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Advantage of mixed trees in the trade-off between soil water storage and tree biomass: A meta-analysis from artificially planted forests in Chinese Loess Plateau

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ABSTRACT

Afforestation is an effective measure to combat land degradation and mitigate climate change. However, afforestation tends to consume a tremendous amount of soil moisture while increasing vegetation biomass and coverage. Although convincing evidence indicates that mixed trees have higher resistance and resilience to climate change and natural disturbance than pure trees, it is unclear how tree mixtures affect the relationship between soil water storage and tree biomass. By conducting a meta-analysis of 86 observations from 27 studies, we showed that there was a trade-off between soil water storage and tree biomass in artificially planted trees on the Loess Plateau, with an average root mean square deviation (RMSD) value of 0.22. The RMSD value between soil water storage and tree biomass for mixed trees was significantly lower than that for pure trees, and the relative benefits of the trade-off were biased toward soil water storage. In dry areas (aridity index (AI) < 0.3), the RMSD value between soil water storage and tree biomass of artificially planted trees was the highest, and this value of mixed trees was significantly lower than that of pure trees. In terms of different plantation ages, the RMSD value between soil water storage and tree biomass for mixed trees was significantly lower than that for pure trees in plantations aged >20 years. Additionally, RMSD values between soil water storage and tree biomass under different afforestation patterns were negatively correlated with the initial water storage and soil organic carbon content. Our results show that tree mixtures optimize the trade-off between soil water storage and tree biomass in arid and semiarid areas.

1. Introduction

Ecosystem services (ESs) refer to the benefits which people obtain from the ecosystem (Costanza et al., 1997). However, people often seek to maximize the supply of one ES, which may lead to a decrease in the supply capacity of another ES, and ultimately lead to a trade-off between different ESs (Maes et al., 2012; Howe et al., 2014; Juerges et al., 2021). Afforestation is an important means to alleviate the pressure on natural forests, and it has great potential to provide a variety of commodities and ESs, such as increasing wood and fiber production, reducing soil erosion, alleviating climate warming, and increasing recreational and esthetic values (Berthrong et al., 2012; Knoke et al., 2014; Valente et al., 2021). However, planted forests are mainly carried out as monocultures, which usually have many negative effects on the supply of ESs (Asner et al., 2008; Felton et al., 2010; Fragniere et al., 2021). Especially in arid and semiarid areas, due to evapotranspiration, canopy interception, and root water absorption, fast-growing and high-yielding single tree species often exhibit a trade-off between soil water and vegetation biomass (Kirilenko and Sedjo, 2007; Chisholm, 2010; Yu et al., 2019; Lan et al., 2021). Determining the best method to balance vegetation biomass and soil water storage is a common concern in arid and semiarid environments. In contrast, mixed forests are more advantageous for improving soil fertility, preventing soil erosion, and enhancing carbon sequestration, biodiversity, and other ESs, making practices oriented toward mixed tree species a new paradigm for increasing the supply of ESs (Hooper et al., 2012; Felipe-Lucia et al., 2018; Ammer, 2019; Pardos

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et al., 2021). However, the impact of species diversity on the trade-off between soil water storage and tree biomass remains unclear.

Inherent differences in structural, physiological, and functional characteristics of tree species usually affect the interactions between vegetation biomass and soil water among multiple species (Bispo Pda et al., 2016; Forrester and Bauhus, 2016; Schnabel et al., 2019). Multi-species structures can improve the utilization efficiency of resources (e.g., light, water, and nutrient resources) from increased niche complementarity, thereby reducing competition between species (Barbier et al., 2008; Morin et al., 2011; Anderegg et al., 2018). Previous studies have shown that increased species diversity generally reduces water stress caused by climate warming and promotes a sustainable increase in vegetation productivity (Amazonas et al., 2018; Pardos et al., 2021). In contrast, vegetation with the same growth cycle or leaf phenology usually leads to increased competition for resources among different species (Drossler et al., 2018; Gong et al., 2020). For example, Borden et al. (2016) found that the roots of poplars and alders may overlap and compete for water sources, thereby reducing the productivity of vegetation. Similarly, de-Dios-García et al. (2018) showed that mixed forest stands formed only by conifers may show higher competition for resources than conifer-broadleaved admixtures due to more similar plant characteristics. In addition, differences in the impacts of mixed forests on the trade-off may also be caused by plant type, forest age, topographical conditions, soil physical and chemical properties, and climatic conditions (Forrester, 2014; Bonal et al., 2017). Therefore, the quantitative synthesis of multiple studies may help quantify the overall effects of tree mixtures on the trade-off between soil water storage and tree biomass and determine the sources of variation (Gurevitch et al., 2018).

The highly erodible loessial soil, steep topography, frequent high-intensity rainstorms, and improper land use have led to severe land degradation in the Loess Plateau (Shi and Shao, 2000; Liu et al., 2007). To control soil erosion and restore the ecological environment, the Chinese government has launched the "Grain for Green" program (GGP) in the Loess Plateau, which aims to restore degraded arable land to woodland, shrubs, and grassland (Cao et al., 2009). Large-scale afforestation not only significantly reduces runoff and sediment erosion but also strengthens a variety of ESs, such as increasing carbon storage and soil fertility (Chen et al., 2015; Li et al., 2019). However, plantation forests are mainly composed of fast-growing, short-rotation single species (e.g., *Robinia pseudoacacia*), which exacerbate soil water depletion and form dry soil layers (Wang et al., 2015; Jia et al., 2017). Extreme consumption of soil moisture further causes the degradation of ecological functions in plantation forests, such as low biomass and loss of biodiversity (Cao et al., 2011; Fang et al., 2016). Mixed forests have become one of the afforestation patterns on the Loess Plateau due to their advantages in controlling water and soil loss and increasing carbon storage (Gao et al., 2018; Gong et al., 2020). Although previous studies have investigated the trade-offs between soil water and vegetation biomass on the Loess Plateau (Lu et al., 2014; Su et al., 2021), these studies mainly focused on pure trees, and there are few studies on the trade-offs between soil water and vegetation biomass in mixed forests. In addition, most studies have been focused on a single species or specific location, while few studies have examined the differences between soil water storage and tree biomass in pure trees and mixed trees on the entire Loess Plateau.

To address this knowledge gap, we studied the relationship between soil water storage and tree biomass under different afforestation patterns (pure trees and mixed trees) on the Loess Plateau. We assume that there is a trade-off between soil water storage and tree biomass under different afforestation patterns. Specifically, the objectives of this study were to determine (1) whether there are differences in the trade-off between soil water storage and tree biomass between different afforestation patterns; and (2) whether plantation age, climate, and soil properties affect the trade-offs under different afforestation patterns.

2. Materials and methods

2.1. Data compilation

The Web of Science and the China National Knowledge Infrastructure (CNKI) were used to search for peer-reviewed studies published between January 1985 and July 2021. Our search terms included "tree mixture" or "mixed forest" or "mixed plantation" or "plant diversity" or "monoculture" and "plant biomass" or "vegetation biomass" or "tree biomass" or "plant production" and "soil water" or "soil moisture" and "Loess Plateau". To avoid publication bias, the following criteria were used to screen the literature:

(1) The experiments were conducted on the Loess Plateau;
(2) Both tree biomass and soil moisture were reported;
(3) The study includes only the data from field surveys and excludes data from laboratory control experiments; and
(4) The study focused only on artificially planted trees, excluding natural forests.

A total of 86 observations from 27 peer-reviewed journal articles were collected (Table S1; Fig. 1). The raw data of plant biomass and soil water storage for different afforestation patterns were extracted from tables. When the data were represented graphically, the original values were extracted by SigmaScanPro version 5.0 (Systat Software Inc., Point Richmond, CA, USA). Other information, including latitude, longitude, mean annual precipitation (MAP), mean annual temperature (MAT), potential evapotranspiration, elevation, slope angle, sample size, and plantation age, was also recorded for the study. For comparison purposes, afforestation patterns were divided into pure trees and mixed trees (Gong et al., 2020). Plantation ages were divided into three categories: 0–20 years, 20–30 years, and > 30 years. The aridity index (AI) was calculated as the ratio of precipitation to potential evapotranspiration to quantify dry conditions and divided into three levels: < 0.3, 0.3–0.5, and > 0.5 (UNEP 1992; Wei et al., 2010).

2.2. Data calculation

2.2.1. Soil water storage

We calculated soil water storage according to the following formula:

$$SWS_i = S_i \times D_i \times H_i \quad (1)$$

where SWS_i represents the soil water storage of the *i*-th layer (mm) and

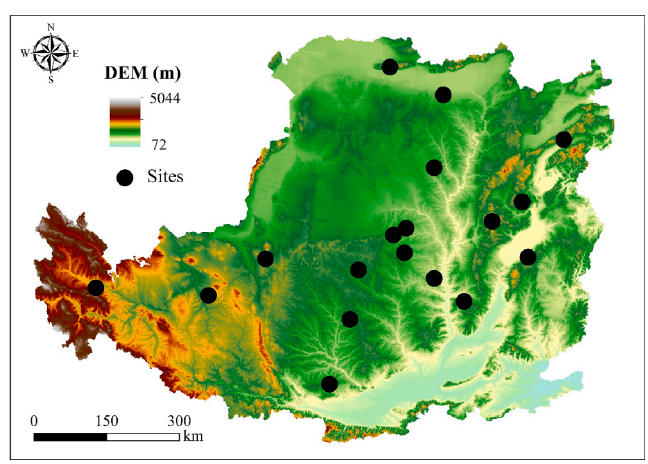

Fig. 1. Distribution of study sites included in this meta-analysis. **Note:** DEM: Digital Elevation Model. The DEM data in this study were obtained from the Resource and Environment Data Cloud Platform (http://www.resdc.cn/Default.aspx).

S_i, D_i, H_i represent the soil water content (%), soil bulk density (BD) (g cm^{-3}) and soil depth (mm) of the i-th layer, respectively. The soil depth of 0–100 cm was chosen for this analysis, as the greater depth is most relevant for comparison of large-scale vegetation, as has been shown in comparative studies (Lu et al., 2014; Su et al., 2021).

2.2.2. Tree biomass

Tree biomass is an integral part of the structure and function of forest ecosystems (Helin et al., 2013; Yang et al., 2017). However, directly measuring tree biomass is usually costly and time-consuming (Brown, 2002). In contrast, the tree biomass equation has a high degree of accuracy, efficiency, and simplicity and is the most commonly used method for estimating tree and forest biomass on various temporal and spatial scales (Chave et al., 2014; Paul et al., 2016). Therefore, in this study, we calculated plant biomass based on the biomass equation formulated in previous studies on the Loess Plateau (Table 1) (Yang et al., 2019; Luo et al., 2020).

2.3. Calculation of trade-offs

Correlation analysis was applied to reveal the trade-offs and synergistic relationships between each ES pair (Maes et al., 2012; Dade et al., 2019). In addition, the root mean square deviation (RMSD) proposed by Bradford and D'Amato (2012) was used to quantify trade-offs between two or more ESs. Specifically, the RMSD value quantifies the difference between the standard deviation of a single ES and the standard deviation of the average ES (Bradford and D'Amato, 2012; Qiu et al., 2021). The higher the RMSD value, the higher the trade-off between a pair of ESs. In two-dimensional coordinates, the RMSD value represents the distance from the coordinates of the ES pair to the 1:1 line. The larger vertical distance between a point and the 1:1 line indicates a higher RMSD value, and the relative position of data points to the line can indicate which ES receives more benefit from the trade-off (Bradford and D'Amato, 2012; Lu et al., 2014) (Fig. 2).

Before calculating the RMSD, the data were standardized to eliminate the influence of dimensions (Bradford and D'Amato, 2012; Wang et al., 2022). The standardized calculation formula for ESs is as follows:

$$\overline{ES} = (ES_{obs} - ES_{min})/(ES_{max} - ES_{min}) \tag{2}$$

where $\overline{\mathrm{ES}}$ is the standardized value of ESs, ES_{obs} is the observed value of ESs, and ES_{min} and ES_{max} are the minimum and maximum observed values of ESs, respectively.

The RMSD value was calculated as follows (Lu et al., 2014; Feng et al., 2017):

$$RMSD = \sqrt{\frac{1}{n-1}\hat{A}\cdot\sum_{i=1}^{n}\left(\overline{ES_i} - ES_{exp}\right)^2} \tag{3}$$

where n is the number of observations; $\overline{\mathrm{ES_i}}$ is the standardized value of ES_i; and ES_{exp} is the expected value of n ESs.

2.4. Data analysis

The Shapiro–Wilk test and Levene's test were used to test the normality and homogeneity of the data, respectively. We employed a mixed effect model with the *lme4* package (Bates et al., 2015) to analyze the effects of afforestation patterns and their interactions with plantation age and the AI on the trade-off between soil water storage and tree biomass. Afforestation patterns, plantation age, the AI, and their interactions were taken as fixed effects, and each "study" was set as a random effect (Hume et al., 2018; Sun et al., 2022). We chose the optimal model based on the Akaike information criterion (AIC) (Ma and Chen, 2016; Bestion et al., 2021) (Table S2). The *emmeans* package was used for post hoc comparisons. Pearson correlation analysis was performed to examine the relationship between soil water storage and tree biomass as well as the relationships between soil properties (soil organic carbon (SOC) content and initial water storage) and RMSD values Jian et al., 2015. Significance was assessed at $P < 0.05$. Unless otherwise stated, data are in the form of mean ± standard error. All statistical analyses were performed in R 4.1.1 (R Core Team, 2021).

Table 1
Biomass equations of different tree species involved in this study.

Regions	Species	Components	Biomass equations	R^2
Shaanxi	*Robinia pseudoacacia L.*	Stem	$\mathrm{Ln}(B) = -2.746 + 2.448 \times \mathrm{Ln}(D)$	0.928
		Branch	$\mathrm{Ln}(B) = -3.428 + 2.346 \times \mathrm{Ln}(D)$	0.859
		Leaf	$\mathrm{Ln}(B) = -3.747 + 1.585 \times \mathrm{Ln}(D)$	0.653
		Root	$\mathrm{Ln}(B) = -2.032 + 2.084 \times \mathrm{Ln}(D)$	0.889
Shaanxi	*Pinus tabuliformis Carrière*	Stem	$B = 0.02492 \times (D^2H)^{0.92029}$	0.994
		Bark	$B = 0.00381 \times (D^2H)^{0.98766}$	0.990
		Branch	$B = 0.00844 \times D^{2.70902}$	0.981
		Leaf	$B = 0.01052 \times D^{2.87777}$	0.986
		Root	$B = 0.01065 \times (D^2H)^{0.88818}$	0.978
Shanxi		Stem	$B = 1.373 \times D^{0.465}e^{0.113D}$	0.978
		Branch	$B = 0.483 \times D^{0.870}e^{0.060D}$	0.944
		Leaf	$B = 0.320 \times D^{0.810}e^{0.058D}$	0.959
		Root	$B = 0.340 \times D^{0.839}e^{0.082D}$	0.947
Gansu	*Platycladus orientalis (L.) Franco*	Stem	$B = -1.855 + 3.379 \times (D^2H)$	0.901
		Branch	$B = -0.618 + 4.080 \times (D^2H)$	0.915
		Leaf	$B = -0.581 + 0.772 \times (D^2H)$	0.826
		Bark	$B = -0.677 + 1.178 \times (D^2H)$	0.882
		Cone	$B = -0.173 + 0.324 \times (D^2H)$	0.894
		Root	$B = -0.463 + 0.251 \times (D^2H)$	0.936
		Stump	$B = -0.808 + 1.237 \times (D^2H)$	0.812
Shanxi		Stem	$B = 11.237 \times D^{-2.412}e^{0.602D}$	0.932
		Branch	$B = 228.930 \times D^{-8.122}e^{1.603D}$	0.915
		Leaf	$B = 1533.497 \times D^{-11.713}e^{2.250D}$	0.949
		Root	$B = 10.331 \times D^{-2.919}e^{0.688D}$	0.932
Shaanxi	*Hippophae rhamnoides Linn.*	Whole tree	$B = 0.0000098 \times G^{4.7033}$	0.951
Shaanxi	*Caragana Korshinskii Kom*	Whole tree	$B = 0.0059 \times (G^2H)^{0.9686}$	0.904
Gansu	*Armeniaca sibirica (L.) Lam*	Stem	$\mathrm{Ln}(B) = -1.605 + 0.670 \times \mathrm{Ln}(D^2H)$	0.849
		Branch	$\mathrm{Ln}(B) = 0.003 + 0.263 \times \mathrm{Ln}(D^2H)$	0.709
		Bark	$\mathrm{Ln}(B) = -1.424 + 0.287 \times \mathrm{Ln}(D^2H)$	0.601
		Leaf	$\mathrm{Ln}(B) = -2.477 + 0.495 \times \mathrm{Ln}(D^2H)$	0.965
		Root	$\mathrm{Ln}(B) = 0.04 + 0.153 \times \mathrm{Ln}(D^2H)$	0.742

Note: B: Biomass (kg); D: Diameter at breast height (cm); G: Basal diameter (cm); H: Tree height (cm).

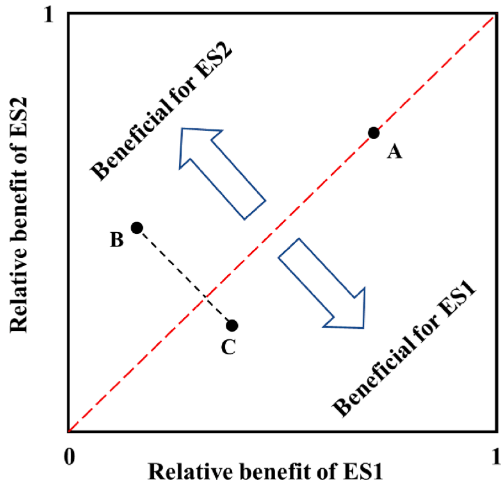

Fig. 2. Illustration of the trade-off between two ecosystem services. **Note:** ES: ecosystem service. The RMSD value of point B is greater than that of point C, and the RMSD value is zero for point A. Point B is beneficial to ES2, and point C is beneficial to ES1.

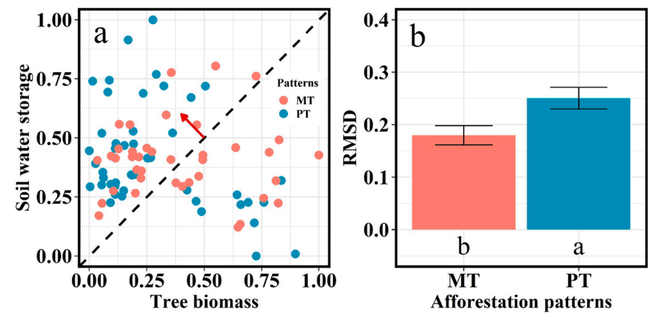

Fig. 3. Effects of different patterns on the trade-off between soil water storage and tree biomass. **Note:** PT: pure trees; MT: mixed trees. Values are the mean ± standard error. Different letters indicate significant differences ($P < 0.05$). A larger vertical distance between a point and the 1:1 line indicates a higher trade-off. The arrow indicates which ES has the higher relative benefit.

3. Results

3.1. Trade-offs between soil water storage and tree biomass under different afforestation patterns

Overall, the tree biomass and soil water storage of mixed trees were significantly higher than those of pure trees (Table 2). There was a significant negative correlation between soil water storage and tree biomass (Table 2), implying a trade-off between them. In the comparison of afforestation patterns, there was a significant negative correlation between soil water storage and tree biomass in pure trees, while no significant correlation was found in mixed trees (Table 2). Additionally, the relative benefits of the trade-off tended to be biased toward soil water storage, and no significant difference was observed in this relative benefit between different afforestation patterns (Fig. 3a, Table 3). These results indicated that when tree biomass conflicted with soil water storage, soil water storage was more important than tree biomass. Through further calculations of RMSD values between soil water storage and tree biomass, it was found that the RMSD value of pure trees (0.25 ± 0.02) was significantly higher than that of mixed trees (0.18 ± 0.02) (Fig. 3b).

3.2. Trade-offs between soil water storage and tree biomass along a drought gradient

Across the areas with different levels of the AI, the relative trade-off benefit was mainly biased toward soil water storage across the Loess Plateau (Fig. 4a-c). Meanwhile, the relative benefits of soil water storage in mixed trees were higher than those in pure trees; however, these differences were not significant (Table 3). Regarding RMSD values between soil water storage and tree biomass, the RMSD value of pure trees was the highest (0.29 ± 0.03) in areas with AI < 0.3 and was significantly higher than that in areas with AI > 0.5 (0.16 ± 0.02), but there was no significant difference from areas with AI between 0.3 and 0.5 (0.25 ± 0.04) (Fig. 4d). For mixed trees, there was no significant difference in RMSD values between soil water storage and tree biomass among different levels of the AI (Fig. 4d). In addition, when AI < 0.3, the RMSD value between soil water storage and tree biomass for mixed trees (0.19 ± 0.03) was significantly lower than that for pure trees (0.29 ± 0.03) (Fig. 4d). In areas with AI > 0.3, there was no significant difference in RMSD values between soil water storage and tree biomass under different afforestation patterns (Fig. 4d).

Table 2
Tree biomass and soil water storage and their relationship under different afforestation patterns.

Parameters	Tree biomass (Mg ha^{-1})	Soil moisture storage (mm)	Correlation coefficients
Pure trees	10.65 ± 1.07b	142.04 ± 5.26b	−0.460*
Mixed trees	14.88 ± 1.34 a	161.42 ± 6.78 a	−0.161
Total	12.57 ± 0.87	150.83 ± 4.31	−0.307*

Note: Values are mean ± standard error. Different letters indicate significant differences among different afforestation patterns ($P < 0.05$). *, $P < 0.05$.

Table 3
The change in the relative benefits of trade-offs.

ESs	Indicators	Levels	Pure trees	Mixed trees
Tree biomass	AI	<0.3	0.26 ± 0.05 a	0.31 ± 0.07 a
		0.3–0.5	0.37 ± 0.08 a	0.40 ± 0.07 a
		>0.5	0.23 ± 0.07 a	0.29 ± 0.06 a
	Ages (year)	<20	0.44 ± 0.08 a	0.46 ± 0.12 a
		20–30	0.19 ± 0.05b	0.36 ± 0.06 a
		>30	0.31 ± 0.06 a	0.38 ± 0.05 a
	Total		0.28 ± 0.04b	0.39 ± 0.04 a
Soil water storage	AI	<0.3	0.42 ± 0.03 a	0.50 ± 0.05 a
		0.3–0.5	0.39 ± 0.07 a	0.45 ± 0.04 a
		>0.5	0.41 ± 0.06 a	0.44 ± 0.08 a
	Ages (year)	<20	0.30 ± 0.06 a	0.35 ± 0.06 a
		20–30	0.45 ± 0.06 a	0.44 ± 0.04 a
		>30	0.43 ± 0.04 a	0.39 ± 0.04 a
	Total		0.42 ± 0.03 a	0.41 ± 0.03 a

Note: AI: aridity index. Values are mean ± standard error. Different letters indicate significant differences among different afforestation patterns ($P < 0.05$).

3.3. Trade-offs between soil water storage and tree biomass under various plantation ages

The trade-off between soil water storage and tree biomass differed among plantations of different ages (Fig. 5). In particular, the trade-off benefit under different afforestation patterns was mainly biased toward tree biomass in plantations aged < 20 years, and the relative benefit was slightly higher for mixed trees than that for pure trees (Fig. 5a, Table 3). In contrast, when the plantations aged > 20 years, the relative benefits were biased toward soil water storage (Fig. 5b-c, Table 3). Furthermore, the RMSD value between soil water storage and tree biomass for pure trees was the highest in plantations aged from 20 to 30 years (0.30 ± 0.03) and was significantly higher than those in plantations aged > 30 years (0.20 ± 0.03) (Fig. 5d). However, RMSD values between soil water storage and tree biomass of mixed trees decreased with increasing plantation age (Fig. 5d). RMSD values between soil water storage and tree biomass for mixed trees from

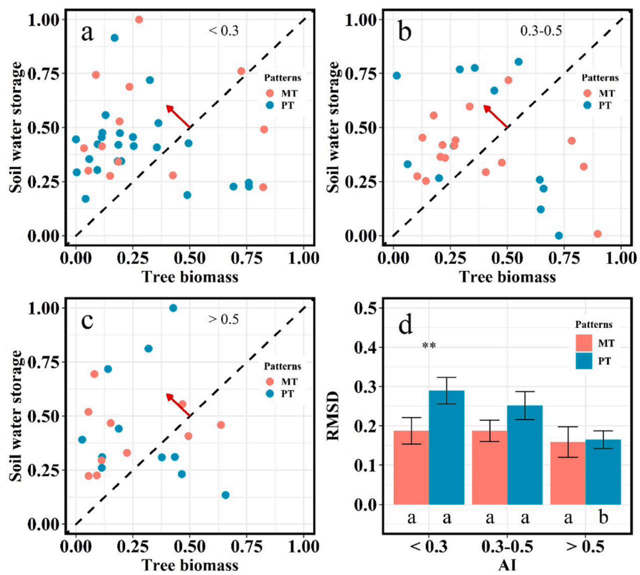

Fig. 4. Effects of aridity on the trade-off between soil water storage and tree biomass. **Note:** PT: pure trees; MT: mixed trees; AI: aridity index. Different letters indicate significant differences among different AI levels ($P < 0.05$). Asterisks indicate significant differences between different afforestation patterns (*, $P < 0.05$; **, $P < 0.01$). A larger vertical distance between a point and the 1:1 line indicates a higher trade-off. The arrow indicates which ES has the higher relative benefit.

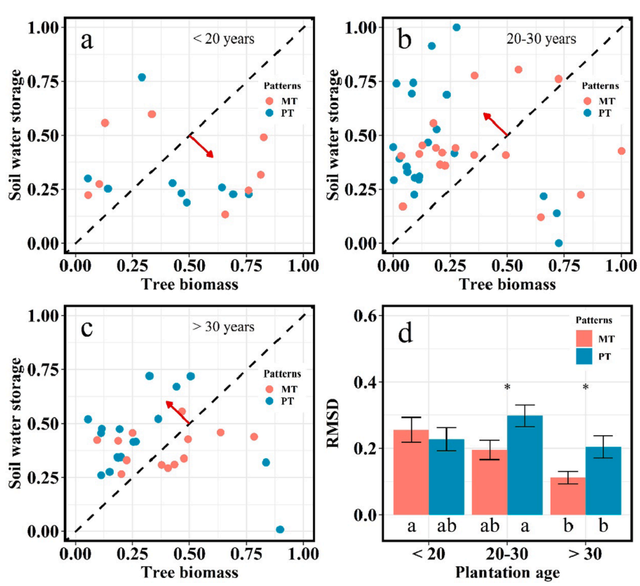

Fig. 5. Effects of plantation age on the trade-off between soil water storage and tree biomass. **Note:** PT: pure trees; MT: mixed trees. Different letters indicate significant differences among different plantation ages ($P < 0.05$). Asterisks indicate significant differences between different afforestation patterns (*, $P < 0.05$; **, $P < 0.01$). A larger vertical distance between a point and the 1:1 line indicates a higher trade-off. The arrow indicates which ES has the higher relative benefit.

plantations aged 20–30 years (0.20 ± 0.03) and > 30 years (0.11 ± 0.02) were significantly lower than those for pure trees (For 20–30 years: 0.30 ± 0.03; For > 30 years: 0.20 ± 0.03) (Fig. 5d). In addition, for plantations 0–20 years old, the RMSD value between soil water storage and tree biomass for mixed trees (0.26 ± 0.04) was higher than those for pure trees (0.22 ± 0.03), but the difference was not significant (Fig. 5d).

3.4. *Correlations between the RMSD values and soil properties*

Correlation analysis showed that RMSD values between soil water storage and tree biomass under different afforestation patterns were negatively correlated with the initial soil water storage and SOC (Table 4). Specifically, regardless of whether it was the mixed or the pure trees, RMSD values between soil water storage and tree biomass were significantly negatively correlated with the initial soil water storage (Table 4). It is worth noting that the SOC content had no significant effect on the RMSD values between soil water storage and tree biomass for pure trees (Table 4). In contrast, the RMSD value between soil water storage and tree biomass for mixed trees was significantly negatively correlated with SOC content (Table 4).

4. Discussion

4.1. *Effects of afforestation patterns on the trade-off between soil water storage and tree biomass*

Our research demonstrated that afforestation on the Loess Plateau resulted in the trade-off between soil water storage and tree biomass, which supported our hypothesis (Fig. 3, Table 2). Similarly, previous studies also showed that there was a trade-off between soil water and vegetation biomass on the Loess Plateau (Lu et al., 2014; Su et al., 2021). Furthermore, this meta-analysis shed more light on the impact of different afforestation patterns on the trade-off between soil water storage and tree biomass. Specifically, we found that the RMSD value between soil water storage and tree biomass for mixed trees was significantly lower than that for pure trees (Fig. 3d). Several physiological mechanisms underlie this phenomenon. First, the multispecies stand may use water from different soil layers and improve water use efficiency in a limited water environment, thereby improving the drought resistance and productivity of the plants (Forrester et al., 2010; Amazonas et al., 2018; Fichtner et al., 2020). Similarly, Wang et al. (2020) found that the coexisting plants in the mixed plantation exhibited water source segregation on the Loess Plateau. Tang et al. (2019) also indicated that water source partitioning, stomatal adjustment, and N facilitation promoted stable coexistence of N_2-fixing species and neighbor species in water- and N-limited environments. Furthermore, complementary effects explain the increases in the water use efficiency and biomass yield of vegetation with increasing species richness (Grossiord et al., 2013; Schwendenmann et al., 2015).

Second, multi-species plantations can increase the quantity of litter, decomposition rates, and root exudates (Cotrufo et al., 2013; van der Plas, 2019), which can increase soil nutrients (e.g., soil carbon and nitrogen content) and improve soil structures (e.g., aggregate stability and porosity), thus improving soil water retention capacity and promoting plant growth (Özcan et al., 2013; Metz et al., 2016). Zhang and Chen (2007) showed that soil physical and nutrient conditions, community structure, and species diversity were better in mixed forests than that in pure forests. In addition, on the Loess Plateau, severe soil erosion usually results in loss of soil moisture capacity and nutrient retention, thereby reducing soil water storage and plant productivity (Fu et al., 2000; Gao et al., 2018). Due to the diverse spatial structures and distribution patterns of vegetation, multispecies forests can reduce rainfall erosion by reducing raindrop kinetic energy and strengthening soil stability, which can increase soil moisture and vegetation productivity to a certain extent

Table 4
Pearson's correlation coefficients between RMSD and soil properties.

Soil properties	Pure trees	*P* value	Mixed trees	*P* value
SOC	−0.234	0.282	−0.481*	0.032
ISW	−0.503**	0.009	−0.654**	0.002

Note: SOC: soil organic carbon content (g kg^{-1}); ISW: initial soil water stocks (Mg ha^{-1}). *, $P < 0.05$; **, $P < 0.01$.

(Zhou et al., 2002; Wang et al., 2014; Zema et al., 2021).

4.2. Effects of aridity on the trade-off between soil water storage and tree biomass

Drought affects not only the soil water content but also the growth and physiological characteristics of vegetation (Breda et al., 2006; D'Orangeville et al., 2018; Lamoureux et al., 2018). We found that with increasing AI, RMSD values between soil water storage and tree biomass under different afforestation patterns gradually decreased (Fig. 4). Previous studies have shown that higher precipitation not only promotes the growth of vegetation but also compensates for the soil water loss caused by the increase in evapotranspiration (Liu et al., 2018; Wang et al., 2019).

In addition, this meta-analysis found that in areas with AI < 0.3, the RMSD value between soil water storage and tree biomass for mixed trees was significantly lower than that for pure trees, while there was no significant difference between the two afforestation patterns in the other regions (Fig. 4d). According to the stress gradient hypothesis (SGH), in resource-constrained areas, facilitative interactions and complementarities between species usually dominate (Bertness and Callaway, 1994; Brooker et al., 2008). Previous studies have shown that compared with pure stands, tree mixing can improve the resistance of forest ecosystems to drought by increasing the water use efficiency of different species (Pretzsch et al., 2013; Gazol et al., 2016). For example, Steckel et al. (2020) showed that mixed forests drive hydraulic power enhancement under drought conditions, which may increase the amount of water available, thereby enhancing drought resistance. Other studies have shown that favorable interactions between heterogeneous neighbors in mixed stands usually improve forest resistance to environmental disturbances and fluctuations, indicating that trees can maintain growth even under suboptimal growth conditions (Pretzsch et al., 2013; Jactel et al., 2017).

4.3. Effects of plantation ages on the trade-off between soil water storage and tree biomass

Plantation age is considered the main factor driving changes in forest structure and function (Kerhoulas et al., 2013; Gong et al., 2021). We found that the RMSD value between soil water storage and tree biomass of pure trees was the highest in plantations aged from 20 to 30 years (Fig. 5). Previous studies have shown that *R. pseudoacacia* plantations in the Loess Plateau reached maturity around 30 years, and soil moisture content showed a consistent decrease with age at all soil depths until maturity of plantations (Wang et al., 2012; Kou et al., 2016; Wang et al., 2021). We also found that the RMSD value between soil water storage and tree biomass of pure trees was the lowest in plantations aged > 30 years (Fig. 5). Previous studies found that soil moisture decline driven by afforestation can usually be retarded upon maturity of trees (Jin et al., 2011; Jia et al., 2017). This phenomenon may be attributed to litter and decaying roots of trees gradually accumulating with stand age, thereby increasing the infiltration and retention of soil water via enhancing the formation of soil aggregates and improving soil porosity (Zhang et al., 2018; Jia et al., 2020). Furthermore, previous research reported that the water uptake depth of plants shifts from shallow to deeper soil layers increases along with plantation age (Huo et al., 2018; Nan et al., 2019; Huang et al., 2021). In this research, we focused on soil water storage only at depths of 0–100 cm, which reduced the RMSD value between soil water storage and tree biomass to a certain extent.

We also found that the RMSD value of mixed trees decreased with increasing plantation age, and that the RMSD value between soil water storage and tree biomass for mixed trees was significantly lower than that for pure trees in > 20 years (Fig. 5d). Generally, as plantation age increased, the effect of mixed forest on ecological function was stronger (Guerrero-Ramírez et al., 2017; Chen et al., 2021). Previous studies have also shown that older forest stands are more resistant and resilient to drought, and this effect is stronger in mixed forests than in single-species forests (Thurm et al., 2016; Pardos et al., 2021). In addition, we found that the RMSD value between soil water storage and tree biomass for mixed trees was slightly higher than that for pure trees in < 20 years (Fig. 5d). Previous studies have shown that in the early stage of afforestation, a mixed forest stand did not exert significant effects and caused water deficits (Kunert et al. 2012; Grossiord et al., 2013). Sheng et al. (2020) found that black locust neighbors did not improve Chinese pine growth and exacerbated water stress in the early plantation stage. Similarly, the impacts of mixed forests on soil water and tree biomass usually manifest slowly, and the trade-off between soil water storage and vegetation biomass may not be apparent in the short term (Lu et al., 2014; Su et al., 2021). Therefore, long-term research is needed to correctly estimate the impact of tree mixtures on the trade-off between soil water storage and vegetation biomass.

4.4. Relationships between RMSD values and soil properties

Our research showed that RMSD values between soil water storage and tree biomass under different afforestation patterns were significantly negatively correlated with the initial water content (Table 4). Generally, the initial water content is a key factor determining vegetation biomass and soil water (Deng et al., 2016; Gong et al., 2020). Previous studies have shown that soil moisture and vegetation biomass are usually negatively correlated with initial water content (Deng et al., 2016; Su and Shangguan, 2019). We also found that RMSD values between soil water storage and tree biomass under different afforestation patterns were positively correlated with SOC content (Table 4). As an important factor in soil structure, SOC can bind soil mineral particles together to form aggregates, which tends to increase soil moisture infiltration and water retention capacity by increasing porosity (Yang et al., 2014; Chaplot and Cooper, 2015).

However, we found that the effect of SOC on RMSD was significant in mixed trees, but not single species trees (Table 4). An increasing number of studies have shown that mixed trees are more beneficial for improving soil nutrients than pure trees (Bardgett et al., 2014; Barry et al., 2020; Chen et al., 2021). For example, Gong et al. (2020) showed that tree mixtures in the Loess Plateau could significantly increase SOC content and reduce soil BD compared to monocultures. Chen et al. (2018) also showed that a mixed forest consisting of *Robinia pseudoacacia* and *Pinus tabulaeformis* significantly improved the soil physical and chemical properties.

4.5. Implications for plantation management and policy-making

Trade-off analysis has become an important tool for ecological management and decision-making (Ruijs et al., 2013; Gissi et al., 2016). By quantifying the trade-offs between ESs, managers can find more ways to coordinate the sustainable development of multiple ESs (Bennett et al., 2009; Wu et al., 2017). In the past few decades, planted forests have made important contributions to ESs (e.g., carbon sequestration) in China (Liu et al., 2008; Tong et al., 2018). However, due to inappropriate overexpansion, poor management, and intensified climate change, afforestation failures have been common in China (Jiang et al., 2006; Cao, 2008). Therefore, methods to scientifically manage plantations have become the top priority for the sustainable development of forest ecosystems.

Considerable evidences show that there are positive correlations between plant species richness and multiple ESs (e.g., the provision of plant biomass, soil carbon sequestration, and the improvement of water and air quality) (Gamfeldt et al., 2013; Jactel et al., 2017). Similarly, our research indicated that the RMSD value between soil water storage and tree biomass for mixed trees was significantly lower than that for pure trees. However, this study also found that the RMSD value between soil water storage and tree biomass of plantations in areas with AI < 0.3 was higher than that in areas with AI > 0.3 (Fig. 4). Previous studies have shown that afforestation is not a useful option in areas where rainfall is close to or below the potential evapotranspiration (Deng et al., 2016). In addition, as other studies have demonstrated, because of its relatively low water consumption, grasslands can support a higher water supply while helping to maintain other ESs (Wu et al., 2020; Mei et al., 2018). Therefore, before any afforestation plan is implemented, the adaptability of tree species and the ecological significance of establishing plantations should be comprehensively considered (Cao, 2011; Yu et al., 2019). On the basis of achieving a single ecological goal, future afforestation efforts should focus on improving the quality of forest ecosystems and the performance of multiple functions. Combined with related research studies (Felton et al., 2016; Jactel et al., 2017), in areas suitable for afforestation, future ecological restoration projects should consider a combination of multiple species rather than the single species.

5. Conclusion

Afforestation has caused a trade-off between soil water storage and tree biomass on the Loess Plateau. For different afforestation patterns, the RMSD value between soil water storage and tree biomass for mixed trees was significantly lower than that for pure trees. In addition, plantation age, the AI, and soil properties also affect the response of RMSD values to different afforestation patterns. In particular, in areas with AI < 0.3, the RMSD value between soil water storage and tree biomass for mixed trees was significantly lower than that for pure trees. These results can be applied in the scientific management of plantation forests. In the face of an increasingly warming climate and frequent drought events, increasing tree species richness is an effective way to alleviate the trade-off between soil water storage and tree biomass.

Credit authorship contribution statement

Chen Gong: Conceptualization, Methodology, Software, Investigation, Writing-original draft,Writing – review & editing, Formal analysis, Visualization. **Qingyue Tan:** Data curation, Methodology, Formal analysis, Visualization. **Guobin Liu:** Methodology, Validation,Writing – review & editing. **Mingxiang Xu:** Conceptualization, Methodology, Supervision, Investigation, Validation,Writing – review & editing, Resources, Project administration, Funding acquisition.

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.

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Appendix A. Supplementary material

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