Trade-off between soil water maintenance and carbon sequestration during the implementation of ecological restoration programs in semi-arid Loess Plateau

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Abstract

Converting degraded ecosystems into perennial vegetation in water-limited regions creates potentially conflicting demands for soil water maintenance and carbon sequestration. Current understanding of these competing demands remains still limited. In this study, to quantify the trade-off between them resulting from land-use conversion (converting cropland into forest, shrub and grassland usually) in the Loess Plateau, 2775 observations for soil organic carbon (SOC) stocks (to a depth of 100 cm) and 2654 observations for soil water storage (SWS) (to a depth of 500 cm) from peer-reviewed papers and measured data were synthesized. Results showed that (1) Land-use conversion influenced the trade-off greatly, and in general, converting cropland into natural grassland and evergreen trees performed relatively better in carbon sequestration and soil water maintenance; (2) In rainfall zone less than 550 mm, natural grassland exhibited higher capability in increasing SOC stock but maintaining a lower SWS depletion while forest was a better choice in rainfall greater than 550 mm; (3) With restoration age increasing, SOC stock and SWS depletion both increased significantly, and nevertheless natural grassland appeared to be sustainable and stable to achieve a win-win result. Moreover, with ages increasing, an accumulation of 0.7 Mg ha-1 SOC stock in the upper 100 cm was associated with an approximately 5.14 mm SWS decrease in the 0-500 cm soil layers. Overall, this study provides practical insights for land and water managers on how to achieve the win-win results between soil- and water- related ecosystem services during ecological restoration in water-limited regions.

Keywords

trade-off; ecological restoration; soil organic carbon stock; soil water storage; ecosystem services; Loess Plateau

1 Introduction

The arid and semi-arid region comprises about 47.2% of the global terrestrial ecosystem surface and contributes to the carbon cycle profoundly (Lal, 2004). However, dryland ecosystems generally have been subjected to soil erosion and land degradation seriously due to irrational land use (e.g., overgrazing or excess land reclamation) (Lu*et al.* , 2018). Converting croplands into perennial vegetation has been regarded as an effective way to restore degraded ecosystems worldwide, and its positive effect for carbon sequestration was well documented in arid and semi-arid areas (Deng *et al.* , 2014a; Zhao*et al.* , 2015; Deng *et al.* , 2018; Yu *et al.* , 2018). In the Chinese Loess Plateau, large-scale ecological restoration by converting cropland into forest, shrub and grassland was implemented since 1999 (Deng *et al.* , 2014a). Although the initial goal was to control the soil erosion, it has been instrumental in increasing both the rate and overall quantity of carbon sequestered in the soil (Chang*et al.* , 2011). Nevertheless, land-use conversion in this area has led to negative effects, one of the most important of which is that local soils have become extremely dry in both the shallow and deeper layers (Wang *et al.* , 2013; Cao *et al.* , 2018) due to low precipitation, high evaporation and high water consumption for the introduced vegetation (Wang *et al.* , 2013). Thus, vegetation restoration has often failed due to the lack of soil water, resulting in reductions in vegetation biomass or stunted growth, localized and/or regional vegetation die-off, and poor renewal from a lack of natural germination. Consequently, strong trade-off between soil water maintenance and carbon sequestration may exist during the implementation of ecological restoration in this region (Lu *et al.* , 2014; Feng*et al.* , 2017; Wang *et al.* , 2017b).

Soil moisture in arid and semi-arid areas is the basis for vegetation restoration and therefore for other ecosystem services, e.g., carbon sequestration, biodiversity and soil erosion control (Feng *et al.* , 2017). In this sense, we can treat soil water maintenance as a supportive service and it is the vital variable regulating many ecological functions in water-limited landscapes (Asbjornsen *et al.* , 2011). Feng *et al.* (2016) concluded that revegetation in Chinese Loess Plateau was approaching sustainable water resource limits in terms of the carbon sequestration. This indicates that sustainable and effective ecological restoration with the goal of carbon sequestration in water-limited areas should take the trade-off between soil water maintenance and carbon sequestration into consideration. However, the general patterns of the trade-off between these two vital ecological soil functions at regional scale remain challenging due to the expenses and time particularly associated with deep sampling.

Previous studies revealed that land-use conversion types, climatic gradients, restoration ages exerted main influences on the processes of soil carbon sequestration or soil water dynamics. For example, land-use conversion from cropland to forest, shrub and grassland strongly influences the carbon cycle by changing SOC sequestration, carbon turnover, soil carbon loss and vegetation reservoirs (Post and Kwon, 2000; DeGryze *et al.* , 2004; Xiao *et al.* , 2018). Additionally, different vegetation types and structures exhibited significantly influences on soil water content in both shallow and deep depths. Moreover, Choudhury *et al.* (2016) reported that climatic gradients affected the soil water availability and the decomposition of soil organic matter. Similar results were also reported by Ruiz-Sinoga and Martinez-Murillo (2009). In terms of restoration age, there is an increase in the quantity of carbon inputs, accompanied by a new microclimatic regime and enhanced organic matter protection that promote SOC accumulation with time (Laganiare *et al.* , 2010). Nevertheless, soil desiccation intensified with the restoration ages especially in the deep soil layer (Wang *et al.* , 2010). Summarily, the factors mentioned above would significantly affect the trade-off between soil water maintenance and carbon sequestration especially in water-limited areas. How to achieve the win-win results between them remains in need of further study, to support the implementation of ecological restoration programs especially under the multi-target trade-off in the Loess Plateau to promote sustainable development.

Therefore, a thorough analysis of available literature and original measured data on changes of SOC stock and the depletion of soil water storage resulting from re-vegetation practices may help design such restoration programs. In particular, the evaluation of the effects of land-use conversion on SOC stock and depletion of soil water storage may help improve the design of future ecological programs and achieve the specific goal of sustainable ecosystem development from the perspective of water resources protection and carbon sequestration.

In this study, we examined the published articles and original measured data to assess the effectiveness of three main land-use conversion types, namely forest, shrub and abandoned grassland, in maintaining soil water while increasing SOC stock. The aims of this study were to quantify the effects of land-use conversion types, rainfall zones and restoration ages on the trade-off between the soil carbon sequestration and water maintenance, and identify the optimal restoration models to achieve a win-win situation in increasing soil carbon but with a lower water depletion.

2 Method and material

2.1 data compilation

To estimate the effectiveness of different land-use conversion types on soil water maintenance and carbon sequestration in the Loess Plateau, we built the database in this study mainly including two parts: (1) data extracted from peer-reviewed publications and (2) our original measured data. For the first data source, we collected relevant data on soil organic carbon (SOC), SOC stock, soil water content (SWC) and soil water storage (SWS) by searching peer-reviewed publications through the Web of Science (www.webofknowledge.com), Google Scholar search engines (scholar.google.com) and China National Knowledge Infrastructure (www.cnki.net) with the keywords "soil organic carbon" or "soil water" or "soil moisture" and "Loess Plateau". Common criteria for selecting papers were: (1) each paper compared at least one of the land-use conversion types (converting croplands into forest, shrub and natural grassland) in relation to control land-use (cropland); (2) at least one of variables (SOC, SOC stock, SWC or SWS was measured in both control and vegetated plots; (3) the number of years since cropland conversion were either given or could be directly derived. Nevertheless, specific criteria were used for different variables. For papers related to SOC or SOC stock, only afforestation of the first rotation was considered and data for 0-100 cm or within 100 cm (at least up to 60 cm) were extracted. For papers related to SWC or SWS, soil moisture (gravimetric or volumetric) determined from various depths within the 0-500 cm (0-100 cm, 100-200 cm, 200-300 cm, 300-400 cm, 400-500 cm) and in the field (laboratory experiments excluded). Methods used to determine soil moisture were oven-dry at 105 (Yang *et al.* , 2012) or neutron probe (Jia *et al.* , 2015).

Original measured data was related to SOC not SWC and were collected in the Zhifanggou watershed (Zhang *et al.* , 2016) and Ziwuling Forest area (An *et al.* , 2008) in Ansai and Fu Counties of Shaanxi Province, respectively. Land use in both sites were experienced dramatic changes due to the "Grain for Green" project, and a great deal of croplands were converted to grassland, shrub and forest. When sampling at each site, stands of the three typical revegetation types (i.e., grassland, shrub and forest) were selected, and nearby slope cropland stands were chosen for comparison. The slope gradients and aspects of the selected stands were similar to each other. All of the grassland, shrub and forest sites were converted from long-term cultivated cropland, and they had similar histories and management practices before revegetation. The restoration ages of grassland, shrub and forest were 10 or more years, 18-42 years and 10-35 years, respectively, which were determined from the local farmers and government. At each sampling site, three plots (20 m * 20 m for forest, 10 m * 10 m for shrub and 1 m * 1 m for grassland) were established in the stands of the three revegetation types, and a detailed vegetation survey was conducted in each plot.

Soil samples from the Zhifanggou watershed were collected in July 2011 by digging 400 cm profiles at 20 cm intervals from 0-200 cm and at 40 cm intervals from 200-400 cm, whereas samples from the Ziwuling Forest area were collected in August 2014 at 20 cm intervals from the 0-200 cm profile. In this study, only the first one meter was used. After removing the ground litter, soil samples were collected from three random points in each plot and then mixed to form one soil sample from each soil layer at these two sites. Finally, laboratory analysis was carried out to determine SOC by the potassium dichromate volumetric method, and BD was determined by drying the material at 105 to a constant mass and weighing it.

In total, the final dataset comprised 89 studies published between 2000-2020, including 2775 and 2654 observations for databases related soil carbon and water, respectively, covering 55 sites in 6 provinces (Fig.1).

The raw data were either obtained from tables or extracted by digitizing graphs using the GetData Graph Digitizer (version 2.24, Russian Federation). For each paper, the following information was compiled: sources of data, location (longitude and latitude), climatic condition (mean annual temperature and precipitation), land-use conversion types [cropland, grassland, shrub and forest (evergreen and deciduous)], years since cropland conversion, soil depth, soil bulk density, and amount of SOC or SOC stocks in each layer of 0-100 cm soil, and amount of SWC or SWS in each layer of 0-500 cm soil. When more than one depth was sampled, SOC stock or SWS at all depth were summed together. The age of ecological restoration was divided into four groups: 0-10, 10-20, 20-30 and >30 years. The precipitation was divided into three groups: <450, 450-550 and >550 mm.

2.2 data calculation

Calculation of SOC stocks and soil water storage

SOC stocks were calculated using the following equation (Guo and Gifford, 2002):

$SOCS_d = SOC_d$ x BD x d (1)

$SOCS_{100} = \sum_{d=20}^{100} SOCS_d$(2)

In which, $SOCS_d$ is soil organic carbon stocks in every d depth (Mg ha^{-1}); SOC_d is the soil organic carbon concentration in d depth (g kg^{-1}); BD (g cm^{-3}) is the soil bulk density; d is soil thickness (cm); $SOCS_{100}$ is the soil organic carbon stocks in the whole 100 cm depth (Mg ha^{-1}).

Soil water storage (SWS) was calculated for every 100 cm depth using the following equations (Wang *et al.* , 2013):

$SWS_d = SWC_\vartheta$ x d x ρ^{-1}x UFC (3)

$SWS_{500} = \sum_{d=100}^{500} SWS_d$(4)

Where, SWS_d is the soil water storage (mm) in every d depth; SWC_ϑ is the volumetric soil water content (cm^3 cm^{-3}); d is the soil thickness (cm); ρ is the water density (g cm^{-3}), and UFC is a unit conversion factor (10 mm cm^{-1}); SWS_{500} is the total soil water storage (mm) in the 0-500 cm depth.

Estimation and validation of soil bulk density

For those studies in which soil bulk density (BD) had been measured but lacked data in specific depth, for example, data was measured in the first 60 cm but lacked that in the 60-80 cm and 80-100 cm. We constructed the quantitative relationship among upper and lower layers based on the random forest model in the Loess Plateau, and then predicted the lacked data using this established model (Fig.2). All predicted models were tested by 10-fold Cross-validation (the code was showed in the Supplementary Box1). In this study, the accuracy (R^2) of BD predicted models was between 0.62-0.71 which was generally higher than the published models (Table.1). Wang*et al.* (2013) compared the first five models in Table.1 using local data and resulted in lower accuracy (0.06-0.54). This indicates that published BD predicted models may result extra uncertainties in different regions due to the differences in climate, soil series or vegetation types. The predicted models in this study using the data in the Loess Plateau may be more suitable. Nevertheless, for those studies in which BD had not been measured, we used the empirical relationship (Eqs. (5) and (6)) between SOC and BD (Wu *et al.* , 2003) which was commonly accepted (Guo and Gifford, 2002; Deng *et al.* , 2014a) if there was only the SOC. The input variables needed in this model are much less than Model6 (Wang *et al.* , 2016) but had a similar R^2 (Table.1).

$BD = -0.1229 \times \ln(SOC) + 1.2901$ (for SOC < 6%) (5)

$BD = 1.3774 \times e^{-0.0413SOC}$ (for SOC > 6%) (6)

Transform and estimation of SOC and SWC in deep soil layers

Of the data related SOC collected from the literature, the SOC stocks units were all transformed into "Mg ha^{-1}". If the samples reported only soil organic matter (SOM), their SOC values were calculated by the relationship between SOM and SOC using the Eqs.(7) (Guo and Gifford, 2002):

SOC = 0.58 x SOM (7)

To increase the comparability of SOC or SWC derived from different studies, the random forest model was used following the steps: (1) establishing the quantitative relationship between upper and lower layers based on training dataset, in which the relationships included SOC_{40-60} & SOC_{60-80} (Fig.3 A), SOC_{60-80} & SOC_{80-100} (Fig.3 B), $SWC_{200-300}$ & $SWC_{300-400}$ (Fig.4 A), $SWC_{300-400}$ & $SWC_{400-500}$ (Fig.4 B); (2) performing 10-fold Cross-validation for the established models based on testing dataset; (3) predicting the missing data based on established models.

Estimation and validation of soil water storage based on empirical formula

For those studies in which the SWC was determined volumetrically (cm^3 cm^{-3}), SWS is calculated by the Eqs (3) and (4) directly. However, for those studies in which the SWC was determined gravimetrically (g g^{-1}), pedotransfer functions were used according to Jia *et al.* (2017) (Eqs.8) and Bai (2009) (Eqs.9) that were established in the Loess Plateau. Jia*et al.* (2015) suggested that this formula was considered valid for all soil depth in the Loess Plateau.

$SWC_\vartheta = 0.5891 \text{ x } CR + 0.0089$ ($R^2 = 0.93$, $p < 0.001$) (8)

$SWC_g = 35.403 \text{ x } CR + 1.2834$ ($R^2 = 0.98$, $p < 0.001$) (9)

In which, SWC_ϑ is the volumetric soil water content (cm^3 cm^{-3}); CR is the slow neutron counts; SWC_g is the gravimetric soil water content (g g^{-1}).

Consequently, we can get the conversion formula between SWC_ϑ and SWC_g (Eqs.(10)) and further a computative soil water storage (SWS_g) (Eqs.(11)) based on Eqs (6), (8), (9) and (10):

$SWC_\vartheta = 0.01664 \text{ x } SWC_g - 0.0125$ (10)

$SWS_g = SWC_\vartheta \text{ x d x } \rho^{-1} \text{x UFC}$ (11)

It's necessary to test the relationship between computative SWS_g and practical SWS_r. Therefore, we collected another 2686 observations (within 1000 cm soil layer with 20 cm interval) from peer-reviewed papers in the Loess Plateau that included the gravimetric SWC and BD which allowed us to calculated the practical SWS_r using the Eqs. (12). Although the data used to test contains various vegetation types (forest, shrub, grassland and cropland), depths (100 to 1000 cm), climatic conditions (220 to 600 mm), interestingly, we get a constant (k = 1.33) between SWS_r and SWS_g as following (Eqs. (13) and Fig.5). This indicates that, at regional scale, we may get the approximate SWS based on the formulas and this value is about 1.33 times than the practical SWS. Nevertheless, its implication in other spatial scales or specific conditions may need further validation.

$SWS_r = SWC_G \text{ x BD x d x } \rho^{-1} \text{ x UFC}$ (12)

$SWS_r = (SWS_g + 2.54) / 1.33$ ($R^2 = 0.94$, $p < 0.001$) (13)

In which, SWSr is the practical soil water storage (mm) that can be calculated based on data given in the peer-reviewed publications; SWC_G and BD are the gravimetric soil water content and bulk density in the peer-reviewed publications; d is the soil thickness (cm); ρ is the water density (g cm^{-3}), and UFC is a unit conversion factor (10 mm cm^{-1}); SWS_g is the computative soil water storage.

Meta-analysis

For single layer, the size of the effect in each investigation was calculated as the response ratio which was defined as the change degree in SOC stock or SWS after the cropland conversion:

$r = LU_n / LU_0 - 1$ (14)

where LU_n is the SOC stock or SWS under current land use and LU_0 is the SOC stock or SWS under cropland, the same as the initial SOC stock. As is typical in meta-analysis, most of the published papers reported mean values for treatment and control plots but not standard deviations or standard errors. To maximize the number of observations included in the present analysis, we used unweighted meta-analysis, as described in earlier studies (Deng *et al.* , 2016; Su and Shangguan, 2019).

For the whole profile, three indices were employed to compare the effects of land-use conversion types on SOC sequestration and soil water maintenance. These included the SOC sequestration effect in the 100 cm profile (SSE_{100}), the soil water storage (SWS) depletion effects in the 500 cm profile ($SWDE_{500}$) and the ratio with absolute value between SOC sequestration and SWS depletion (RSSWD). These indices were calculated as follows (Deng *et al.* , 2016):

$SSE_{100} = \frac{SOCS_{100} - SOCS_{ck100}}{SOCS_{ck100}}$ (15)

$SWDE_{500} = \frac{SWS_{500} - SWS_{ck500}}{SWS_{ck500}}$ (16)

$RSSWD = \left| \frac{SSE_{100}}{SWDE_{500}} \right|$ (17)

Where $SOCS_{100}$ and $SOCS_{ck100}$ represent the SOC stock for the vegetated and control plots in the 100 cm depth (Mg ha^{-1}); SWS_{500} and SWS_{ck500} represent soil water storage for the vegetated and control plots in the 500 cm depth (mm).

A method reported earlier (Luo *et al.* , 2006; Luo *et al.* , 2009) was used for calculating 95% confidence interval (CI) of the means for SSE_{100} or $SWDE_{500}$, as shown in Eqs. (18) and (19):

$SE_{total} = \sqrt{\frac{V_s}{N}}$ (18)

$95\%CI = 1.96 \times SE_{total}$ (19)

Where SE_{total} denotes the standard error of the response size for SSE_{100} or $SWDE_{500}$ and Vs and N are the variances of response size for SSE_{100} or $SWDE_{500}$ and the number of observations, respectively. In this study, 95%CI was calculated for the overall data and for each category: the observed response sizes were considered statistically different from zero if the 95%CI did not include zero.

2.3 Data analysis

The Kruskal-Wallis rank sum test, performed by the *kruskal.test*function in R, was used to test the effect of land-use conversion types, tree species, rainfall zones, restoration ages, slope aspects and gradients on SOC stock or SWS changes and their trade-off. Differences were evaluated at $P < 0.05$. This method is equivalent to single-factor ANOVA but is used when only a few individuals are included in at least one of the samples and the data are not normally distributed.

The random forest model based on the R package *randomForest*(*https://www.rdocumentation.org/ packages/ randomForest*) was used to quantify the relationship of BD, SOC and SWC between different soil layers and predict the lacked data according to these quantitative relationships. Compared with the traditional regression models or other machine learning methods, random forest model can perform a better prediction without any hypothesis for the data (Breiman, 2001). To assess the model stability, self-written code for 10-fold Cross-validation was used (Supplementary Box1). In this study, the mean standardized mean square error of the testing dataset (MNMSE) in all the established models was basically equal to $1 - R_f^2$ and the $MNMSE_0$ of training dataset was relatively low. This indicates that the models established in this study to predict BD, SOC and SWC are stable and valid.

3 Results

3.1 The effects of land-use conversion on the trade-off between SSE_{100} and $SWDE_{500}$

When land was brought under perennial vegetation as part of the entire ecological restoration program, the changes of SOCS and SWS showed distinct directions irrespective of type of vegetation, whether forest, shrub or grassland (Fig.6 and Supplementary Fig.S1 and Fig.S2). In detail, the mean SSE_{100} of forest (0.67 $\pm$ 0.14, Fig.6 A) was higher than in shrub (0.54 $\pm$ 0.13, Fig.6 B) and in grassland (0.38 $\pm$ 0.11, Fig.6 C). In contrast, the mean $SWDE_{500}$ in forest, shrub and grassland were -0.40 $\pm$ 0.03, -0.40 $\pm$ 0.02 and -0.21 $\pm$ 0.04, respectively. Grassland had the relatively low water consumption but also low soil C sequestration which was different with forest and shrub. However, the RSSWD in different land-use conversion types was ranked in the following order: grassland (1.86) > forest (1.66) > shrub (1.37).

Interestingly, tree species exhibited significant impact on trade-off between soil water maintenance and carbon sequestration (Fig.6). For example, similar $SWDE_{500}$ was found between deciduous (0.41 $\pm$ 0.05) and evergreen (0.41 $\pm$ 0.04) trees but the latter showed much higher RSSWD (2.40) than the former (1.47). These results mean that the performance of grassland in maintaining soil water and increasing SOC in semi-arid areas was higher than the ability of forest and shrub, and that of evergreen trees was higher than deciduous.

3.3 The effects of rainfall zones on the trade-off between SSE_{100} and $SWDE_{500}$

Rainfall zones affected the trade-off between soil water maintenance and carbon sequestration significantly, and its effects were differed among three land-sue conversion types (Fig.7). For example, in the case of forest, higher SSE_{100} (0.75 ± 0.25) and lower $SWDE_{500}$ (-0.24 ± 0.11) occurred which resulted a higher RSSWD (3.06) in the >550 mm rainfall zone (Fig.7 A). Nevertheless, the RSSWDs in the 450-550 mm and <450 mm was 1.59 and 0.38, respectively. In the case of shrub, the higher SSE_{100} means higher $SWDE_{500}$, and vice versa. The RSSWDs in the zones of <450, 450-550 and >550 mm was 1.07, 1.28 and 0.17, respectively (Fig.7 B). Natural grassland had lower water depletion (-0.08 to - 0.23) especially the >550 mm rainfall zone (-0.08 ± 0.13), and therefore, relatively higher RSSWD was found (1.56 - 2.95) compared with shrub (0.17 - 1.28) (Fig.7 C). These results mean that converting croplands into forest in the rainfall zone of >550 mm may contribute to achieving the goal of maintaining soil water and increasing carbon sequestration. Furthermore, grassland may be a better restoration way in the rainfall zones of <450 mm and 450-550 mm compared with forest and shrub to achieve this goal.

3.4 The effects of restoration ages on the trade-off between SSE_{100} and $SWDE_{500}$

Overall, the number of years that had elapsed after restoration had adverse impacts on soil water and carbon sequestration, and the trends among different vegetation types were similar (Fig.8). In the cases of forest and shrub, $SWDE_{500}$ during the >10 yr was significantly lower than in <10 yr, and remained relatively stable levels (-0.42 to -0.48 in forest, -0.38 to -0.47 in shrub) (Fig.8 A, B). In addition, with the accumulation of SOC, the higher RSSWD occurred after 20 yr while the RSSWD was lower than 1 in the first 20 yr (Fig.8 A, B). Although the depletion of SWS increased with restoration ages (-0.14 to -0.30), RSSWD in grassland was between 1.41 and 3.23 (Fig.8 C). These results indicate that converting cropland into grassland may get a stable benefit of maintaining soil water and increasing SOC than forest and shrub.

4 Discussion

4.1 Trade-off between soil water maintenance and carbon sequestration during the implementation of ecological restoration programs

Land-use conversion types

The contribution of vegetation restoration to ecosystem services generally varies according to the vegetation types, rainfall zones, restoration periods and topographic conditions (Lu *et al.* , 2014; Feng *et al.* , 2017; Wang *et al.* , 2017a). Converting cropland into forest and shrub exhibited higher ability in carbon sequestration and soil water consumption than grassland (Fig.6). This can be explained by higher organic material input through root biomass or exudation and higher water consumption by transpiration. Nevertheless, SOC stock in natural grassland increased by 38.43% within 100 cm depth (lower than forest (67%) and shrub (54%)) but resulted about half of water depletion (21%) in a depth of 500 cm compared with forest (40%) and shrub (40%) (Fig.6). Grassland in arid and semi-arid regions is characterized by extensive root systems in shallow layers (Tate and Ross, 1997), efficient accumulation of biomass via photosynthesis, longer growing seasons due to earlier and later seasonal growing periods, and the allocation of plant resources. Wang *et al.* (2016) confirmed this view point that SOC stocks were significantly lower under shrub than grassland in semi-arid regions. Deng *et al.* (2014b) reported that in arid environment converting cropland into grassland had the highest soil carbon sequestration rate compared with forest and shrub and meantime the water depletion in grassland was much lower than other two land-use types due to shallow roots and weak transpiration (Deng *et al.* , 2016). For tree species, evergreen trees in this study may sequester more SOC than deciduous trees at a similar water depletion (Fig.6). This can be explained by lower soil temperature, higher fine root biomass and productivity in evergreen tree species (Yuan and Chen, 2010; Sun *et al.* , 2020). Compared with deciduous trees, the evergreen trees can allocate more photosynthetic products for fine root production (Vogt *et al.* , 1986) which was supported by Gao and Huang (2020). In terms of soil water depletion, Su and Shangguan (2019) reported that there were no significant differences between deciduous and evergreen tree species in the Loess Plateau at a regional scale which was consistent with our results (Fig.6). Overall, the vegetation types or tree species exhibited great impacts on the trade-off between soil water maintenance and carbon sequestration, and grassland has the potential to achieve this win-win situation. In addition, evergreen trees may be better if soil water was not limited.

Rainfall zones

Rainfall plays decisive roles in determining the net primary productivity and ecosystem structure in arid and semi-arid ecosystems (Iglesias *et al.* , 2012), which in turn have the potential to affect SOC accumulation through biotic processes associated with both plant productivity and organic matter decomposition (Carvalhais *et al.* , 2014; Campo and Merino, 2016). In this study, higher RSSWD occurred in the relatively high rainfall zone (Fig.7), e.g., >550 mm, and converting croplands into forest had the highest RSSWD than shrub and grassland in this zone (Fig.7). Deng*et al.* (2016) reported that after the conversions, soil water in zones with rainfall below 600 mm decreased significantly than the zone with rainfall greater than 600 mm. This is basically consistent with our results that land-use conversion sequestered more carbon but induced less water depletion in rainfall zone greater than 550 mm. Our results also support that in sufficient rainfall zone (e.g., >550 mm), converting cropland into forest may have the greatest potential to sequester more carbon due to developed root system however without severe soil water depletion. Wang *et al.* (2017a) found that the trade-off between SOC and gravimetrical soil moisture within 100 cm depth decreased at rainfall > 570 mm in semi-arid region. However, in rainfall zones less than 550 mm, higher RSSWD than forest and shrub occurred in grassland. This is agreed with Collins and Bras (2007) who reported that plants exposed to water stress in arid and semi-arid regions often had deeper and more developed root systems. In addition, Jackson *et al.* (1997) found that although the deep root system was less distributed, its root system had high water absorption efficiency and great potential. Therefore, converting cropland into abandoned grassland in water-limited region may be a better way to reduce the trade-off between these two ecological functions. In addition, Tuo *et al.* (2018) showed that grassland restoration resulted in more SOC accumulation than shrub and forest in areas with mean annual precipitation <510 mm, whereas there were losses in SOC in sites with rainfall >510 mm. Chang *et al.*(2011) reported that grassland had a stronger effect on SOC sequestration in the northern Loess Plateau than in the middle and southern regions. In contrast, forest could increase more SOC in the middle and southern Loess Plateau than in the northern Loess Plateau. Although these results are consistent with our results, few of them take both carbon sequestration and deep soil water consumption into consideration especially under different rainfall zones, and therefore the comprehensive assessment of trade-off between the two vital soil functions was limited. However, recent study suggested that positive carbon sequestration by afforestation in short term may be further weakened by water shortage, making our ability to restore degraded land in semi-arid regions more challenging (Chai *et al.* , 2019). From this perspective, ecological restoration, e.g., tree planting, is not a simple solution and it must be planned carefully and implemented to achieve desired outcomes in the long run particularly in eco-fragile regions (Holl and Brancalion, 2020).

Restoration age

Previous studies suggested that restoration age was an important factor that influenced the water and carbon cycle in soils (Wang *et al.* , 2010; Deng *et al.* , 2014a; Deng *et al.* , 2014b; Liang*et al.* , 2018). Generally speaking, with increased time, the quantity of carbon input increased through root biomass, exudation, litter and microbial biomass, accompanied by a new microclimatic regime and enhanced organic matter protection that promotes SOC accumulation. In contrast, the depletion of soil water intensified with time after converting croplands into perennial vegetation. Our results related to SOC stocks and SWS support these viewpoints (Fig.8), and quantitatively, an accumulation of 0.7 Mg ha^{-1} in the upper 100 cm was associated with an approximately 5.14 mm decrease in the 0-500 cm soil layers (Fig.9). Interestingly, from the perspective of trade-off between SSE_{100} and $SWDE_{500}$, converting cropland into natural grassland exhibited a steady RSSWD that was greater 1 in all restoration periods but the long-term benefit for carbon sequestration in forest and shrub may be constrained by soil water shortage. Wang *et al.* (2012b) concluded that the relationships between soil moisture and plant growth can be divided into five stages: (1) the initial stage: water supply from rainfall and deep soil layer was enough to support rapid growth; (2) the second stage: more water was needed and deep soil moisture was extracted and utilized by the roots; (3) the third stage:

roots deepened continuously and the plant maintained the exuberant growth; (4) the fourth stage: the growth of plant become relative stable at a certain level that highly depended on the amount of annual rainfall; (5) the last stage: deep soil moisture deficit may recovery gradually due to the physiological senescence of trees. This conclusion supported our results except for the fifth. Nevertheless, we suggest that natural grassland may be a sustainable way to sequester carbon in soil in the long term without severe soul water depletion.

4.2 Uncertainty analysis and implications for land management

Uncertainty analysis

This synthesis offers the most accurate estimate of land use conversion-driven SOC stock and SWS changes following the implement of "Grain for Green" project on the Loess Plateau. Strict accuracy is limited due to the uneven distribution of data collected from peer-reviewed papers. In addition, we only incorporated the carbon sequestrated in soils rather than the above- and below-ground biomass carbon which was also an important carbon pool, especially the forest and shrub. Nevertheless, soils comprise the largest terrestrial carbon pool and has the greatest potential to sequester carbon in the future. Further studies should try to include the carbon stored in the whole ecosystem to perform an overall evaluation for trade-off. Moreover, it is necessary to take the changes of SOC stock in the deep soil layers ($>$ 100 cm) into consideration and the reasons are in the following: (1) vegetation in semi-arid Loess Plateau usually developed the extensive root system that increased the carbon input due to low precipitation and thick soils and the root penetration depth can be up to 1000 cm; (2) deep soil layers exhibit large accumulated SOC stocks but low SOC contents, resulting in an unsaturated state of mineral surfaces. The specific surface area of fine mineral particles plays an important role in the formation of mineral-organic associations, which represents one of the main mechanisms regulating SOC stabilization (Li*et al.* , 2020). Overall, despite of the existing uncertainties in this study, we provide a thorough analysis for trade-off between carbon sequestration and water maintenance and pay much attention to the deep soil layers and influencing factors as far as possible.

Implications for management

Soil water is fundamental in the tight coupling exists between ecosystem productivity, surface energy balance, biogeochemical cycles, and water resource availability in drylands (Wang *et al.* , 2012a) where soil water plays the central role in the soil-plant systems, particularly, the soil water in deep layer (Wang *et al.* , 2017a; Cao *et al.* , 2018). This study has proved that vegetation types, tree species, rainfall zones and restoration age exhibit great influences on the trade-off between soil water maintenance and carbon sequestration. Natural grasslands appeared more effective in maintaining deep soil water storage and increasing SOC sequestration, especially in water-limited area. Importantly, converting croplands into natural grasslands may be much more sustainable than the forest and shrub in the long term. Recent study also showed that grassland was the best choice for optimizing the trade-off between catchment water yield and soil conservation during the implementation of ecological restoration programs in semi-arid regions and proved the feasibility of the measures taken by the Grain-for-Green Chinese program relying on grassland restoration to maintain runoff while reducing soil erosion (Liu *et al.* , 2020). Overall, the restoration of natural grassland in the semi-arid Loess Plateau should be paid more attention due to its sustainable ecological functions. In addition, if the soil water is not the limited factor, forest especially evergreen trees are welcomed to achieve this win-win situation.

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Table.1 Published pedotransfer functions on soil bulk density prediction

Models	Input variables	n	R^2	Reference
Model1	SOC	721	0.46	Alexander (1980)
Model2	SOC	19651	0.41	Manrique and Jones (1991)
Model3	SOC, clay, silt	224	0.62	Kaur *et al.* (2002)
Model4	SOM, clay, depth	408	0.67	Balland *et al.* (2008)
Model5	SOM, clay, depth	161	0.48	Balland *et al.* (2008)
Model6	SOC, clay, silt, slope	1254	0.59	Wang *et al.* (2016)
Model7	SOC	784	0.58	Wu *et al.* (2003)

Note: SOC and SOM mean soil organic carbon and soil organic matter, respectively; n means the number of observations; R^2means the accuracy of predicted models.

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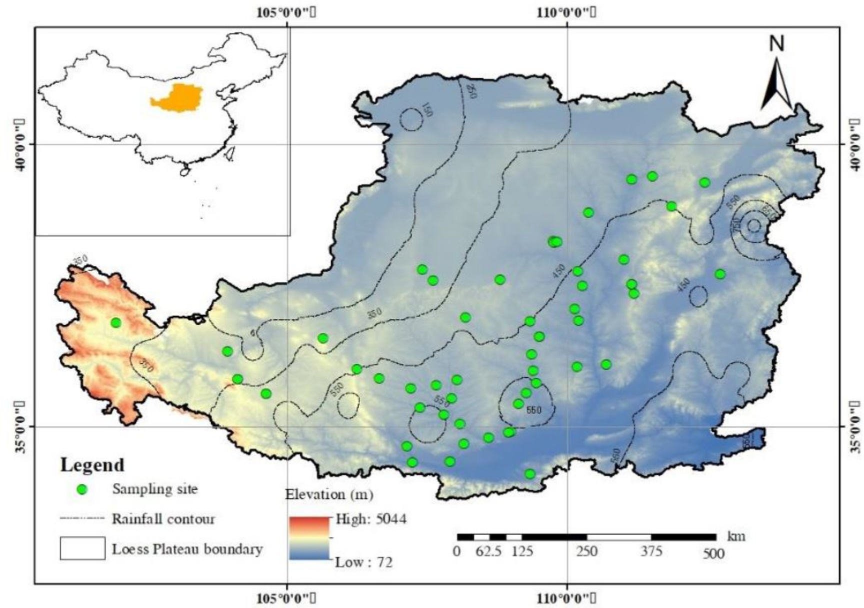
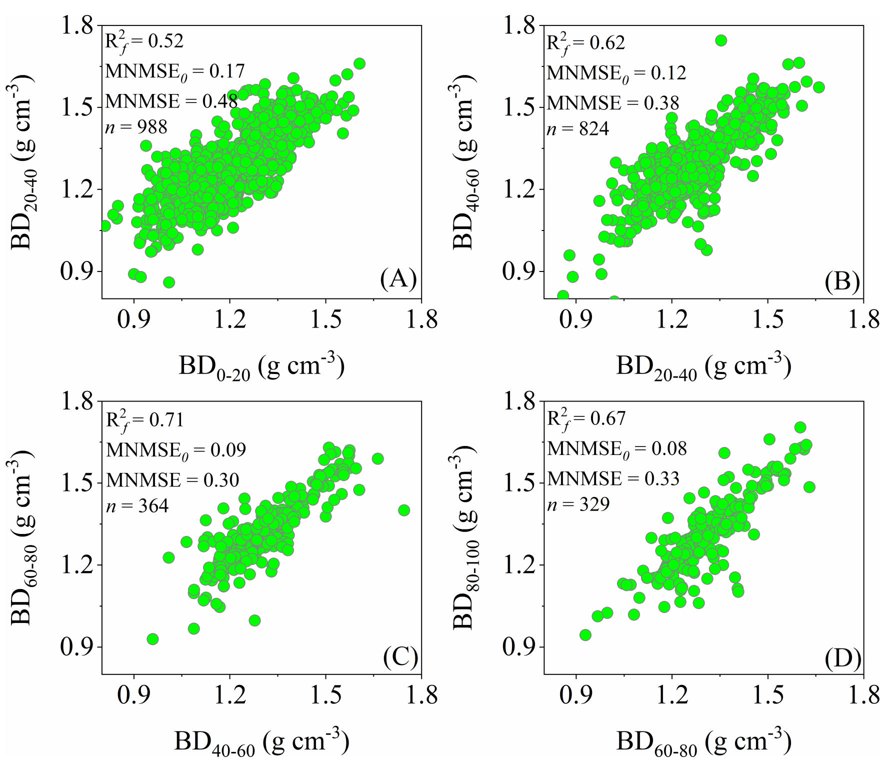
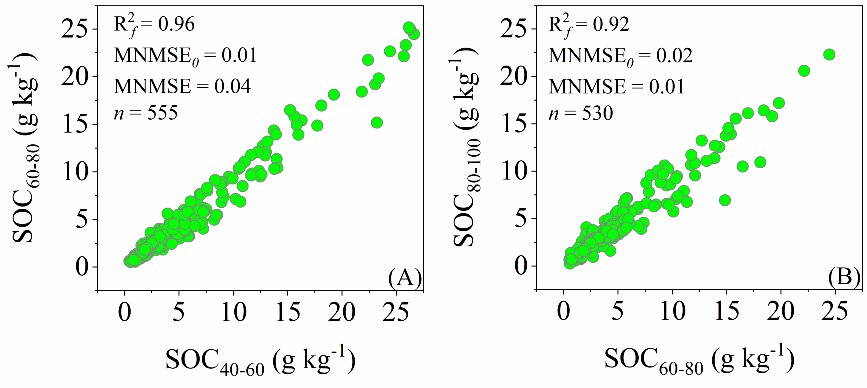
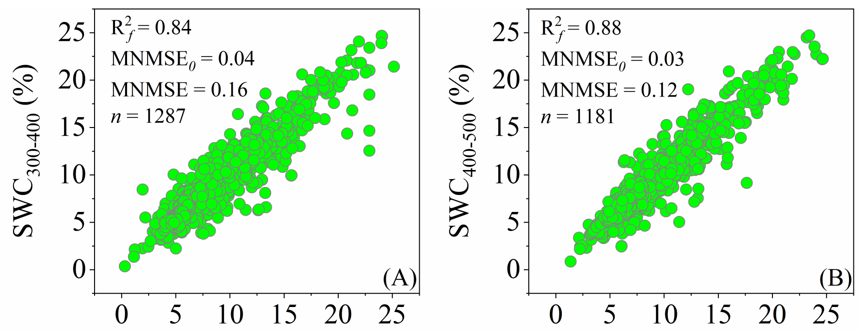
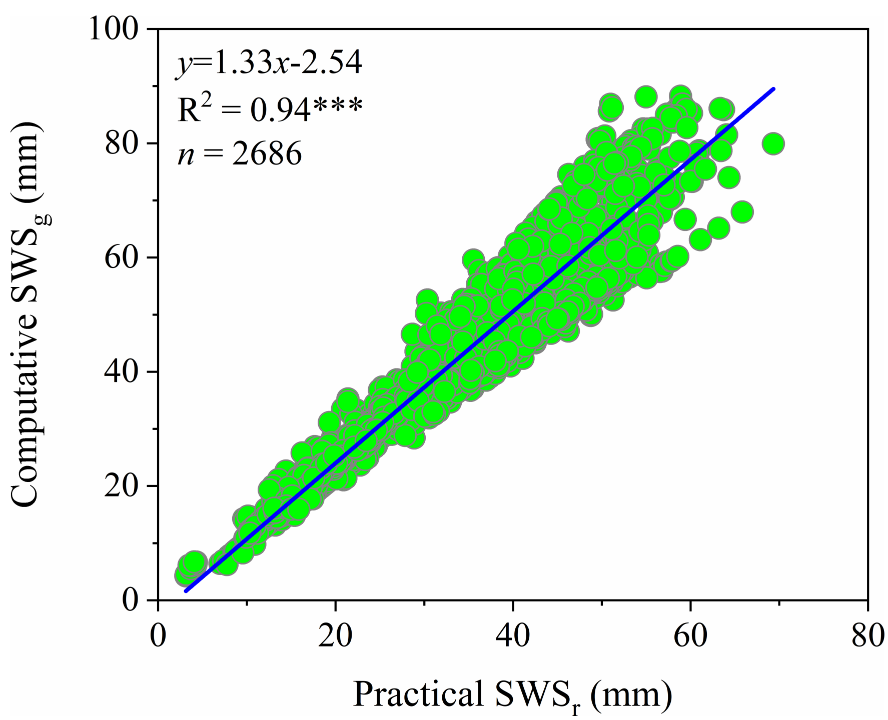
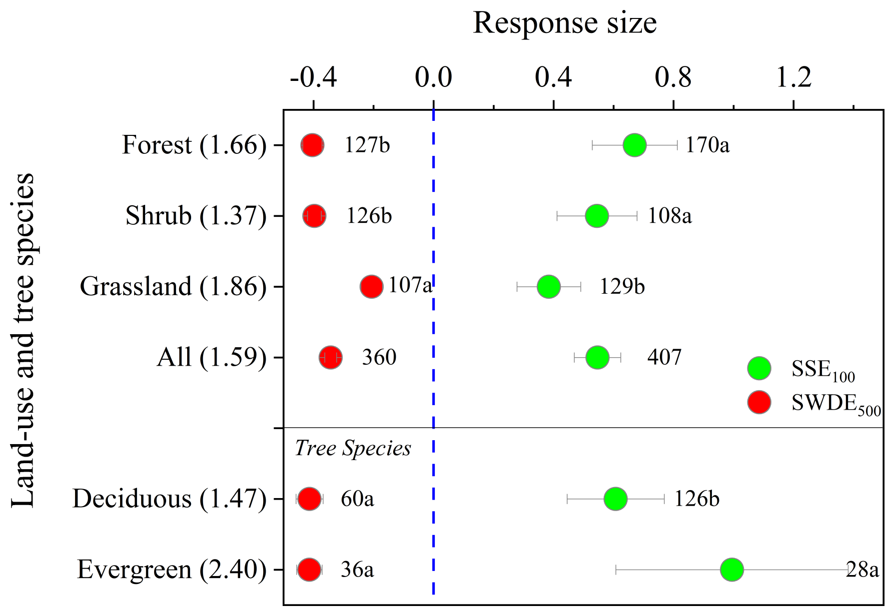

105°0'0"
110°0'0"
40°0'0"
35°0'0"
N
Legend
Sampling site
Rainfall contour
Loess Plateau boundary
Elevation (m)
High: 5044
Low : 72
0 62.5 125 250 375 500 km


(A)
R^2_f = 0.52
$MNMSE_0$ = 0.17
MNMSE = 0.48
n = 988
BD_{20-40} (g cm^{-3})
BD_{0-20} (g cm^{-3})
(B)
R^2_f = 0.62
$MNMSE_0$ = 0.12
MNMSE = 0.38
n = 824
BD_{40-60} (g cm^{-3})
BD_{20-40} (g cm^{-3})
(C)
R^2_f = 0.71
$MNMSE_0$ = 0.09
MNMSE = 0.30
n = 364
BD_{60-80} (g cm^{-3})
BD_{40-60} (g cm^{-3})
(D)
R^2_f = 0.67
$MNMSE_0$ = 0.08
MNMSE = 0.33
n = 329
BD_{80-100} (g cm^{-3})
BD_{60-80} (g cm^{-3})
0.9
1.2
1.5
1.8

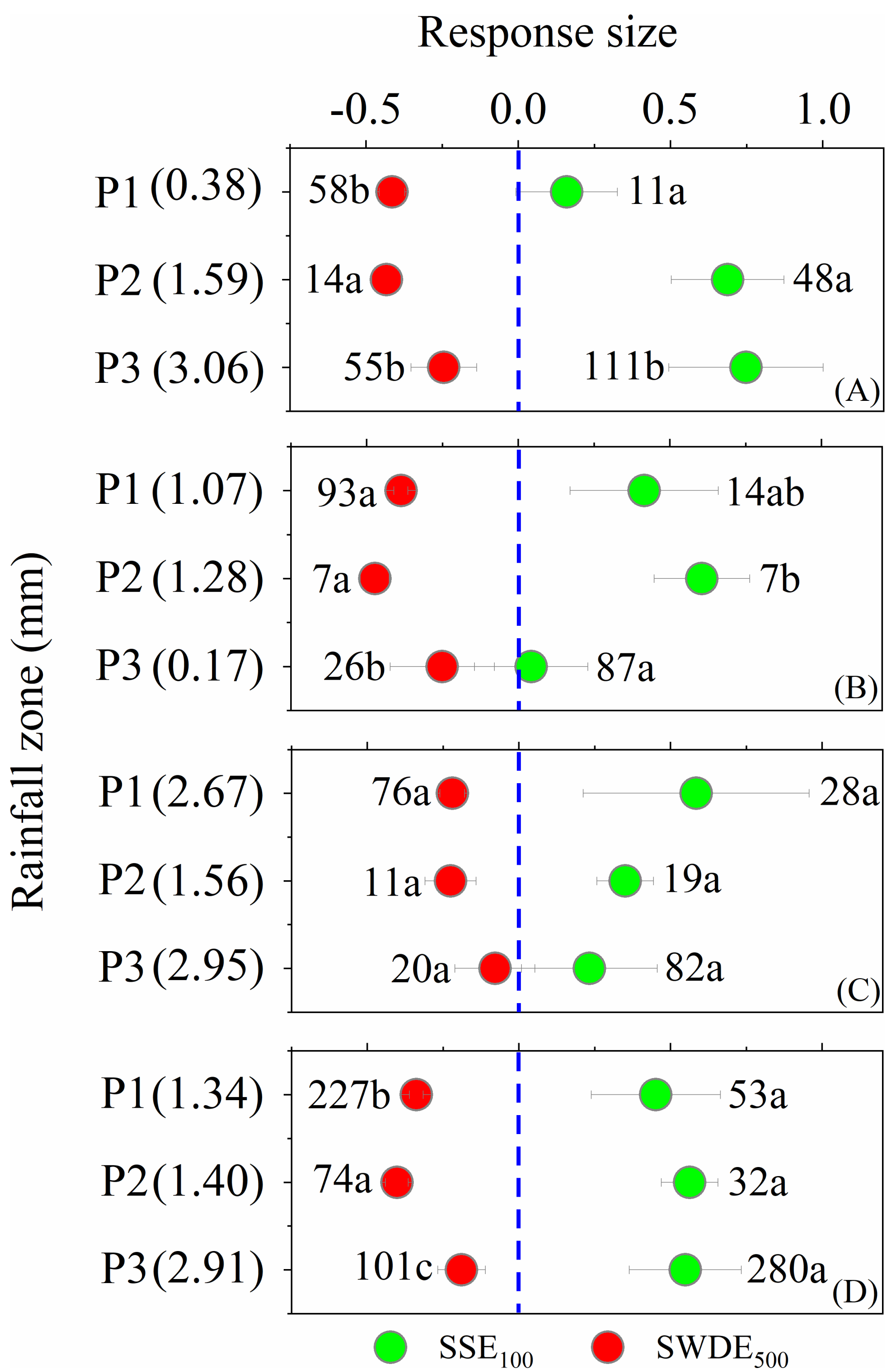

R^2_f = 0.96
MNMSE$_0$ = 0.01
MNMSE = 0.04
n = 555
SOC$_{60\text{-}80}$ (g kg^{-1})
SOC$_{40\text{-}60}$ (g kg^{-1})
(A)
R^2_f = 0.92
MNMSE$_0$ = 0.02
MNMSE = 0.01
n = 530
SOC$_{80\text{-}100}$ (g kg^{-1})
SOC$_{60\text{-}80}$ (g kg^{-1})
(B)

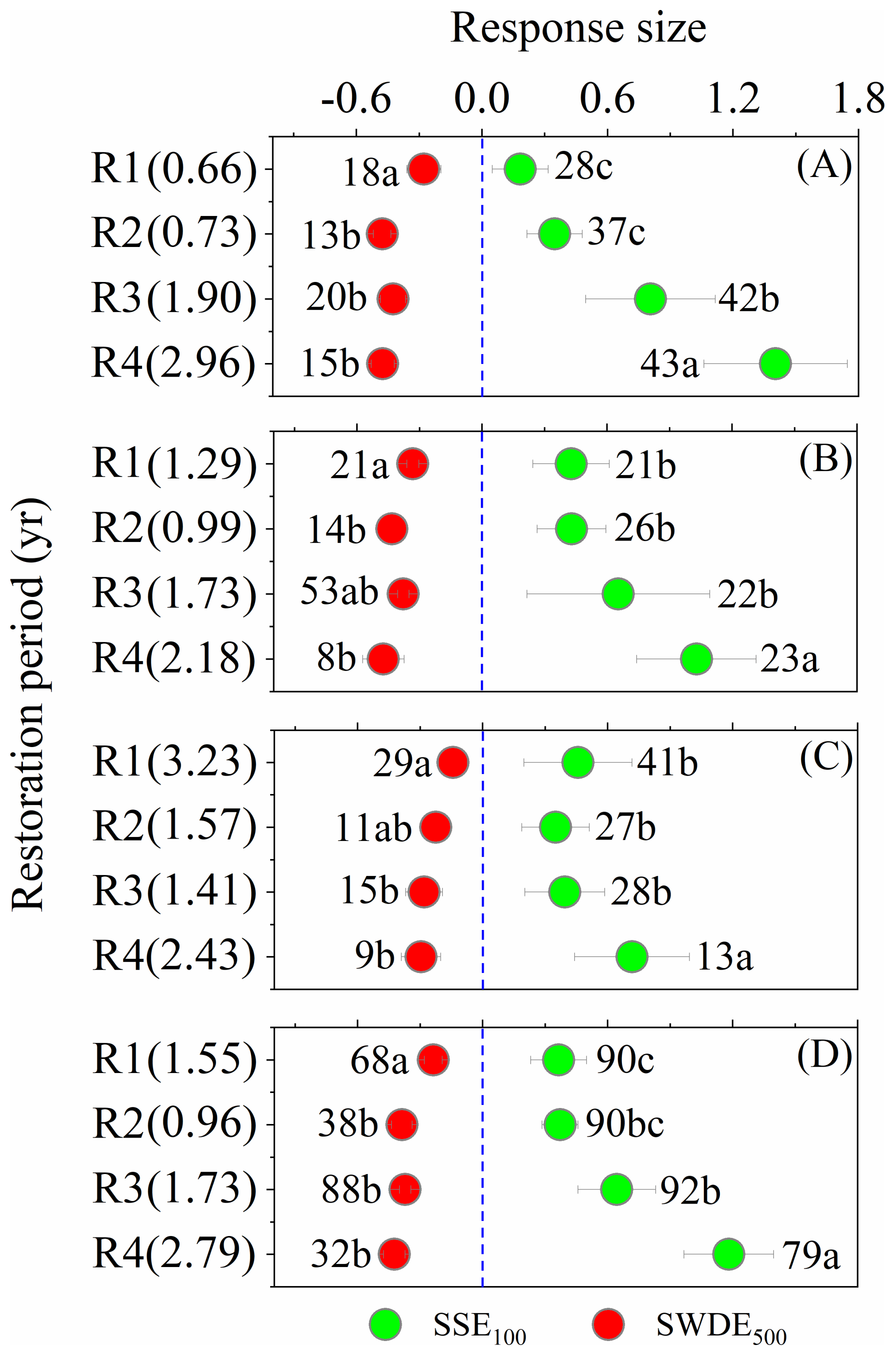

R^2_f = 0.84
MNMSE$_0$ = 0.04
MNMSE = 0.16
n = 1287
SWC$_{300\text{-}400}$ (%)
(A)
R^2_f = 0.88
MNMSE$_0$ = 0.03
MNMSE = 0.12
n = 1181
SWC$_{400\text{-}500}$ (%)
(B)


y=1.33x-2.54
R^2 = 0.94***
n = 2686
Computative SWS$_g$ (mm)
Practical SWS$_r$ (mm)

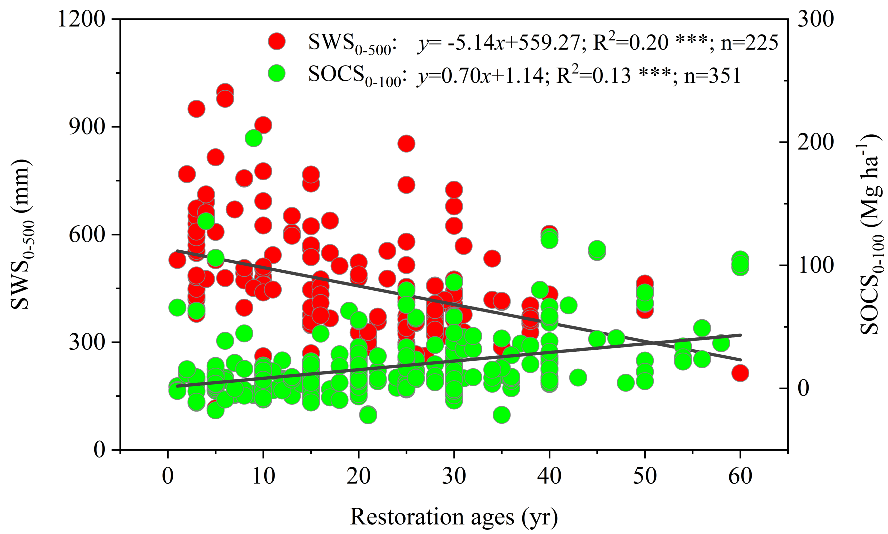


Response size
-0.4
0.0
0.4
0.8
1.2
Land-use and tree species
Forest (1.66)
Shrub (1.37)
Grassland (1.86)
All (1.59)
Tree Species
Deciduous (1.47)
Evergreen (2.40)
127b
170a
126b
108a
107a
129b
360
407
60a
126b
36a
28a
SSE_{100}
$SWDE_{500}$


Response size
-0.5
0.0
0.5
1.0
Rainfall zone (mm)
P1 (0.38)
P2 (1.59)
P3 (3.06)
58b
11a
14a
48a
55b
111b
(A)
P1 (1.07)
P2 (1.28)
P3 (0.17)
93a
14ab
7a
7b
26b
87a
(B)
P1 (2.67)
P2 (1.56)
P3 (2.95)
76a
28a
11a
19a
20a
82a
(C)
P1 (1.34)
P2 (1.40)
P3 (2.91)
227b
53a
74a
32a
101c
280a
(D)
SSE_{100}
$SWDE_{500}$



Response size
-0.6
0.0
0.6
1.2
1.8
Restoration period (yr)
(A)
R1(0.66)
R2(0.73)
R3(1.90)
R4(2.96)
18a
13b
20b
15b
28c
37c
42b
43a
(B)
R1(1.29)
R2(0.99)
R3(1.73)
R4(2.18)
21a
14b
53ab
8b
21b
26b
22b
23a
(C)
R1(3.23)
R2(1.57)
R3(1.41)
R4(2.43)
29a
11ab
15b
9b
41b
27b
28b
13a
(D)
R1(1.55)
R2(0.96)
R3(1.73)
R4(2.79)
68a
38b
88b
32b
90c
90bc
92b
79a
SSE100
SWDE500


SWS0-500: y= -5.14x+559.27; R2=0.20 ***; n=225
SOCS0-100: y=0.70x+1.14; R2=0.13 ***; n=351
SWS0-500 (mm)
SOCS0-100 (Mg ha-1)
Restoration ages (yr)
1200
900
600
300
0
300
200
100
0
0
10
20
30
40
50
60