Trade-off analyses of multiple ecosystem services by plantations along a precipitation gradient across Loess Plateau landscapes

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Abstract Trade-off is defined as a situation where one ecosystem service (ES) increases while another decreases. In a broader sense, trade-off also refers to unidirectional changes with uneven paces or rates in ESs. Although trade-off analysis for multiple ESs is more integral for ecosystem assessment and management, studies regarding trade-offs are rare in the literature, especially at the landscape scale or across large environmental gradients. Here, we evaluated the co-variations of multiple ESs of black locust (*Robinia pseudoacacia*) plantations along a precipitation gradient (400–650 mm) on the Loess Plateau using a quantitative trade-off approach. The multiple ESs had complex relationships, with significant regional variations along the gradient. Aboveground carbon, soil organic carbon (SOC), soil total nitrogen (STN), and soil water content (SWC) showed increasing trends with precipitation, but understory plant diversity

(UPD) did not. The highest trade-offs were between UPD and SWC and the lowest trade-offs were between SOC and STN among all of the ES pairs. The differences in the trade-offs of varied ES combinations could be the result of unique competition relationships, mass allocation strategies, and time lags. Stand age appeared to be another critical variable in determining the values of ESs and their trade-offs along the precipitation gradient. The decreasing SWC with stand age indicated that the gaining of the other ESs was at the cost of SWC consumption. Because multiple ESs and their trade-offs exhibit high spatial variations across the landscape, spatially explicit management is needed to maintain the benefits while mitigating negative impacts in this water-limited landscape.

Keywords Trade-off analysis · Ecosystem services · Afforestation · Ecosystem management

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Introduction

Ecosystems can provide multiple goods and services—ecosystem services (ESs)—that are beneficial and essential to human beings. It has been increasingly recognized that human activities aiming to promote certain ESs may lead to negative outcomes for other ESs (Goldstein et al. 2012; Maskell et al. 2013). The relative gain/loss of the ESs due to management

activity also depends on the environmental conditions. For example, afforestation can generally promote timber production, soil conservation, and carbon sequestration, but can simultaneously lead to a reduction in soil water due to high evapotranspiration (ET) (Jackson et al. 2005; Chisholm 2010; Nave et al. 2013). For a water-limited landscape, the lowered soil moisture availability may reduce ecosystem productivity, while it may not affect the ESs in a water-unlimited landscape. Therefore, it is important for managers to deliberately consider the advantages and disadvantages of the outcomes of afforestation in different climatic conditions in order to ensure the sustainability of the ESs through ecosystem management.

A trade-off is generally defined as a situation “in which one service increases and another one decreases” (Bennett et al. 2009) (i.e., negatively correlated). Synergy is the opposite situation “in which both services either increase or decrease” (i.e., positively correlated). In a broader sense, trade-off also refers to unidirectional changes with uneven paces or rates in ESs. Trade-off analysis is a method used to explore the interactions, trends, and drivers of multiple ESs, which is helpful for an in-depth understanding of the mechanisms and ecosystem dynamics toward the establishment of adaptive management (Rodríguez et al. 2006; Maron and Cockfield 2008; Bennett et al. 2009; Raudsepp-Hearne et al. 2010). Due to the increased awareness and concern regarding trade-offs among ESs, trade-off analysis has emerged as a new research field in recent years. However, to date, few studies have developed approaches for trade-off quantification and simultaneously evaluating multiple ESs and their trade-offs at the landscape scale or along a large environmental gradient (Chazdon 2008; Nelson et al. 2009; Dickie et al. 2011; Maskell et al. 2013).

The Loess Plateau (34°–40°N, 103°–114°E, 64×10^4 km²) is the largest continuous loess region in the world (Fig. 1). The annual precipitation ranges from 100 to 800 mm across the region. Loess is a pale yellow or buff-like soil, porous, friable, and typically non-stratified, which can develop into a very rich soil under appropriate climatic conditions and can be very valuable as agricultural land. After long-term land cultivation and harvest of natural vegetation, soil erosion became a very serious problem on the Plateau (Fu 1989). Since the 1980s, a series of large-scale

ecological restoration projects that focus on water-soil conservation, such as the Grain for Green Project (GGP), have been implemented on the Plateau. The afforestation effort under the GGP was primarily in the semi-arid to semi-humid areas. As a result, the cropland decreased by 10.8 % in 2008 while the forest and grassland increased by 4.9 and 6.6 %, respectively, compared to 1999 (Lü et al. 2012). These afforestations were conducted over a period of time and resulted in mosaics of different-aged forests across the landscape.

The implementation of the restoration projects has led to a great reduction of soil erosion (Fu et al. 2011), while altering other ESs at the same time. The changes in carbon storage of the plantations, for example, is of obvious interest because re-vegetation has been recognized as a potential management option for increasing carbon sequestration strength and mitigating climate change (i.e., climate regulation service) (Maskell et al. 2013). Soil water availability, a water-provisioning indicator, is the foremost limiting factor influencing vegetation dynamics and ecological processes in arid to semi-arid areas. Soil nitrogen is another important indicator of soil quality and a nutrient cycling service, regardless of its indispensable role in carbon sequestration because of the intrinsic coupling relationship between soil carbon and nitrogen (Iverson et al. 2010). Understory plant diversity (UPD) provides a meaningful measure for forest composition, structure, and succession. Maintenance and enhancement of carbon sequestration, nutrient storage, and native species as well as their interactions with soil water, therefore, have been proposed as the research and management priorities for the Plateau.

Stand age is a critical variable for understanding and quantifying ecosystem processes and services (Bradford and Kastendick 2010; Beck and Powers 2014). It is widely expected that the changes in ESs as well as the trade-offs of an ecosystem are age-dependent. In this study, we focus on the five most important indicators of ESs: aboveground carbon (AGC) storage, soil organic carbon (SOC) storage, soil total nitrogen (STN) storage, soil water content (SWC), and UPD. Our objective is to quantitatively assess the changes in these ESs and their trade-offs across precipitation gradients and plantation ages. We focused on black locust (*Robinia pseudoacacia*) plantation—a dominant plantation type on the Plateau. Specifically, we attempted to: (1) evaluate the changes

Fig. 1 Distributions of precipitation, woodlands, and study sites (multiple plots at each site) on the Loess Plateau

of the five ESs provided by the plantations across the precipitation gradients and plantation ages, (2) quantify the trade-offs among the ESs, and (3) compare the potential differences in the trade-offs across the precipitation gradients and plantation ages.

Methods

Study sites

A total of 39 different-aged plots distributed in eight sites (or small catchments) with typical hilly loess landscapes were established along the precipitation gradient ranging from 400 to 650 mm on the Loess Plateau (Fig. 1). Five precipitation classes (i.e., 400–450, 450–500, 500–550, 550–600, and 600–650 mm) and two age classes (i.e., 5–15 and 20–30 years) were used to allocate the sampling plots. One to three sites were selected for each of the five precipitation classes (2, 3, 1, 1, and 1, respectively) by assuring sufficient replications for each age class. For each precipitation-age combination, there were three to six plots with similar landform characteristics (i.e., similar elevation, slight slope grade, and upper slope positions). Stand age was determined based on tree cores and communication with local farmers. The field investigation was conducted from July to August, 2009 (30 plots), with nine supplementary plots investigated in July, 2010.

Sampling design

In each 20×20 m plot, tree height and diameter at breast height (DBH) of each individual was measured. Based on the DBH frequency distribution, four standard trees at percentiles of 25, 50, 75, and 100 % were selected to represent different DBH classes of all of the individuals in the plot. Four 1×1 m subplots (1 m from the trunk of each of the standard trees) were established to collect soil samples at 0–1 m with a 10 cm interval using cylindrical cores. We took four samples for layering. The soil samples were air-dried (for SOC and STN estimation) or preserved in sealed aluminum cans (for SWC estimation) before lab analysis. Four 2×2 m vegetation subplots were randomly established next to each sampling tree for the understory vegetation survey. The understory vegetation included all herbaceous plants, tree seedlings, shrubs, and vines. All plants were identified to species by name and recorded for number of individuals, mean height, and mean coverage in each subplot.

Quantification of ES indicators

Aboveground carbon (AGC) storage

The total AGC stored in trees was used as an indicator of carbon storage. Aboveground biomass of the trees was estimated as the sum of the biomass of different

tree components, including stem, branch, leaf, and bark, based on the biometric equations from DBH (Tian et al. 1997). The aboveground biomass for all individual trees was scaled to the stand-level using plot size and it was converted to AGC by assuming that 50 % of the dry mass was carbon. Aboveground tree carbon storage is not the only carbon pool but it usually represents the most dynamic carbon pool in forest ecosystems and it is most directly influenced by forest management (Fahey et al. 2010).

Soil organic carbon (SOC) storage

The fraction of SOC (SOC_i , g kg^{-1}) was estimated using the potassium-dichromate oxidation method (Lu 1999), where the total amount of SOC (Mg C ha^{-1}) stock was estimated as the sum of the products of SOC_i , bulk density (g cm^{-3}), and depth. Bulk density was estimated as the ratio of dry soil mass at 105 °C to the volume of the cylindrical core. Because the fraction of stone or gravel (η) is small in the loess soils, it was ignored in calculating SOC (i.e., $\eta = 0$). SOC storage was estimated for three depths at 0–10, 10–20, and 50–60 cm.

Soil total nitrogen (STN) storage

The fraction of STN (STN_i , g kg^{-1}) was analyzed using the dry combustion method with a Vario EL Element Analyzer. The total amount of STN (Mg N ha^{-1}) stock was estimated as the sum of the products of STN_i , bulk density, and soil depth by depth of 0–10, 10–20, and 50–60 cm.

Soil water content (SWC)

Soil water content (%) was estimated as the ratio of the weight of soil water to the weight of dried soil at 105 °C in the soil sample. SWC was estimated for ten depths between 0 and 100 cm.

Understory plant diversity (UPD)

The importance value of each species was calculated as the mean of relative frequency, relative height, and relative coverage. The Shannon–Wiener diversity index (H') was used to quantify UPD:

$$H' = - \sum_{i=1}^s (P_i) \cdot \ln P_i$$

where P_i is the ratio of the importance values of species i to all species and s is the total number of species present in the subplot. The dominant species in the understory layer were found to be native species. A few exotic species such as *Medicago sativa*, *Lolium temulentum*, and *Sonchus oleraceus* were also present, but they had low importance values in all plots.

All of the ES indicators vary with time. We conducted the field investigations at roughly the same period of time of the main growing season to make the data more comparable. Although the data from two-year sampling may bring some uncertainties (especially for SWC), the comparisons of the indicators among the treatments are reasonable. First, as how the plots were sampled in the first year (30 plots), the supplementary plots in the second year (9 plots) were also distributed in separated precipitation and age classes (400–450 mm class: age 10 and 20 yr; 450–500 mm class: age 3, 15, and 30 yr; 550–600 mm class: 15 and 30 yr; 600–650 mm class: 8 and 30 yr). Also, the climatic conditions (precipitation and air temperature) by the sampling time were similar between the years. In addition, the different time of sampling did not affect the division of age classes, i.e., stand age was the age of the sampling year.

Calculation of the trade-offs

The statistical parameter root mean square deviation (RMSD) was used as the indicator to quantify trade-offs among two or more ESs following Bradford and D'Amato (2012). In brief, it extends the meaning of trade-off from negatively correlated relationships (i.e., traditional sense) to the inclusion of uneven rates of same-direction changes between ESs. It is a simple but effective way to represent the degrees of trade-offs between any two or more ESs, no matter how they are correlated to each other.

Data standardization was required before calculating RMSD to eliminate the effects of unit for each ES. Following Bradford and D'Amato (2012), the standardized ES, or the relative benefit of an ES, is defined as:

$$\text{ES}_{\text{std}} = (\text{ES}_{\text{obs}} - \text{ES}_{\text{min}}) / (\text{ES}_{\text{max}} - \text{ES}_{\text{min}}) \quad (1)$$

where ES_{std} is the standardized value of any ES, ES_{obs} is an observed value, and ES_{min} and ES_{max} are the minimum and maximum observed values. The individual ES_{std} ranges from 0 to 1:

Fig. 2 Illustration of the trade-off between two ecosystem services (ESs). The trade-off is represented by the root mean square deviation (RMSD) of multiple ESs. In two dimensions (i.e., a trade-off between two ESs), RMSD is the distance from the coordinate of a pair of ESs to the 1:1 line of the linear correlation, where the two ESs are equal. For example, the trade-off is zero for point A and it is greater for B than C. In addition, the relative position of the data point to the 1:1 line also indicates which ES is more beneficial at the given condition. It is more beneficial for ES-2 at point D and more beneficial for ES-1 at point B, although B and D have the same degree of trade-off (i.e., the same distances to the 1:1 line). This figure is modified from Bradford and D'Amato (2012)

$$\text{RMSD} = \sqrt{\frac{1}{n-1} \cdot \sum_{i=1}^n (\text{ES}_i - \hat{\text{ES}})^2} \quad (2)$$

where ES_i is the standardized value of ES i and $\hat{\text{ES}}$ is the expected value of the i number of ESs. RMSD quantifies the average difference between an individual ES_{std} and the mean ES_{std} , which describes the magnitude of scattering from the mean. In a two-dimensional coordinate system, $\hat{\text{ES}}$ is on the 1:1 line, from which a vertical line can be drawn to connect the coordinates of the two ESs (Fig. 2). In other words, when quantifying the trade-offs between two ESs, the physical meaning of the RMSD value represents the distance from the coordinates of an ES pair to the 1:1 line or the goodness of fit to the 1:1 line. The relative position of a data point to the line indicates which ES is more beneficial.

Because there are many combinations from multiple ES indicators, we focused on comparisons of RMSD values between any two indicators (ten combinations in total). The trade-offs among the three soil-based ES

indicators, including SOC, STN, and SWC and all of the five studied indicators, were also calculated.

Statistical analyses

A two-way ANOVA was used to test the differences in the relative benefits and trade-offs of the five ESs by age and precipitation classes. First, the tests were conducted for the two age classes and the five precipitation classes (2×5 design). We found that the differences in the trade-offs were insignificant among the five precipitation classes ($P > 0.05$). Therefore, the same tests were then conducted for broader precipitation classes. We detected significant differences with 550 mm as a breaking point for precipitation classification (i.e., 400–550 and 550–650 mm) (2×2 design). Due to the unequal sampling sizes among the treatments (i.e., unbalanced design), the estimated marginal means and Type III sums of squares were used for the test. The Bonferroni method was used for the multivariate comparison. The independent effects of precipitation and age were tested based on the linearly independent pairwise comparisons among the estimated marginal means using SPSS 13.0 software.

Results

ESs across precipitation and age gradients

Precipitation and stand age had different effects on the ESs of the plantations (Fig. 3). Increasing precipitation had an overall positive effect on AGC, SOC, STN, and SWC ($P < 0.01$). The pairwise comparison indicated that precipitation of 500–550 mm tended to be the transition zone for ESs to be significantly different across the gradient of 400–650 mm. In other words, the significant changes of most ESs tended to occur at the boundary between the semi-arid (400–550 mm) and the semi-humid (550–650 mm) areas. AGC, SOC, and STN were significantly higher ($P < 0.006$) but SWC was relatively lower ($P = 0.40$), yet insignificant, in the older than in the younger plantations. However, UPD did not show significant differences among the precipitation classes or between the age classes ($P > 0.05$). Further, precipitation and stand age also had significantly positive effects on the mean of the five ESs ($P < 0.001$) (Fig. 3). Precipitation-age interactions did not have significant effects on the ESs.

Fig. 3 Changes of the ESs along the precipitation gradient. **a** aboveground carbon (AGC) storage, **b** soil organic carbon (SOC) storage in 0–20 cm, **c** soil total nitrogen (STN) storage in 0–20 cm, **d** soil water content (SWC) in 0–100 cm, **e** understory plant diversity (UPD), and **f** the mean of the relative values of the five ESs. The primary vertical axis represents the standardized ES scaled from 0 to 1 and the secondary vertical axis represents the ES in the absolute unit in each small figure. Error bars are standard errors. Different capital letters represent significant differences in the ESs between the two age classes and different small letters represent significant differences in the ESs between the five precipitation classes at $P = 0.05$

Trade-offs for paired ESs

The trade-offs varied greatly among the different ES pairs (Fig. 4a, b). On the whole, SOC and STN fell mostly on the 1:1 line in the scatter plot, suggesting a

Fig. 4 Scatter plot matrices of paired ESs (see abbreviations in Fig. 3) by **a** precipitation class and **b** age class. The ES values are standardized to the range of 0–1. The spikes are drawn from the origin of the coordinate (0, 0). The larger degree of angle between the spikes and the 1:1 line would indicate higher trade-offs given the same length of spike and vice versa

very low trade-off between SOC and STN (overall mean = 0.04) (Fig. 5). For the pairs of AGC and SOC and AGC and STN, they deviated from the 1:1 line to some extent, indicating medium trade-offs (overall mean = 0.14 for both). The highest trade-offs occurred

Fig. 5 Trade-offs (i.e., RMSD values) of ES pairs by precipitation and age classes. The precipitation was used to delineate semi-arid areas (SA, 400–550 mm) and semi-humid areas (SH, 550–650 mm). The scale of vertical axis is 0–0.6. Different capital letters indicate the significant differences in the trade-

offs between the two age classes, while small letters are differences in trade-offs between the two precipitation classes. The dotted line in each small figure represents the mean RMSD level for the ES pair

with UPD-related ES pairs (overall mean = 0.20–0.24). The trade-offs between SWC and other ESs were also high (overall mean = 0.15–0.22).

The varied deviation of the data points from the 1:1 line between the precipitation and age classes suggested that the trade-offs among different ES pairs had different sensitivities to the changes of precipitation and stand age (Fig. 4a, b). The RMSD values among the ten ES pairs showed no significant differences among the five precipitation classes. However, the trade-offs between some ES pairs had significant differences when the precipitation class had a wider range (Fig. 5). Specifically, the RMSD values between AGC and SOC, AGC and STN, and AGC and UPD were significantly lower in the 400–550 mm

class than those in the 550–650 mm class ($P < 0.05$). On the contrary, the trade-offs were significantly higher for the ES pairs of SWC and SOC and SWC and UPD in the 400–550 mm class than in the 550–650 mm class ($P < 0.05$). The RMSD values for SOC and STN were consistently low along the precipitation gradient, indicating a steady synergistic relationship between the two ESs across the large precipitation gradient. Stand age affected the trade-offs of the ES pairs of SOC and AGC, STN and AGC, and UPD and STN, with the RMSD values being significantly higher in the older than in the younger stands ($P < 0.05$). The differences were not significant between the two age classes for other pairs of ESs (Fig. 5). The precipitation-age interactions did not

Fig. 6 Vertical change in the trade-offs among the three soil-based ESs (i.e., SOC, STN, and SWC) along the precipitation gradient. **a** among the three variables, **b** between SOC and STN, **c** between SOC and SWC, and **d** between STN and SWC

have significant effects on the trade-offs for any ES pairs.

Trade-offs among multiple ESs

Trade-offs among three soil-based ESs

The overall mean trade-offs among the three soil-based ESs (i.e., SOC, STN, and SWC) were 0.14, 0.16, and 0.11 for the soil depths of 0–10, 10–20, and 50–60 cm, respectively. The RMSD values were not significantly different between the age classes, but significantly lower trade-offs were observed in the 400–550 mm class than those of 550–650 mm class for all depths.

The vertical changes in the trade-offs among multiple ESs along the soil profile showed that the RMSD values among the three ESs tended to decrease

with increases in soil depth, with the exception of the precipitation class of 600–650 mm (Fig. 6a). This suggested that higher trade-offs tended to occur in the surface soil layers. The vertical changes in the ES pairs further indicated that SWC might be the dominant factor influencing the overall trade-offs among the three ESs (Fig. 6c, d) for the synthetic relationship between SOC and STN (RMSD generally less than 0.1) (Fig. 6b).

Overall trade-offs of the five ESs

The trade-offs among the five ESs were relatively high (overall mean = 0.20), reflecting the complex interactions among multiple ESs. The overall trade-offs among the five ESs were not significantly different by precipitation or stand age ($P > 0.05$).

Discussion

Sensitivities of trade-offs to precipitation and stand age

The variations of multiple ESs along precipitation gradients have been extensively studied. However, few efforts have been made to understand the trade-off relationships of ESs with changing precipitation. We compared the differences in the trade-offs of five ES indicators along a precipitation gradient and found that no single trade-off of any paired ES showed a significant difference among the narrowly classified precipitation areas (i.e., five classes across 400–650 mm with a 50 mm interval), although some ES indicators (e.g., SOC, STN, and SWC) did. This indicated that the trade-offs of the ESs may not be as sensitive as the ES indicators themselves to the 50 mm interval of change along the precipitation gradient. Meanwhile, the area of 500–550 mm tended to be a sensitive zone for the changes in trade-offs as significant differences in the RMSD values between the 400–550 and 550–650 mm precipitation classes were detected.

Stand age has been recognized to be a significant driver for many ESs such as species composition, timber volume, and water yield (Bradford and Kastendick 2010; Beck and Powers 2014; Cademus et al. 2014). We found significantly higher AGC, SOC, and STN values and relatively lower SWC values in the old than those in the young stands. Additionally, the trade-offs between AGC and SOC, AGC and STN, and UPD and STN differed significantly between the young and old age classes. Because this study included only age classes of 5–15- and 20–30-year-old stands, we suspected that the trade-offs would be different for older age classes (>30 years). Further studies based on long-term observations of the ES indicators along with trade-off analyses across multiple temporal scales are needed.

Variations in trade-offs and possible explanations

Some possible explanations for trade-offs among ESs may include time scales, time lags, mass allocation strategies, and competitive relationships among ESs. Generally, ESs tend to change by time scales but vary among ESs because ESs are the result of ecosystem processes that are scale-dependent. For example, supporting services usually change more over longer

time scales than do provisioning services (MA 2005). The scale-dependent nature of ESs makes the integral trade-off evaluation very difficult and complex (Bennett et al. 2009). Mass allocation and competition, as other examples, are usually related to the manner of resource utilization and partitioning (e.g., light, water, and nutrient) within the same or among different populations (Gamfeldt et al. 2013).

In our study, the trade-off between AGC and SOC could be explained by the carbon allocation strategy in accumulating aboveground and belowground biomass as well as the time lags between the two processes. The different trade-offs across the precipitation and age gradients may relate to different allocation strategies for young and old trees under the changing climate. In a global synthesis study, Mokany et al. (2006) showed that the root: shoot ratio has a negative relationship with forest age and precipitation. This is because trees in drier areas have to grow more roots to obtain as much water as possible. In addition, aboveground biomass is a major source for soil carbon through litterfall. The conversion of litter biomass to soil carbon has a certain turnover rate, suggesting a time lag between AGC and SOC (Farley et al. 2004). Whereas, the time lag could be shorter in wetter areas where more available water favors litter decomposition. Similarly, the trade-offs between AGC and STN may be partly related to the time lags of releasing biomass nitrogen into the soil as litter is a main N source for the soil in addition to atmospheric N deposition and N fixation by plant roots (Davidson et al. 2007).

The extremely low RMSD values between SOC and STN in our study were additional evidence for the synergic relationships that have been reported worldwide (Yang et al. 2011). The synergic relationship was also found to be steady with plantation age and precipitation in our study. It has been recognized that there are multiple pathways for mitigating the degree of nitrogen limitation effects on carbon sequestration. For black locust, one of the processes that can accumulate extra nitrogen is nitrogen fixation by the mycorrhizae, which may be another reason for the high SOC accumulation rates in our study sites relative to the mean values of forest plantations of temperate zones (Poeplau et al. 2011; Lu et al. 2013). Some scholars suggest that a natural ecosystem may have the intrinsic ability to accumulate N for carbon sequestration with the development of forest age over short

and intermediate time scales (Davidson et al. 2007; Yang et al. 2011). The synergic relationship between SOC and STN across the precipitation gradient found in this study has the practical importance that afforestation anywhere in the semi-arid to semi-humid Loess Plateau may achieve similar benefits to SOC and STN.

The interactions between UPD and other ESs are the most complex issues because understory plants take part in all of the processes of soil water uptake as well as C and N cycling, during which they are competitive or synergic with overstory trees. We found that the trade-offs between UPD and other ESs were the highest among all of the trade-off relationships. The lower trade-off between UPD and SWC in the semi-arid than semi-humid areas reflected the comparatively competitive strength (i.e., a higher competition intensity) between understory and overstory in the dry areas. In contrast, the significantly higher trade-offs between UPD and AGC in the semi-arid than those in the semi-humid areas may be caused by a weak competitive relationship. This may be partly due to the constraint of shading effects of trees on the understory vegetation (Barbier et al. 2008; February et al. 2013). Therefore, AGC sequestration outcompeted the development of UPD in the dry ecosystems.

In terms of the changes with stand age, we found that the relative benefit of SWC tended to be higher than those of other ESs in the young plantations (except for UPD). On the contrary, SWC tended to be lower than those of other ESs in the old plantations. This suggests that the carbon and nitrogen sequestration are at the cost of soil water availability as the plantations grow older. Because soil water is the foremost variable regulating many ecosystem processes in water-limited landscapes (Asbjornsen et al. 2010), it presents a bottleneck or constraint for other ESs in our landscape. Previous studies have extensively found that afforestation in the semi-arid areas has dried the soils of the Loess Plateau (Zhao et al. 2007; Wang et al. 2010). We found that SWC had relatively high trade-offs with other ESs compared to other paired ESs. It is possible that AGC, SOC, and STN would be constrained when SWC continued to decrease in the older plantations, where the competition for water between the understory and the overstory may lead to changes in community structures.

The trade-offs between two ESs reflected their direct interactions. The trade-offs among multiple ESs

were more complex to calculate and understand. Using three soil-based ES indicators, SOC, STN, and SWC, as examples, the coupling relationships were extremely complicated to explore (Amador et al. 2005). SWC is a critical regulating factor for SOC and STN, while STN is often a limiting factor for SOC. Therefore, their trade-offs were determined by these complex processes among the three variables. Future efforts should focus on the multiple interactions as well as the underlying processes.

Limitation of this study and further directions

More efforts are needed for in-depth trade-off analyses on multiple ESs in the future. Firstly, although the five selected ES indicators are among the most important ESs of the plantations, other important indicators (such as soil conservation and runoff) were not included in the study. They need to be considered in further studies. Secondly, the indicators of SOC, STN, and AGC that we used were carbon or nitrogen storage measures; yet, carbon and nitrogen sequestration services should be better quantified based on annually continuous observations of the stands. Thirdly, we only focused on black locust afforestation in the hope that further studies will simultaneously quantify multiple ESs and the trade-offs for other species and ecosystems (e.g., shrub plantations, pastures, croplands, etc.) in the landscape. As some studies have already suggested, pastures may have a higher chance of success than tree plantations over the long term in the areas with precipitation less than 500 mm in this region (Hou et al. 1991). However, comparative analyses on the potential differences in multiple ESs and their trade-offs of different vegetation types have rarely been conducted. Lastly, as trade-offs exist across different spatial and temporal scales (Groot et al. 2007), a well-designed sampling scheme is indispensable to make the spatial scale match the corresponding time scale within the dataset and ensure that the analyzed ES data are intrinsically correlated in a dynamic ecosystem. For example, as vegetation uses soil water at different soil depths at different times, e.g., time of day, season, or changing precipitation pattern (Kurc and Small 2007), the assessment of trade-offs for soil-based ESs must depend on how the variables are measured. Therefore, one should be cautious about the spatial scale of sampling and data analyses of different variables in order to make trade-

off analyses more meaningful. More specific variations in trade-offs along the soil vertical profile and across different time scales should be assessed in further studies.

Conclusions

Afforestation resulted in varied magnitudes and changes in ESs as well as their trade-offs. Integral assessment of the effects of plantations should consider the overall benefits and the trade-offs among the ESs in different rainfall regimes and stand dynamics. Special attention needs to be paid to the ESs that show large trade-offs with other ESs, as they could threaten the sustainability of other ESs over long time periods.

The trade-off analysis provides us a new perspective to rethink our systems in a more integrative and dialectical way. Different ESs can be cohesively connected to each other based on their intrinsic mechanisms within an ecosystem, a fact that we might have previously overlooked. Exploring the mechanisms of the entangled interactions among multiple ESs is very difficult; yet, new knowledge would be created based on the crossing of multidisciplinary information, which would also be helpful for producing a more scientific and integrated method for managing ecosystems and their landscapes.

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