Soil desiccation trends after afforestation on the Loess Plateau of China

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Abstract

Purpose Soil moisture is the main factor limiting the growth of vegetation in semiarid areas. A large area of afforestation land on the Loess Plateau has been restored for 20 years from the beginning of afforestation in 1999. How will soil moisture of afforested land change in the next 20 years is important for sustainable ecological restoration, especially because the species planted were not native.

Methods The effects on soil moisture content (SMC) of afforestation (*Robinia pseudoacacia* and *Caragana korshinskii*) with different recovery durations (10, 20, 30 and 40 years) on the Loess Plateau were examined. Meanwhile, a comparative with natural restoration grassland for the same age intervals were conducted.

Results SMC of *R. pseudoacacia* plots on south-facing slopes and *R. pseudoacacia* and *C. korshinskii* plots on north-facing slopes was lowest when vegetation coverage was greatest after 20 and 30 years, respectively; SMC increases over time following natural grassland restoration; soil moisture consumption of all vegetation types was greater in the shallow soil layer (20-200 cm) than in the deep soil layer (200-500 cm) in each recovery period; and based on a three-way ANOVA, the interaction among afforestation year, vegetation type and soil depth had significant effects on SMC.

Conclusion In response to societal demand for wood, existing plantations should be thinned, with afforested lands located on north-facing slopes being thinned every 10-30 years (approximately 20 years).

Keywords: *Robinia pseudoacacia*; *Caragana korshinskii*; afforestation years; soil moisture content; Loess Plateau

1. Introduction

Soil moisture is an important hydrological element in terrestrial hydrological cycles and a key interface for conversion among precipitation, surface water and groundwater. (Legates et al., 2011; Liu et al., 2015; Jiménez et al., 2017). Soil moisture, as the basic determinant of the global water-energy-carbon cycle, controls the surface evapotranspiration, water migration, and carbon cycle processes (Fang et al. 2018). The main source of plant moisture is soil moisture, and many studies have shown that the advantages and disadvantages of soil moisture conditions are an important indicator of vegetation productivity (Karavani et al., 2018; Zhang et al., 2019). Soil moisture not only has an important impact on plant communities and physical and chemical soil properties (Fortier et al. 2013) but also has a critical effect on the growth processes of plants, especially in arid and semiarid areas. Due to scarce precipitation and deep groundwater, soil moisture is the main factor limiting the growth of vegetation in these areas, thereby limiting ecosystem productivity (whether it is an agricultural ecosystem or a natural ecosystem) (Mathur et al. 2016). For example, water supply and distribution are the main factors limiting wheat production in the semiarid regions of the southern United States (Thapa et al. 2020), and the development of effective water-saving agriculture is critical to increasing wheat productivity in semiarid regions of China (Ali et al. 2018). Soil moisture controls the productivity of Acacia woodland in semiarid central Australia (Cleverly et al. 2016), and soil moisture has become the main driving force of ecosystem changes in the African dryland ecosystem, with changes in soil moisture explaining approximately 48% of the vegetation changes (Wei et al. 2019). Therefore, the dynamic changes in soil moisture have become issues that must be considered in improving the yield of agricultural ecosystems and the ecological reconstruction and restoration of natural ecosystems.

The dynamic changes in soil moisture in arid and semiarid areas are affected by various factors. First, various environmental factors have an impact on soil moisture. The spatial distribution of soil moisture is complicated and shows strong environmental sensitivity. The difference in environmental conditions makes soil moisture exhibit different spatial and temporal distribution characteristics (Gómez-Plaza et al., 2001; Zhao et al., 2010; Gao et al., 2015). In recent years, research on the spatiotemporal variability of soil moisture in arid and semiarid areas has become a hot spot in ecological research. At the regional scale, the spatial distribution of precipitation directly affects the spatial differentiation of soil moisture. For example, studies of soil moisture variability in arid regions of the central United States have shown that soils with higher water holding capacity can alleviate short-term precipitation insufficiency, while soils with lower water holding capacity show a state of deep soil water shortage (Salley et al. 2016). Additionally, soil moisture and rainfall in the arid regions of western India are positively correlated (Vezhapparambu et al. 2020), and different forms of precipitation in the Qilian Mountains in China have different effects on soil moisture (Yang et al. 2017). Soil moisture in natural grasslands in the semiarid loess hilly region of China is also sensitive to precipitation (Zhang et al. 2017). Previous studies have also investigated the temporal stability of soil moisture. For example, the spatial pattern of soil moisture between two identical seasons in an oasis in northwestern China usually has a high temporal stability (Yang et al. 2017). As environmental pressure increases, the interaction between plants in dryland ecosystems shifts from competition to promotion (Butterfield et al. 2016), and the temporal stability of soil moisture in typical subalpine ecosystems in Northwest China and the Badain Jaran Desert also increases with increasing soil depth (Zhou et al. 2018; Zhu et al. 2020). In addition, terrain also has a certain effect on soil moisture (Majdar et al. 2018; Yu et al. 2019). Furthermore, soil moisture is also affected by human factors. Changes in soil moisture under different land uses are important to ensure the effective use of water and soil resources. At the same time, studying the effects of different vegetation types on soil moisture dynamics will help to understand the mechanisms that cause water shortages. These are crucial to afforestation sustainability in arid and semiarid ecosystems. Changes in land use and vegetation restoration can cause changes in soil moisture. For example, afforestation in eight provinces in northern China can severely reduce soil moisture (Deng et al. 2016). Soil moisture in Brazil's semiarid regions changes with changes in land use (de Queiroz et al. 2020), and natural grasslands in the arid regions of China can retain soil moisture better than artificial grasslands (Huang et al. 2019). In addition, grazing, mining, and fire can also affect soil moisture (Pereyra et al. 2017; Stavi et al. 2017; Byrne et al. 2017). Among all the influencing factors, afforestation is a major variable in artificially changing soil moisture regime (Montenegro and Ragab, 2012; Cohen et al., 2014).

To control soil erosion, afforestation measures have been adopted worldwide, including in China. In the past four decades, China has planted billions of trees to combat soil erosion and desert expansion (Zastrow, 2019), especially in the Loess Plateau, which suffers from severe soil erosion associated with intense human activities (Zhao et al., 2012; Yang et al., 2015; Zhao et al., 2018). Since the implementation of the Grain for Green project in 1999, soil erosion has been effectively controlled, although some studies have found that this project has caused negative effects, such as soil drying (Zhu et al. 2014; Chen et al., 2015; Wang et al., 2015). Therefore, the positive and negative implications of afforestation on the vegetation ecology on the Loess Plateau have become a topic of discussion among scholars (Woziwoda and Kopec, 2014; Oelofse, 2016; Viedma et al., 2017). As an example, afforestation on the Loess Plateau has been deemed unsustainable because many introduced plants transpire more water than the native vegetation (Zastrow, 2019). Through field investigations and experiments, some studies have found that afforestation reduced soil moisture content (SMC) and that the vegetation growth rates were poor (Liu et al. 2016). Some studies have also shown that vegetation has absorbed rainfall and reduced runoff. Coupled with a continental semiarid monsoon climate, these processes may cause water shortages for humans, indicating that afforestation on the Loess Plateau has approached the limit of the sustainable use of water resources (Feng et al., 2013). A better understanding of the temporal evolution of SMC response to the restoration of different vegetation species can help to identify critical situations and improvement measures.

Due to the high growth rate and nitrogen fixation capacity of *Robinia pseudoacacia* and *Caragana korshinskii*, these plants are considered the most promising species for afforestation and have been planted in large areas on the Loess Plateau (Liang et al., 2018; Chen et al., 2008). It has been 20 years since large-scale afforestation started. How will soil moisture of afforested land change in the next 20 years? In response to this question, we hypothesized that SMC in the artificial forestland decreased after afforestation. This question is relevant to understanding the long-term effects of these practices on soil moisture, especially because the planted species are not native. Some studies have shown that they strongly absorb moisture from the soil, resulting in the formation of a dry soil layer (Fang et al., 2016; Liu et al., 2016). There is still relatively little information on how soil desiccation occurs over time under different vegetation types from the year of establishment of the plantation. To better understand the trends of SMC in afforestation plots, we designed a set of experiments to study the changes in SMC after afforestation with two species on the Loess Plateau after different years following establishment (10, 20, 30 and 40 years). We also conducted a comparative study with natural restoration grassland for the same age intervals and propose some management practices to preserve soil moisture and maintain the local ecological balance.

2. Materials and methods

2.1 Study area

The study area is located in the Danangou watershed (109°16'~109°18'E and 36°54'~36°56'N). The study area covers an area of approximately 3.5 km^2 and ranges in elevation from 1075-1370 m. The Danangou watershed has a continental semiarid monsoon climate. This area belongs to the typical loess hilly area (Wang et al., 2001). The annual average temperature in the region is 8.8ºC (with an average maximum of 22.5ºC in July and an average minimum of 7ºC in January), and the average precipitation is 520 mm. Heavy rains are mainly concentrated in August and September. Since the soil in the study area is loess, the area is vulnerable to soil erosion (Qiu et al., 2001). In addition, the groundwater table in this area is especially deep, and plants cannot access the groundwater.

This study considered 48 plots (Fig. 1), including 12 *R. pseudoacacia* plots (south-facing slopes), 12 *R. pseudoacacia* plots (north-facing slopes), 12 *C. korshinskii* plots (north-facing slopes) and 12 natural grassland plots (north-facing slopes). The south- and north-facing slopes are oriented towards the south and north, respectively. The south-facing slopes in this study area receive more sunlight than the north-facing slopes. The recovery periods for each type of vegetation are 10, 20, 30 and 40 years. Each plot is represented by a symbol: Tsouth (10, 20, 30, 40) and Tnorth (10, 20, 30, 40) indicate *R. pseudoacacia* plots located on south-facing and north-facing slopes in different afforestation years, respectively; and Shrub (10, 20, 30, 40) and Herb (10, 20, 30, 40) representing *C. korshinskii* plots and natural grasslands in different afforestation years. The effects of different recovery periods on SMC in the afforestation plots were analyzed by measuring the coverage, density and SMC. Natural grassland plots of the same age were used as controls, and the age of the natural grassland refers to the year of the transition from farmland to grassland. The initial tree densities (2 m × 2 m) in the afforestation plots were similar. The area of the afforestation plots was 100 m^2

(with a side length of 10 m). The area of the natural grasslands was 4 m^2 (with a side length is 2 m). The angle of the slopes was approximately 20~30°. We selected three samples as replicates in each plot.

Figure 1 is located approximately here.

2.2 Field measurement and data analysis

The field experiment was conducted in July-August 2017. Vegetation surveys were conducted for each plot and included analysis of the tree, shrub and herb layers. We recorded the species name, height, abundance, and vegetation coverage. A 5 cm diameter soil auger was used to obtain 0-5 m deep soil samples, with samples collected every 20 cm to a depth of 5 m. Three repetitions were conducted in each plot. Overall, 3600 disturbed soil samples were collected. Details regarding the specific steps and collection methods are available in a previous article (Wang et al., 2019). SMC was assessed using the gravimetric method, and samples were brought to the laboratory and dried in an oven for 24 hours (Zheng et al., 2015; Zhang et al., 2017). The soil agglomerates (SA) were determined from undisturbed samples, which were collected using large cutting rings (2000 cm^3) and processed using the Savinoff dry and wet sieve methods. The particle size (PZ) of the samples was measured with air-dried disturbed soil by a Malvern MS2000 laser particle size analyzer. We chose to sample during periods of no rainfall.

The vertical change in SMC in each plot was analyzed by a linear regression model. One-way analysis of variance (ANOVA) was used to analyze the change in SMC of different vegetation types in each restoration year and the change in SMC of each vegetation type with different restoration years. Three-way ANOVA was used to analyze the impacts of the interaction among three factors (years, vegetation type and soil depth) and the interaction between any two factors on SMC. The correlation between SMC and other factors was analyzed by using Pearson's correlation coefficient and principal component analysis (PCA). PCA was achieved by CANOCO 5.0.

3. Results

3.1 Changes in SMC in different afforestation years

3.1.1 Vertical distribution of SMC with increasing afforestation years

The three-way ANOVA (Table 1) indicated that the interaction among the three factors (afforestation years, vegetation type and soil depth) and the interactions between any two factors had a significant ($p < 0.01$) effect on SMC.

SMC for afforestation plots located on north-facing slopes decreased for afforestation ages from 10 to 30 years but increased for those from 30 to 40 years ($p < 0.05$) (Fig. 2). The change trend of SMC for *R. pseudoacacia* located on south-facing slopes was consistent with that located on north-facing slopes, with the minimum value appearing at 20 years ($p < 0.05$). SMC in natural grasslands gradually increased from 10 to 40 years, and there were significant differences ($p < 0.05$) among all recovery years.

For SMC of different soil layers in slopes with different aspects, SMC of each afforestation age decreased as the soil depth increased across the depth range of 0-500 cm (Fig. S1). SMC of the topsoil layer (0-20 cm) in the north-facing slope was significantly ($p < 0.01$) higher than that in the south-facing slope for each afforestation age. This confirms that

R. pseudoacacia plots located on north-facing slopes reduce soil surface evaporation to a greater extent than those located on south-facing slopes. In the 20-200 cm soil layer, SMC in *R. pseudoacacia* plots located on south- and north-facing slopes decreased with decreasing soil depth for all afforestation ages. SMC of the 20-200 cm soil layer was significantly different between the different aspects ($p < 0.05$). In the 200-500 cm soil layer, SMC for *R. pseudoacacia* plots located on south- and north-facing slopes with ages of 20, 30, and 40 years decreased continuously with decreasing soil depth, and the differences in SMC between the south- and north-facing slopes of *R. pseudoacacia* gradually decreased before the age of 30 years and gradually increased after the age of 30 years (Fig. S1). One-way ANOVA indicated that significant differences ($p < 0.05$) were found among all recovery years in each aspect.

Fig. S2 shows that there was a significant difference in SMC between different vegetation types ($p < 0.05$), with the following order of magnitude: *R. pseudoacacia* plots ＜ *C. korshinskii* plots ＜ natural grasslands. Fig. S2 also shows that there was a significant difference ($p < 0.05$) in SMC of the topsoil layer (0-20 cm) between different vegetation types (*R. pseudoacacia* plots ＞ natural grasslands ＞ *C. korshinskii* plots). In the 20-200 cm soil layer, SMC of all vegetation types decreased with increasing soil depth, and the reduction in SMC for *R. pseudoacacia* was greatest among all the vegetation types. Soil moisture consumption of natural grassland is mainly concentrated at depths of 20-100 m and 20-200 m at 10 and 40 years and 20 and 30 years, respectively. For soil depths of 200 to 500 cm, SMC for afforestation plots decreased with increasing soil depth, except for the age of 10 years.

The reduction in SMC in *R. pseudoacacia* plots was significantly larger ($p < 0.05$) than that in *C. korshinskii* plots. In contrast, SMC in natural grassland plots increased with increasing soil depth from 200 to 500 cm for all ages.

Figure 2 is located approximately here.

Table 1 is located approximately here.

3.1.2 Deep soil moisture consumption with increasing afforestation years

Soil moisture consumption in the 20-200 cm soil layer of *R. pseudoacacia* plots exceeded that in the *C. korshinskii* and natural grassland plots (Fig. 3). Soil moisture consumption in the natural grassland plots was negative after 10 years. Beyond that time, soil moisture consumption of the natural grassland gradually increased with increasing restoration years from 20 to 40 years. For the 200 to 500 cm soil depth, soil moisture consumption of all vegetation types in different recovery years was less ($p < 0.05$) than that of the 20-200 cm soil layer, especially for the natural grassland.

Figure 3 is located approximately here.

3.2 Relationship between SMC and other environmental factors

3.2.1 Changes in vegetation and other factors with increasing afforestation years

Table 2 shows that the values of vegetation coverage, clay, silt and SA of the *R. pseudoacacia* plots located on the south-facing slope were highest (74.000%, 7.061%, 71.037% and 3.216, respectively) at 20 years. The values of vegetation coverage, clay, silt and SA of the *R. pseudoacacia* plots located on the north-facing slope were highest (75.000%, 7.484%, 72.075% and 5.125, respectively) at 30 years. The trends of the vegetation coverage, clay, silt and SA in the *C. korshinskii* plots with increasing afforestation years are the same as those in the *R. pseudoacacia* plots located on the north-facing slope. The clay, silt and SA of the natural grassland increased with increasing afforestation years.

Table 2 is located approximately here.

3.2.2 PCA between SMC and other factors

In the afforestation plots, the coverage was significantly positively correlated ($p < 0.05$) with SMC in the 0-20 m layer, while it was significantly negatively correlated ($p < 0.05$) with SMC in the deep soil layers (Fig. 4). SMC in the deep soil layer was significantly negatively correlated ($p < 0.05$) with clay, silt and SA. In the natural grasslands, SMC was significantly positively correlated ($p < 0.01$) with other soil properties in each soil layer. In addition, SMC values (20-200 cm and 200-500 cm soil layers) of plots Tsouth20, Tnorth30, Tnorth40 and Shrub30 were lower than the average value in the afforestation plots. SMC values in all soil layers and coverage of plots Herb30 and Herb40 were higher than the average value in the natural grassland, and the highest SMC value was observed in plot Herb40.

Figure 4 is located approximately here.

4. Discussion

4.1 Vertical variation mechanism of SMC in different afforestation years

Afforestation has produced great outcomes on the Loess Plateau (Yang et al., 2014). However, some studies have indicated that the introduction of exotic species with high evapotranspiration rates has reduced SMC (Zhang et al., 2017). This study indicated that SMC associated with a particular vegetation type varies significantly over time after afforestation. SMC of the topsoil (0-20 cm) in afforested areas increases with the increase in vegetation recovery years before reaching maturity. There are two possible reasons: i) the increasing coverage of vegetation reduces the amount of light received by the soil surface, leading to reduced evaporation of surface soil moisture, and ii) the shallow soil layer (20-200 cm) soil moisture supplements the topsoil soil moisture. For the natural restoration of grassland, SMC of 0-20 cm increases with the increase in afforestation years due to the change in coverage. In addition, there are more root systems in the shallow soil layer than in deeper soil layers. Therefore, soil moisture consumption of all vegetation types in the shallow soil layer is much larger than that in the deep soil layer (200-500 cm) in each recovery year.

SMC in the same soil layer under different afforestation types also varies. The greater vegetation coverage of *R. pseudoacacia* is conducive to the preservation of surface soil moisture (Kou et al., 2016). Therefore, SMC in the 0-20 cm soil layer in the *R. pseudoacacia* plots is greater than that in the other plots. The 20-200 cm layer is the soil layer that has the lowest SMC under all vegetation types, and this result is consistent with the results of Amin et al.'s study on soil moisture in arid regions around the world (Amin et al., 2020). *R. pseudoacacia* consumes the most soil moisture, and the natural grassland consumes the least soil moisture. With the succession of herbaceous communities, the roots of dominant species gradually change from straight roots to fibrous roots. Fibrous root systems of plants are generally located at depths of less than 100 cm. Therefore, natural grassland not only does not consume soil moisture in the deep soil layer but also shows an increasing trend (Huang et al., 2019). In addition, SMC of artificial vegetation was negatively correlated with soil silt, clay and agglomerates. This result is the opposite of findings in previous studies (Zuo et al., 2009; Tang et al., 2010), which can be explained by the roots also having a great influence on soil silt, clay and agglomerates.

4.2 Variation mechanism of total SMC with increasing afforestation years

Many studies have shown that SMC decreases with increasing afforestation years (Jia and Shao, 2014; Jian et al., 2015). Our study confirmed this trend, but we also found that SMC of *R. pseudoacacia* plots located on south-facing slopes decreased to a certain extent, and there was an increasing trend due to the vegetation reaching maturity at 20 years (Fig. 5). When the coverage and density of the vegetation reached its maximum, the root biomass of *R. pseudoacacia* reached its maximum, and the plants absorbed more soil moisture. After that point, some plants died due to a lack of water, and the plants appeared to exhibit self-relaxing behavior. As a result, the vegetation coverage and density began to decline, and SMC increased again. The trend of SMC in the *R. pseudoacacia* plots located on north-facing slopes is consistent with that on south-facing slopes, and SMC reached its lowest point at 30 years. For the same reason, SMC of *C. korshinskii* plots also reached its lowest point after 30 years of recovery. However, SMC of the natural grasslands in the control group showed a different trend than the artificial vegetation. SMC of the natural grassland increased with increasing restoration years, and no threshold was observed. The results in our study are consistent with those of other studies (Zhu et al., 2015; Deng et al., 2016). Therefore, there is a mechanism for the change in SMC in afforested areas after different periods of restoration. We propose soil moisture-vegetation dynamic balance model for afforestation over the course of 10-40 years (Fig. 6). This model notes that (1) in the early stage of vegetation growth, although the vegetation grows rapidly and soil moisture begins to decline, the vegetation growth and soil moisture consumption are balanced; (2) in the middle stage of vegetation growth, moisture consumption is increases, and vegetation growth is restricted, resulting in self-relaxation; and (3) in the late stage of vegetation growth, vegetation growth and soil moisture consumption gradually rebalance, and soil moisture begins to increase.

Figure 5 is located approximately here.

Figure 6 is located approximately here.

Some previous studies have shown that the total SMC in afforested land is less than that in natural grassland (Yang et al., 2012; Fang et al., 2016; Wang et al., 2017), and the results of our study are consistent with those findings. *R. pseudoacacia* is a tree species that uses a well-developed root system to absorb a large amount of water to support the growth of the aboveground parts. *C. korshinskii* is a shrub species with a well-developed root system, and its root system also absorbs a large amount of moisture for the growth of the aboveground parts. However, the aboveground parts of *C. korshinskii* require less water than those of *R. pseudoacacia* (Kou et al., 2016). The natural grassland plants are herbaceous species, and their root systems are far less developed than those of the tree and shrub species because the aboveground parts require less water (Zhang et al., 2017). Thus, less soil moisture is consumed in the natural grasslands than in afforested lands.

4.3 Recommendations for future afforestation

The introduction of inappropriate species to the Loess Plateau and excessive planting density have led to some negative effects (Fang et al., 2016; Deng et al., 2016). Our research showed that when soil moisture consumption is large, some plants will die, and the density of vegetation will decrease. SMC will then increase as a result of the reduced demand for water by vegetation. The relationship between SMC and vegetation is dynamically balanced. Therefore, to maintain the balance of the local ecosystem and control soil desiccation, some measures need to be taken to help the sustainable development of local afforestation projects. Some studies have indicated that thinning is an effective way to balance soil moisture supply and consumption in high-density plantations (Jia et al., 2017; Cao et al., 2018). In addition, the results of the three-way ANOVA indicated that the interaction among afforestation duration, vegetation type and soil depth had a significant ($p < 0.01$) effect on SMC. Among the three factors, the effect of different soil layers on SMC is mainly due to differences in root biomass among different vegetation types and afforestation durations. This shows that in addition to the afforestation duration, the vegetation type also has a very important effect on the change in SMC. It is important to take appropriate thinning measures for different vegetation types. Therefore, according to our soil moisture-vegetation dynamic balance model and the results of the three-way ANOVA, *R. pseudoacacia* and *C. korshinskii* need to be thinned before an imbalanced system develops. *R. pseudoacacia* plots located on south-facing slopes should be thinned every 10-20 years, with an optimal period of 15 years, and *R. pseudoacacia* plots located on north-facing slopes should be thinned every 10-30 years, with an optimal period of 20 years. Although SMC values of the *C. korshinskii* plots were greater than the average SMC of all plots, the consumption of soil moisture in these plots was greater than that in natural grassland. *C. korshinskii* should be thinned every 10-30 years, with an optimal period of 20 years. We investigated the coverage and density of *R. pseudoacacia* for each afforestation period, which can be used as a reference for thinning density (Wang et al., 2019), but further research is needed on the density of *C. korshinskii*. For the natural grassland, its growth over time is a natural succession process, and SMC increased with increasing recovery duration. Therefore, for future afforestation in the study area, a more sustainable approach for afforestation should be based on natural succession or the planting of shallow-rooting herbs. In the case of policies aimed at increasing human demand for wood or trees to prevent sandstorms, thinning methods or planting native trees with low moisture consumption levels should be considered to control the development of soil desiccation.

5. Conclusion

This study analyzed soil desiccation trends over time following afforestation. We found that SMC of *R. pseudoacacia* plots located on south-facing slopes reached its minimum when the coverage reached a maximum value at 20 years. The *R. pseudoacacia* and *C. korshinskii* plots located on north-facing slopes reached their minimum when the coverage reached a maximum value at 30 years. This result is the same as that hypothesized for some afforestation years, but there are still differences among them. SMC of the natural grassland increases with the increase in restoration duration. In addition, vegetation coverage has a greater impact on SMC under different afforestation durations. Based on the changes in SMC in afforested land with afforestation duration, we proposed a soil moisture-vegetation dynamic balance model for afforestation over 10-40 years. That is, from the early stage to the late stage of plant growth, the relationship between SMC and plant growth changes from a balanced state to an unbalanced state and finally returns to a balanced state. The relationship between vegetation growth and SMC is a dynamic balance process. Therefore, to maintain the balance in the local ecosystem and control the development of soil desiccation, we recommend thinning measures to help the sustainable development of local afforestation projects. Soil moisture consumption of *R. pseudoacacia* was the highest in all soil layers and among all vegetation types, while that of the natural grassland was the lowest. Therefore, in the future, if the human demand for wood and the prevention of sandstorms are considered, it is recommended that thinning methods be applied to forestland and that native trees with low moisture consumption rates be chosen, as these are effective measures to maintain healthy and sustainable ecosystems. Otherwise, a natural succession approach to afforestation and the planting of some shallow-rooting herbs are good options.

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Table

Table 1 Three-way ANOVA results for the effects on SMC of afforestation year, vegetation type, soil depth and their interaction.

Factors	F	P
Afforestation year	4.813	< 0.01
Vegetation type	233.985	< 0.001
Soil depth	435.827	< 0.001
Afforestation year * Vegetation type	5.302	< 0.001
Afforestation year * Soil depth	18.098	< 0.001
Vegetation type * Soil depth	69.070	< 0.001
Afforestation year * Vegetation type * Soil depth	3.146	< 0.001

Notes: Afforestation years refers to 10, 20, 30 and 40 years; vegetation type refer to *R. pseudoacacia* plots located on south-facing slopes and north-facing slopes, *C. korshinskii* plots and natural grasslands; soil depth refers to the soil layers 0-20 cm, 20-200 cm and 200-500 cm.

Table 2 Average values of other environmental factors

	Coverage (%)	Clay (0-0.002 mm)	Silt (0.002-0.05 mm)	Sand (0.05-2 mm)	SA (mm)	SL (°)
Tsouth 10	62.00±3.60	5.57±0.24	62.85±1.11	31.58±0.99	3.19±0.11	20.00±0.25
Tsouth 20	74.00±4.90	7.06±0.29	71.04±1.58	21.90±1.16	3.22±0.06	20.20±0.09
Tsouth 30	65.00±3.60	6.72±0.10	67.22±1.14	26.06±1.01	2.85±0.03	20.30±0.83
Tsouth 40	60.00±3.30	5.54±0.18	65.35±1.22	29.11±1.00	2.82±0.02	20.20±0.84
Tnorth 10	55.00±3.60	6.38±0.29	64.23±1.03	29.39±1.00	3.21±0.15	20.20±0.73
Tnorth 20	63.00±4.20	7.19±0.24	71.77±1.01	21.03±0.04	3.97±0.13	20.10±0.63
Tnorth 30	75.00±4.60	7.48±0.30	74.08±2.10	20.44±1.00	5.13±0.15	20.20±1.34
Tnorth 40	70.00±4.40	6.29±0.24	66.49±1.14	27.22±1.12	2.84±0.16	20.30±0.45
Shrub 10	30.00±2.50	6.88±0.29	67.83±1.17	28.29±0.88	3.15±0.18	20.30±0.89
Shrub 20	45.00±3.00	7.03±0.22	71.81±1.78	21.17±1.00	3.73±0.20	20.10±0.55
Shrub 30	70.00±2.70	7.76±0.20	77.68±2.12	14.56±1.99	4.84±0.25	20.20±0.67
Shrub 40	50.00±3.20	7.44±0.25	70.72±1.99	21.84±2.46	2.63±0.15	20.20±0.29
Herb 10	40.00±4.00	6.96±0.22	70.51±1.79	22.53±1.45	1.84±0.08	20.10±0.89
Herb 20	60.00±8.00	7.62±0.21	75.98±2.00	16.40±1.00	2.05±0.10	20.30±0.51
Herb 30	70.00±6.00	7.90±0.19	80.63±2.46	11.47±1.59	2.51±0.13	20.20±0.73
Herb 40	75.00±6.00	8.88±0.26	83.99±2.13	7.13±1.10	2.70±0.11	20.10±0.98

Notes: Tsouth (10, 20, 30, 40) is *R. pseudoacacia* plots located on south-facing slopes in different afforestation years; Tnorth (10, 20, 30, 40) is *R. pseudoacacia* plots located on north-facing slopes in different afforestation years; Shrub (10, 20, 30, 40) is *C. korshinskii* plots in different afforestation years; Herb (10, 20, 30, 40) is natural grasslands in different recovery years; SL is slope; SA is soil aggregates.

Figure captions

Fig. 1 Study area and locations of the sampled plots

Tree represents *R. pseudoacacia* plots, Shrub represents *C. korshinskii* plots, and Herb represents natural grasslands.

Fig. 2 Comparison of SMC distribution at different ages for the same vegetation restoration type

(a). SMC distribution at different ages for *R. pseudoacacia* plots located on south-facing slopes (Tsouth). (b). SMC distribution at different ages for *R. pseudoacacia* plots located on the north-facing slope (Tnorth). (c). SMC distribution at different ages for *C. korshinskii* (Shrub). (d). SMC distribution at different ages for natural grasslands (Herb).

Fig. 3 Comparison of deep soil moisture consumption among different vegetation types in different stages

(a). Soil moisture consumption at 20-200 cm. (b). Soil moisture consumption at 200-500 cm. Tsouth is *R. pseudoacacia* plots located on south-facing slopes; Tnorth is *R. pseudoacacia* plots located on north-facing slopes; Shrub is *C. korshinskii* plots located on north-facing slopes; and Herb is natural grasslands located on north-facing slopes. Positive values indicate a reduction in soil moisture, and negative values indicate an increase.

Fig. 4 PCA for soil moisture and environmental factors

(a). PCA ordination diagram of afforestation plots. (b). PCA ordination diagram of natural grasslands. Tsouth (10, 20, 30, 40) is *R. pseudoacacia* plots located on the south-facing slope in different afforestation years; Tnorth (10, 20, 30, 40) is *R. pseudoacacia* plots located on the north-facing slope in different afforestation years; Shrub (10, 20, 30, 40) is *C. korshinskii* plots in different afforestation years; Herb (10, 20, 30, 40) is natural grasslands in different recovery years; 0-20 cm is SMC in the 0-20 cm soil layer; 20-200 cm is SMC in the 20-200 cm soil layer; 200-500 cm is SMC in the 200-500 cm soil layer; SL is slope; SA is soil aggregates; Clay, Silt and Sand are the proportion of clay, silt and sand particles, respectively.

Fig. 5 Schematic diagram of total soil moisture consumption in the 0-5 m soil layer with vegetation restoration time

The blue area represents soil moisture reservoir, and smiles of all colors represent soil moisture consumption in the 0-5 m soil layer. The upper row and the lower row in Figure (a) show the change in vegetation characteristics and soil moisture consumption of the *R. pseudoacacia* plots located on south- and north-facing slopes with increasing afforestation period, respectively. The upper row and the lower row in panel (b) show that the change in vegetation cover and soil moisture consumption of *C. korshinskii* plots and naturally restored grassland with increases in the recovery period, respectively.

Fig. 6 Block diagram of soil moisture-vegetation dynamic balance model

The green arrow indicates rapid growth of vegetation grows faster, and the downward arrow indicates slow growth or death of vegetation. The blue arrow indicates that SMC increases, and the downward arrow indicates that SMC decreases.