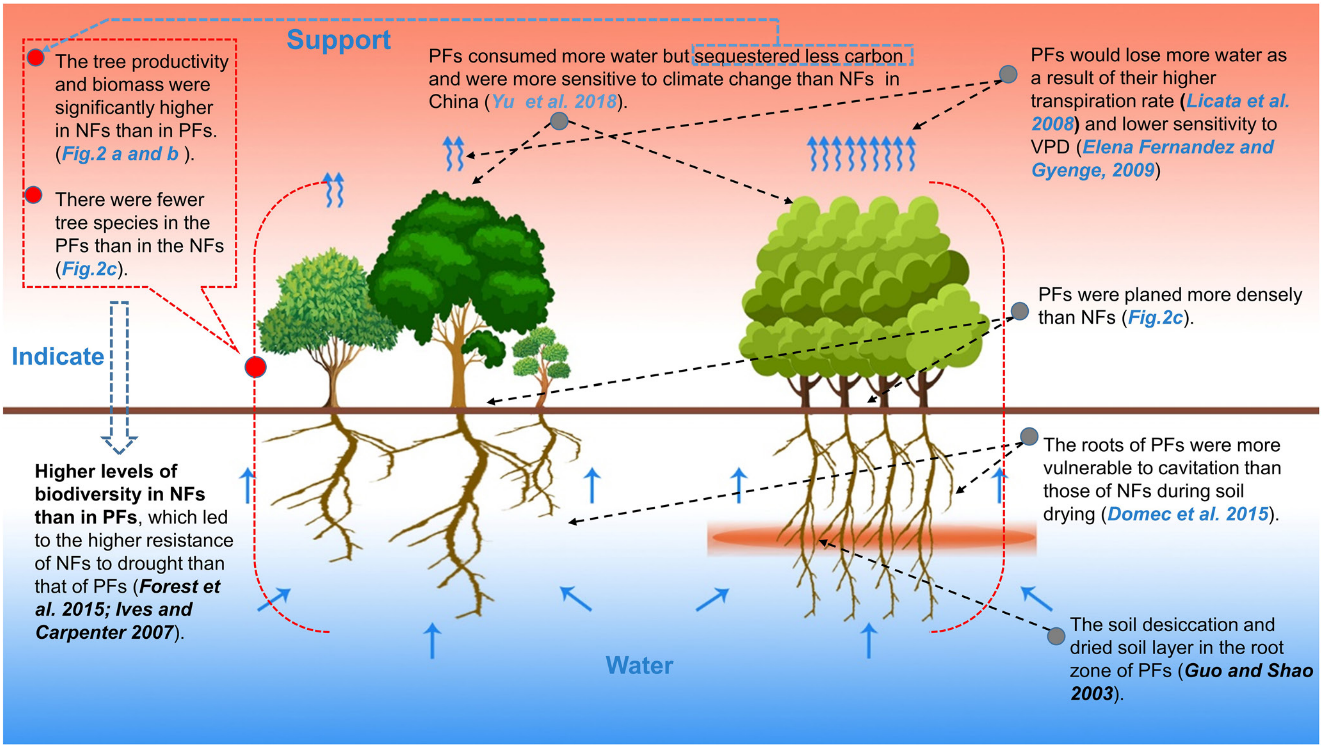

Figure 6. Conceptual model for the reasons for different sensitivities of natural forests (NFs) and planted forests (PFs) to drought.

finding that PFs was more sensitive to drought than NFs still holds in most areas of southern China. In addition, the window size used might have influenced our results. We reexamined the sensitivity of PFs and NFs to droughts using a new 0.5° window and concluded similar results (Figures S11–S13 in Supporting Information S1).

4.2. Reasons for the Different Sensitivity of NFs and PFs to Drought

By summarizing knowledge from previous studies (Figure 6), we attributed the observed different sensitivities of NFs and PFs to drought conditions mainly to the different water regulation capacity and the ecosystem resistance to external disturbances between NFs and PFs.

It had been reported that NFs were more sensitive to vapor pressure difference (VPD) because NFs had a stronger stomatal control of leaf water potential and transpiration (Elena Fernandez et al., 2009). Hence, PFs would lose more water and be more severely hit under water stress as a result of their higher transpiration rate and lower sensitivity to VPD. In addition, compared to NFs, PFs need more water to maintain high growth rates (Licata et al., 2008; Zhou et al., 2013). A previous study in China also suggested that PFs consumed more water and were more sensitive to climate change than NFs (Z. Yu et al., 2019). Furthermore, we found that the plant density of PFs was significantly higher than that of NFs (Figure 2c), which increased the competition for water and the additive effects of drought on growth in very dense PFs (Martín-Benito et al., 2010). Additionally, PFs' roots are more vulnerable to cavitation than that of NFs. As a result, PFs could extract a lower proportion of water as soil dried (Domec et al., 2015). Some researches in a local scale also found the soil desiccation and dried soil layer in the root zone of PFs (Chen et al., 2005; Z. Guo & Shao, 2003), which could restrain the water uptake of PFs and further increase the negative impact of drought on PFs.

From the perspective of ecosystems, it has been reported that higher levels of biodiversity could increase the resistance of ecosystems to climate events (Forest et al., 2015; Ives & Carpenter,, 2007). With high biodiversity, species responses to environmental fluctuations would be asynchronous (Loreau et al., 2013), which would generate differences in the speed at which species responded to perturbations. Because of different factors that may be either internal or external to a community, different species have different intrinsic rates of natural increase that allow them to respond at various speeds to perturbations. These differences in their response speeds also tend to generate asynchronous population dynamics and so promote ecosystem resistance (Fowler, 2009; Rooney et al., 2006). While there are no direct biodiversity data to support this view, some researches in a local scale suggested that the biodiversity in NFs was higher than that in PFs (Suo et al., 2009; J. Wang et al., 2010). Additionally, the biodiversity can be indirectly reflected by the species richness. There were fewer tree species in the PFs (one or two generally) than in the NFs (Figure 2c), implying that PFs would be less stable to drought events than NFs.

Previous studies have reported a significant positive linear relationship between productivity and species richness (Cardinale et al., 2007; Gillman & Wright,, 2006; Liang et al., 2016; X. Pan et al., 2012), which means that the more productive NFs (Figure 2a) are likely to house more species and so should be more resistant to drought. The influence of plant productivity to the sensitivity to drought was examined using the NDVI and EVI as proxies. Figure S14 in Supporting Information S1 shows that, as the difference in NDVI or EVI between NFs and PFs increased, the corresponding differences in the NDVI or EVI-scPDSI correlations and NDVI or EVI anomalies under drought conditions between NFs and PFs also increased. These results suggest that the difference in response to drought between NFs and PFs increased as the difference between their productivities increased.

4.3. Other Reasons for the Different Sensitivity of NFs and PFs to Drought

Besides the intrinsic ecosystem differences between NFs and PFs, external conditions may also affect the sensitivity of NFs or PFs to drought. As shown in Figures S15 and S16 in Supporting Information S1, as the AI index increased (which indicates wetting conditions), the differences in the NDVI or EVI-scPDSI correlations and NDVI or EVI anomalies under drought conditions between NFs and PFs gradually decreased. This means that the difference between the response of NFs and PFs to drought is greater in dry conditions than in humid conditions, because PFs would need more water than NFs to maintain high growth rates (Licata et al., 2008; Zhou et al., 2013).

Other factors, especially human management practices, may also contribute to the different sensitivities of NFs and PFs to droughts. In some regions, such as southwestern China, it is thought that PFs have generally been managed more intensively through human selection, plowing, the citing of planting areas, and applying herbicides and fertilizers than NFs (L. Hui et al., 2016), with the result that as also observed in this study, PFs are less sensitive to drought in those areas (Figures 3a–3c).

Interestingly, although PFs are more sensitive to drought than NFs, we observed that PFs took less time to recover from drought disturbances than NFs. We speculate that this difference may be attributed to the different layers of soil water used by NFs and PFs. Because PFs are younger and have shallower root systems than NFs, plants in PFs can promptly recover once the SM in shallow layers recovers. On the other hand, NFs would only recover when deeper soil water recharged. In addition, as shown by Schwalm et al. (2017), higher productivity plants tend to need more time to recover from drought than lower productivity plants. Additionally, the human managements such as irrigation and the use of fertilizers received by PFs (L. Hui et al., 2016) would also help them recover faster than NFs after being affected by drought. These reasons may explain why the drought recovery time of NFs was longer than that of PFs.

4.4. Implications for Future Plantation

Reforestation efforts in China are still ongoing and the area of PFs in China is still growing. At the same time, the frequency and severity of drought can be expected to increase in China in the context of climate change (Dai, 2013). The fact that, as shown by this study, PFs are more sensitive to droughts than NFs, which means that PFs should be more properly managed to reduce drought damage, especially under extreme drought conditions. It is also important to reduce the sensitivity of PFs to external influences by, for example, changing the planting density and regulating the species richness. We also observed that the differences between the sensitivities of NFs and PFs decreased as the climate aridity increased, implying that much more management should be concentrated on PFs than NFs in relatively dry regions, such as northwestern China when droughts occur. In this study, we simply analyzed the potential reasons for the different sensitivities of plants in NFs and PFs to drought. In the future, more in-depth studies based on long-term field observations are still needed.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The MODIS NDVI, EVI, and land-cover product can be downloaded from the following URL (https://search.earthdata.nasa.gov/). The precipitation data can be downloaded from the following URL (http://data.cma.cn/site/). The scPDSI data can be downloaded from the following URL (https://www.gleam.eu/). The GLEAM root-zone soil moisture data can be downloaded from the following URL (https://www.gleam.eu). The ESA CCI soil moisture data can be downloaded from the following URL (https://www.esa-soil-moisture-cci.org/).

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References

Anderegg, W. R. L., Berry, J. A., Smith, D. D., Sperry, J. S., Anderegg, L. D. L., & Field, C. B. (2012). The roles of hydraulic and carbon stress in a widespread climate-induced forest die-off. *Proceedings of the National Academy of Sciences of the United States of America*, *109*, 233–237. https://doi.org/10.1073/pnas.1107891109

Bennett, A. C., McDowell, N. G., Allen, C. D., & Anderson-Teixeira, K. J. (2015). Larger trees suffer most during drought in forests worldwide. *Nature Plants*, *1*, 15139. https://doi.org/10.1038/nplants.2015.139

Brodrick, P. G., Anderegg, L. D. L., & Asner, G. P. (2019). Forest drought resistance at large geographic scales. *Geophysical Research Letters*, *46*, 2752–2760. https://doi.org/10.1029/2018gl081108

Cardinale, B. J., Wright, J. P., Cadotte, M. W., Carroll, I. T., Hector, A., Srivastava, D. S., et al. (2007). Impacts of plant diversity on biomass production increase through time because of species complementarity. *Proceedings of the National Academy of Sciences of the United States of America*, *104*, 18123–18128. https://doi.org/10.1073/pnas.0709069104

Chen, H., Wang, K., & Shao, M. (2005). A review on the effect of vegetation rehabilitation on the desiccation of deep soil layer on the Loess Plateau. *Scientia Silvae Sinicae*, *41*, 155–161.

Clark, J. S., Iverson, L., Woodall, C. W., Allen, C. D., Bell, D. M., Bragg, D. C., et al. (2016). The impacts of increasing drought on forest dynamics, structure, and biodiversity in the United States. *Global Change Biology*, *22*, 2329–2352. https://doi.org/10.1111/gcb.13160

Dai, A. (2013). Increasing drought under global warming in observations and models. *Nature Climate Change*, *3*, 52–58. https://doi.org/10.1038/nclimate1633

Domec, J. C., King, J. S., Ward, E., Christopher Oishi, A., Palmroth, S., Radecki, A., et al. (2015). Conversion of natural forests to managed forest plantations decreases tree resistance to prolonged droughts. *Forest Ecology and Management*, *355*, 58–71. https://doi.org/10.1016/j.foreco.2015.04.012

Doughty, C. E., Metcalfe, D. B., Girardin, C. A. J., Farfán Amézquita, F., Galiano Cabrera, D., Huaraca Huasco, W., et al. (2015). Drought impact on forest carbon dynamics and fluxes in Amazonia. *Nature*, *519*, 78–82. https://doi.org/10.1038/nature14213

Elena Fernandez, M., Gyenge, J., & Schlichter, T. (2009). Water flux and canopy conductance of natural versus planted forests in Patagonia, South America. *Trees*, *23*, 415–427. https://doi.org/10.1007/s00468-008-0291-y

Fang, J., Chen, A., Peng, C., Zhao, S., & Ci, L. (2001). Changes in forest biomass carbon storage in China between 1949 and 1998. *Science*, *292*, 2320–2322. https://doi.org/10.1126/science.1058629

Fashing, P. J., Nguyen, N., Luteshi, P., Opondo, W., Cash, J. F., & Cords, M. (2012). Evaluating the suitability of planted forests for African forest monkeys: A case study from Kakamega forest, Kenya. *American Journal of Primatology*, *74*, 77–90. https://doi.org/10.1002/ajp.21012

Forest, I., Dylan, C., Connolly, J., Michel, L., Schmid, B., Carl, B., et al. (2015). Biodiversity increases the resistance of ecosystem productivity to climate extremes. *Nature*, *526*, 574–577.

Forzieri, G., Alkama, R., Miralles, D. G., & Cescatti, A. (2017). Satellites reveal contrasting responses of regional climate to the widespread greening of Earth. *Science*, *356*, 1180–1184. https://doi.org/10.1126/science.aal1727

Fowler, M. S. (2009). Increasing community size and connectance can increase stability in competitive communities. *Journal of Theoretical Biology*, *258*, 179–188. https://doi.org/10.1016/j.jtbi.2009.01.010

Gillman, L. N., & Wright, S. D. (2006). The influence of productivity on the species richness of plants: A critical assessment. *Ecology*, *87*, 1234–1243. https://doi.org/10.1890/0012-9658(2006)87[1234:tiopot]2.0.co;2

Goulden, M. L., & Bales, R. C. (2019). California forest die-off linked to multi-year deep soil drying in 2012–2015 drought. *Nature Geoscience*, *12*, 632–637. https://doi.org/10.1038/s41561-019-0388-5

Greve, P., Orlowsky, B., Mueller, B., Justin Sheffield, J., Reichstein, M., Sonia, I. S. (2014). Global assessment of trends in wetting and drying over land. *Nature Geoscience*, *7*, 716–721. https://doi.org/10.1038/ngeo2247

Guo, Q., & Hai, R. (2015). Productivity as related to diversity and age in planted versus natural forests. *Global Ecology and Biogeography*, *23*, 1461–1471.

Guo, Z., & Shao, M. (2003). Soil water carrying capacity of vegetation and soil desiccation in artificial forestry and grassland in semi-arid regions of the Loess Plateau. *Acta Ecologica Sinica*, *23*, 1640–1647.

Hua, T., Wang, X., Zhang, C., Lang, L., & Li, H. (2017). Responses of vegetation activity to drought in Northern China. *Land Degradation & Development*, *28*, 1913–1921. https://doi.org/10.1002/ldr.2709

Hui, D., Wang, J., Le, X., Shen, W., & Ren, H. (2012). Influences of biotic and abiotic factors on the relationship between tree productivity and biomass in China. *Forest Ecology and Management*, *264*, 72–80. https://doi.org/10.1016/j.foreco.2011.10.012

Hui, L., Zhou, T., Wu, H., Zhao, X., & Zheng, L. (2016). Contrasting responses of planted and natural forests to drought intensity in Yunnan, China. *Remote Sensing*, *8*, 635.

Ives, A. R., & Carpenter, S. R. (2007). Stability and diversity of ecosystems. *Science*, *317*, 58–62. https://doi.org/10.1126/science.1133258

Kolb, T. E., Fettig, C. J., Ayres, M. P., Bentz, B. J., Hicke, J. A., Mathiasen, R., et al. (2016). Observed and anticipated impacts of drought on forest insects and diseases in the United States. *Forest Ecology and Management*, *380*, 321–334. https://doi.org/10.1016/j.foreco.2016.04.051

Li, Y., Piao, S., Chen, A., Ciais, P., Laurent, Z., & Li, X. (2019). Local and tele-connected temperature effects of afforestation and vegetation greening in China. *National Science Review*, *7*, 897–912.

Li, Y., Piao, S., Laurent, Z., Li, X., Chen, A., Wang, X., et al. (2018). Divergent hydrological response to large-scale afforestation and vegetation greening in China. *Science Advances*, *4*, eaar4182. https://doi.org/10.1126/sciadv.aar4182

Liang, J., Crowther, T. W., Picard, N., Wiser, S., Zhou, M., Alberti, G., et al. (2016). Positive biodiversity-productivity relationship predominant in global forests. *Science*, *354*, aaf8957. https://doi.org/10.1126/science.aaf8957

Licata, J. A., Gyenge, J. E., Elena Fernández, M., Schlichter, T. M., & Bond, B. J. (2008). Increased water use by ponderosa pine plantations in northwestern Patagonia, Argentina compared with native forest vegetation. *Forest Ecology and Management*, *255*, 753–764. https://doi.org/10.1016/j.foreco.2007.09.061

Liu, D., Chen, Y., Cai, W., Dong, W., Xiao, J., Chen, J., et al. (2014). The contribution of China's Grain to Green Program to carbon sequestration. *Landscape Ecology*, *29*, 1675–1688. https://doi.org/10.1007/s10980-014-0081-4

Loreau, M., de Mazancourt, C., & Duffy, E. (2013). 'Biodiversity and ecosystem stability: A synthesis of underlying mechanisms. *Ecology Letters*, *16*, 106–115. https://doi.org/10.1111/ele.12073

Lu, F., Hu, H., Sun, W., Zhu, J., Liu, G., Zhou, W., et al. (2018). Effects of national ecological restoration projects on carbon sequestration in China from 2001 to 2010. *Proceedings of the National Academy of Sciences of the United States of America*, *115*, 4039–4044. https://doi.org/10.1073/pnas.1700294115

Martens, B., Miralles, D. G., Lievens, H., Van Der Schalie, R., Richard, A., De Jeu, M., et al. (2017). 'GLEAM v3: Satellite-based land evaporation and root-zone soil moisture. *Geoscientific Model Development Discussions*, *10*, 1–36. https://doi.org/10.5194/gmd-10-1903-2017

Martín-Benito, D., Del Río, M., Heinrich, I., Helle, G., & Canellas, I. (2010). Response of climate-growth relationships and water use efficiency to thinning in a Pinus nigra afforestation. *Forest Ecology and Management*, *259*, 967–975. https://doi.org/10.1016/j.foreco.2009.12.001

Ni, J., Zhang, X. S., Jonathan, M., & Scurlock, O. (2001). Synthesis and analysis of biomass and net primary productivity in Chinese forests. *Annals of Forest Science*, *58*, 351–384. https://doi.org/10.1051/forest:2001131

Pan, X., Liu, F., & Zhang, M. (2012). Comment on "Productivity is a poor predictor of plant species richness". *Science*, *335*, 1441. https://doi.org/10.1126/science.1214786

Pan, Y., Birdsey, R. A., Fang, J., Houghton, R., Kauppi, P. E., Kurz, W. A., et al. (2011). A large and persistent carbon sink in the world's forests. *Science*, *333*, 988–993. https://doi.org/10.1126/science.1201609

Peng, S.-S., Piao, S., Zeng, Z., Ciais, P., Zhou, L., Laurent, Z., et al. (2014). Afforestation in China cools local land surface temperature. *Proceedings of the National Academy of Sciences of the United States of America*, *111*, 2915–2919. https://doi.org/10.1073/pnas.1315126111

Reichstein, M., Bahn, M., Ciais, P., Frank, D., Mahecha, M. D., Seneviratne, S. I., et al. (2013). Climate extremes and the carbon cycle. *Nature*, *500*, 287–295. https://doi.org/10.1038/nature12350

Rooney, N., McCann, K., Gellner, G., John, C. M. (2006). Structural asymmetry and the stability of diverse food webs. *Nature*, *442*, 265–269. https://doi.org/10.1038/nature04887

Sánchez-Salguero, R., Camarero, J. J., Dobbertin, M., Fernández-Cancio, Á., Vilà-Cabrera, A., Manzanedo, R. D., et al. (2013). Contrasting vulnerability and resilience to drought-induced decline of densely planted vs. natural rear-edge Pinus nigra forests. *Forest Ecology and Management*, *310*, 956–967. https://doi.org/10.1016/j.foreco.2013.09.050

Schrier, G. V. D., Barichivich, J., Briffa, K. R., & Jones, P. D. (2013). A scPDSI-based global data set of dry and wet spells for 1901–2009. *Journal of Geophysical Research: Atmospheres*, *118*, 4025–4048. https://doi.org/10.1002/jgrd.50355

Schumacher, D. L., Keune, J., van Heerwaarden, C. C., Vilà-Guerau de Arellano, J., Teuling, A. J., & Miralles, D. G. (2019). Amplification of mega-heatwaves through heat torrents fuelled by upwind drought. *Nature Geoscience*, *12*, 712–717. https://doi.org/10.1038/s41561-019-0431-6

Schwalm, C. R., Anderegg, W. R. L., Michalak, A. M., Fisher, J. B., Tian, H., Koch, G., et al. (2017). Global patterns of drought recovery. *Nature*, *548*, 202–205. https://doi.org/10.1038/nature23021

SFAPRC. (2013). *Eighth National Forest Resource Inventory report (2009-2013)*. In State Forestry Administration of the People's Republic of China, Beijing.

Sloan, S., & Sayer, J. A. (2015). Forest Resources Assessment of 2015 shows positive global trends but forest loss and degradation persist in poor tropical countries. *Forest Ecology and Management*, *352*, 134–145. https://doi.org/10.1016/j.foreco.2015.06.013

Solano, R., Kamel, D., Jacobson, A., & Huete, A. (2010). MODIS vegetation index user's guide (MOD13 series). In *Vegetation index and phenology lab* (pp. 1–38). The University of Arizona.

Sun, G., Zhou, G., Zhang, Z., Wei, X., Mcnulty, S. G., & Vose, J. M. (2006). Potential water yield reduction due to forestation across China. *Journal of Hydrology*, *328*, 548–558. https://doi.org/10.1016/j.jhydrol.2005.12.013

Suo, L., Luo, Y. Q., Wu, J., Xiang, S. Z., Yao, G. L., Yuan, L., et al. (2009). Community structure and biodiversity in plantations and natural forests of seabuckthorn in southern Ningxia, China. *Forestry Studies in China*, *11*, 49–54.

Tang, X., Zhao, X., Bai, Y., Tang, Z., Wang, W., Zhao, Y., et al. (2018). Carbon pools in China's terrestrial ecosystems: New estimates based on an intensive field survey. *Proceedings of the National Academy of Sciences of the United States of America*, *115*, 4021–4026. https://doi.org/10.1073/pnas.1700291115

van der Molen, M. K., Dolman, A. J., Ciais, P., Eglin, T., Gobron, N., Law, B. E., et al. (2011). Drought and ecosystem carbon cycling. *Agricultural and Forest Meteorology*, *151*, 765–773. https://doi.org/10.1016/j.agrformet.2011.01.018

Wang, J., Liu, J., Chen, X., Wen, Q., Duan, Z., & Lai, X. (2010). Comparison of community structures and species diversity in natural forests and forest plantation of Pinus yunnanensis. *Forest Research*, *23*, 515–522.

Wang, L., Zhang, Y., Berninger, F., & Duan, B. (2014). Net primary production of Chinese fir plantation ecosystems and its relationship to climate. *Biogeosciences*, *11*, 5595–5606. https://doi.org/10.5194/bg-11-5595-2014

Wells, N., Goddard, S., & Michael, J. H. (2004). A self-calibrating Palmer Drought Severity Index. *Journal of Climate*, *17*, 2335–2351. https://doi.org/10.1175/1520-0442(2004)017<2335:aspdsi>2.0.co;2

Xiao, J. (2014). Satellite evidence for significant biophysical consequences of the "Grain for Green" Program on the Loess Plateau in China. *Journal of Geophysical Research: Biogeosciences*, *119*, 2261–2275. https://doi.org/10.1002/2014jg002820

Yu, D. Y., Shi, P. J., Han, G. Y., Zhu, W. Q., Du, S. Q., & Xun, B. (2011). Forest ecosystem restoration due to a national conservation plan in China. *Ecological Engineering*, *37*, 1387–1397. https://doi.org/10.1016/j.ecoleng.2011.03.011

Yu, Z., Liu, S., Wang, J., Wei, X., Schuler, J., Sun, P., et al. (2019). Natural forests exhibit higher carbon sequestration and lower water consumption than planted forests in China. *Global Change Biology*, *25*. https://doi.org/10.1111/gcb.14484

Yuan, W., Liu, D., Dong, W., Liu, S., Zhou, G., Yu, G., et al. (2014). Multiyear precipitation reduction strongly decreases carbon uptake over northern China. *Journal of Geophysical Research: Biogeosciences*, *119*, 881–896. https://doi.org/10.1002/2014jg002608

Zhou, J., Zhang, Z., Sun, G. E., Fang, X., Zha, T., McNulty, S., et al. (2013). Response of ecosystem carbon fluxes to drought events in a poplar plantation in Northern China. *Forest Ecology and Management*, *300*, 33–42. https://doi.org/10.1016/j.foreco.2013.01.007