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Carbon stock and sequestration of planted and natural forests along climate gradient in water-limited area: A synthesis in the China's Loess plateau☆

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ABSTRACT

Large-scale afforestation has been widely implemented for restoring the degraded lands and mitigating climate change while naturally regenerated forests should be protected to preserve carbon (C) in land ecosystems. However, a critically needed comparison on the effectiveness of C sequestration between planted forest (PF) and natural forest (NF) in water-limited areas has rarely been conducted at a regional scale. This study synthesized 275 publications to examine the changes of C stock in above-ground biomass (AGB), below-ground biomass (BGB) and deep soils (0-200 cm) between PF and NF in the China's Loess Plateau, a typical water-limited region with extensive afforestation. We found that, NF stored more than twice as much C as did PF in both biomass and soil. But PF allocated relatively higher proportion of C stock to BGB and deep soil layer (> 100 cm) than NF. Moreover, the C sequestration rates in biomass and soil for PF were 1.42 and 1.72 Mg C ha^{-1} yr^{-1}, respectively, much higher than that of NF (0.13 and -1.38 Mg C ha^{-1} yr^{-1}). In addition, afforestation in areas with the mean annual precipitation (MAP) greater than 505 mm may promote both biomass and soil C accumulation without causing severe soil water deficit. Moreover, the increase in mean annual temperature (MAT) could significantly promote the C accumulation in both biomass and soil of PF but accelerated the soil C loss of NF. Overall, our results indicate that afforestation in water-limited areas may exhibit higher potential to sequester C than naturally regeneration, and afforestation is worth promoting with careful consideration of planting density and rainfall zones to avoid causing excessive water depletion. This study has important implications for the forest management in water-limited areas particularly under global climate change.

1. Introduction

Afforestation is an effective measure to restore degraded land and enhance carbon (C) sequestration, and it is also important to alleviate the impacts of adverse climate change (Don et al., 2009; Yang et al., 2010). Afforestation may lead to extensive land-use changes, which may alter the key ecological processes and ecosystem functions, one of which is the C sequestration in forest above-ground biomass (AGB), below-ground biomass (BGB) and soils (Bárcena et al., 2014; Bukoski et al., 2022). The role of forest C stocks in AGB, BGB and soils has been widely discussed due to their importance in global C cycles (Dixon et al., 1994; Hanan et al., 2021; Spawn et al., 2020), indicating that substantial changes can be expected when implementing the afforestation (Don et al., 2009; Gao et al., 2020). Thus, understanding the dynamics of C stocks in forest AGB, BGB and soils following afforestation and the related controlling factors are of great importance for policy-making in relation to C sequestration through afforestation (Hanan et al., 2021; Morris et al., 2007).

Afforestation has been recommended in The Kyoto Protocol as an effective way to reduce atmospheric CO_2. However, recent studies have challenged the effectiveness of planted forest (PF) in this respect. For example, Lewis et al. (2019) demonstrated that the natural forest (NF) was, on average, 40 times than PF at storing total live biomass C (sequestering 12 and 0.3 Pg C per 100 Mha by 2100, respectively). Hua et al. (2022) reported that the C stock in AGB of PF was 32.8% lower than in NF, and even after a long period of recovery (>40 yr), this value

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was still 24% lower. These studies emphasize that the NF exhibits higher C sequestration than PF and expanding NF to store C, instead of planting more trees, may be a more effective way to mitigate climate warming (Cook-Patton et al., 2020). Nevertheless, the data used in these critical reviews mainly come from tropical or subtropical areas and lack the comprehensive comparison including the C stocks in AGB, BGB and soils, leaving that many questions regarding those topics remain limitedly answered. One of the questions is the differences in C stock changes between NF and PF in water-limited areas, especially at regional scale. During the last decades, there have been several great works promoting global afforestation, with those in water-limited areas estimated to account for 36%~42% of the potential restoration area (Bastin et al., 2019; Liu et al., 2022). However, C dynamics of forests in water-limited areas have received less attention than other biomes, such as tropical or subtropical areas (Hanan et al., 2021). This knowledge gap may lead to the current debate on whether PF or NF are more effective in sequestering atmospheric CO_2. Besides forest type, both forest biomass and soil C stock are affected by intrinsic factors (e.g., age), which are commonly represented by the relationship between C sequestration and forest age (Hudiburg et al., 2009; Ryan et al., 2004; Zhou et al., 2015). Extrinsic factors (e.g., climate or soil properties) can also affect the carbon stock and sequestration rate (Deng et al., 2014; Zhu et al., 2018a). Thus, exploring the temporal changes of C stocks in both biomass and soils and the controlling factors for PF and NF in water-limited areas is a necessary informational backdrop allowing ecosystem management practices to relate C sequestration values more precisely to afforestation.

The Chinese Loess Plateau is a typical ecologically vulnerable and water scarcity regions in the world due to intensive human activities, which have largely altered the land-use (Fu et al., 2017). To curb land degradation, the large-scale ecological restoration project named "Grain for Green" (usually converting cropland into grassland, planted shrubland, and planted forest) was implemented (Deng et al., 2014). The large-scale land-use change undertaken for the afforestation may indeed change the C sequestration capacity in the ecosystems regionally. Numerous studies at local scale have investigated C stocks changes in biomass or soils following afforestation (Chai et al., 2019; Chang et al., 2012; Jia et al., 2017; Zhang et al., 2013). Nevertheless, there has been little comprehensive assessment of C stock changes in both biomass and deep soil for PF and NF at regional scale. At present, only a few reports have comprehensively analyzed the soil C stock in the top 20 cm soil layers changes regionally (Chang et al., 2011; Deng et al., 2014) and deep soil C (>100 cm) (Li et al., 2021a), but their study did not consider biomass C and lacked the comparison between PF and NF. In addition, it still remains challenging to reveal the relationship between C stock and climate gradient due to the limited sample points in previous studies. Understanding the different role of PF and NF as C reservoirs in the long-term and responses to climatic gradients is crucial for improving predictions of current and future effects of changes in land use and land cover on the global and regional C cycle (Bonner et al., 2013; Marín-Spiotta and Sharma, 2013).

In this study, the arid and semi-arid Chinese Loess Plateau was chosen as typical research area in order to identify the C stock changes of NF and PF in water-limited areas. The objectives of this study were to (1) identify the difference of C stocks and allocation in AGB, BGB, and deep soils (0-200 cm) between the PF and NF; (2) determine the relationships of C stocks in biomass and soils with climatic factors, including mean annual precipitation (MAP) and temperature (MAT). We hypothesized that the C stocks and their changes of PF and NF might be significantly different, and the former may have more significant C sequestration potential in water-limited areas. We also compared the results in the Loess Plateau with those in the global temperate and tropical zones to discuss the effects of afforestation on C stock and sequestration among different regions.

2. Methods and materials

2.1. Study area

The Loess Plateau, which is located in the arid and semi-arid regions of North China (Fig. 1), covers an area of 640,000 km^2, and is the source of livelihood for more than 108 million population. The Loess Plateau is one of the largest and thickest loess plateaus in the world (Kapp et al., 2015), with an average thickness of 105.7 m (Zhu et al., 2018b). The mean annual precipitation was in the range of 300 to 800 mm, and the mean annual temperature varied from 4.3 to 14.3°C across the Loess Plateau (Fu et al., 2017). It is characterized by severe soil erosion and water scarcity due to the limited rainfall, high erodibility of loess soils, low vegetation cover, and intensive human disturbance (Fu et al., 2017; Lu and Stocking, 2000). Consequently, the Loess Plateau has been considered ecologically vulnerable due to the ever-increasing impacts of climate change and human activities. Current efforts are concentrated on improving the ecological functions by implementing "Grain for Green" project and "Natural Forest Protection" in the Loess Plateau. Large areas of degraded croplands have been converted to PF over the past several decades, resulting in significant changes in ecosystem structure and therefore the C stocks. At present, the forest area of the Loess Plateau has increased by about 50,000 km^2, and the existing forest area is about 123,700 km^2, accounting for 20% of the total area, with proportion of PF and NF being about 60% and 40%, respectively (Wang et al., 2018). Thus, the Loess Plateau provides an ideal platform for studying C stock changes in NF and PF of water-limited areas given long-term anthropogenic perturbations from degradation to restoration.

In the Loess Plateau, NF are mainly deciduous broadleaf forests of which the climax vegetation is the *Quercus liaotungensis* forest (Deng et al., 2013). The secondary forests naturally regenerated on abandoned land after many residents were displaced during the national conflict of 1842~1866, and the recovery period of *Q. liaotungensis* forests was determined to be roughly 150 years (Deng et al., 2013). As for PF, the tree species used to restore the degraded land comprise the native species (for example, *Pinus tabuliformis, Platycladus orientalis, Prunus armeniaca, Larix principis-rupprechtii, Ulmus pumila, Prunus davidiana*) and exotic species (for example, *Robinia pseudoacacia, Simon poplar, Populus bolleana*) (Peng and Coster, 2007). Of all the tree species, *Robinia pseudoacacia* are widely distributed in this region due to its drought resistance and fast growth (Liang et al., 2018).

2.2. Data collection

We constructed the forest biomass and soil C databases by conducting a literature search, field survey, and sampling. The literature search was through the *Clarivate Web of Science* (*www.webofscience.com*) and *China National Knowledge Infrastructure* (CNKI, *www.cnki.net*) with the keywords, "afforestation" or "Grain for Green" or "land-use change", "carbon", and "Loess Plateau" between 1988~2021, in which we focused on studies estimating the C stock in soil or biomass including AGB, BGB or their sums. We excluded studies that were derived from pot culture experiments or model simulation. Specifically, only the studies at plot or slope scale were used, and there was clear information on the two forest types (PF and NF). It should be noted that in order to maximize the sample size, the data on PF and NF in this study were collected independently rather than using the very limited paired data, which was always used in the data synthesis analysis work (Deng et al., 2014; Hua et al., 2022). Then, the raw data were either obtained from tables or extracted by digitizing graphs using the *GetData Graph Digitizer* (version 2.24). Of the data collected from the literature, the units of C stocks were all transformed into "Mg C ha^{-1}".

For each paper, the following information was compiled: sources of paper, location (longitude and latitude), climatic information (MAP and MAT), forest types (PF and NF), forest ages, tree diameter at breast height (DBH), tree height, stand density, total biomass, above-ground

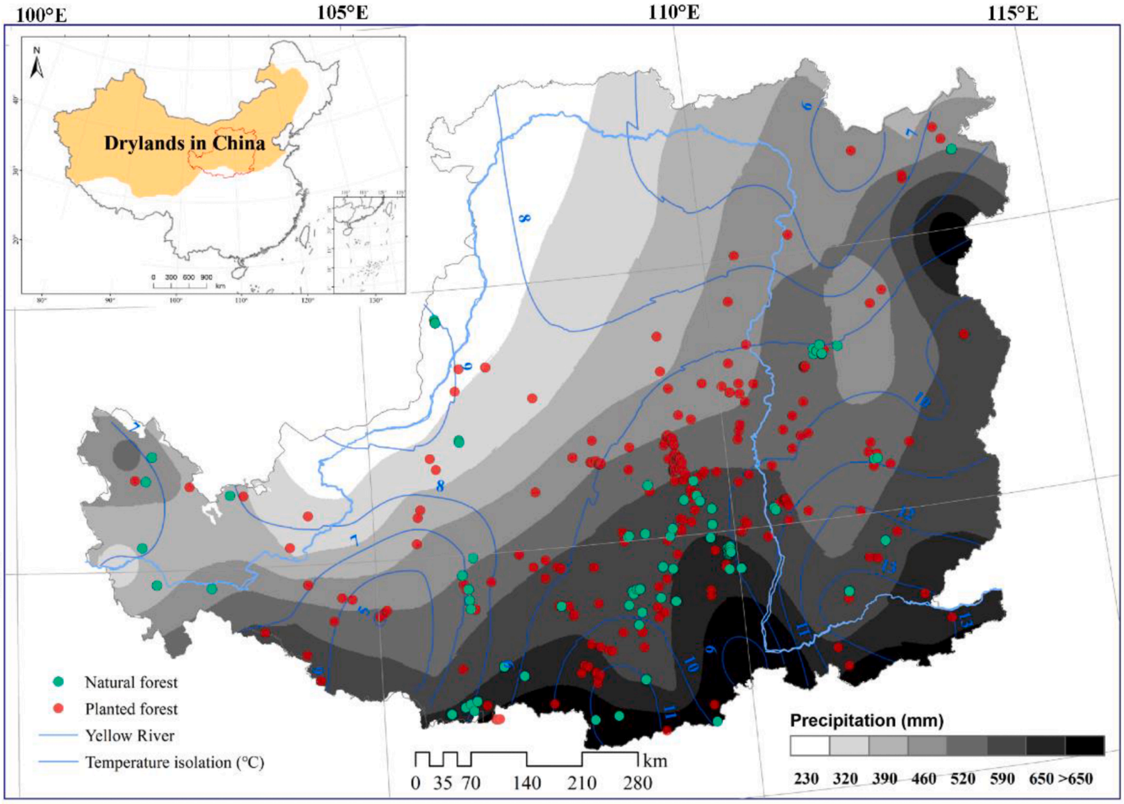

Fig. 1. The spatial distribution of sampling points for planted forest and natural forest in the Loess Plateau.

biomass, below-ground biomass, C content in biomass, amount of soil C content or soil C stocks to a max depth of 200 cm, soil bulk density (BD). Additionally, soil C stocks at all depths were summed together when sampled more than one depth. Since soil water was a key factor that restricted biomass or soil C sequestration in water-limited areas, we collected soil water data in PF and NF to a max depth of 500 cm with 100 cm interval. The detailed information on the data collection of soil moisture was described in our previous study (Li et al., 2021b). The final database contained 275 peer-reviewed papers and 9,348 observations, including 5,993 observations for forest biomass (2,009, 1,992, and 1, 992 observations for C stocks in AGB, BGB, and total biomass, respectively) and 3,355 observations for soil (1,067, 696, 796, and 796 observations for 0-20 cm, 20-100 cm, 100-200 cm, and 0-200 cm), of which 8,360 observations had clearly known age sequences. The 0-20 cm, 20-100 cm and 100-200 cm depth were usually considered as topsoil, subsoil and deep soil layers, respectively, to estimate soil carbon stocks in the Loess Plateau (Deng et al., 2014; Li et al., 2021a).

2.3. Calculation of biomass C stock

For biomass C, we recorded any estimates of dry biomass or C stored per unit area (Mg ha^{-1} or Mg C ha^{-1}) in total biomass, AGB, or BGB of PF and NF. Importantly, it is reported that the C stocks in tree biomass and soils in the Loess Plateau could account for 96.55~99.54% of that in the whole ecosystem (Cao and Chen, 2017). Therefore, the C stocks in understory vegetations were not taken into consideration in this study.

For those studies in which dry biomass or C stored per unit area were not reported, the C stocks in AGB (including stem, branch, leaf, and bark) and BGB (including root) were obtained by the biomass allometric growth models (BAGM) method using the parameter of DBH or (DBH and height). To increase the accuracy, the site-specific and species-specific BAGMs at different climate zones were collected according to previous literature in this region (Li and Liu, 2014; Cao and Chen, 2017; Yang et al., 2019). Since most of the BAGM results were per plant biomass (g or kg), the stand density (plants per ha) was used to convert the results into unit biomass or C stock (Mg ha^{-1} or Mg C ha^{-1}). For studies that reported only dry biomass per unit area, we estimated the C fraction based on the coefficient related to C content in stem, branch, leaf, bark, or root, rather than using one common constant which may also improve the accuracy.

2.4. Calculation of soil C stock

The soil C stocks were calculated using the following equation (Deng et al., 2014):

$$SoilCstock = \sum \mathrm{SOC}_i \times BD_i \times (1 - ST_i) \times D_i \tag{1}$$

where SOC_i is the soil C content of the ith layer (g kg^{-1}), BD_i is the soil bulk density of the ith layer (g cm^{-3}), and D_i is the depth of the ith layer (cm). ST_i is the volumetric percentage of coarse fraction (>2 mm) of the ith layer, and it can be set as zero in the Loess Plateau (Gao et al., 2020).

If the samples reported only soil organic matter (SOM), their SOC was calculated by the relationship between SOM and SOC using the formula (Guo and Gifford, 2002):

$$\mathrm{SOC} = 0.58 \times \mathrm{SOM} \tag{2}$$

For those studies in which BD had not been measured, we used the empirical relationship between SOC and BD in the Loess Plateau (Deng et al., 2014; Li et al., 2021a):

$$\mathrm{BD} = -0.1229\ln(\mathrm{SOC}) + 1.2901\left(\mathrm{SOC} < 60\mathrm{gCkg}^{-1}\right) \tag{3}$$

$$\mathrm{BD} = 1.3774e^{-0.0413}\mathrm{SOC}\left(\mathrm{SOC} > 60\mathrm{gCkg}^{-1}\right) \tag{4}$$

To increase comparability of data derived from different studies, we established localized parameters for estimating deep soil C stocks in the Loess Plateau (Text S1; Fig. S1 and S2). The original soil C data were converted to soil C stocks in the 200 cm using the depth distribution functions that was previously used by Jobbagy and Jackson (2000) according to the following equations:

$$\gamma_d = a - b\beta^d \tag{5}$$

$$X_{100} = \frac{\gamma_{100}}{\gamma_{60}} \times X_{60} \tag{6}$$

$$X_{200} = \frac{\gamma_{200}}{\gamma_{100}} \times X_{100} \tag{7}$$

where γ_d represents the proportion of the cumulative soil C stock from the soil surface to depth d (cm) over the soil C stock in 0-200 cm depth; a, b and β are the parameters that demonstrate the relative rate of decrease

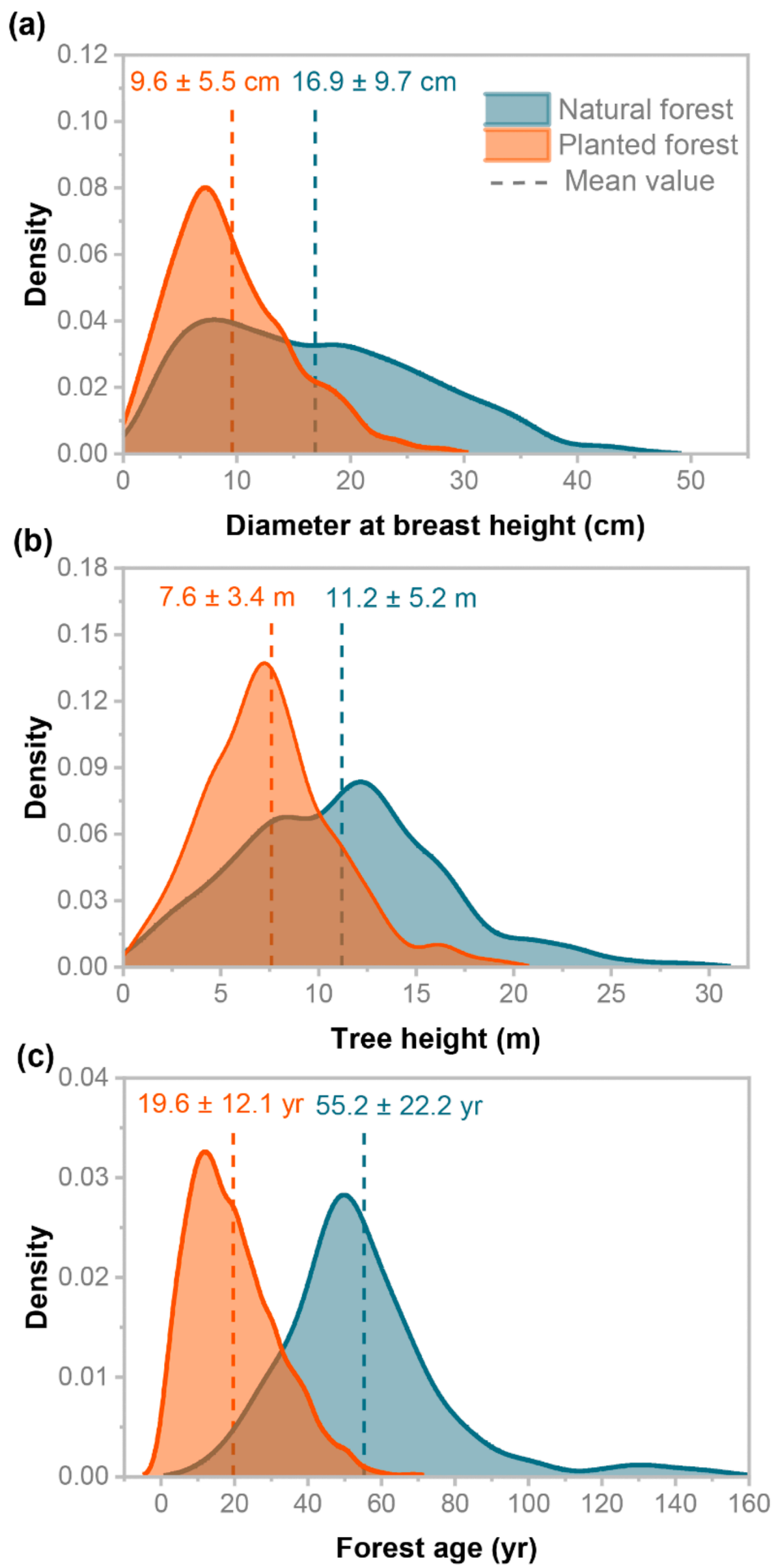

Fig. 2. The density distribution of (a) diameter at breast height (DBH), (b) tree height and (c) forest age of planted forest and natural forest in the Loess Plateau.

in the soil C stock with soil depth, and in this study, they are estimated to be 2.741, 2.590 and 0.998, respectively, as shown in Text S1; X_{60}, X_{100} and X_{200} denotes the soil C stock in the 0-60 cm, 0-100 cm, and 0-200 cm layers, respectively.

Here, we used Eq. (6) to estimate the soil C stock in 0-100 cm layer when the soil depth of individual study reached 60 cm but not 100 cm, and Eq. (7) to estimate the soil C stock in 0-200 cm layer when the soil depth reached 100 cm but not 200 cm. The specific procedure for the establishment of localized parameter can be found in Text S1 and Fig. S1 and S2.

2.5. Data analysis

The rate of biomass or soil C stock was estimated depending on the changes in biomass or soil C stocks along the forest age sequences. The first-order derivative of biomass or soil C stock with respect to the restoration age can represent the change rate of biomass or soil C stock. A linear regression equation between C stock and forest ages was conducted (Deng et al., 2014):

$$Cstock = f(age) = y_0 + k \times age \tag{8}$$

where k represents the rate of biomass or soil C stock change, and the constant y_0 may be different in different forest age groups.

The Kruskal-Wallis rank-sum test performed by the *kruskal.test* function in R package *agricolea* was used to test the difference in tree DBH, tree height, forest ages, C stocks of AGB, BGB, and soils between PF and NF. Differences were evaluated at $p < 0.05$. This method is equivalent to single-factor ANOVA but is used when only a few individuals are included in at least one of the samples, and the data are not normally distributed. A Piecewise regression model is selected to detect the nonlinear relationship between biomass or soil C stock and MAP and MAT based on the R package *segmented*. Piecewise regression with two segments separated by a breakpoint can be useful to quantify an abrupt change of the response function of a varying influential factor (Li et al., 2021a).

3. Results

3.1. C stocks and allocation

On average, the DBH (9.6 ± 5.5 cm) and height (16.9 ± 9.7 m) of PF were significantly lower than in NF (16.9 ± 9.7 cm and 11.2 ± 5.2 m) (Figs. 2a and 2b), and the forest age of NF (55.2 ± 22.2) was approximately three times as old as PF (19.6 ± 12.1) (Fig. 2c). The C stocks in both biomass and soils of PF were significantly lower than that of NF (Fig. 3). The average C stocks in AGB and BGB of PF were 22.0 ± 23.3 and 7.7 ± 7.7 Mg C ha^{-1}, and the corresponding values of NF were 49.5 ± 35 and 12.1 ± 6.8 Mg C ha^{-1}, respectively (Fig. 3). In addition, the C stocks in the 0-20 cm, 20-100 cm, and 100-200 cm soil depths of NF (46.3 ± 28, 92.4 ± 72, and 63.1 ± 36.6 Mg C ha^{-1}) were approximately 2.25, 2.38 and 1.74 times higher than those in PF (20.6 ± 15.1, 38.9 ± 39.1, and 36.3 ± 31.3 Mg C ha^{-1}). Totally, the biomass and soil C stocks in PF was on average 125.5 Mg C ha^{-1}, which was about half of that in NF (263.4 Mg C ha^{-1}) (Fig. 3).

Despite the large differences in C stocks, the relative proportions of biomass C stock and soil C stock in PF (23.6% vs 76.4%) and NF (23.2% vs 76.9%) were close to each other (Fig. 3), equaling approximately to 0.31. We also noted that for both PF and NF the proportion of soil C stocks in the 20-100 cm (31%~35.1%) and 100-200 cm (28.4% ~28.9%) layers was much higher than those in the 0-20 cm layer (16.4% ~17.6%), and the C stocks below 20 cm accounted for about 80% of the soil C pools (Fig. 3). Specifically, an interesting point showed that the relative proportions of C allocation in AGB, 0-20 cm and 20-100 cm soils were higher in NF (18.8%, 17.6% and 35.1%) than in PF (17.5%, 16.4% and 31%), while that in BGB and deep soils (100-200 cm) were relatively higher in PF (6.1% and 28.9%) than in NF (4.6% and 24%) (Fig. 3).

3.2. C stock changes along forest age gradients

Overall, NF performed more poorly than PF in both biomass and soil C sequestration rates with forest age increasing in this water-limited area (Figs. 4a and 4b). In detail, the sequestration rate of total biomass C in PF was 1.42 Mg C ha^{-1} yr^{-1} ($p < 0.001$) which was about 11 times that of NF (0.13 Mg C ha^{-1} yr^{-1}; $p > 0.05$) (Fig. 4a). In addition, the C stocks in AGB and BGB of PF increased at rates of 1.16 Mg C ha^{-1} yr^{-1} ($p < 0.001$) and 0.30 Mg C ha^{-1} yr^{-1} ($p < 0.001$) while that of NF exhibited non-significant changes (Table 1). Our results estimated the

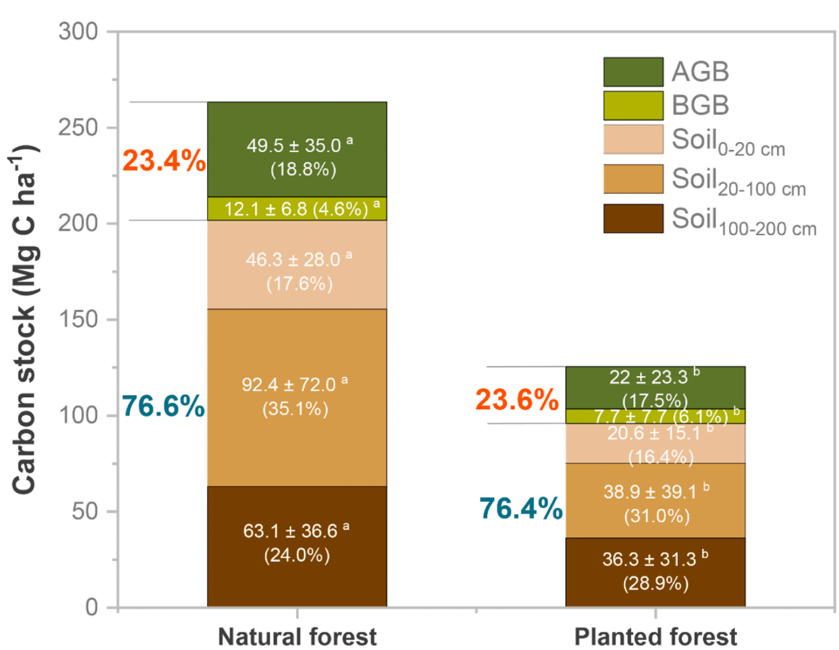

Fig. 3. The C stocks and proportions in biomass and soil for planted forest and natural forest in the Loess Plateau. The number in each bar denote mean value ± standard deviation; Percentage in parentheses denotes the proportion of C stock in each component; Different lower-case letters mean significant differences under the same component between planted forest and natural forest; AGB and BGB denote C stocks in the above-ground biomass and below-ground biomass, respectively; $Soil_{0\text{-}20cm}$, $Soil_{20\text{-}100cm}$ and $Soil_{100\text{-}200cm}$ denote the soil C stocks at 0-20 cm, 20-100 cm, and 100-200 cm depths, respectively.

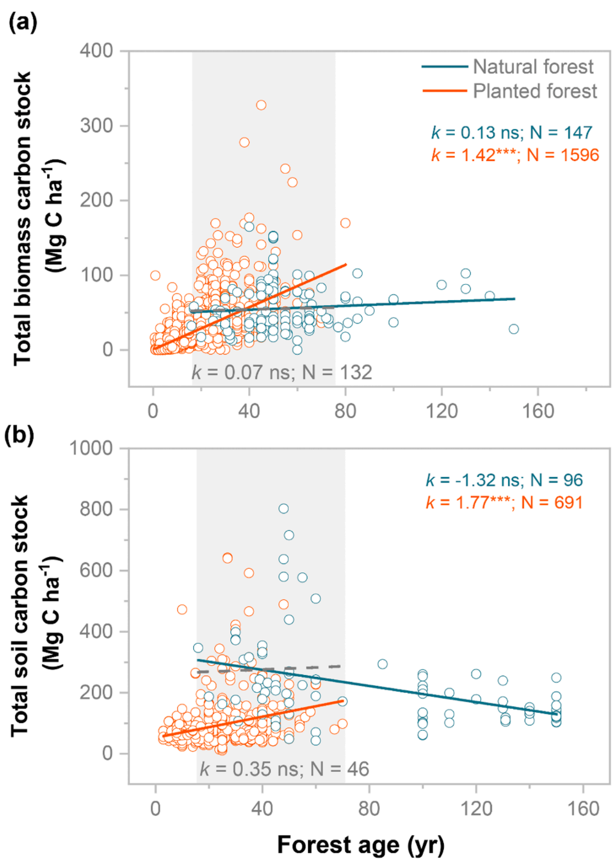

Fig. 4. The changes of total biomass and soil C stocks in planted forest and natural forest with forest age in the Loess Plateau. Grey rectangle and grey dashed line indicate the C stock changes of natural forest at similar age period with planted forest; "***", "**", "*", and "ns" indicate significant at $p < 0.001$, $p < 0.01$, $p < 0.05$ and $p > 0.05$, respectively.

Table 1
The linear regression equation between components of C stock and forest age in planted forest (PF) and natural forest (NF) in the Loess Plateau.

Components of C stock	Planted forest (PF)			Natural forest (NF)		
	Equation	*Sig*	N	Equation	*Sig*	N
AGB	y = 1.16x + 0.04	***	1613	y = 0.14x + 0.10	ns	145
BGB	y = 0.30x + 1.46	***	1596	y = -0.005x + 10.98	ns	145
$Soil_{0\text{-}20\ cm}$	y = 0.40x + 11.01	***	793	y = -0.18x + 62.54	**	155
$Soil_{20\text{-}100\ cm}$	y = 0.72x + 21.34	***	512	y = -0.71x + 158.19	**	96
$Soil_{100\text{-}200\ cm}$	y = 0.64x + 20.96	***	512	y = -0.35x + 95.69	***	96

Note: AGB and BGB denote the above-ground biomass and below-ground biomass, respectively; $Soil_{0\text{-}20\ cm}$, $Soil_{20\text{-}100\ cm}$, and $Soil_{100\text{-}200\ cm}$ denote the soil C stocks in 0-20 cm, 20-100 cm, and 100-200 cm depths, respectively; "***", "**", "*" and "ns" denote the significant levels at $p < 0.001$, $p < 0.01$, $p < 0.05$ and $p > 0.05$, respectively; N denotes the number of sampling points.

total soil C sequestration rate of PF to be 1.72 Mg C ha^{-1} yr^{-1} (Fig. 4b), whereas a decreasing trend was observed in soils of NF at a rate of -1.32 Mg C ha^{-1}yr^{-1} ($p < 0.001$) (Fig. 4b). The soil C stock change rates in 0-20 cm, 20-100 cm, and 100-200 cm of PF were 0.40, 0.72, and 0.64 Mg C ha^{-1}yr^{-1}, while they were -0.18, -0.71, and -0.35 Mg C ha^{-1}yr^{-1} in NF, respectively (Table 1). Across the similar age periods, C stock changes in both biomass and soils also exhibited lower rates in NF than in PF (Figs. 4a and 4b; grey rectangle area).

3.3. C stock changes along the precipitation and temperature gradients

Along the precipitation gradients, both biomass and soil C stock in PF and NF showed an initial decrease and then an increase where there was a turning point (Fig. 5). For instance, total biomass C stock in PF decreased at the rate of -0.14 Mg C ha^{-1} mm^{-1} ($p < 0.05$) and subsequently increased at the rate of 0.15 Mg C ha^{-1} mm^{-1} ($p < 0.001$) when MAP was more than 459 mm (Fig. 5a). In contrast, the total biomass C stock in NF changed slightly before the turning point (588 mm) and then increased significantly at a rate of 0.09 Mg C ha^{-1} mm^{-1} (Fig. 5a). Soil C stock in PF exhibited similar trends with biomass C with the change rates being -0.29 and 0.79 Mg C ha^{-1} mm^{-1} before and after the turning point (505 mm), respectively (Fig. 5b). Soil C stocks in NF deceased at rate of -1.38 Mg C ha^{-1}mm^{-1} when MAP reaching 581 mm and then remained relatively stable (Fig. 5b).

Along the temperature gradients, the trends of biomass and soil C stock changes in PF and NF were different (Fig. 6). For these two forest types, no effective turning points were detected as the total biomass C stock changed along the temperature gradients, in which total biomass C stock of PF increased linearly at rate of 3.68 Mg C ha^{-1} ℃$^{-1}$ ($p < 0.001$; Fig. 6a) whereas NF decreased at rate of 1.08 Mg C ha^{-1} ℃$^{-1}$ ($p > 0.05$; Fig. 6a). With the temperature increase, soil C stock in PF and NF decreased at -119.6 Mg C ha^{-1} ℃$^{-1}$ and -70 Mg C ha^{-1} ℃$^{-1}$ (Fig. 6b), respectively, before the turning points (7.2 ℃ and 7.8 ℃, respectively). However, after the turning point, soil C stock in PF increased at a rate of 9 Mg C ha^{-1} ℃$^{-1}$ ($p < 0.001$), but there was a continuously decreasing trend for NF (Fig. 6b).

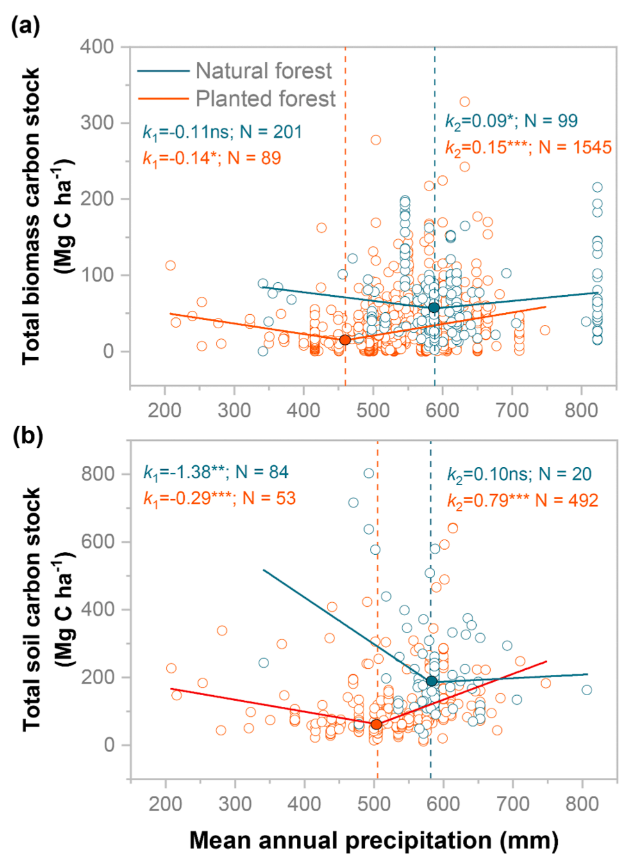

Fig. 5. The changes of biomass and soil C stocks in planted forests and natural forests along the precipitation gradients in the Loess Plateau. k_1 and k_2 indicate the regression slopes before and after the turning point; "***", "**", "*", and "ns" indicate significant at $p < 0.001$, $p < 0.01$, $p < 0.05$ and $p > 0.05$, respectively.

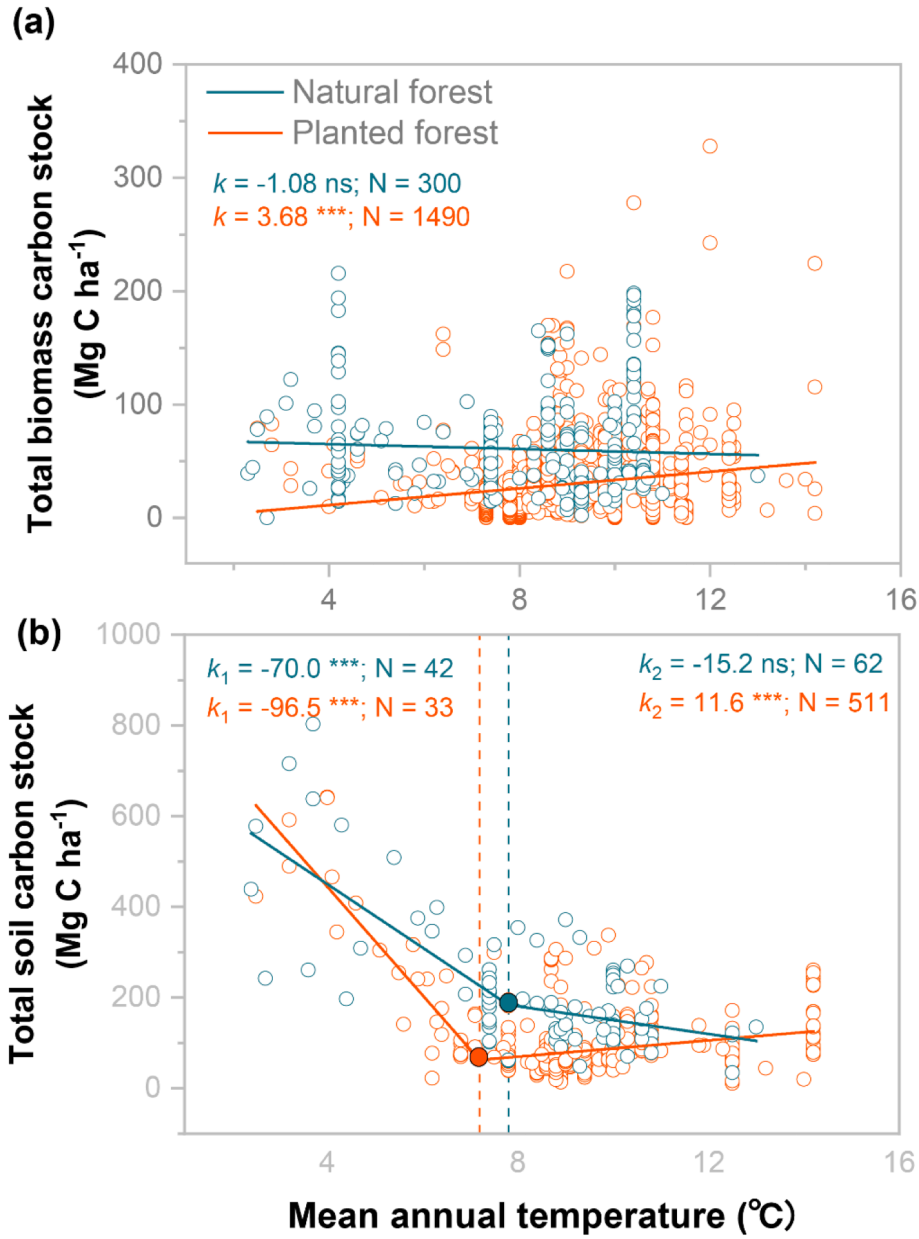

Fig. 6. The changes of biomass and soil C stocks in planted forest and natural forest along the temperature gradients in the Loess Plateau. k_1 and k_2 indicate the regression slopes before and after the turning point; "***", "**", "*", and "ns" indicate significant at $p < 0.001$, $p < 0.01$, $p < 0.05$ and $p > 0.05$, respectively.

4. Discussion

4.1. Differences of C stocks and allocation between planted and natural forests

Consistent with prevailing understanding (Hua et al., 2022; Lewis et al., 2019), NF stored more C than PF, both in biomass and soils (Fig. 3). However, in terms of C allocation patterns, our results showed that PF invested more biomass C to below-ground (6.5%) than NF (4.6%) and accumulated more soil C in deep layer (28.9%) than NF (24%) in the arid and semi-arid Loess Plateau (Fig. 3). At field scale, Sun et al. (2020) reported the similar results that the proportion of C stock in BGB of PF (*Robinia pseudoacacia*) was 5.9% higher than that in NF (*Quercus liaotungensis*), and the proportion of deep soil C stock (100~200 cm) was 8.4% higher in PF than NF in the Loess Plateau as found in Song et al. (2016). Theoretically, in water-limited areas, trees tend to input more biomass into below-ground to accelerate deep root growth, and therefore acquire more soil water and nutrients (Mokany et al., 2006; Ye et al., 2021). In the Loess Plateau, deep-rooted tree species replaced the original shallow-rooted crops, such as maize and millets, when implementing afforestation (Wang et al., 2015). Due to the limited rainfall and competetion for water and nutrient, deep roots in PF accumulated rapidly with increasing forest age, and it is reported that the fine root biomass in 100~2400 cm could account for approximately 90% of the total root biomass at 20-25 ages in this region (Li, 2019). In constrast, NF may avoid excessive competition for resources by adjusting stand density, and therefore relatively less biomass will be invested to deep soils. This is confirmed in this study that a rapid decrease in stand density of NF with increasing forest age was observed (Fig. S3).

Importantly, the total C stock in PF (125.5 Mg C ha^{-1}) in the Loess Plateau was lower than that in the global temperate zone (200.3 Mg C ha^{-1}) and tropical zone (172.9 Mg C ha^{-1}), but the C stock of NF in the Loess Plateau (263.4 Mg C ha^{-1}) was higher than that in the global temperate zone (142.4 Mg C ha^{-1}) and similar with that in the global tropical zone (263.9 Mg C ha^{-1}), as evident from comparing Fig. 3 and Fig. 7. The details of estimation of biomass and deep soil C stocks in global temperate and tropical zones were given in Text S2. Specifically, the relative proportions of biomass and soil C stock in the Loess Plateau were similar to those in the global temperate and tropical zones (approximately 1:3), except for NF in the global temperate zone (approximately 1:1). The inconsitsent proportion for NF in the global temperate zone could be attributed to the unmatched ages between the forest used in estimation of soil and biomass C stocks (Table S1), in which the forest age used in soil carbon estimation are much older than that for biomass carbon. Overall, this study highlights that forests in water-limited areas have considerable C stocks. In addition, we also emphasize the need to consider both biomass and soil carbon pools when assessing C stock in dryland forests, particularly in below-ground and deep soils.

4.2. Differences of C sequestration rates between planted and natural forests

Consistent with our hypothesis, PF exhibited higher biomass and soil C sequestration rates than NF (Fig. 4; Table 1). The forest age, MAP and MAT could explain 58.1% variation of biomass C stock and 74.4% variation of soil C stock changes for PF, which was higher than that of NF (22.3% and 49.1%, respectively) (Fig. S4). In detail, forest age had the highest importance in explaining the variation of biomass C stock for PF, while the MAT was the most important factor in explaining the variations of soil C stock for PF and both biomass and soil C stock for NF (Fig. S4). It should be noted that soil properties are also important influencing factors of carbon stock and sequestration, and more related data should be collected to investigate this issue.

Particularly, with forest age increasing, C stocks in AGB and BGB of NF changed non-significantly while that in soils exhibited significantly decreasing trends (Table 1). A possible explanation for the quick C increment in PF may be that tree species used to afforest in this area were usually fast-growing and high-yielding (Yu et al., 2019), and most PF was in the young stage (Fig. 2c) and thus maintained a high growth rate. However, the rates of C sequestration in both biomass and soils of PF did not always increase linearly, in which there was an increasing trend in the first 20 years and then decreased sharply at 21-30 age period (Fig. S5). We attributed this phenomenon to the changes in soil water status due to its essential role in controlling vegetation productivity and C sequestration in water-limited areas (Huang and Shao, 2019). Our previous studies confirmed that both soil water content and its availability decreased significantly with forest age increasing, and soil water status deteriorated severely during the 21-30 age period in which they approached a state where vegetation failed to uptake (Li et al., 2021b, 2021c). Excessive water depletion may reduce the rate of biomass C accumulation, which in turn affects soil C. The strong tradeoff between soil water retention and C sequestration in PF has been reported by many scholars in this region (Feng et al., 2016; Lu et al., 2014).

Compared with PF, soil moisture in NF in the Loess Plateau is overall higher (Fig. 8) and it does not seem to decrease with forest age increasing (Fig. 9). Then, an interesting question arises why biomass or soil C stocks in NF do not show significant increases with forest age increasing? This seems to be contrary to the existing common knowledge (Cook-Patton et al., 2020). First, the non-significant changes of C stocks in AGB, BGB or total biomass in NF may be due to self-thinning during long-term succession in water-limited areas. The negative relationship between stand density and forest age well explained this phenomenon (Fig. S3). Similarly, Sea and Hanan (2012) presented data from savanna sites in South Africa to suggest that self-thinning among woody plants in water-limited areas could be detected due to the competition for resources. Therefore, at ecosystem scale, the decrease in biomass due to lower stand density may offset the increase in individual biomass with age. Second, the non-significant increases in NF biomass may also be due to the limited growth potential with age (Odum, 1969). For example, Zhu et al. (2018a) reported that the biomass growth potential of North American mature forests appeared limited and reached biomass saturation. Third, the significant decreases in soil C stock in NF across all ages may be driven by the quick soil C accumulation around 50 years, and after this period, soil C stock seemed to show a stable trend (Fig. 4b). Deng et al. (2013) compared soil C stock (0~60 cm) at different vegetation succession stages along 150-year chronosequence of NF in the Loess Plateau. They found that soil C stock increased rapidly and tended to be at their highest at roughly the 50-year restoration mark, and concluded that soil C stock accumulated mainly in the early restoration stages. In the later stages of succession, C input (for example, root biomass, root exudate, litter, microbial-derived C) and output (for example, microbial mineralization) may reach a state of equilibrium, although the overall trend in soil C stocks was decreasing (Deng et al., 2013).

Globally, the biomass C sequestration rate of NF was about 3-6.9

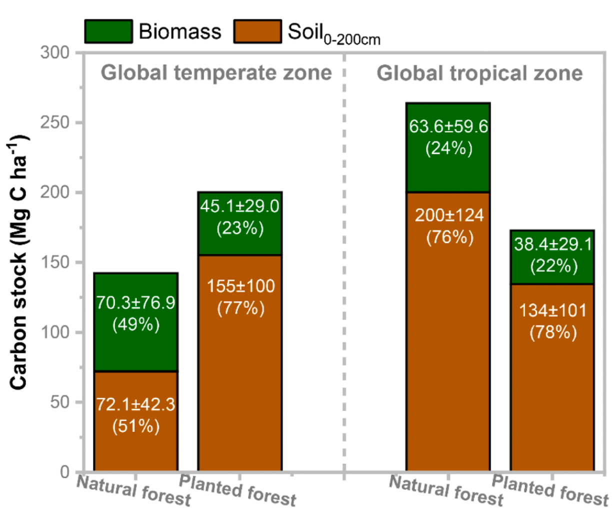

Fig. 7. Biomass and soil carbon stock of planted and natural forests in global temperate and tropical zones. The number in each bar denote mean value ± standard deviation; Number in parentheses denotes the proportion of carbon stock. The detail information on the synthesized data can be seen in the supplementary Text S2.

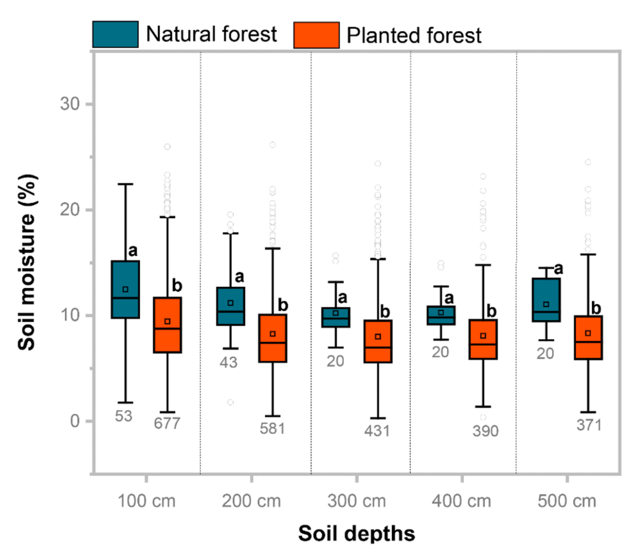

Fig. 8. The average soil moisture at different depths in planted forest and natural forest in the Loess Plateau. Number in brackets denote the number of observations; Different lower-case letters mean significant difference.

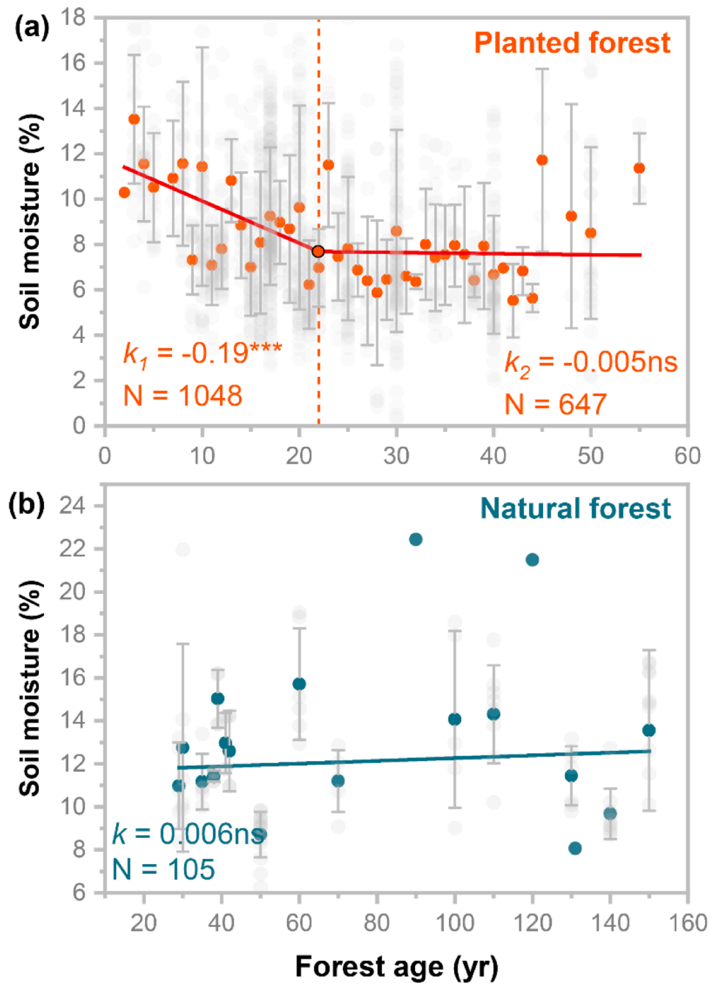

Fig. 9. Temporal changes of deep soil moisture in planted forest and natural forest with age increasing in the Loess Plateau. "***", "**", "*", and "ns" indicate significant at $p < 0.001$, $p < 0.01$, $p < 0.05$ and $p > 0.05$, respectively.

times higher than that of PF in both temperate and tropical zones (Figs. 10a and 10c), which was contrary to the results in the Loess Plateau (Fig. 4a). Consequently, estimation of biomass C sequestration rates in dryland PF using global data may result in underestimation. Interestingly, in the global temperate and tropical zones, soil C sequestration rate in NF was much lower than that in PF (Figs. 10b and 10d). In detail, the soil C sequestration rate of NF in temperate zone decreased with aging (-0.17 Mg C $ha^{-1}yr^{-1}$), while that of PF increased with rate of 0.96 Mg C $ha^{-1}yr^{-1}$ ($p < 0.001$) (Fig. 10b). Moreover, there was no significant change in tropical zone for soil C stocks in NF (0.38 Mg C $ha^{-1}yr^{-1}$) while that in PF increased with rate of 2.24 Mg C $ha^{-1}yr^{-1}$ ($p < 0.001$) (Fig. 10d). These results were consistently with those in the Loess Plateau, which may support an important implication that afforestation may promote both biomass and soil C accumulation in whether drylands or globe.

4.3. Effects of climate on C stock changes in planted and natural forests

An understanding of the relationship between forest C stock and climate is needed to predict the impacts of climate change on C dynamics (Deng et al., 2014; Stegen et al., 2011). However, a consensus on the responses of biomass and soil C to climate factors has yet to be achieved (Deng et al., 2014; Raich et al., 2006; Stegen et al., 2011). Our results showed that MAP exerted non-linear impacts on the changes of biomass and soil C stocks in both PF and NF (Fig. 5), indicating that the effect of MAP on forest C stock changes in water-limited areas cannot be simply characterized by a linear model, which may lead to biased estimates. With the MAP increase, both the biomass and soil C stocks in PF showed a trend of first decreasing and then increasing (Fig. 5), which could be attributed to the changes of soil moisture induced by MAP (Saiz et al., 2012; Barbeta et al., 2015). Soil moisture is the critical limiting factor for vegetation productivity in the Loess Plateau (Huang and Shao, 2019), and its deficit will directly affect forest C sequestration (Granier et al., 2007). In this study, we provided evidence that the soil moisture at 0~500 cm depth of PF showed a nonlinear change along the precipitation gradient, and the soil moisture in the depth of 300~400 cm and 400~500 cm first decreased and then increased with the increase of MAP, and the inflection point was about 480 mm (Fig. S6). Before the turning point (e.g., MAP < 480 mm), the slight increase in MAP may stimulate plant growth and then intensify the water demand. However, such an increment in MAP could not replenish the soil water decrease induced by plant consumption (Li et al., 2021b). This may intensify the soil water deficit, which in turn affects C sequestration in both biomass and soils. This is probably the reason why biomass and soil C stock exhibit a first decrease and then an increase along the precipitation gradients. Considering the responses of biomass and soil C stocks, and soil moisture to the MAP in PF, in which the turning points were approximately 459 mm, 505 mm and 480 mm, respectively, we recommend planting forests in areas above 505 mm. This not only promotes the accumulation of biomass and soil C stocks but also cause no severe soil water deficits.

Along the temperature gradients, no turning points were detected in

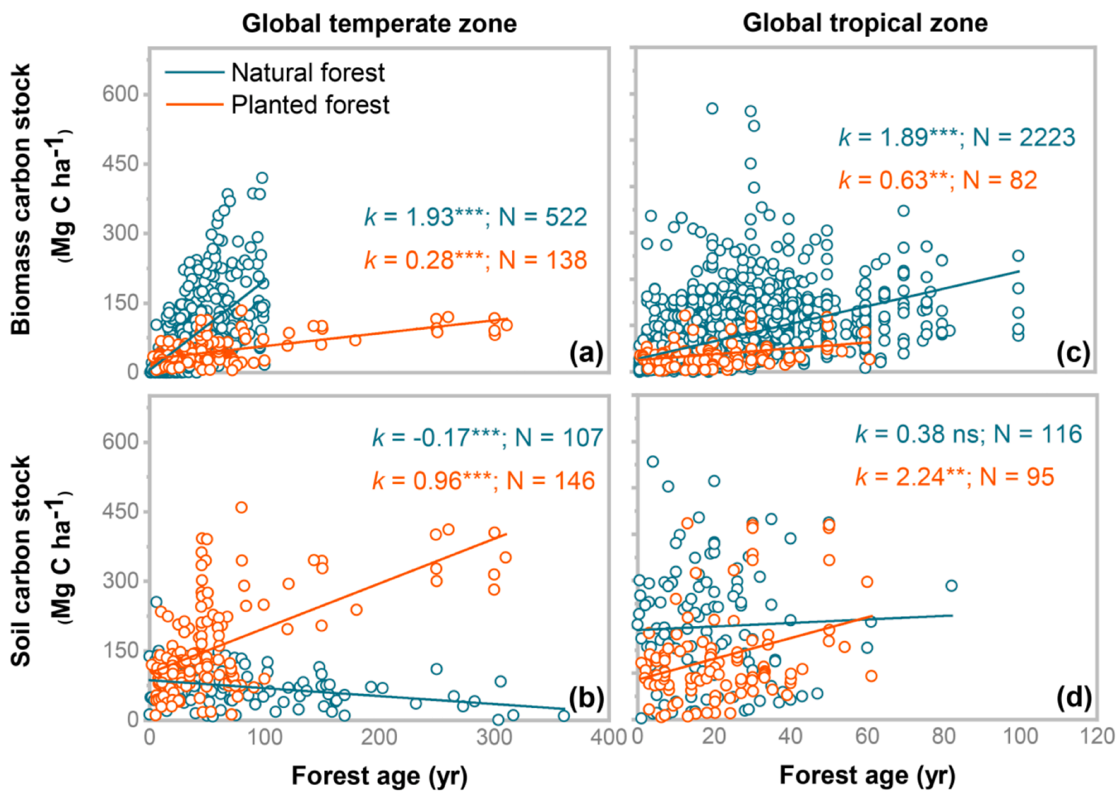

Fig. 10. Changes of biomass and soil carbon stock of planted and natural forests with forest age in global temperate and tropical zones. "***", "**", "*", and "ns" indicate significant at $p < 0.001$, $p < 0.01$, $p < 0.05$ and $p > 0.05$, respectively. The detail information on the synthesized data can be seen in the supplementary Text S2.

biomass C stock changes for PF and NF (Fig. 6). The increase in MAT could promote the accumulation of biomass C stock in PF while exerting little influences on NF (Fig. 6a), indicating the biomass C pool in the mature forest was less sensitive to temperature (Besnard et al., 2021). This also suggests that global warming may increase the biomass C accumulation in PF rather than NF in water-limited areas. However, different responses for soil C stock in PF and NF were observed along the temperature gradients (Fig. 6b). NF exhibited continuous reductions to varying rates with the temperature increase (Fig. 6b). This sharp decrease of soil C stock before the turning point may be attributed to the changes from alpine altitude in the west to the loess hilly region in the east because warming may stimulate microbial activity and accelerate the mineralization of soil C (Cates et al., 2019; Song et al., 2021), particularly there is no significant increment in the biomass C stock of NF (Fig. 6a). After the turning point, the soil C accumulation in PF through biomass input may exceed the mineralization induced by warming compared with NF, and exhibited an accumulation trend (Fig. 6b). This implies that warming exerts different impacts on biomass and soil C stocks in NF and PF, and warming may promote the C sequestration in PF but accelerate the C loss in NF (Wang and Huang, 2020; Fig. 6). Overall, with global warming intensifying, the role of PF and NF in C sequestration should be revisited in water-limited areas. Promoting plantations in water-limited areas may be an effective measure to mitigate global warming, provided that it does not lead to excessive soil water consumption.

4.4. Limitations and implications

This synthesis features a relatively larger number of observations, which offers the relatively accurate estimate of C sequestration for PF and NF across the arid and semiarid Loess Plateau. However, strict accuracy is limited due to the uneven distribution of data collected in each group. Additionally, many studies have no long-term observations, which may add to the uncertainty. Therefore, considerable knowledge gaps about the differences of C dynamics between NF and PF still exist, for example, the C stocks in litter and understory vegetation, and especially soil inorganic carbon. More paired data and model simulations are needed to further compare the changes of C sequestration between natural and planted forests and revealed the underlying mechanisms. The observation and model simulation should be combined to investigate the carbon dynamics over a long period. Despite these limitations, our synthesis provides several exciting and informative implications as following that reflect the C sequestration between PF and NF in water-limited areas, which may contribute to forest management in the regions.

When assessing the dryland forest C stock, the components of AGB, BGB, top- (<100 cm) and deep soils (>100 cm) should be considered. It is estimated that the global dryland C pools in AGB and BGB could account for about 22% and 38% of these total C pools, respectively (Spawn and Gibbs, 2020). However, tree biomass in water-limited areas is often set at or near zero (that is, underestimated) (Hanan et al., 2021). In addition, total soil C stock in deep layers (0-200 cm) in global drylands has been reported to be equivalent to approximately 32% of global soil C pool (Plaza et al., 2018). The latest report illustrates that dryland forests account for about 27% of the world's forest area (Patriarca et al., 2019). Schimel (2010) found that PF in water-limited area, such as the Yatir forest in Israel, sequestered C at rates were similar to those of pine forests in continental Europe, indicating that the C sequestration potential of dryland afforestation may be high.

Notably, dryland afforestation, if carefully planned and implemented, may provide local benefits, including prevention of soil erosion, recreation, local evaporative cooling, and possibly increased precipitation (Syktus and McAlpine, 2016; Yosef et al., 2018; Stavi., 2019). Some scholars also argued that dryland afforestation had less potential to mitigate climate change (Rohatyn et al., 2022), but they also acknowledged that dryland afforestation could sustain large carbon sinks over a long-time due to their large potential soil C stocks (Qubaja et al., 2020). The uncertainty of C sequestration by dryland afforestation in mitigating climate change is currently under intense discussion, and it is necessary to assess the mitigation potential of drylands for climate change in the future (Rohatyn et al., 2022; Rotenberg and Yakir., 2010; Hanan et al., 2021). In addition, extending the results in our study to the global carbon cycle needs to be cautious. It remains great challenges to quantify the detailed distribution of dryland forest including NF and PF around the world, and evaluate the effects of vegetation restoration on C sequestration in specific climate zone.

Under the premise of considering the water resource carrying capacity, the idea of afforestation in water-limited areas to help sequester C should be preferred to that of forest regeneration naturally. Despite the low vegetation cover of dryland forests compared to other biomes, their role in the global C cycle has been highlighted (Ahlstrom et al., 2015; Bastin et al. 2019; Poulter et al. 2014; Rotenberg and Yakir, 2010). However, the threat to water resources posed by dryland afforestation has also caused widespread concern and was once an influential factor in reducing afforestation in water-limited areas. Consequently, it is critical to identify a rainfall threshold for dryland afforestation that will not cause transitional water depletion and support sustainable C sequestration. Dryland ecosystems are limited by water availability and are vulnerable to climate change, which is particularly dependent on future precipitation changes. Based on the piecewise regression model, this study analyzed the thresholds between forest C stock, soil moisture and precipitation in the Loess Plateau, which may provide ideas for achieving synergistic development of C sequestration and water conservation in dryland afforestation. Future research on the reciprocal feedback mechanisms between forest C pools and climate change in water-limited areas should be strengthened, because the changes in precipitation would initiate dryland forest productivity, vegetation structure and soil C stocks.

5. Conclusions

Our synthesis in the China's Loess Plateau showed that afforestation in water-limited areas exhibited much higher advantages in sequestering carbon into biomass or soil than that of naturally regenerated forest, in which climate factor, e.g., mean annual precipitation and temperature, exerted strong and nonlinear impacts. However, severe soil moisture depletion induced by afforestation should be paid attention. Specifically, we identified the threshold related to precipitation to achieve the synergistic effect of carbon sequestration and water conservation during afforestation in water-limited areas, according to the responses of carbon stock and soil moisture to precipitation. Overall, the role of planted forest and natural forest in water-limited areas should be reconsidered when carbon sequestration is the goal of management. Our synthesis suggests that afforestation in water-limited areas may be worth promoting in the future with careful consideration of planting density and rainfall zones to avoid causing excessive water depletion.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.agrformet.2023.109419.

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