Catena 197 (2021) 104946

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Trade-off analyses of plant biomass and soil moisture relations on the Loess Plateau

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ARTICLE INFO

Keywords:
Aboveground biomass
Belowground biomass
Soil moisture
Root mean square deviation
Loess Plateau

ABSTRACT

Plant biomass is a crucial parameter for terrestrial ecosystem carbon cycling. Water plays a crucial role in biomass production, especially in arid and semi-arid regions. However, the trade-off relationships between the plant biomass and soil moisture have not been well investigated on the Loess Plateau. In our study, we synthesized 615 pairs of data to evaluate the trade-off between the plant biomass and soil moisture in different precipitation areas and vegetation restoration ages on the Loess Plateau using the quantitative trade-off method. The results showed that precipitation had the strongest effect on soil moisture content (SMC), and aboveground biomass (AGB) was controlled more by vegetation restoration type and elevation, whereas belowground biomass (BGB) was controlled more by vegetation restoration age and elevation. SMC had a higher relative benefit than AGB and BGB in most precipitation areas. In addition, vegetation restoration age is another critical variable to determine the trade-offs between AGB and SMC and between BGB and SMC. For forest, the minimum trade-off of restoration years was > 10 years, but it was < 10 years for shrubland and grassland. Because the trade-offs between AGB and SMC and between BGB and SMC revealed a large spatial change on the whole Loess Plateau, the vegetation in different precipitation areas should identify suitable management strategy to maintain benefits. Understanding the relationship between the plant biomass and soil moisture will improve our ability to sustainably manage vegetation construction and water resources.

1. Introduction

Ecosystem services (ESs) are the benefits that people derive from ecosystems, and they mainly contain provisioning, regulating, supporting and cultural services that directly affect people (Millennium Ecosystem Assessment, 2005). People often over pursue or consume one or several types of ESs, and enhancement of some ESs, especially provisioning services, may lead to declines in some regulating services. Trade-offs occur when one ES increases at the cost of another ES (Bennett et al., 2009). For example, afforestation enhances carbon sequestration, while increases evapotranspiration and reduces water availability in the process of tree growth (Engel et al., 2005). Consequently, the purpose of coordinating the trade-off relationship between ESs, especially between provisioning services and regulating services, is to avoid or alleviate the conflicts among multiple ESs and enhance their synergy, which is the difficulty and important challenge in the scientific research of ecosystem services.

Human activities such as afforestation, deforestation and grazing (Bebber and Butt, 2017; Deng and Shangguan, 2017; Zhou et al., 2019) have seriously changed the carbon cycle, which has resulted in the elevation of the atmospheric carbon dioxide concentration. The global climate change caused by elevated carbon dioxide concentrations and other greenhouse gas emissions have increasingly attracted worldwide attention. In recent years, the impact of climate change on terrestrial ecosystems has become a hot issue in ecology, botany and geography (Fang et al., 2018; Frank et al., 2015; Gao et al., 2016; Kardol and Wardle, 2010; Li et al., 2018; Peñuelas et al., 2018). The Paris Agreement, signed in 2016, provides for global action to address climate change after 2020, and the importance of reducing emissions from deforestation and forest degradation through sustainable management of forest and the enhancement of forest carbon stocks is highlighted in the Treaty. The Chinese government has taken a series of measures, the most famous of which is the implementation of the 'Grain for Green' Programme in 1999. Large-scale afforestation brought about a large amount area of new forest and thus enhanced the carbon sequestration capacity in the terrestrial ecosystems where they were planted (Persson

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https://doi.org/10.1016/j.catena.2020.104946
Received 29 March 2020; Received in revised form 30 June 2020; Accepted 1 October 2020

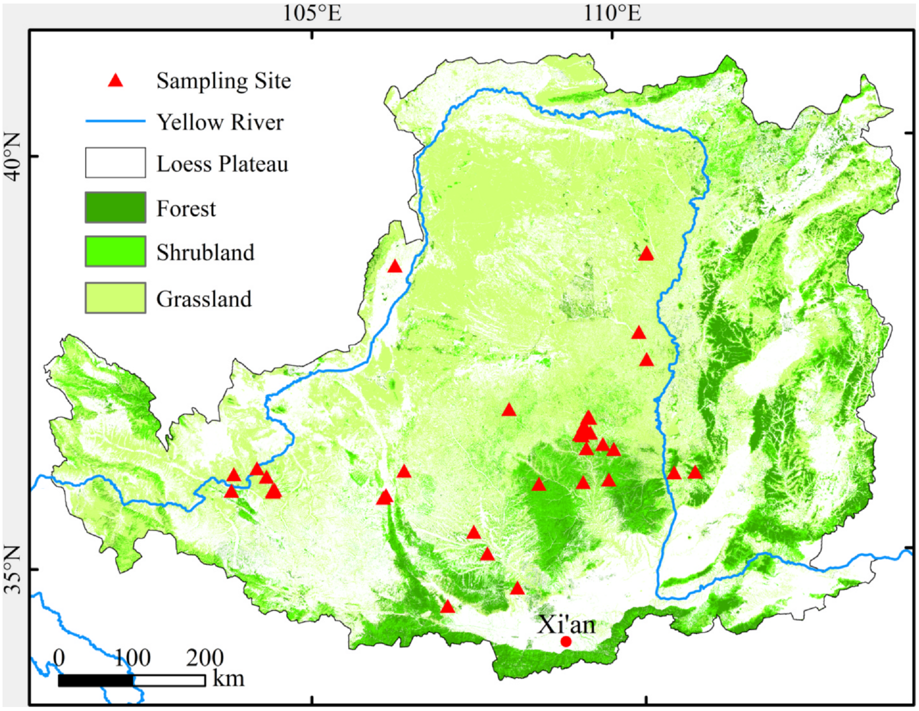

Fig. 1. Distribution of sampling sites on the Loess Plateau. Land use and land cover database was obtained from National Earth System Science Data Center, National Science & Technology Infrastructure of China (http://www.geodata.cn).

et al., 2013; Shi et al., 2016). Biomass is a basic parameter of the structure and function of vegetation ecosystems and plays a critical role in research on ecosystem productivity as characteristic data. Furthermore, AGB and BGB are important components for estimating carbon storage in terrestrial ecosystems (Liu et al., 2018; Yang et al., 2017), and they play a prominent role in the global carbon cycle (Helin et al., 2013).

The climate is now experiencing significant change characterized by global warming. The temperature increases due to global warming will affect vegetation productivity and lead to a reduction in carbon storage in ecosystems (Wu et al., 2017). At the same time, climate warming leads to the intensification of evaporation, especially in arid and semi-arid regions, which accelerates the degree of soil drying with no associated increase in precipitation. Water is a fundamental factor that affects the productivity and sustainability of terrestrial ecosystems (Yao et al., 2016), particularly in arid and semi-arid areas, as it covers approximately one-third of the Earth's land surface (Hao et al., 2016). Without sufficient water, vegetation can hardly survive and can not provide any ecosystem services (Pan et al., 2013). If the protection of water resources is neglected in cases of limited precipitation and if vegetation construction is carried out blindly regardless of ecological environment, it will not only cause waste of water resources, but also lead to serious economic losses and the destruction of ecosystem. The Loess Plateau, located in western China, is known for its fragile ecosystem and its susceptible to water scarcity (Wang et al., 2010), where soil moisture plays an important role in biomass allocation (Jia et al., 2020) as the evapotranspiration on the Loess Plateau substantially exceeds the available precipitation. Therefore, it is necessary to study the trade-off between biomass and soil moisture on the Loess Plateau and other similar arid and semi-arid areas under the background of global climate change.

There have been many studies on the biomass and soil moisture relevance on the Loess Plateau; however, most were observation approaches and focused on single species that were in correlative relationships with the plant biomass and soil moisture content (Deng et al., 2016; Hao et al., 2016; Tateno et al., 2017; Wu et al., 2014; Yang et al., 2018). Despite the progress made to date, there is little information available on the changes in the relative benefits of AGB, BGB and SMC in different precipitation areas, and trade-off analyses between the biomass and soil moisture. In addition, most of the literature focused on sampling points or local areas on the Loess Plateau, and few examined the whole Loess Plateau for forest, shrubland and grassland. Therefore, it is necessary to elucidate a trade-off relationship between the plant biomass and soil moisture content of different vegetation types in different precipitation areas on the Loess Plateau.

Here, we examined the relationships between the soil moisture and plant biomass of forest, shrubland and grassland on the Loess Plateau. We hypothesized that AGB, BGB and SMC are strongly influenced by meteorological factors, topographic factors and vegetation restoration factors, and we hypothesized that there is a trade-off relationship between plant biomass and soil moisture. The objectives of this study were to (1) examine the effects of influencing factors on AGB, BGB and SMC; (2) explore the relative benefit of soil moisture and plant biomass as influenced by vegetation restoration; and (3) identify the trade-off relationship between the plant biomass and soil moisture across a precipitation sequence and various restoration ages on the Loess Plateau. Elucidating the relationship between the plant biomass and soil moisture of different vegetation types is of great significance to the sustainable management of vegetation ecosystems on the Loess Plateau and other similar regions.

2. Materials and methods

2.1. Study area

The study area was the Loess Plateau (33°41′ − 41°16′ N, 100°52′ − 114°33′ E), covering an area of 640,000 km^2 with an elevation of 200–3000 m (Fig. 1). This region is in the semi-humid and semi-arid transitional zone and has a mean annual precipitation increasing from 150 mm in the northwest to 800 mm in the southeast. The annual potential evaporation is > 1,000 mm (Zhang et al., 2013). The mean annual temperature is 3.6 °C in the northwest and 14.3 °C in the southwest. The vegetation distribution has obvious zonality, with forest, forest-steppes, steppes, desert-steppes and steppes from southeast to northwest (Lu et al., 2003). However, natural vegetation has mostly been destroyed, causing severe soil erosion and land degradation. Since the 1950s, the government has taken a series of measures to control soil erosion, including vegetation restoration, terrace and check dam construction. The most successful is the 'Grain for Green' programme implemented in 1999. Following this programme, vegetation coverage increased from 31.6% in 1999 to 59.6% in 2013 due to the conversion of farmland into forest, shrubland, and grassland (Chen et al., 2015).

2.2. Data sources

Web of Science and the China Knowledge Resource Integrated Database were used to search for peer-reviewed publications during 2000–2018 that reported on the plant biomass and soil moisture content of the Loess Plateau in accordance with the following criteria: (1) The biomass must be dried biomass; and the soil moisture content must be gravity soil moisture content. Additionally, biomass was obtained by direct measurements rather than model calculation. (2) Data were included in our analysis only if the samples were collected from field investigations rather than pot experiments. (3) Experiments without human interference were chosen to avoid the differences caused by different treatments. (4) At least one of AGB or BGB must have been reported, and only BGB and SMC of the 0–1 m soil layer were included in the literature collected. A total of 615 pairs of observations were compiled, which covered three vegetation types (i.e., 70 pairs of forest, 86 pairs of shrubland and 459 pairs of grassland) on the Loess Plateau (Appendix 1, Fig. 1).

Different restoration types (RT) were divided into natural and artificial restoration in this study. Precipitation areas were divided into < 250 mm, 250–350 mm, 350–450 mm, 450–550 mm, 550–650 mm, and > 650 mm, and restoration age (RA) classes were divided into three classes: 0–10 years, 10–20 years and > 20 years.

Latitude (LAT), longitude (LON), elevation (ELE), mean annual precipitation (MAP) and mean annual temperature (MAT) were reported by the investigators based on the sites or nearby weather stations; when the site information was not reported; Latitude, longitude and elevation were estimated from Google Earth based on the descriptions of the locations, and MAP and MAT were provided from weather station. In addition, slope direction (SD), slope gradient (SG), topographic position (TP), growth form (GF), community types, family and dominant species of each sampling site were also given in Appendix 1.

2.3. Calculation of benefits and trade-offs

Benefit for a single ES is defined as the relative deviation between the given observation value and the average value. The overall benefit can be estimated by calculating the mean of individual benefits, which can be weighted according to the importance of all ESs (Bradford and D'Amato, 2012). We assumed that ESs (AGB/$g{\cdot}m^{-2}$, BGB/$g{\cdot}m^{-2}$ and SMC/$g{\cdot}g^{-1}$) involved in our study are equally important.

The trade-off between two benefits is a measure of ecosystem service management option when considering very different ecosystem services. In our study, the root mean square deviation (RMSD) was used to quantify the trade-off between the plant biomass and soil moisture according to Bradford and D'Amato, 2012. It has been proven to be a simple but effective way to balance two or more ecosystem services (Feng et al., 2017; Langner et al., 2017; Lu et al., 2014; Wu et al., 2017). In the two-dimensional coordinate system, the x value and y value of a point represent the relative benefit of ES1 and ES2, respectively, where more points fall above the 1:1 line, which means ES2 benefits more and vice versa. RMSD represents the vertical distance from the coordinate point of ES pair to 1:1 line (Fig. 2).

The standardization of data was required before calculating the RMSD to eliminate the dimensional relationships between variables so that the data were comparable but without changing the correlations between the data. The standardized ES or the relative benefit of an ES (Bradford and D'Amato, 2012) is defined as:

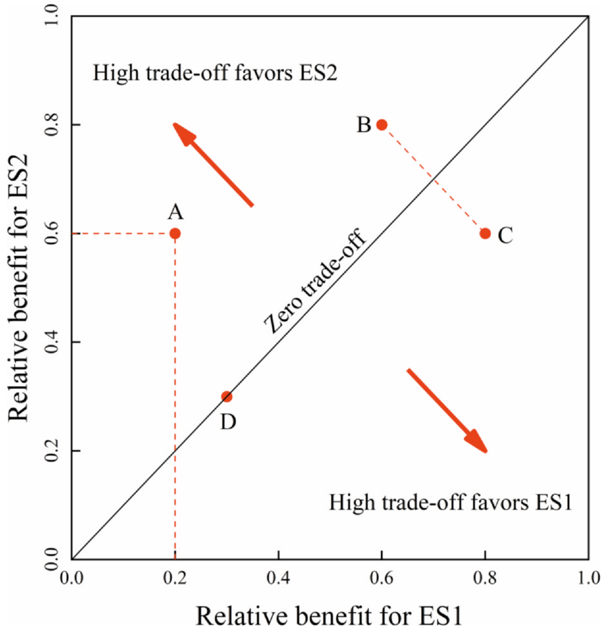

Fig. 2. Illustration of the trade-off between two ecosystem services (ESs). For point A, the relative benefit of ES1 is 0.2 and the relative benefit of ES2 is 0.6. Point B is beneficial to ES2, and point C is beneficial to ES1, and point B and point C are the same distance from 1:1 line with the equal trade-off value, but their trade-offs are less than point A. The trade-off value is zero for point D. This figure is modified from Bradford and D'Amato, 2012.

$$ES_{std} = (ES_{obs} - ES_{min})/(ES_{max} - ES_{min}) \tag{1}$$

where ES_{std} is the standardized value of an ES, ES_{obs} is the observation value of the ES, ES_{min} and ES_{max} are the minimum and maximum value of the ES. Accordingly, the RMSD is calculated as follows:

$$RMSD = \sqrt{\frac{\sum_{i=1}^{n}(ES1_{(i)} - ES2_{(i)})^2}{n-1}} \tag{2}$$

where $ES1_{(i)}$ and $ES2_{(i)}$ are the standardized values of ES1 and ES2; and n is the number of observations.

2.4. Data analysis

The normality of the data frequency distributions of AGB, BGB and SMC were tested, and the data were statistically analyzed through one-way analysis of variance (ANOVA). Multiple comparisons were conducted using the least significant difference (LSD) method. Significant differences were evaluated at the 0.05 level. Correlation analysis and multiple regression analysis were used to investigate for the effects of vegetation, meteorological and topographic factors (i.e. RA, RT, MAP, MAT, ELE, LON, LAT, SD, SG and TP) on AGB, BGB and SMC. Character variables are assigned separately. Restoration types were assigned to natural restoration with 0 and artificial restoration with 1, respectively. Slope direction factors were assigned according to the duration of sunshine as follows: sunny slope with 1.0, the top of Mao with 1.25, semi-sunny slope with 1.5, semi-shady slope with 2.0 and shady slope with 2.5, respectively. All statistical analyses were performed with IBM SPSS version 22.0, and figures were plotted with ArcGIS 10.6 and R version 3.5.2.

Table 1
The above– and belowground biomass, root-shoot ratios and soil moisture content for forests, shrublands and grasslands. Note: N is the number of data points.

Vegetation types	Precipitation (mm)	Aboveground biomass (AGB)/g·m^{-2}		Belowground biomass (BGB)/g·m^{-2}		Root-shoot ratios (R/S)	Soil moisture content (SMC)/g·g^{-1}	
		Mean	N	Mean	N		Mean	N
Forest	< 250	–	–	390.80	8	–	9.44	8
	350–450	–	–	–	–	–	9.06	6
	450–550	3974.73	13	1468.99	12	0.37	10.59	25
	550–650	1542.00	17	604.82	20	0.39	12.29	29
Shrubland	250–350	627.22	8	–	–	–	5.76	8
	350–450	323.97	17	89.11	10	0.28	5.87	21
	450–550	1405.62	28	206.39	12	0.15	10.41	31
	550–650	517.50	8	–	–	–	10.01	14
Grassland	250–350	220.06	149	2006.09	4	–	10.31	149
	350–450	348.22	59	835.81	14	2.40	9.14	59
	450–550	286.98	142	746.48	41	2.60	11.43	149
	550–650	339.07	9	243.50	7	0.72	12.57	15
	> 650	260.42	21	1617.46	11	6.21	22.82	21

3. Results

3.1. AGB, BGB and SMC

Table 1 provides the basic information about AGB, BGB and SMC of three vegetation types in different precipitation areas. The AGB of three vegetation types presented the order of forest > shrubland > grassland, whereas the BGB showed the order of grassland > shrubland, and the BGB varied largely in different precipitation areas for each vegetation type. Moreover, we calculated the root-shoot ratios (BGB/AGB) based on the average AGB and BGB data of each precipitation area. Our results showed that the root-shoot ratios of forest in the 450–550 mm and 550–650 mm areas were 0.37 and 0.39, respectively, those of shrubland in the 350–450 mm and 450–550 mm areas were 0.28 and 0.15, respectively, and those of grassland in the 350–450 mm, 450–550 mm, 550–650 mm and > 650 mm areas were 2.40, 2.60, 0.72 and 6.21, respectively. The mean values for SMC of forest ranged from 9.06 to 12.29 g·g^{-1}, and the mean values for SMC of shrubland was lower than forest, ranging from 5.76 to 10.41 g·g^{-1}, and the mean values for SMC of grassland varied largely and ranged from 9.14 to 22.82 g·g^{-1}.

3.2. Influencing factors of AGB, BGB and SMC

We analyzed the correlations between AGB, BGB, SMC and meteorological factors, topographic factors, vegetation restoration factors (Fig. 3). ELE was negatively correlated with AGB, and RT, RA, and SD were significantly positively correlated with AGB ($P < 0.05$). ELE was significantly negatively correlated with BGB ($P < 0.05$), and RA was significantly negatively correlated with BGB ($P < 0.05$). SD and MAP had a significantly positive correlation to SMC, and RT was significantly negatively correlated with SMC ($P < 0.05$). Moreover, RT, LON and MAP had no correlation to BGB ($P > 0.05$), and RA had no correlation to SMC ($P > 0.05$).

After removing the irrelevant indicators from the regression results, the multiple stepwise regression was further carried out to examine the factors affecting AGB, BGB and SMC (Table 2). RT, ELE, RA, LAT and SD have significant simulations of above-ground biomass, but only account for 20.8% of AGB variation. ELE, RA and SG were the main determinants of BGB, which can account for 34.5% of BGB. The simulation results of SMC by MAP, ELE, SG, RT, LAT and LON reached a significant level, which could explain 40.8% of SMC changes.

3.3. The change of relative benefits across precipitation gradients

There are different trends of relative benefits of AGB, BGB and SMC with the increase of precipitation for the three vegetation types (Fig. 4). The relative benefit of forest AGB increased by 24.98% in the 550–650 mm area compared with 450–550 mm area. However, there was no significant variation ($P = 0.517$) between the two areas. The relative benefit of shrubland AGB in the 250–350 mm area was highest, which was 0.45. In response to the increase in precipitation, the lowest relative benefit of shrubland AGB appeared in the 450–550 mm area compared to the 250–350 mm, 350–450 mm and 550–650 mm precipitation areas, where the benefit was reduced by 61.31%, 58.03% and 32.84%, respectively. Moreover, there are significant differences ($P = 0.020$) between 250–350 mm area and 450–550 mm area. With regard to the grassland, the relative benefit of AGB reached the highest value of 0.29 in the > 650 mm area, which was significantly higher than those of the 250–350 mm (0.10, $P = 0.000$) and 450–550 mm

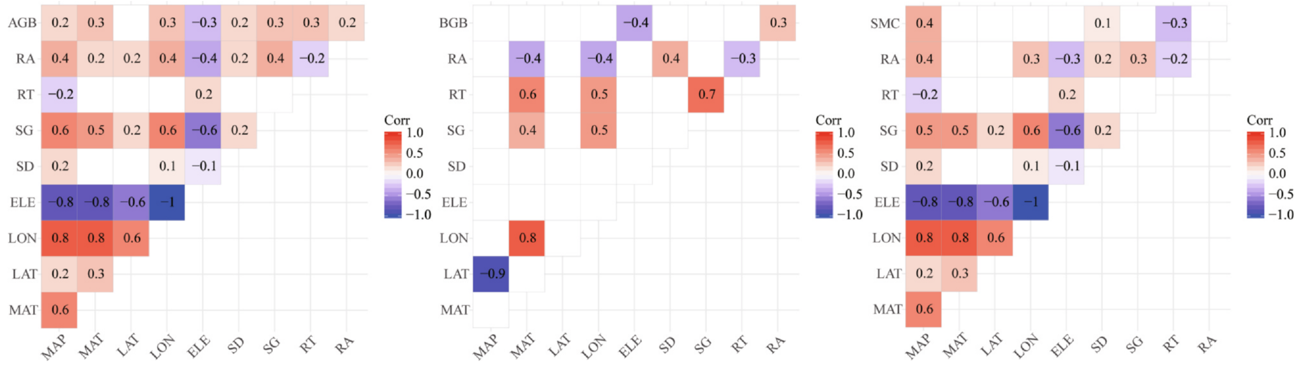

Fig. 3. Correlation coefficients of AGB, BGB and SMC with key environmental factors. The values in the figure are correlation coefficients and are significant at the 0.05 level; insignificant values are blank. MAP, mean annual precipitation; MAT, mean annual temperature; LAT, Latitude; LON, longitude; ELE, elevation; SD, slope direction; SG, slope gradient; RT, restoration type; RA, restoration age.

Table 2

Summary of stepwise regression models to detect relationships between AGB, BGB and SMC and their influencing factors.

	Models	R Square	Adjusted R Square	Sig.
AGB	y = 13148.503 + 1071.986 RT − 0.910 ELE + 23.968 RA − 337.108 LAT + 363.259 SD	0.223	0.208	0.000***
BGB	y = 2313.060 – 1.804 ELE + 12.042 RA + 24.313 SG	0.388	0.345	0.000***
SMC	y = 10.775 + 0.050 MAP + 0.005 ELE − 0.081 SG − 1.253 RT + 1.794 LAT − 0.871 LON	0.410	0.396	0.000***

(0.12, $P = 0.000$) precipitation areas.

There were no significant differences among the precipitation areas of BGB in each vegetation type. Compared with the 450–550 mm and 550–650 mm precipitation areas, the relative benefit of BGB of the forest in the < 250 mm area displayed non-significant differences ($P = 0.986$ and $P = 0.182$, respectively). Similarly, the BGB of the shrubland showed no significant difference between the 350–450 mm and 450–550 mm areas ($P = 0.760$), and the grassland also showed no significant difference ($P = 0.057$) between the highest value of 0.46 in the > 650 mm precipitation area and the lowest value for 450–550 mm precipitation of 0.26.

The relative benefit of the SMC of the forest species reached a maximum value of 0.60 in the 450–550 mm area; and increased by 30.52%, 41.31% and 66.90% compared with the precipitation in the < 250 mm, 350–450 mm and 550–650 mm areas, respectively. However, no significant differences ($P = 0.071$) were found among these areas. With an increase in precipitation, the relative benefit of the shrubland showed a trend of decreasing first and subsequently increasing, reaching a minimum value in the 350–450 mm area, and there were no significant differences ($P = 0.101$) among the different precipitation areas. The highest value of the relative benefit of the grassland SMC was found in the 550–650 mm precipitation area, which was significantly ($P = 0.008$) higher than that in the 250–350 mm precipitation area. In comparison with the minimum value of 0.23 appeared in the 250–350 mm precipitation area, the precipitation in the 350–450 mm, 450–550 mm, 550–650 mm and > 650 mm areas increased by 93.13%, 46.62%, 69.77% and 35.09%, respectively. Compared with the 250–350 mm area, the relative benefits of the 350–450 mm and 550–650 mm areas displayed significant differences ($P = 0.000$ and $P = 0.008$, respectively).

3.4. *The changes in the trade-off between the plant biomass and soil moisture*

The trade-off relationships between AGB and SMC were displayed among different precipitation areas (Fig. 5). In general, the coordinate points were divided into two sides of the 1:1 line, but the relative benefit tended to be SMC across the Loess Plateau. SMC had higher benefit in most areas regardless of vegetation types. However, the relative benefit tended to be AGB for the shrubland in the 350–450 mm area. These results indicated that SMC was more advantageous than AGB when AGB was in contradiction with SMC.

The trade-off relationships were also different between BGB and SMC among different precipitation areas (Fig. 6). For the whole Loess Plateau, SMC had higher benefit than BGB. Most precipitation areas mainly benefited the SMC for three vegetation types, while grassland in the precipitation of > 650 mm was favorable to BGB. Overall, if there was a conflict between BGB and SMC, SMC would have priority in most areas. By comparison, BGB was in a dominant position for grassland in the areas with > 650 mm precipitation.

3.5. *Trade-offs for AGB and SMC, BGB and SMC along precipitation gradients*

As shown in Fig. 7a, the overall mean RMSD1 value of forest, shrubland and grassland was 0.47, 0.41 and 0.38, respectively. With increasing precipitation, the RMSD1 value of forest increases from 450–550 mm to 550–650 mm precipitation area, and the RMSD1 value of grassland increases except for the grassland in the 350–450 mm precipitation area. Moreover, for shrubland, the RMSD1 value was lower than the average value in 250–350 mm and 350–450 mm precipitation areas, but higher than the average value in 450–550 mm and 550–650 mm precipitation areas.

The RMSD2 value of forest in 450–550 mm precipitation area was higher than that in 550–650 mm area. The RMSD2 value of shrubland in 450–550 mm precipitation area was higher than that in 350–450 mm area. The RMSD2 value of grassland reached the minimum value of 0.37 in the area of 450–550 mm, which was less than the average value of 0.46, while the RMSD2 value of other areas was higher than the average value (Fig. 7b).

In general, the RMSD1 and RMSD2 value of forest changed in opposite direction in the precipitation area from 450–550 mm to 550–650 mm. On the contrary, the trends of the RMSD1 and RMSD2 values of shrubland were consistent in the precipitation area from

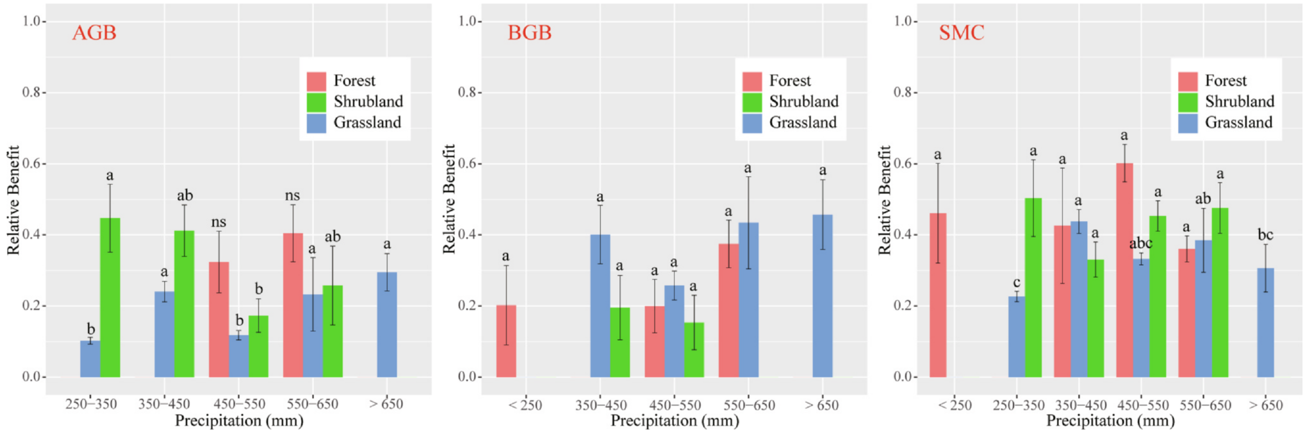

Fig. 4. Changes of relative benefits of AGB, BGB and SMC in forest, shrubland and grassland under different precipitation conditions. Column colors indicate different vegetation types and error bars are standard different precipitation conditions errors. For each vegetation type, the different lower-case letters indicate significant differences among different precipitation conditions at the 0.05 level.

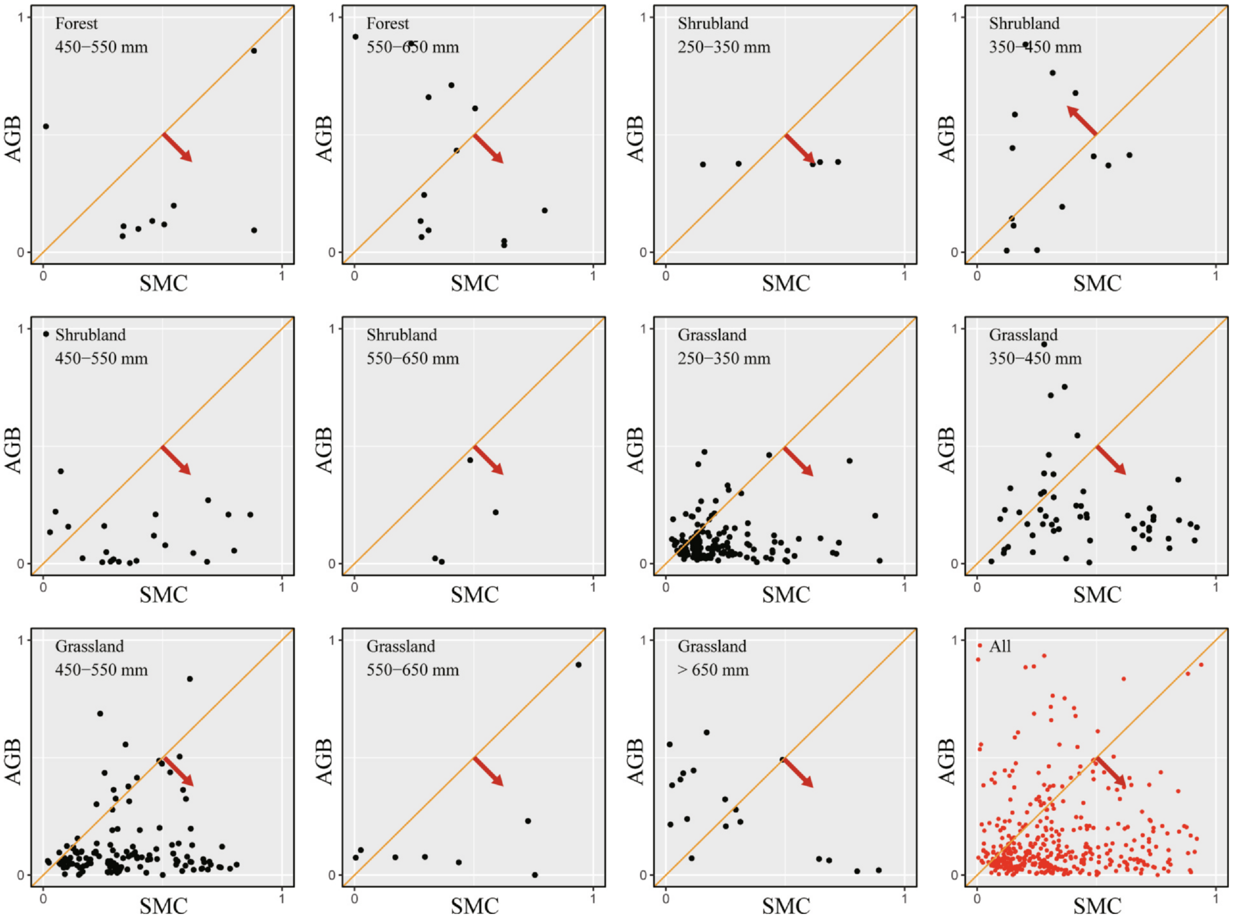

Fig. 5. The trade-off between AGB and SMC. Relative benefits under each precipitation condition (i.e. 450–550 mm and 550–650 mm of forest; 250–350 mm, 350–450 mm, 450–550 mm and 550–650 mm of shrubland; 250–350 mm, 350–450 mm, 450–550 mm, 550–650 mm and > 650 mm of grassland) are represented as black dots, and that of whole area are represented as red dots. The larger vertical distance between the dots and the 1:1 line would indicate higher trade-off and vice versa. The arrow pointing indicates which ES has higher benefit.

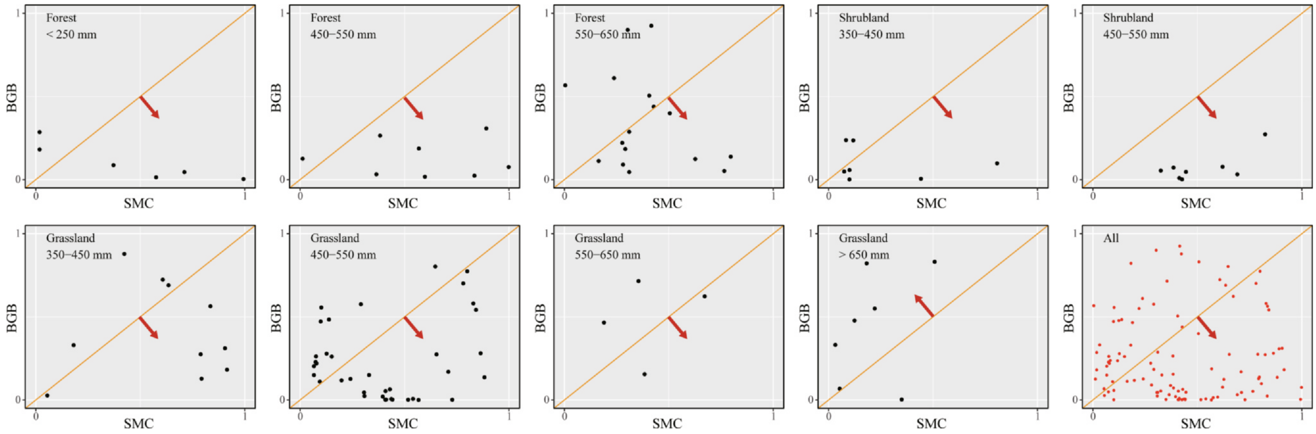

Fig. 6. The trade-off between BGB and SMC. Relative benefits under each precipitation condition (i.e. < 250 mm, 450–550 mm and 550–650 mm of forest; 350–450 mm and 450–550 mm of shrubland; 350–450 mm, 450–550 mm, 550–650 mm and > 650 mm of grassland) are represented as black dots, and that of whole area are represented as red dots. The higher vertical distance between the dots and the 1:1 line would indicate higher trade-off and vice versa. The arrow pointing indicates which ES has higher benefit.

350–450 mm to 450–550 mm; the trend of the RMSD1 value of grassland was consistent with the trend of the RMSD2 value in the precipitation area from 350–450 mm to 550–650 mm.

3.6. Trade-offs between AGB and SMC and between BGB and SMC among various restoration ages

By mapping the trade-offs between AGB and SMC and between BGB and SMC for various restoration ages, we can determine that the distribution of restoration years of the forest, shrubland and grassland were essentially different (Fig. 8). For forest, the RMSD1 value tended

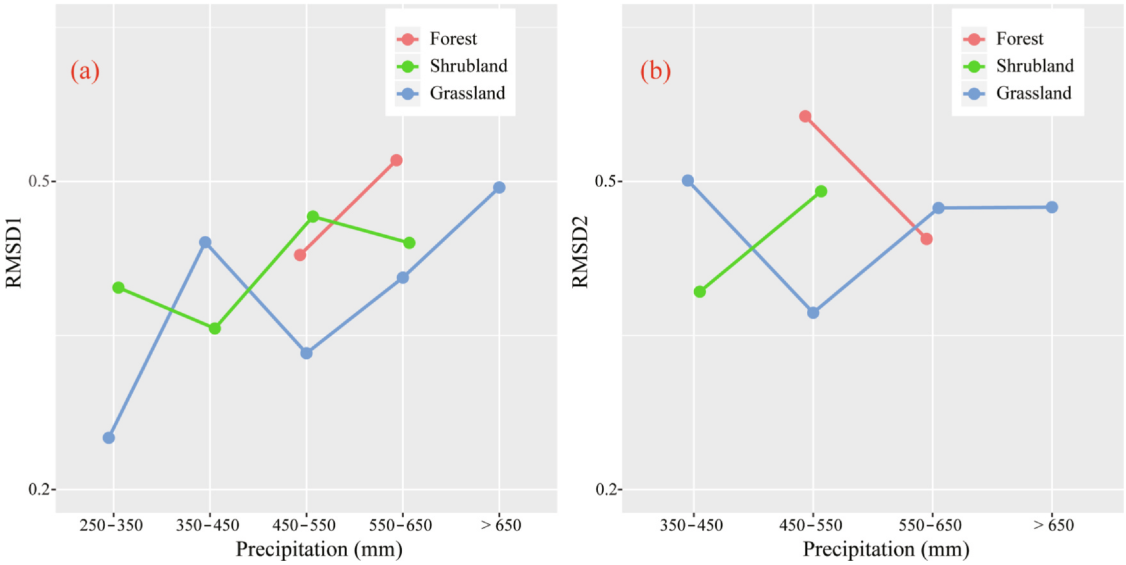

Fig. 7. Changes in the trade-offs of three vegetation types along the precipitation gradient. (a) trade-off between AGB and SMC, was represented as RMSD1; (b) trade-off between BGB and SMC, was represented as RMSD2.

to decrease with increasing restoration ages, and reached minimum values of 0.31 in > 20 years; the RMSD2 value decreased first and subsequently increased with increasing restoration ages, reaching minimum values of 0.46 in 10–20 years. The trade-off value of RMSD1 of 0–10 years was extremely high and was higher than twice as many as that for > 20 years. Due to the lack of data for BGB and SMC, the changes in RMSD1 were only analysed in shrubland. With increasing restoration ages, the RMSD1 values of shrubland increased first and subsequently decreased, which were 0.41, 0.49 and 0.42, respectively, in 0–10, 10–20 and > 20 years. The RMSD1 and RMSD2 values of grassland gradually increased with increasing restoration ages, reaching a minimum value in 0–10 years of 0.25 and 0.45, respectively.

The trade-off values of the shrubland and grassland reached the minimum at 0–10 years, while the forest reached the minimum RMSD1 and RMSD2 value at > 20 years and 10–20 years.

4. Discussion

4.1. Trade-off between plant biomass and soil moisture

From the fitting results of multiple stepwise regression models, we can conclude that precipitation had the strongest effect on SMC, and AGB and BGB were controlled more by elevation, however, these models will vary with spatial and temporal scales. Therefore, the mechanisms of influencing factors affecting SMC, AGB and BGB still need further study. Meanwhile, SMC, AGB and BGB are also affected by other abiotic and biotic factors, such as palnt properties, soil physical and chemical properties (Wang et al., 2013; Yang et al., 2018).

In our study, the trade-offs between AGB and SMC and between BGB and SMC could be explained by the drought environment on the Loess Plateau, where water scarcity restricts vegetation growth. In addition, the inappropriate selection of artificial vegetation tree species and the high density of the surrounding communities lead to a large amount of consumption of soil water, causing the water deficit to intensify. With increasing restoration age, the trade-off relationship did not increase or decrease monotonously. This may be related to the special strategies, water consumption characteristics and competition among different nutrient resources of different vegetation types (Feng et al., 2017; Gao et al., 2017; Tateno et al., 2017). The plant biomass and soil moisture will change greatly with the passage of time, especially under the influences of changeable environmental factors, complex topographic factors and human disturbances (Herben et al., 2018), but it may be still play a reference role in vegetation restoration in other similar regions based on the results of our study on trade-off relationship between different ESs exists combined with existing knowledge.

Although there is evidence of a trade-off relationship between biomass and soil moisture, there remain many limitations in this study. First, we used the BGB and SMC data of the 0–1 m soil layer; however, there were not enough BGB data due to different soil depths given by various studies, and the soil moisture at 0–1 m is greatly affected by

Fig. 8. Changes in the trade-offs of three vegetation types among three restoration age classes. The red line represents RMSD1, i.e. the trade-off between AGB and SMC; The green line represents RMSD2, i.e. the trade-off between BGB and SMC.

precipitation, which may lead to deviations in the results. Second, different species adopt different water use strategies when plant biomass was in contradiction with soil moisture. Our results are only to determine which indicator of vegetation, biomass or soil moisture, is more favorable in a precipitation area, but specific plant species survive in different resource conditions resulting from trade-offs among various indicators. We hope that more data will support the study of afforestation species on the Loess Plateau in different precipitation areas and different restoration ages in the future. Third, although biomass and soil moisture are important ecosystem service indicators in the process of vegetation restoration, other indicators such as carbon or nitrogen storage and soil and water conservation indicators (Nelson et al., 2009) should also be considered in future research.

4.2. Biomass allocation

Plants acquire carbon from the atmosphere and distribute it relative to their aboveground and belowground organs, captured by the root-shoot ratio (Ledo et al., 2018). In this study, we used integrated data to calculate the average AGB and BGB of each precipitation area and then calculated the root-shoot ratio. A global synthesis study reviewed that root-shoot ratios decreased significantly for forest, shrubland and grassland with increasing mean annual precipitation (Mokany et al., 2006). This is inconsistent with the results of our study, which may be due to the different regional scales. The root-shoot ratios of forest we obtained are consistent with those of temperate forest ranging from 0.20 to 0.46 in Mokany et al. (2006). The root-shoot ratios of shrubland we obtained were lower than the median of temperate arid shrubland of 1.06 in Mokany et al. (2006), and it was also lower than that of *Caragana korshinskii* in the range from 0.7 to 2.5 in Deng and Shangguan (2017). The main reason may be that the BGB of 0–1 m soil layer was collected, and the BGB is underestimated due to deep-rooted shrublands included in our study. The reason for the inconsistency also may be attributed to the differences in plant species and environmental factors, such as climate conditions and soil characteristics; different data sources and the limited availability of data also account for parts of the discrepancy. The root-shoot ratios of the grassland were consistent with that ranging from 0.3 to 6.8 obtained by Yang et al. (2018); however, the spatial heterogeneity is very high in different precipitation areas. Although the mechanisms of plant differential investment processes between AGB and BGB are still unclear, the sensitivity of the root-shoot ratios changes also indicates that it is important for us to improve our understanding of carbon allocation and storage in terrestrial ecosystems.

4.3. Implications for vegetation construction

By studying the trade-offs between ecosystem services, we can find more evidence to support the high-level maintenance of most ecosystem services and understand the potential of and ways to achieve high-level maintenance (Bennett et al., 2009; Pan et al., 2013; Wu et al., 2017). In this study, we show how the trade-off relationships between AGB and SMC and between BGB and SMC vary with changes in precipitation and restoration years. The precipitation areas and restoration ages are different when forests, shrublands and grasslands reach the minimum trade-off value. On the one hand, soil moisture is a key variable in many ecosystem processes and is a limiting factor in arid and semi-arid areas. Many previous studies have found that afforestation may cause a dried soil layer (Ren et al., 2018; Su and Shangguan, 2019; Yan et al., 2015) and may threaten the sustainability of vegetation growth for a long time, such as the emergence of small old trees (Shao et al., 2016). Therefore, in the process of vegetation restoration, special attention should be paid to reduce the negative effects of excessive soil water consumption, especially in areas where low benefits of SMC and high trade-offs between soil moisture and plant biomass, and measures such as forest tending and thinning should be taken in these areas to ensure the restoration of ecological environment. On the other hand, regardless of vegetation types, SMC has higher benefits than AGB and BGB in most precipitation areas on the Loess Plateau. Consequently, continued expansion of vegetation recovery on the Loess Plateau could be properly carried out in areas with high benefits of SMC and high trade-offs between soil moisture and plant biomass under the premise of suitable plant species selection and allocation; while in the process of vegetation restoration, plant biomass and soil water consumption vary with the increase of restoration age, so the trade-offs between plant biomass and soil moisture needs to be reconsidered. These findings are also valid for other areas with large-scale afforestation similar to the Loess Plateau. By quantifying the critical importance of the trade-offs between plant biomass and soil moisture, our results highlight the necessity of understanding the trade-offs between multiple ecosystem services at different spatial and temporal scales to better manage ecosystems. Futhermore, the results of this study depend on the selected ES indicators and are not intended to identify the “best” measures for vegetation construction. Our results suggest that it is crucial to determine how to restore vegetation with trade-offs among multiple indicators, which requires us to take effective measures to minimize the trade-offs between ESs.

5. Conclusions

We examined the trade-off relationships between the soil moisture and plant biomass of forest, shrubland and grassland on the Loess Plateau. The results showed that precipitation had the strongest effect on SMC, and AGB was controlled more by vegetation restoration type and elevation, whereas BGB was controlled more by vegetation restoration age and elevation. SMC had a higher relative benefit than AGB and BGB in most precipitation areas. The minimum trade-off of restoration years was > 10 years for forest, but it was < 10 years for shrubland and grassland. It is important to study how to minimize the trade-offs between ESs to better restore vegetation. Accordingly, for areas with large trade-off values between soil moisture and plant biomass, measures such as forest tending and thinning should be taken in areas where low benefits of SMC to reduce the negative effects of excessive soil water consumption, while continued expansion of vegetation recovery on the Loess Plateau could be properly carried out in areas with high benefits of SMC under the premise of suitable plant species selection and allocation. By exploring the trade-off relationships between AGB and SMC and between BGB and SMC, our study can provide a theoretical basis for vegetation construction and water resource management on the Loess Plateau.

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.

Acknowledgments

This work was supported by the Science and Technology Innovation Program of Shaanxi Academy of Forestry (SXLK2020-0101), National Key Research and Development Program of China (2016YFC0501605), and the National Natural Science Foundation of China (41771549, 42077452).

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