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Impacts of species mixture on soil nitrogen stocks in the Loess Plateau of China

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ABSTRACT

Nitrogen (N) is one of the primary limiting elements in terrestrial ecosystems, and vegetation restoration has been regarded as an effective way to increase soil total nitrogen (STN) stocks. Despite compelling evidence indicating that mixed plantations can demonstrate higher vegetation productivity and carbon (C) sequestration capacity than monocultures, the effects of mixed plantations on STN stocks remain unclear. Therefore, we conducted a meta-analysis of 128 observations from 49 peer-reviewed articles across the Loess Plateau of China to evaluate the impact of different afforestation models (i.e., mixed plantations and monocultures) on the dynamics of STN stocks in mineral soil (0–30 cm). The results showed that, compared with monocultures, mixed plantations significantly increased STN stocks by 19.3%. For different mixed types, tree-shrub mixed plantations increased more STN stocks than tree-tree mixed plantations. However, the positive effect of mixed plantations on STN stocks was significant > 20 years after stand establishment. Moreover, for areas with steeper slope (>25°), lower elevation (<1200 m), and climate restricted (MAT < 8℃, MAP < 500 mm), mixed plantations had more advantages in increasing STN stocks than monocultures. Additionally, the response ratio of STN stocks was negatively correlated with the initial STN stocks, response ratios of soil pH, and bulk density (BD) but positively correlated with the response ratio of soil organic carbon (SOC) stocks. Our results demonstrate that increasing tree species richness is an important strategy to increase STN stocks.

1. Introduction

Nitrogen (N) is the main limiting nutrient for the growth of plants, and 88% of the global N demand for plants is supplied by soil N (Cole, 1995; Tang et al., 2019). Therefore, changes in soil N usually affect the growth and productivity of plants, which have an important impact on the processes and functions of ecosystems (Cheng et al., 2010; Esser et al., 2011). Afforestation, forest planting in areas that previously were not classified as forests, is considered an effective method to control soil degradation and increase soil N storage (Li et al., 2012; Deng and Shangguan, 2017). However, monocultures usually dominate in practice for many reasons, such as economic benefits and easy management (Metz et al., 2016; Coll et al., 2018). Although monocultures play an essential role in restoring degraded land, increasing timber production, and protecting natural forests, there is an increasing interest in mixed plantations in the face of climate change and lack of resources (Li et al., 2014a, 2014b; Nguyen et al., 2014). Previous studies have shown that in addition to increasing the productivity and carbon (C) sequestration potential of forest ecosystems, mixed forests also have greater flexibility and resistance to pests and diseases (De Deyn et al., 2004; Haas et al., 2011; Drossler et al., 2015). However, the effect of mixed plantations on soil total nitrogen (STN) stocks remains unclear. Therefore, understanding the mechanism of how different afforestation models (i.e., mixed plantations and monocultures) affect regional STN stocks is crucial for the sustainable development of forests in the future.

Plants are the main way for N to enter the soil, and the type and combination of plants usually play a crucial role in regulating soil N (Lang et al., 2014; Blasko et al., 2020). Studies related to the response of STN stocks to different afforestation models have also shown conflicting results. One view is that due to the complementation of ecological

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niches, multiple species can usually reduce competition and even have a positive impact on each other, which we refer to as "functional complementarity" (Grime, 1997; Amazonas et al., 2018; Liu et al., 2018a). For example, multiple species can increase the STN stocks by increasing litter biomass and root turnover rate (Manzoni and Porporato, 2009; Xu et al., 2018a). In addition, species with specific traits in mixed plantations can often produce "selection effects", which facilitates the coexistence of species (Loreau and Hector, 2001; Ammer, 2019; Blasko et al., 2020). As a typical example, mixed plantations containing N-fixing species can increase the STN stocks through biological N fixation and improve the growth of neighbor species in N-limited areas (Bouillet et al., 2008; Taylor et al., 2017). However, another view is that species with the same functional traits (e.g., leaf phenology, life cycle) usually occupy the same niche, causing increased competition between species, which we refer to as "functional redundancy" (Drossler et al., 2018; Gong et al., 2020a). Mixed species with differences in root depth and density can exploit various underground niches, leading to more nutrient consumption (Dimitrakopoulos and Schmid, 2004; Stubbs and Wilson, 2004). In addition to the effects of afforestation models, previous studies quantitatively assessed the changes in STN stocks after afforestation and identified the driving factors that affect the STN stocks, such as topographic conditions, climate, previous land use, planting density, and forestation age (Shi et al., 2016; Deng and Shangguan, 2017). However, previous studies have focused on changes in soil N in monocultures, and it is unclear whether differences exist in the response of STN stocks to these factors in different afforestation models.

To control soil erosion and restore the degraded ecological environment, a series of ecological protection projects have been implemented on the Loess Plateau in 1999, such as the "Grain for Green" Project (GGP), which aims to restore cropland to forestland, shrubland, and grassland (Cao et al., 2009; Feng et al., 2016). These projects have significantly increased the vegetation coverage and controlled the soil erosion of the Loess Plateau (Chang et al., 2011; Chen et al., 2015). However, most planted forests are composed of a single tree species (e.g., *Robinia pseudoacacia*), which has led to a series of environmental issues (Cao, 2008; Wang et al., 2013). Especially in the arid and semiarid regions, monocultures usually cause severe consumption of soil moisture due to the transpiration of plantation forests and climate drought (van Groenigen et al., 2006; An et al., 2017; Su and Shangguan, 2019), which may lead to soil desiccation and forest degradation. In addition to water consumption, monocultures will also consume soil N pools and reduce soil N availability (Li et al., 2014a, 2014b; Jin et al., 2016). Mixed plantations are also widely planted on the Loess Plateau because of their advantages in controlling soil erosion and alleviating water stress (Chen et al., 2012; Gong et al., 2020a). However, the question as to whether mixed plantations will increase STN stocks more than monocultures remains unclear on the Loess Plateau of China. Previous studies on mixed plantations have focused on several scattered locations or specific vegetation types, resulting in a lack of comparability between results (Tuo et al., 2018). Furthermore, few analyses have fully explored the differences in STN stocks and their influencing factors between mixed plantations and monocultures.

To fill the existing knowledge gaps, a meta-analysis was used to study the effects of different afforestation models on the STN stocks of mineral soils (0–30 cm) on the Loess Plateau of China. Specifically, we wanted to answer the following questions: (1) do mixed plantations have greater STN stocks than monocultures? (2) how do mixed types, plantation age, topographic factors, and climate affect the response ratio of STN stocks? And (3) what is the relationship between soil properties and the response ratio of STN stocks?

2. Materials and methods

2.1. Data collection

Peer-reviewed journal articles that reported STN stocks within different afforestation models (mixed plantations and monocultures) were searched using the ISI Web of Science (United States) and CNKI (China Knowledge Resources Comprehensive Database, China) up to 10 September 2020. Different combinations of terms used for the search were: "mixed forest" or "mixed plantation" or "mixed species" or "tree species" or "species diversity" or "diversity" and "soil total nitrogen" or "soil nitrogen" or "soil nitrogen stocks" and "Loess Plateau". To avoid potential uncertainties in the results, the following detailed criteria were used for studies selection:

(1) STN stocks were given directly or could be derived based on the STN content, bulk density (BD), and soil depths;

(2) the study included at least one species mixture treatment and corresponding monocultures;

(3) only studies with similar soil and climatic conditions for both monoculture and mixture treatment plots were selected;

(4) only include data from field monitoring, excluding laboratory control experiments; and

(5) the study focused only on artificial forestation, excluding natural forests.

Finally, 128 observations from 49 peer-reviewed publications on STN stocks were collected (Fig. 1; Appendix Dataset). The research sites included in this meta-analysis were shown in Fig. 1. The original data of stocks or concentrations of STN was extracted from tables or extracted from figures by using the GetData Graph Digitizer ver. 2.24 (Russian Federation). Moreover, detailed information on the location of the experimental site (longitude and latitude), mean annual temperature and precipitation (MAT and MAP), elevation, slope aspect, slope angle, slope position, soil layer, initial STN stocks, soil organic carbon (SOC) content, soil pH, soil bulk density (BD), and plantation age were also collected. In addition, since shrubs are the dominant species in arid and semi-arid areas, it is considered as a type of forestland by the forestry department of China (Shi et al., 2013). Therefore, we regard shrubs as a kind of afforestation species in this study and subdivide afforestation models into two types: tree-shrub and tree-tree mixed plantations.

2.2. Main calculation

STN stocks

STN stocks were calculated using the following equation:

$$STN_{stock} = STN_c \times BD \times \frac{D}{10} \tag{1}$$

where STN_{stock}, and STN_c represent STN stocks (Mg ha^{-1}) and STN content (g kg^{-1}), respectively; *BD* is the soil bulk density (g cm^{-3}); *D* is the soil layer thickness (cm).

2.3. Uniform soil depth

Due to the inconsistency of the soil depth between different studies, we adopted the method of (Jobbagy and Jackson, 2000) was used to convert the STN stocks at different soil depths to the STN stocks at the mineral layer (0–30 cm):

$$Y = 1 - \beta^d \tag{2}$$

$$STN_{30} = \frac{1-\beta^{30}}{1-\beta^{d0}} \times STN_{d0} \tag{3}$$

where *Y* is the cumulative proportion of STN stocks, β is the relative reduction rate of STN stocks (0.9831) (Li et al., 2012), TN_{30} is the STN stocks in the upper 30 cm, d_0 and STN_{d0} represent the original soil layer (cm) and the STN stocks (Mg ha^{-1}) in the reference study, respectively.

It should be noted that due to the difference in C and N distribution through the soil profile, the conversion of C and N at different soil depths may introduce potential uncertainties. However, Yang et al. (2011) and Liu et al. (2018b) used the same method to convert the original C and N

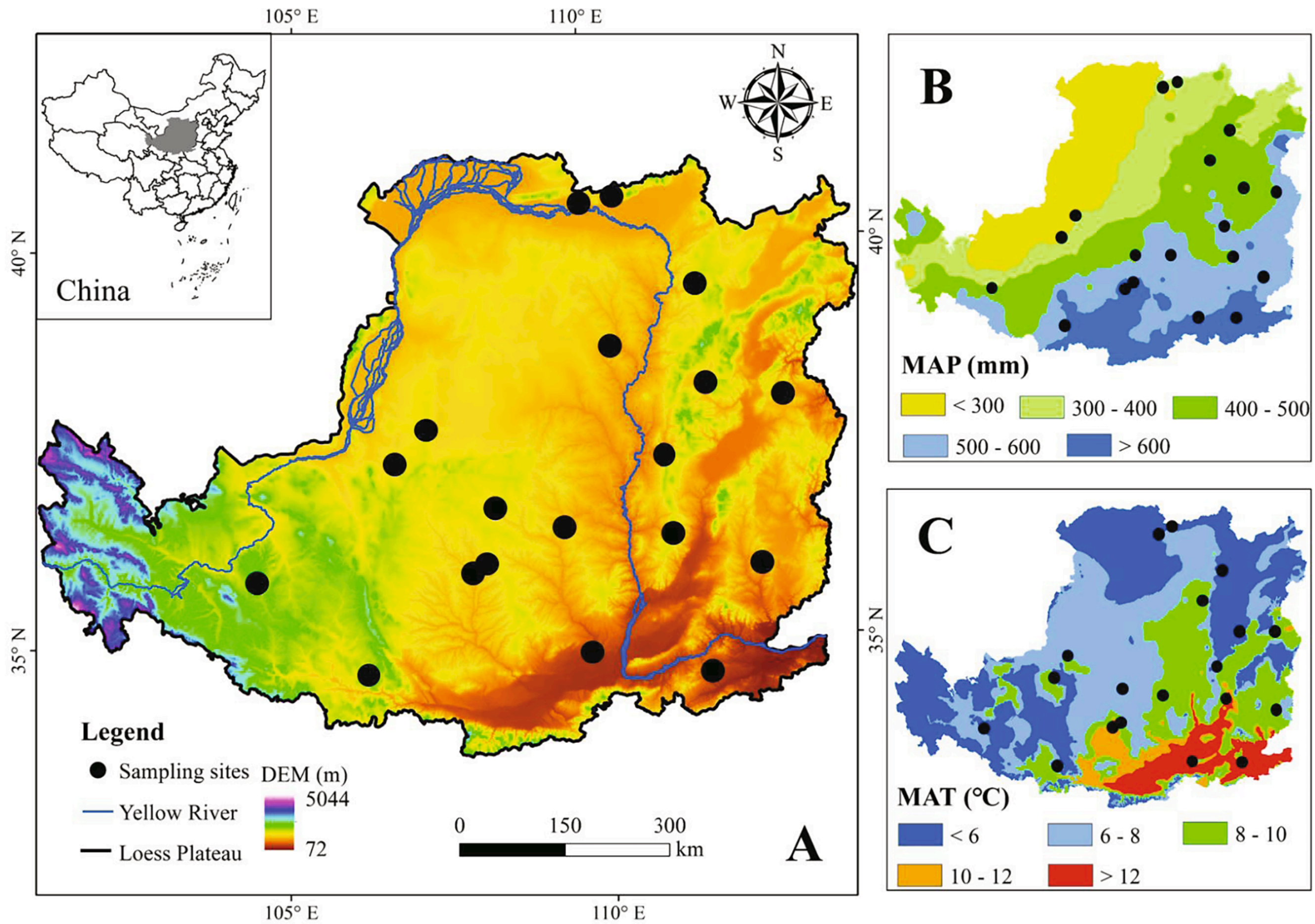

Fig. 1. Location of this study on the Loess Plateau. **Note:** (A) DEM: Digital Elevation Model; (B) MAP: mean annual precipitation; (C) MAT: mean annual temperature. The data of DEM, MAP, and MAT in this study comes from the Resource and Environment Data Cloud Platform (http://www.resdc.cn/Default.aspx).

stocks to the C and N stocks at the same layer, and indicated that depth correction did not alter the overall pattern of soil C and N stock dynamics.

2.4. Meta-analysis

To maximize the number of investigations, the unweighted meta-analysis method was used to calculate the response ratio (RR) and 95% confidence interval (CI) of mean STN stock changes (Deng et al., 2016; Powers et al., 2011), as shown in Eqs. (4), (5) and (6):

$$RR = \frac{N_{mf}}{N_{mn}} - 1 \quad (4)$$

$$SE_{TN} = \sqrt{\frac{V_s}{n}} \quad (5)$$

$$95\%\text{CI} = 1.96 \times \text{SE}_{TN} \quad (6)$$

In which, N_{mf} and N_{mn} are the concerned variable in mixed plantations and monocultures, respectively. SE_{TN}, V_S and N denote the standard error, the variance and sample size of the relative change in STN stocks, respectively. If 95% CIs does not include zero, the mean response ratio is considered to be significantly different from zero.

2.5. Data analysis

The normality and homogeneity of the variables were checked by the Shapiro-Wilk test and Levene's test, respectively. An analysis of variance (ANOVA) was used to test whether the response ratio of STN stocks significantly differed among different categorical variables (mixture types, plantation age, climate and topographic factors), and significant differences for multiple comparisons were obtained with the least significant difference (LSD) test. Furthermore, t-tests were used to evaluate whether plantation age, climate and topographic factors significantly affected STN stocks under different afforestation models. A regression analysis was performed to examine the relationship between the response ratio of STN stocks and soil properties (i.e., initial STN stocks, SOC stocks, soil pH, and soil BD). Differences were tested at $P < 0.05$. All the statistical analysis was performed in the SPSS 24.0 software (SPSS Inc., Chicago, IL) and figures were carried out using Origin 9.0 (OriginLab Corp., Hampton, USA).

3. Results

Overall, compared with monocultures, mixed plantations significantly increased STN stocks by 19.3% (95%CI: 6.5%) (Fig. 2). For different types of mixed plantations, tree-shrub and tree-tree mixed plantations significantly increased STN stocks by 25.7% (95%CI: 9.2%) and 10.5% (95%CI: 8.1%), respectively. In addition, the response ratio of STN stocks for tree-shrub mixed plantations was significantly higher than that for tree-tree mixed plantations (Fig. 2).

The response ratio of STN stocks increased with plantation ages (Fig. 3). Specifically, compared with monocultures, mixed plantations significantly increased STN stocks in mature (20–30 yr) and old stages (>30 yr) by 17.3% (95%CI: 11.1%) and 21.7% (95%CI: 12.2%), respectively, whereas significant differences were not observed in the

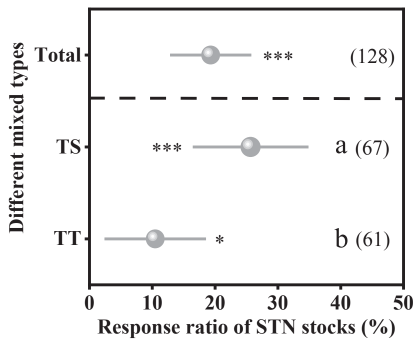

Fig. 2. Effects of mixture types on the changes in STN stocks. **Note:** TS: tree-shrub mixed plantations; TT: tree-tree mixed plantations. Dots with error bars denote the overall mean response ratios and the 95% CIs. Asterisks refer to significant differences from zero (*, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$). Different lower-case letters indicate significant differences among different mixture types ($P < 0.05$). Numbers of observations are in the parenthesis.

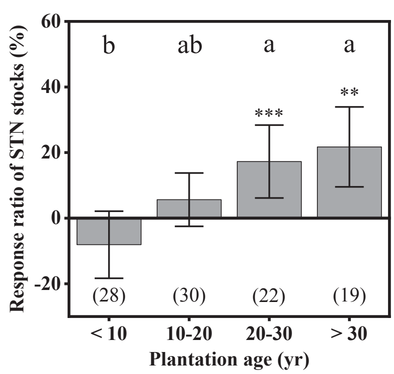

Fig. 3. Effects of plantation age on the changes in STN stocks. **Note:** Dots with error bars denote the overall mean response ratios and the 95% CIs. Asterisks refer to significant differences from zero (*, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$). Different lower-case letters indicate significant differences among different plantation ages ($P < 0.05$). Numbers of observations are in the parenthesis.

medium (5.6%, 95%CI: 8.1%) stage (Fig. 3). In comparison, mixed plantations led to a decrease of 8.1% (95%CI: 10.2%) on STN stocks in the young stage (<10 yr) (Fig. 3). In addition, the response ratio of STN stocks in the old stage was the highest and was significantly higher than that in the young stages (Fig. 3).

Topographic factors (elevation and slope angles) had different effects on the response ratio of STN stocks (Fig. 4). Specifically, mixed plantations did not significantly increase the STN stocks in middle- (1200–1400 m, 8.5%, 95%CI: 12.5%) or high-elevation areas (>1400 m, 6.9%, 95%CI: 9.5%) compared to monocultures, but increased significantly in the low-elevation area (<1200 m, 20.6%, 95%CI: 9.8%) (Fig. 4a). In contrast to elevation, mixed plantations significantly increased the STN stocks by 25.4% (95%CI: 10.7%) and 12.6% (95%CI: 11.4%) on the inclined (15-25°) and steep slopes (>25°), respectively, while mixed plantations effected on STN stocks on the gentle slope (<15°, 8.5%, 95%CI: 11.4%) did not differ significantly from zero (Fig. 4b). Moreover, the effectiveness of mixed plantations in increasing the STN stocks was the highest in those areas with lower elevation (<1200 m) and steeper slope (>25°) (Fig. 4).

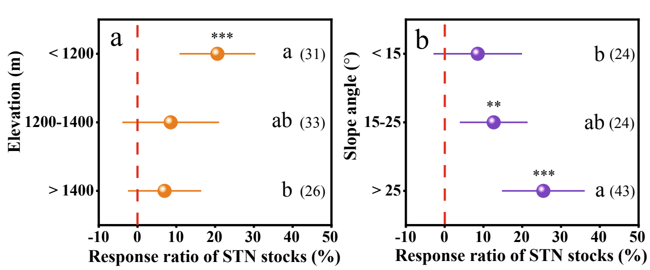

Fig. 4. Effects of topographic factors on the changes in STN stocks. **Note:** Dots with error bars denote the overall mean response ratios and the 95% CIs. Asterisks refer to significant differences from zero (*, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$). Different lower-case letters indicate significant differences among different topographic factors ($P < 0.05$). The red dashed line is the reference of a response ratio of zero, and numbers of observations are in the parenthesis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Overall, the response ratio of STN stocks declined with MAT and MAP (Fig. 5). Specifically, compared with monocultures, mixed plantations significantly increased STN stocks in both low- (<8℃, 28.2%, 95%CI: 11.0%) and middle- (8-10℃, 22.4%, 95%CI: 11.8%) temperature zones, while no significant differences were found in the high-temperature zone (>10℃, 6.8%, 95%CI: 9.3%) (Fig. 5a). In addition, mixed plantations performed better in the low-temperature zone (<8℃) than that in the high-temperature zone (>10℃) in increasing STN stocks (Fig. 5a). Similarly, mixed plantations increased STN stocks the most in the low-precipitation zone (<500 mm, 26.3%, 95%CI: 11.1%) and the least in the high-precipitation zone (>600 mm, 8.8%, 95%CI: 10.2%) compared to monocultures (Fig. 5b).

Linear regression analysis showed that the initial STN stocks (Fig. 6a), response ratios of pH (Fig. 6b) and BD (Fig. 6c) were negatively correlated with the response ratio of STN stocks. Notably, the response ratio of pH did not significantly affect the response ratio of STN stocks (Fig. 6b, $P = 0.19$). In contrast, the response ratio of STN stocks had a significant positive relationship with the response ratio of SOC stocks (Fig. 6d).

4. Discussion

4.1. Effects of different afforestation models and mixed types on STN stocks

Our study found that mixed plantations significantly increased the STN stocks compared to monocultures (Fig. 2). The following reasons may explain this result. Firstly, mixed plantations with higher species diversity and structural diversity can increase the quantity and quality of litter, the root exudates, and turnover rates (Cotrufo et al., 2013; Andivia et al., 2016), thereby increasing the source of TN. Secondly, multi-species usually increase the abundance and activity of microbes, promoting the degradation of litter and immobilization rates of soil N (Zak

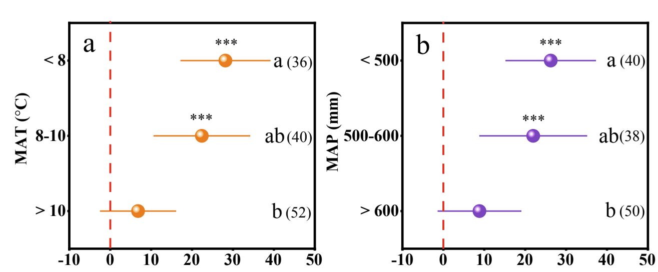

Fig. 5. Effects of climatic zones on the changes in STN stocks. **Note:** MAP: mean annual precipitation; MAT: mean annual temperature. Dots with error bars denote the overall mean response ratios and the 95% CIs. Asterisks refer to significant differences from zero (*, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$). Different lower-case letters indicate significant differences among different climatic zones ($P < 0.05$). The red dashed line is the reference of a response ratio of zero, and numbers of observations are in the parenthesis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

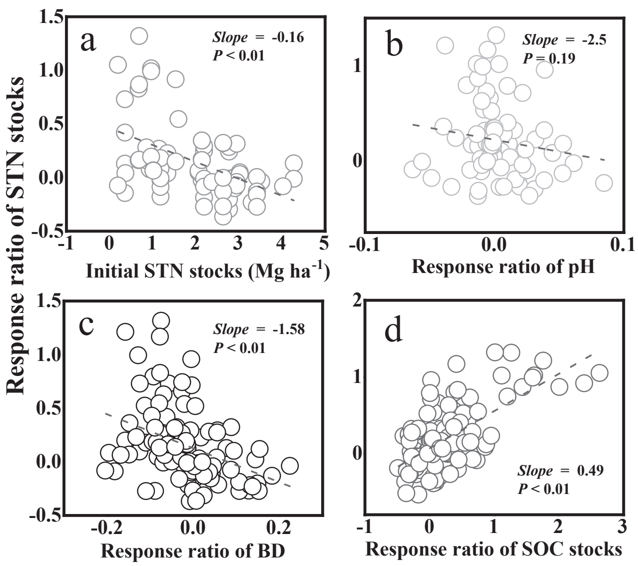

Fig. 6. Relationships between the response ratio of STN stocks and soil properties.**Note:** BD: soil bulk density; SOC: soil organic carbon. Dotted lines represent the regression model fits.

et al., 2003; Rachid et al., 2013). Thirdly, previous studies have also shown that due to the canopy stratification of mixed plantations, the kinetic energy of raindrops is usually reduced by increasing the canopy interception, which may decrease the loss of N caused by soil erosion and prevent N downward migration along with the soil layer (Tilman et al., 1996; Kermavnar and Vilhar, 2017). Simultaneously, this canopy structure also provides more chances to intercept nitric dust and particles in the air so that more N can be eluted from the blade surface (Jin et al., 2011; Xu et al., 2018b).

In addition, mixed plantations containing N-fixing plants can compensate for the N consumed by adjacent vegetation growth by increasing symbiotic N fixation and improving the growth of adjacent non-N-fixing species to increase the STN stocks (Kaye et al., 2000; Forrester et al., 2005; Mo et al., 2008). According to our dataset (Appendix Dataset), 77% of mixed plantations on the Loess Plateau contain N-fixing plants (e.g., *Robinia pseudoacacia-Hippophae rhamnoides*). Similarly, previous studies have also shown that the roots of N-fixing species in the Loess Plateau are often rich in rhizobiales, which will increase the STN stocks by fixing atmospheric N and improving the N-fixation capacity of the microbial community (Hu et al., 2017; Du et al., 2019).

Interestingly, we found that the response ratio of STN stocks of tree-shrub mixed plantations was significantly higher than that of tree-tree mixed plantations (Fig. 2), perhaps because the niche and growth cycle differentiation of trees and shrubs were more distinct, resulting in more favorable utilization of resources (Kahmen et al., 2006; England et al., 2016). Furthermore, this is likely explained by the differences in the biological attributes of plant species (Shi et al., 2013). The shrubs in the Loess Plateau consist mostly of N-fixing species (e.g., *Hippophae rhamnoides*), which increases the STN stocks to a certain extent (Zhang and Chen, 2007). The shrub can also slow down the evaporation rate by reducing the wind speed near the ground, thereby making the temperature gradient in the forest more uniform and higher humidity (Unterseher and Tal, 2006), which increases the local accumulation of soil nutrients and water (Zhang et al., 2006).

4.2. Effects of different plantation age on STN stocks

This meta-analysis found that in the young stage (<10 yr), the response ratio of STN stocks showed a negative value (Fig. 3). This result probably due to mixed plantations with higher productivity consumes more soil N than monocultures, while the positive effects of plant diversity on litter production and soil biota were lagging (Eisenhauer et al., 2010; Ma and Chen, 2018). Sheng et al. (2020) showed that in the early stage of afforestation (<10a), most of the N fixed by N-fixing species was absorbed by neighboring species, resulting in a decrease in soil N. A global meta-analysis has also shown that the effect of mixed plantations on soil N shifted from negative to positive approximately seven years after vegetation restoration (Chen et al., 2020). Our research also found that the response ratio of STN stocks of mixed plantations in the old stage (>30 yr) was highest and significantly higher than that in the young stage (<10 yr) (Fig. 3). Generally, the mixing effect of multiple species tends to increase with plantation age (Wen et al., 2014). Plant diversity increases STN stocks over time by increasing litter and root biomass and reducing N leaching (Mueller et al., 2013; Cong et al., 2014). However, we found that mixed plantations increased STN stocks significantly after 20 years of recovery (Fig. 3). Previous studies have shown that soil N fixation is a slow process (Zhang et al., 2012; Marron and Epron, 2019). Therefore, it is necessary to further study the changes in STN stocks with plantation ages.

4.3. Effects of different topographic factors on STN stocks

Topographic factors (elevation, slope angle) often affect the regional nutrient dynamics by affecting biological (e.g., vegetation, microbe) and abiotic factors (e.g., temperature, rainfall) (Schwanghart and Jarmer, 2011; Yuan et al., 2018; Yu et al., 2020). We found that in the low-elevation area (<1200 m), planting of mixed plantations was more beneficial to increasing STN stocks than monocultures (Fig. 4a). This phenomenon may occur because multiple species have higher canopy stratification and functional traits (e.g., leaf area), which may intercept solar radiation, reducing the temperature in forests (Yang et al., 2008; Prevosto et al., 2016). Relatively low temperature tends to reduce microbes' activity, which in turn leads to the accumulation of moderate and recalcitrant organic N (Schuur and Matson, 2001; Bojko and Kabala, 2016). Simultaneously, for arid and semi-arid regions, low temperature will lead to an increase in the effectiveness of water use by reducing the rate of evapotranspiration, which may increase the vegetation litter and roots, thereby enhancing the accumulation of soil N (Tjoelker et al., 2005; Guan et al., 2019). Soil nutrients moved laterally from top to bottom due to terrain/gravity and eventually gathered in the lower area (Wei et al., 2010). Especially for the Loess Plateau, soil nutrients on slopes tend to accumulate at the bottom of slopes as soil erosion progresses due to erosion (Shi et al., 2019). However, we found that for steep slopes (>25°), the response ratio of STN stocks for mixed plantations was significantly higher than that of monocultures (Fig. 4b). This result may occur because mixed plantations have a larger canopy interception and higher root density, which reduces the soil erosion on the slope to a certain extent and thus maintain the soil nutrients (Cotrufo et al., 2013; Du et al., 2019).

4.4. Effects of different climatic conditions on STN stocks

Climate can affect soil nutrients by affecting the activity of microbes and the characteristics of vegetation communities (Iglesias et al., 2012). We found that in areas of low MAT (<8 ℃) and MAP (<500 mm), mixed plantations significantly increased STN stocks compared to monocultures, and the response ratio of STN stocks was the highest (Fig. 5). Chen et al. (2020) indicated that the positive impact of mixed plantations on total soil N was more apparent in a drier climate. For arid and semi-arid regions, soil water is an important variable to control vegetation growth and development and a key factor to promote soil N cycling (Legates et al., 2011; Deng et al., 2016). Compared with monocultures, mixed plantations can increase the ecosystem's resistance and resilience in drought conditions by increasing species niche differentiation and water use efficiency, which may produce higher litter and root biomass, thereby increasing the source of soil N (Forrester et al., 2016; Gao et al., 2018; Grossiord, 2020). For example, Wang et al. (2020) have shown that the plants in mixed plantations exhibited water source segregation to promote plant coexistence in the Loess Plateau. Furthermore, previous studies have shown that the soil moisture content of mixed plantations was higher than that of monoculture, which may increase soil N retention via enhanced microbial immobilization sink for N (Hicks et al., 2018; Gong et al., 2020a). In addition, for the Loess Plateau, severe soil erosion is the main cause of soil nutrient loss (Huang et al., 2015; Deng et al., 2019). Previous studies have shown that in arid areas, mixed plantations were more conducive to controlling soil erosion than monocultures, which reduced soil N loss to a certain extent (Zhang et al., 2021).

4.5. Relationship between the response ratio of STN stocks and soil properties

Our results also showed a significant negative correlation between the response ratio of STN stocks and the initial STN stocks (Fig. 6a). This phenomenon is consistent with the stress gradient hypothesis (SGH), that is, when the soil nutrient (e.g., N) is limiting, the complementarity effect between species may increase (Bertness and Callaway, 1994; Brooker et al., 2008). However, this complementarity effect of mixtures declines with improving site fertility (Bielak et al., 2014; Toigo et al., 2015). Similarly, in this study, when the initial STN stocks was higher than 3 Mg ha^{-1}, the response ratio of STN stocks was negative (Fig. 6a). Therefore, our results further indicated that mixed plantations are more conducive to increasing STN stocks than monocultures in areas with low initial STN stocks (<3 Mg ha^{-1}). Therefore, the range of initial STN stocks in the area should be widely understood to provide a basis for future ecological restoration. Our study also showed that response the ratio of soil pH was significantly negatively correlated with the response ratio of STN stocks (Fig. 6b). Low soil pH may retard the decomposition of organic matter in the soil, which will lead to a greater accumulation of soil N (Duan et al., 2020; Sellan et al., 2020). However, in this study, soil pH did not show a significant effect on soil N due to its small gradient among different afforestation models (0.2%, 95%CI: 0.6%). In addition, we also found the response ratio of STN stocks was significantly negatively correlated with the response ratio of soil BD (Fig. 6c). This may be because higher BD will reduce soil porosity and infiltration, which may tend to create an anaerobic environment, thereby increasing N loss through denitrification (Jensen et al., 1996; Duan et al., 2020). In contrast, we found that the response ratio of soil N was significantly positively correlated with the response ratio of SOC stocks (Fig. 6d). Previous researches have shown that compared with monocultures, a stronger coupling relationship was observed between the STN and SOC stocks in mixed plantations (Chen et al., 2018; Gong et al., 2020b).

5. Conclusions

Mixed plantations, especially tree-shrub mixed plantations, lead to greater STN stocks in mineral soil (0–30 cm) in the Loess Plateau of China than monocultures. In addition, plantation age, topography factors (slope angle and elevation), climate (MAT and MAP), and soil properties (initial STN stocks, soil BD, pH, and SOC) will also significantly affect the response of STN stocks to different afforestation models. These results provide references for scientifically based plantation management. For arid and semiarid areas, planting mixed plantations is a suitable afforestation practice to alleviate soil N limitation. In addition, to better understand the impact of different afforestation models on STN stocks, more long-term observations are needed in the future to study the characteristics of STN stocks changes with recovery time.

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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Author contributions

Q. T., C.G. and M.X conceived the study. Q. T., C.G., S.L. and M.X. designed the study. S.L., N.M., F.G. and M.X. analyzed the data, all authors wrote and edited the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2021.119145.

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