Engineering 15 (2022) 143–153

Contents lists available at ScienceDirect

Engineering

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

Research
Watershed Ecology—Article

Toward Sustainable Revegetation in the Loess Plateau Using Coupled Water and Carbon Management

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ARTICLE INFO

Article history:
Received 4 August 2020
Revised 15 November 2020
Accepted 15 December 2020
Available online 4 March 2021

Keywords:
Carbon
Land use change
Loess Plateau
Sediment
SWAT-DayCent
Water resources

ABSTRACT

The "Grain-for-Green" project on the Loess Plateau is the largest revegetation program in the world. However, revegetation-induced land use changes can influence both water and carbon cycles, and the diverse consequences were not well understood. Therefore, the reasonability and sustainability of revegetation measures are in question. This study quantifies the impacts of revegetation-induced land use conversions on the water and carbon cycles in a typical watershed on the Loess Plateau and identifies suitable areas where revegetation of forest or grassland could benefit both soil and water conservation and carbon sequestration. We used a coupled hydro-biogeochemical model to simulate the changes of a few key components in terms of water and carbon by designing a variety of hypothetical land use conversion scenarios derived from revegetation policy. Compared to the baseline condition (land use in 2000), both sediment yield and water yield decreased substantially when replacing steep cropland with forest or grassland. Converting cropland with slopes larger than 25°, 15°, and 6° to forest (CTF) would enhance the carbon sequestration with a negligible negative effect on soil water content, while replacing cropland with grassland (CTG) would result in a decline in net primary production but with a substantial increase in soil water content (3.8%–14.9%). Compared to the baseline, the soil organic carbon would increase by 0.9%–3.2% in CTF and keep relatively stable in CTG. Through testing a variety of hypothetical revegetation scenarios, we identified potential priority areas for CTF and CTG, where revegetation may be appropriate and potentially beneficial to conserving soil and water and enhancing carbon sequestration. Our study highlights the challenges in future water and carbon coupling management under revegetation policy, and our quantitative results and identification of potential areas for revegetation could provide information to policy makers for seeking optimal management on the Loess Plateau.

1. Introduction

Revegetation policies such as afforestation programs and declaration of protected areas are widely made to restore degraded ecosystems at regional and global scales [1]. Revegetation can lead to land use change, which plays an important role in the terrestrial ecosystems, because it is explicitly linked with the water, carbon, and nutrient cycles [2]. Land use changes can influence hydrological processes (e.g., surface runoff, water yield, flood frequency, and base flow) [3–6] and carbon cycles (e.g., vegetation production, soil carbon storage, and CO_2 fluxes) [7–10] through altering vegetation coverage and land surface processes. Understanding the comprehensive environmental impacts of land use changes induced by revegetation is of vital importance for ecosystem management and associated policy formation [11,12].

Revegetation in China is an important program for ecosystem restoration and soil and water conservation [13,14]. The well-known strategy related to wide-scale revegetation, named the "Grain-for-Green" project (GGP) launched by the Chinese Government in 1999, aimed to convert low-yield and steep-slope cropland to forest or grassland. The Chinese Loess Plateau is well-known for its severe soil erosion due to its sparse vegetation cover [9,15], making it the pilot region of the GGP. The primary goal of GGP in the Loess Plateau is to convert the cultivated land on steep slopes (mostly above 15° or more) to forest or grassland to alleviate soil erosion [16,17]. It was reported that the vegetation coverage on the Loess Plateau has increased from 31.6% in 1999 to 59.6% in

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https://doi.org/10.1016/j.eng.2020.12.017

2013, and about 16 000 km^2 of steep-slope cropland has been converted to planted vegetation (forest or grass) during the past two decades [18,19]. Consequently, the water and carbon cycles have largely changed due to the revegetation-induced land use changes [20,21]. The Chinese Government plans to invest another 9.5 billion USD in revegetation on the Loess Plateau by 2050 [22]. In this sense, the land use will undergo continuous change in the future, which will exert both positive and negative effects on key environmental components including water, sediment, and carbon sequestration.

During the past several decades, many studies have investigated the revegetation-induced land use change effects on water or carbon cycles on the Loess Plateau [23–26]. Qiu et al. [5] reported that the conversions of steep-slope cropland (slope > 15°) to forest could reduce surface runoff and soil water content in a typical loess hilly–gully watershed of the Loess Plateau. Yin et al. [27] found that the streamflow was increasingly influenced by land use change since the GGP implementation. Wang et al. [19] also concluded that the revegetation program was the dominant factor in reducing both runoff and sediment yield in the Loess Plateau. Lü et al. [16] used a multiple regression approach to quantify the afforestation effect on the regional soil organic carbon (SOC) sequestration and found that conversions from cropland to forest and grassland could enhance carbon sequestration. Through analyzing remote sensing data, Xiao [28] found that afforestation has significantly increased the ecosystem productivity. These studies are valuable for understanding the effects of land use change on water, sediment, and carbon dynamics. However, they only focused on one single aspect (e.g., water or carbon), and few studies have evaluated the comprehensive impacts, and this may skew the land use plans especially considering the trade-offs among water, sediment, and carbon. More importantly, some grand challenges related to land use conversions driven by GGP remain unsolved [13,29–31]. For example, there are many questions on how much land with slopes between 15° and 25° should be returned to forest or grassland [13], and how to enhance the carbon sequestration to mitigate climate change while maintaining regional water security through revegetation. Answering these questions involves many challenges, such as the rudimentary interpreting models, more realistic scenarios settings, and identification of potential revegetation areas to inform policy makers.

To address the above-mentioned challenges, we applied, for the first time, a coupled hydro-biogeochemical model (SWAT-DayCent) to investigate the potential environmental impacts of land use conversions driven by GGP and optimize the revegetation policies. Unlike previous studies, this study concentrated on multiple environmental indices associated with water and carbon to gain a more comprehensive understanding of the revegetation-induced environmental impacts. A typical loess hilly and gully watershed—the Jinghe River Basin (JRB)—was selected as a case study area. Through setting a series of potential land use conversion scenarios under the GGP, we used SWAT-DayCent to simulate the changes of a few key components in terms of water (e.g., water yield, soil water, and sediment yield) and carbon (e.g., net primary production (NPP) and SOC). The study attempted to answer the following questions: ① How do the revegetation-induced land use changes affect the water and carbon cycles? And ② are there any opportunities for revegetation measures to be beneficial to water, soil, and carbon sequestration simultaneously? The outcomes of this study may inform sustainable revegetation management for balancing the developments of socioeconomic system and natural ecosystems on the Loess Plateau.

2. Materials and methods

2.1. Study area

The JRB is a large typical loess hilly–gully watershed on the Loess Plateau in northwest China (Fig. 1). The JRB covers an area of 45 421 km^2 and lies in the semi-humid and semi-arid transitional zone with a typical temperate continental climate. The Jinghe River originates from the Liupan Mountains with a total length of approximately 455 km. The mean annual precipitation and temperature are about 350–600 mm and 8–13 °C, respectively. The climate varies from semi-humid to semi-arid from the southern to northern areas due to the spatial variation of precipitation. The major land use types in the basin are cropland, grassland, and forest, which account for 90% of the area. In terms of different biophysical and climatic conditions, the JRB can be classified into four bioclimatic zones: semi-humid forest, semi-humid to semi-arid forest–grassland, semi-arid grassland, and arid and semi-arid desert–grassland [32]. Because of the dry climate and loosened soil, the basin is often subject to severe water shortage and soil erosion.

2.2. Model description

The coupled SWAT-DayCent model [33] was developed by integrating the widely-used watershed distributed hydrological model (Soil and Water Assessment Tool (SWAT)) [34] and the principal biogeochemical model (Daily version of CENTURY model, DayCent) [35,36]. In the coupling of SWAT-DayCent, the SWAT model was set as the basic framework and DayCent was embedded into SWAT with a few new functions for data transformation and message passing. During the running processes, the SWAT model first simulates the hydrological process based on hydrologic response unit (HRU) and generates the DayCent-required data. DayCent can then automatically obtain the specific information of each HRU and simulate the biogeochemical cycles across all HRUs. Major outputs include hydrological components (e.g., water yield, streamflow, soil water, and evapotranspiration (ET)) yielded by SWAT and biogeochemical components (e.g., NPP, SOC, soil respiration, and biomass) yielded by DayCent, enabling us to analyze both water and carbon cycles at the watershed scale. Details and applications of SWAT-DayCent can be found in our previous studies [33,37–39]. This coupled hydro-biogeochemical model can simultaneously simulate the hydrological and biogeochemical cycles at the watershed scale, and thus can support integrated water–carbon analysis and management. Actually, to our knowledge, no single model is capable of simulating the hydrological and biogeochemical processes at the watershed scale [40]. The application of SWAT-DayCent could thus provide a proper perspective for investigating the impacts of anthropogenic activities on both water and carbon cycles at the watershed scale.

2.3. Model input and verification

A geographic information system (GIS) interface, ArcSWAT, was used to delineate the watershed and automate the model input parameters. The required spatial inputs for ArcSWAT include topography, land use, soil type, and meteorological information. The digital elevation model (DEM) was obtained from the Shuttle Radar Topography Mission (SRTM) with a 90 m resolution. The land use data of 2000 with 30 m resolution were obtained from the Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences. The soil property data were supplied by the Ecological and Environmental Science Data Center for west China with 1 km resolution. The daily meteorological data were obtained from the data center of China Meteorological Administration (CMA).

We used the monthly streamflow (1973–1979 for calibration and 1980–1990 for validation) and sediment yield (1973–1978 for calibration and 1979–1987 for validation) data from Zhangjiashan (ZJS) station (Fig. 1) to calibrate and validate the SWAT part and used the annual remotely-sensed NPP (2000–2010) to verify the DayCent part. For SWAT, we identified most sensitive parameters using the sensitivity analysis (Table S1 in Appendix A). For DayCent, the most important and sensitive parameter "PRDX" was selected based on our own experience and previous studies [36,39,41,42]. In terms of the numeric criteria, the Nash–Sutcliffe efficiency (NSE), correlation coefficient (R^2), and percentage bias (PB) of streamflow simulation were 0.70, 0.71, and 6.7%, respectively, whereas they are 0.58, 0.71, and −24.9%, respectively, for sediment simulation (Fig. 2). Based on the model evaluation criteria [43], these statistical evaluations showed that SWAT was calibrated well. For validation, the SWAT model also performed well, with NSE, R^2, and PB of streamflow simulation being 0.54, 0.62, and 5.3%, respectively; whereas these three terms were 0.60, 0.67, and 30.2%, respectively, for sediment simulation. For DayCent, we used Model-R coupler to implement the verification, and this calibration scheme can be found in our previous studies [9,39]. The statistical evaluation measures showed that the |PB| values were less than 5% for all the three ecosystems (crop, forest, and grass), R^2 ranged from 0.21 to 0.55, and root mean squared error (RMSE) varied from 20.8 to 39.3 gram of carbon per square meter per year ($g\ C{\cdot}m^{-2}{\cdot}a^{-1}$) (Fig. 3). Although DayCent performed not as well as SWAT, its performance can be regarded satisfactory considering the greater uncertainty in remotely-sensed NPP and carbon modeling as well.

2.4. Revegetation policy options

2.4.1. Revegetation project outline

The GGP was implemented by the Chinese Government to restore the country's forests and grasslands to alleviate soil erosion [44]. One of the most important criteria in GGP implementation is the steepness of the slope—cropland with a slope steeper than a certain degree (named the target slope) should be converted to forest or grassland. In northwest China where the Loess Plateau is located, the target slope is 15° [13]. This suggests that cropland with a slope steeper than 15° would be highly recommended for conversion to forest or grass. Further, the lands with slopes less than 6° need to be protected for agriculture use because of their low level of soil erosion, relatively higher soil fertility, and need for food production [45]. Based on the above policy and requirements, we set several land use conversion scenarios as described in the following section.

2.4.2. Revegetation scenarios

First, in terms of GGP, we established six potential revegetation scenarios based on the actual 2000 land use (Table 1):

(1) CTF: convert the steeply-sloped cropland to forest. Scenarios S1–S3 refer to conversions of cropland with slopes larger than 25°, 15°, and 6° to forest.

(2) CTG: convert the steeply-sloped cropland to grassland. Scenarios S4–S6 refer to conversions of cropland with slopes larger than 25°, 15°, and 6° to grassland.

In addition to slope, the bioclimatic condition should also be taken into account for suitability and sustainability of revegetation [46]. In our study, the JRB was divided into four bioclimatic zones: Forest, Forest–Grass, Grass, and Desert–Grass (Fig. 1). As known

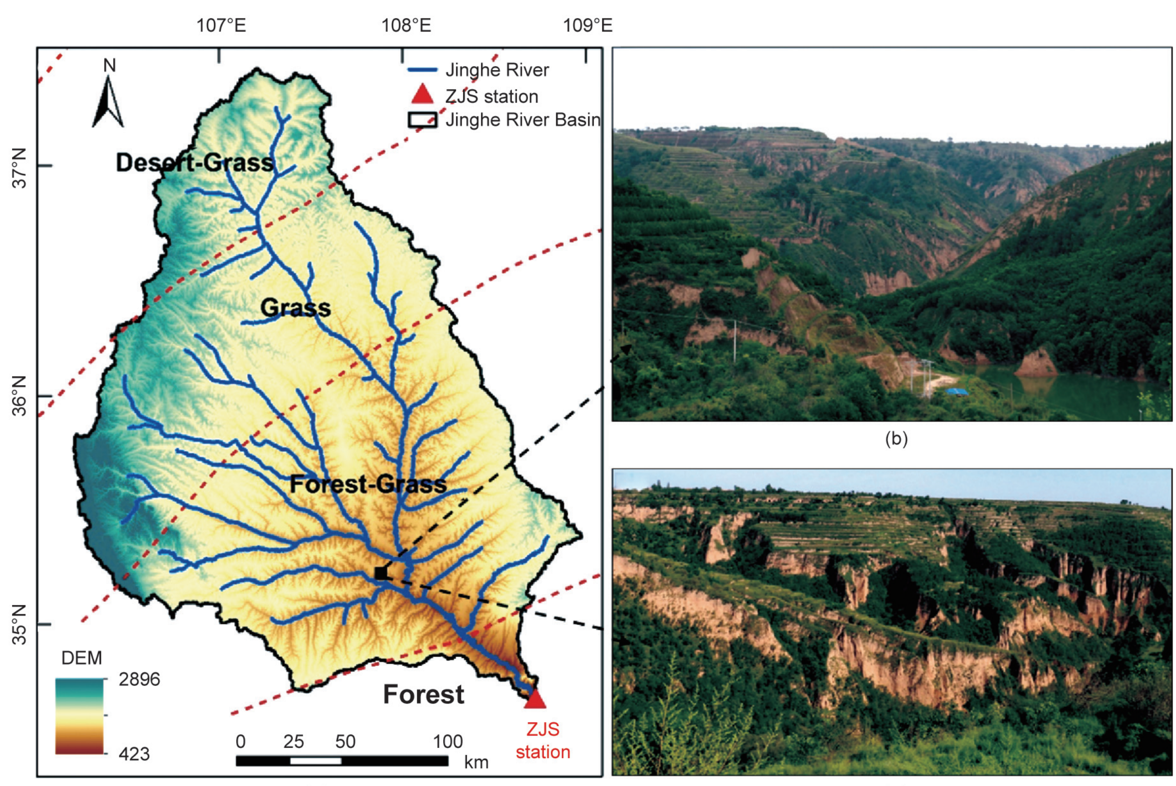

Fig. 1. (a) Location and digital elevation of the JRB. Dashed red lines indicate the bioclimatic boundary and the JRB is divided into four zones: Forest (zone for semi-humid forests), Forest–Grass (zone for semi-humid to semi-arid forest–grasslands), Grass (zone for semi-arid typical grasslands), and Desert–Grass (zone for arid and semi-arid desert–grasslands). Photos of (b) typical loess landforms and (c) slope lands. The photos were shot by Fubo Zhao in September 2018 at a typical loess hilly–gully location of the JRB. DEM: digital elevation model (m). The simulations of this study were carried out based on Zhangjiashan (ZJS) station.

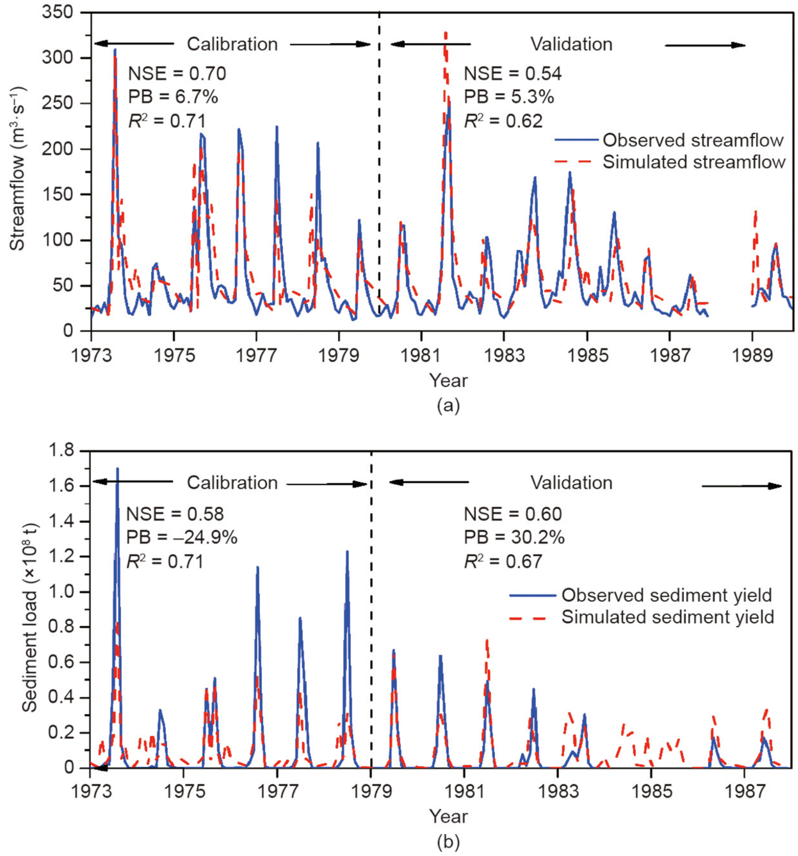

Fig. 2. Monthly (a) streamflow and (b) sediment yield simulations at the ZJS station.

and understood, Forest and Forest–Grass zones are suitable for afforestation, whereas Grass and Desert–Grass zones can be for grass plantation. Driven by this suitability, we established three additional revegetation scenarios.

(3) CTFG: convert cropland with slopes larger than 25°, 15°, and 6° to forest in the Forest and Forest–Grass zones or grass land in the Grass and Desert–Grass zones, respectively. These conversions were represented by Scenarios S7–S9.

The corresponding land use proportions are listed in Table 2. The SWAT-DayCent model with baseline condition (land use in 2000) and nine revegetation scenarios were built up and run for 30 years using historical climate forcing data (1976–2005).

2.5. Impact analysis

We quantified the basin-average environmental impacts of revegetation by comparing the difference between the baseline condition and the revegetation-induced scenarios. To identify areas that are suitable for forest or grass plantation, we performed the overlay analysis (raster calculation) to calculate the net changes for a specific HRU. Trade-offs are suggested if there is a conflict between target elements—one element increases as the other decreases, while synergies would occur if water availability, soil conservation, and carbon sink increase simultaneously [47]. The candidate areas that would be suitable for revegetation were identified if the revegetation could be beneficial to water (increase in soil water content), soil (sediment reduction), and carbon (SOC increment) simultaneously. We defined five recommendation degrees—very low, low, moderate, high, and very high—for CTF or CTG of the candidate areas based on the total influencing magnitude on soil water content, sediment yield, and SOC. The calculation of the total influencing magnitude is to normalize the influence of revegetation (CTF or CTG) on each individual indicator (i.e., soil water, sediment, or SOC) followed by summing their normalized values [47,48]. The very low recommendation degree can be determined when the total influencing magnitude (TIM) for a specific target area (an HRU) was below the 5% percentile and the low was determined when the TIM was above or equaled 5% but below 25% percentiles, the high was defined when the TIM was above 75% but below or equaled 95% percentiles and the very high degree was defined when the TIM was above the 95% percentile, and a specific area can be marked moderate recommendation degree when its TIM was between 25% and 75% percentiles. Very high recommendation degree suggests that the afforestation or grass plantation could achieve the maximum environmental benefits (i.e., the positive effects on the above-mentioned environmental indices: soil water content, sediment yield, and SOC storage), followed by high, moderate, low, and very low recommendation degrees.

3. Results

3.1. Variations in environmental indices

(1) CTF. Compared to the baseline condition, conversion from cropland to forest could have different impacts among specific scenarios (S1–S3, Fig. 4), but both water yield and sediment yield would decrease. The relative decline of water yield and sediment yield varied from −4.7% and −5.2% in S1 to −17.0% and −19.1% in S3, respectively. This indicated that increasing forest cover on slope lands could cause reduction of water resource but alleviate soil erosion.

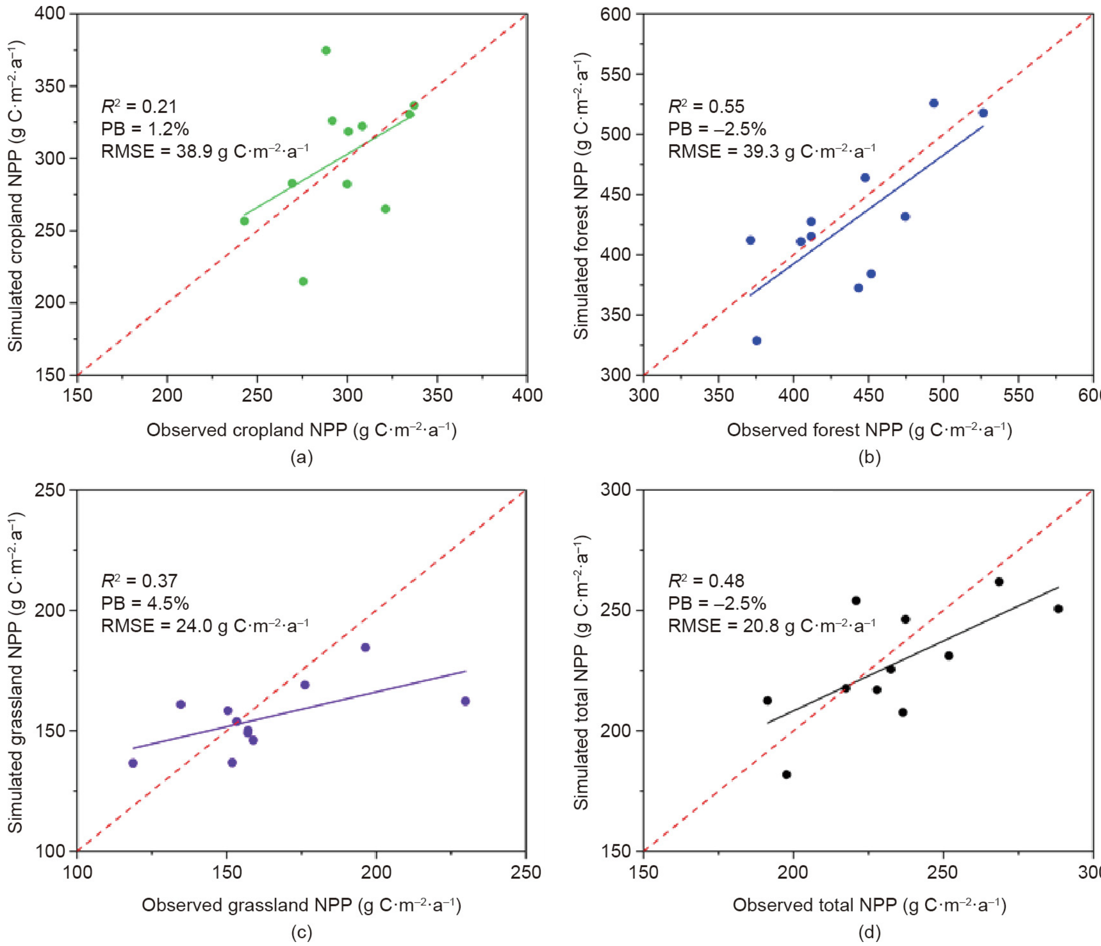

Fig. 3. Comparison of the remotely-sensed NPP and DayCent simulated NPP for (a) the cropland, (b) forest, (c) grassland, and (d) the entire basin. The red dash line represents the 1:1 line.

Table 1
Abbreviations and definitions of the potential revegetation scenarios.

Abbreviation	Description
BS	Actual land use in 2000
S1	Cropland with slope > 25° to forest
S2	Cropland with slope > 15° to forest
S3	Cropland with slope > 6° to forest
S4	Cropland with slope > 25° to grassland
S5	Cropland with slope > 15° to grassland
S6	Cropland with slope > 6° to grassland
S7	Cropland with slope > 25° to forest in the Forest and Forest–Grass zones or grassland in the Grass and Desert–Grass zones
S8	Cropland with slope > 15° to forest in the Forest and Forest–Grass zones or grassland in the Grass and Desert–Grass zones
S9	Cropland with slope > 6° to forest in the Forest and Forest–Grass zones or grassland in the Grass and Desert–Grass zones

The simulation results also showed CTF may have slight influences on the soil water content in the root zone (Fig. 4). Besides, NPP increased by 1.3% to 4.7% (S1–S3), and SOC increased by 0.9%–3.2% depending on the afforestation acre, suggesting enhanced carbon sequestration capacity due to afforestation.

(2) CTG. Similar to those in CTF, conversion from cropland to grassland can lead to the decline in water yield and sediment yield (Fig. 4). Water yield showed a decreasing tendency with more slope croplands being converted to grassland, but the magnitude of decline was less than that in CTF. The water yield decreased by 2.4% when cropland with slope larger than 25° was converted to grassland (S4), while this decreasing magnitude would reach 8.6% when cropland with slope larger than 6° was converted (S6). The sediment yield would decrease with the increase in grassland. The decreasing magnitude would vary from −5.6% in S4 to −10.7% in S6, a relatively lower amount compared to CTF scenarios. It was clear that soil water content increased substantially varying from a 3.8% increase in S4 to a 14.9% increase in S6. In addition, NPP decreased substantially with the magnitude ranging from −3.9% in S4 to −14.7% in S6, which can be attributable to the lower production of grass. SOC kept relatively stable across different scenarios in CTG, indicating a slight impact of CTG on SOC.

(3) CTFG. The relative changes in water yield and sediment yield under the CTFG scenarios were similar to those in CTF and CTG (Fig. 4). Relative to the baseline condition, the magnitude of decreases in water yield and sediment yield ranged from −5.4% and −5.9% in S7 to −17.3% and −16.5% in S9. Similar to CTG, soil water content would increase with more steep-slope croplands converted to forest and grassland. However, the magnitude of increase was lower than that in CTG, and the largest increment of 6.9% occurred in S9. Besides, NPP under Scenarios S7 to S9 would decrease slightly (−0.8% to −4.2%) compared to the baseline condition while SOC increased slightly with the magnitude ranging from 0.6% in S7 to 1.8% in S9.

3.2. Spatial patterns of changes in environmental indices

Spatial patterns of changes of environmental indices were heterogeneous and varied among scenarios. In CTF (Fig. 5), the water yield and sediment yield showed similar changing patterns.

Table 2
Percentage of the land use proportions in 2000 land use and the proposed revegetation options (%).

Scenario	Forest	Grass	Crop	Shrub	Water body	Development	Barren
BS	7.4	33.0	44.1	14.1	0.1	1.1	0.1
S1	14.3	—	37.3	—	—	—	—
S2	22.2	—	29.3	—	—	—	—
S3	31.6	—	19.9	—	—	—	—
S4	—	39.8	37.3	—	—	—	—
S5	—	47.8	29.3	—	—	—	—
S6	—	57.2	19.9	—	—	—	—
S7	10.5	36.8	37.3	—	—	—	—
S8	13.6	41.6	29.3	—	—	—	—
S9	17.5	47.1	19.9	—	—	—	—

"—" indicates no change when compared to 2000 land use. BS represents the actual land use in 2000.

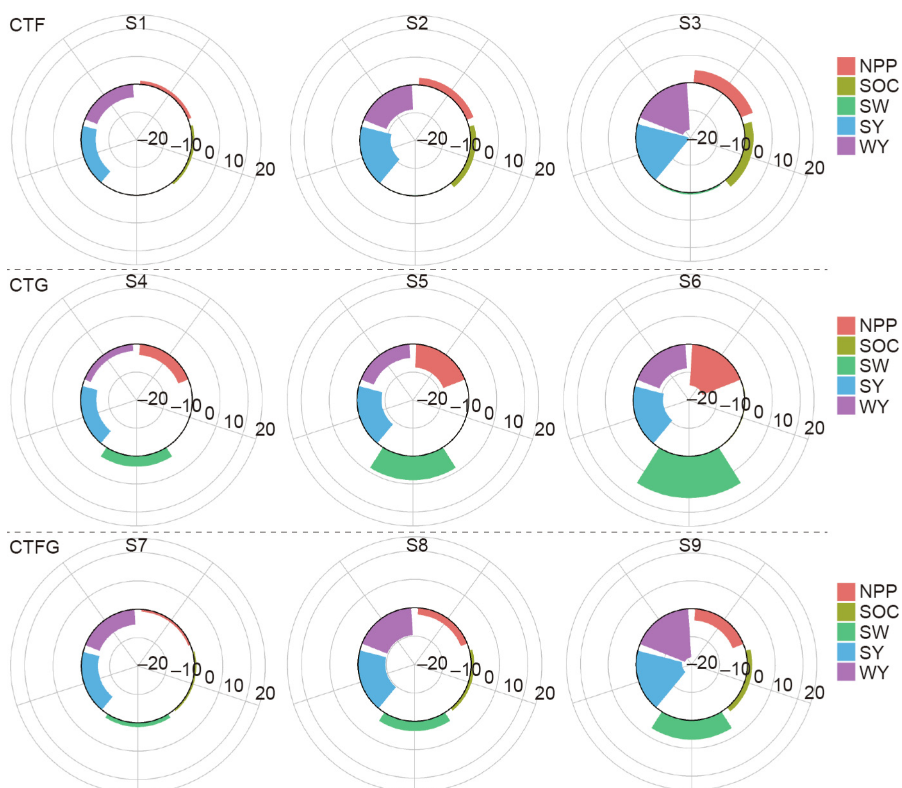

Fig. 4. Percent changes in basin-average water yield (WY), sediment yield (SY), soil water (SW), NPP, and SOC between the 2000 land use and the proposed revegetation options. Numbers on the radial axes denote percent changes relative to the 2000 land use (%).

With the increasing afforestation (Scenarios S1 to S3), more areas of the JRB (especially the northern basin) showed decreases in the water yield and sediment yield. The decline of soil water was primarily found in the northern areas, indicating the semi-arid areas were relatively more sensitive to afforestation. NPP and SOC showed obvious increases with expansion of afforestation, whereas the increasing magnitude in NPP was relatively higher than the SOC.

In CTG (Fig. 6), water yield showed a decline in northern and central areas with the increase of grassland area (Scenarios S4 to S6). The changing patterns in sediment yield were similar to those of the water yield. However, some areas in western and southern regions showed a slight increase in sediment yield. Unlike CTF, the soil water content in southern and northern areas showed a slight increase, indicating the positive effects of grassland plantation on soil water conservation. With the increasing grassland plantation, more areas of the JRB showed a decrease in NPP due to the lower productivity of grass when compared to crop, while the SOC kept relatively stable.

The areas where both water yield and sediment yield declined continuously increased with the forest and grassland plantation (Scenarios S7 to S9, Fig. 7). This phenomenon demonstrated that both afforestation in the semi-humid portion and grass plantation in the semi-arid portion could help conserve the soil but reduce the water yield. The hybrid scenarios would generate slightly positive effects on the soil water content, and only small portions showed a decrease in soil water content. The NPP showed obvious differences between grass plantation and afforestation—planting grasses reduced the productivity and afforestation improved the productivity. Changes in SOC were spatially heterogeneous, and the hybrid scenarios would also generate slightly positive effects on the SOC.

3.3. Areas suitable for revegetation

As stated previously, revegetation reduced soil erosion but caused reduction of water availability, and may increase carbon sequestration in most areas. This indicated that there were trade-

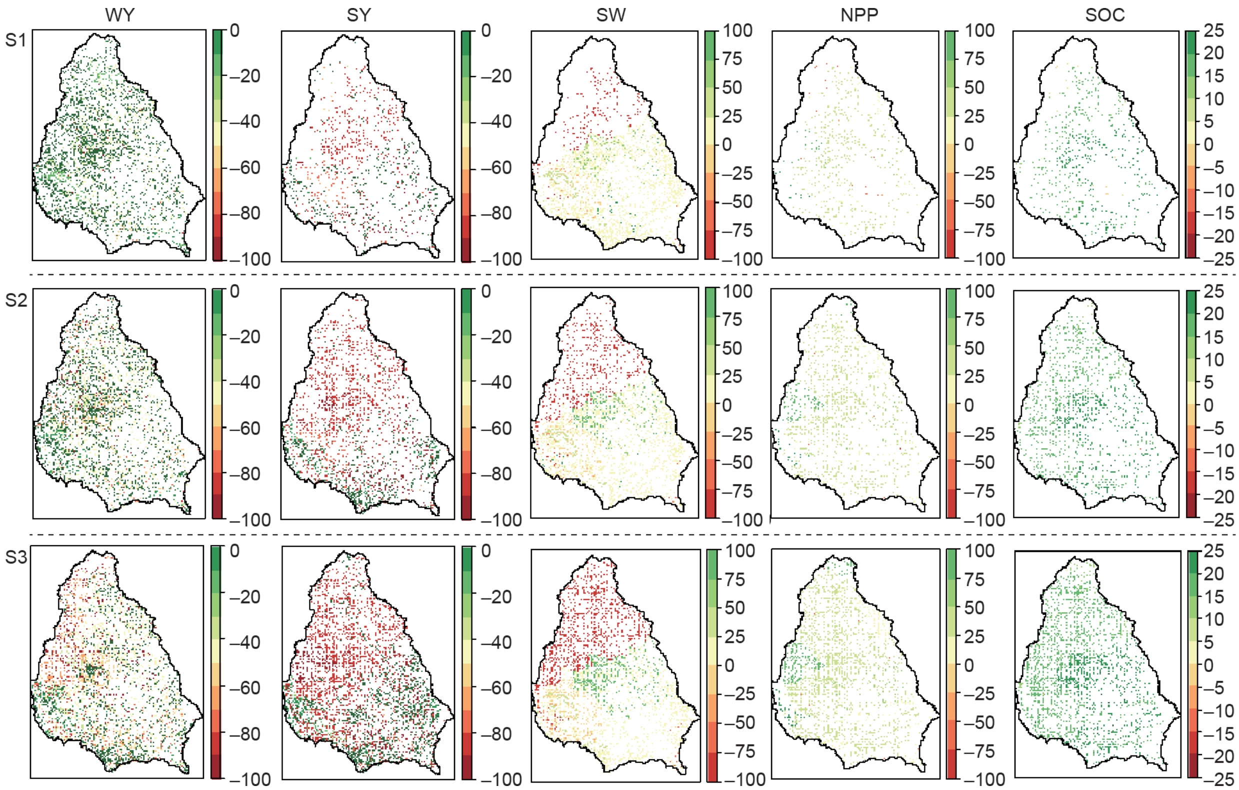

Fig. 5. Spatial patterns of changes in WY, SY, SW, NPP, and SOC under CTF scenarios (S1–S3). Numbers indicate the percent changes relative to 2000 land use (%). Blanks indicate areas with no-change.

offs or synergies among the water–sediment–carbon nexus under the revegetation program. The question is whether there are any areas where CTF or CTG conversions (i.e., steep-slope cropland to green land) would be beneficial to water resource, soil retention, and carbon sequestration. To address this question, we overlaid the spatial maps of these key environmental indices. The potential

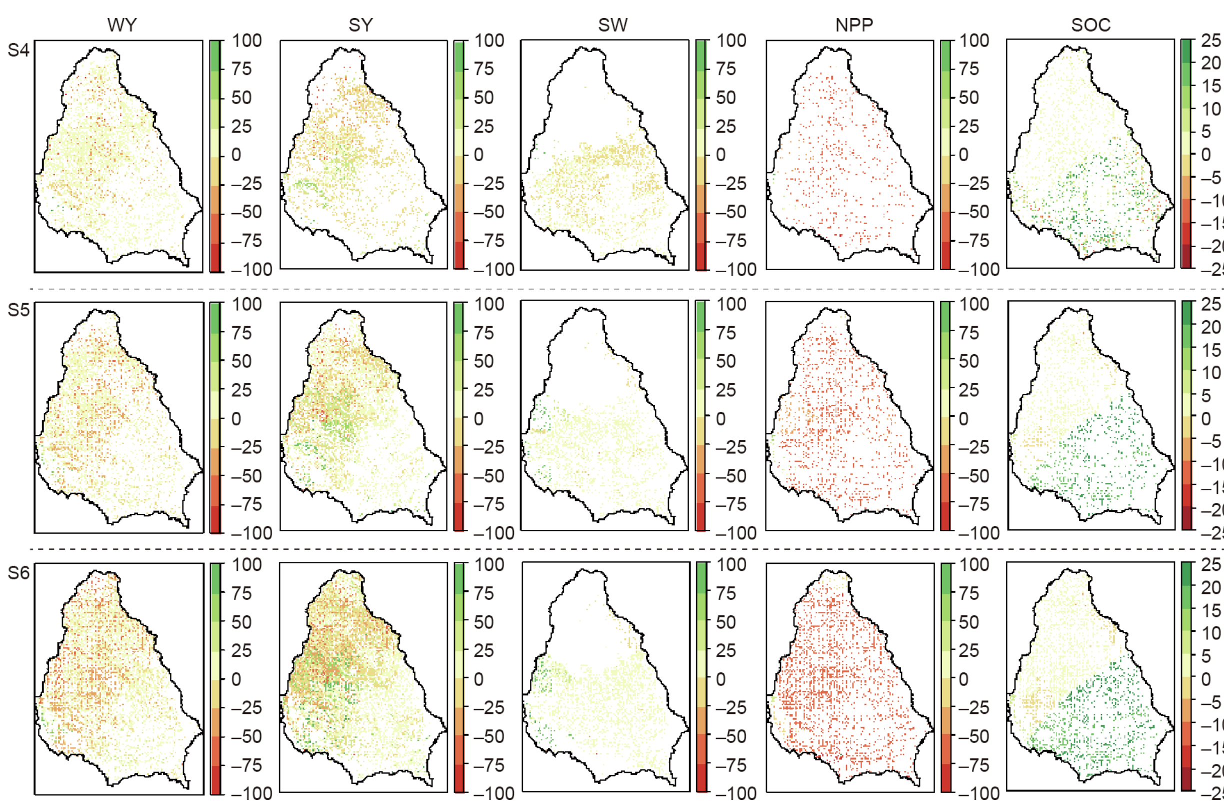

Fig. 6. As in Fig. 5, but under the CTG scenarios (S4–S6).

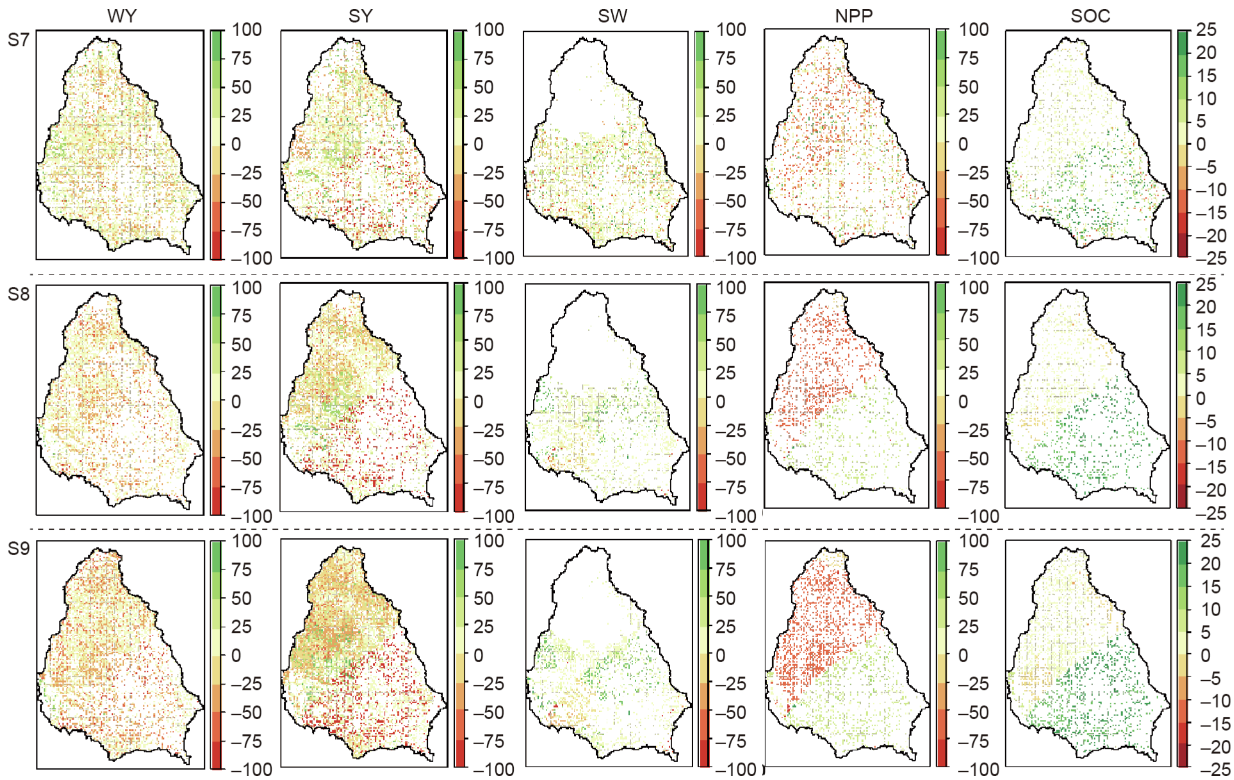

Fig. 7. As in Fig. 5, but under the CTFG scenarios (S7–S9).

CTF areas with slopes larger than 25°, 15°, and 6° were identified, as shown in Fig. 8(a), where CTF would not cause negative impacts in terms of water, sediment, and carbon. These candidate areas were primarily located in the central and southern basin. In terms of the magnitude of effects on water, sediment, and carbon, we set three different recommendation degrees (low, moderate, and high, see Section 2.5). As shown in Fig. 8, large areas in the southern basin with slopes larger than 25°, 15°, and 6° were highly (including very high and high degrees) recommended for conversion (i.e., CTF). Most areas were moderately recommended for conversion

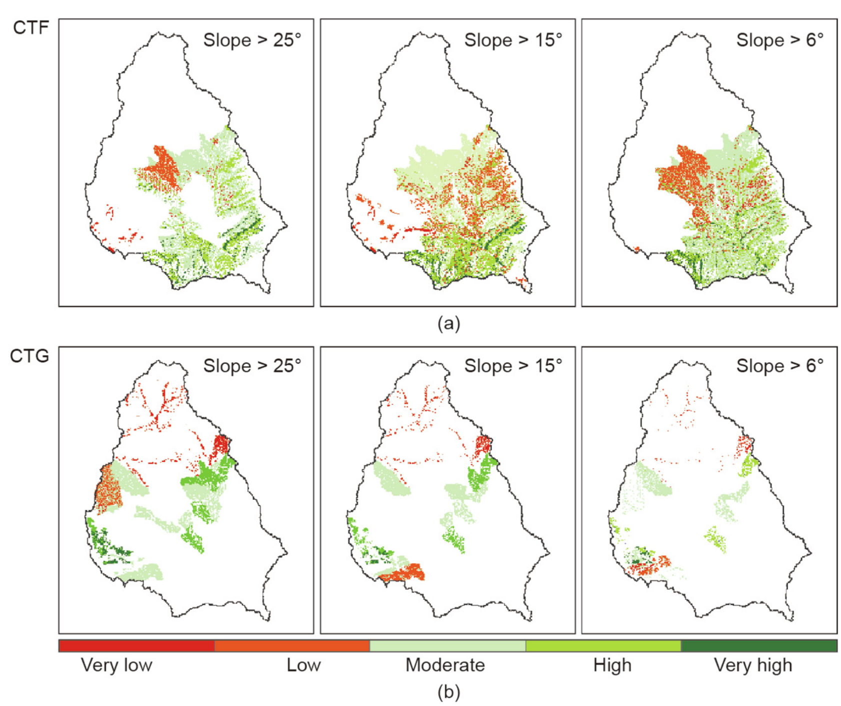

Fig. 8. Potential areas where land use conversions from slope cropland can be beneficial to water resource, soil retention, and carbon sequestration: (a) CTF and (b) CTG. The color shows the degree a specific area is recommended, and red, orange, shallow green, green, and dark green refer very low, low, moderate, high, and very high recommendations, respectively.

and some portions in the central and western margin were in low and very low recommendations. The candidate CTG areas with slopes larger than 25°, 15°, and 6° were marked in Fig. 8(b), and most of them were located in the central and northern basin with only some parts in the southern basin. Only small portions with slopes larger than 25°, 15°, and 6° in the western margin were in high and very high recommendation for conversion (i.e., CTG), while large areas in the northern basin were mostly in very low recommendation. Interestingly, the recommended CTF or CTG areas were generally consistent with the bioclimatic classification: The recommended CTF areas were primarily located in the semi-humid Forest and Forest–Grass zones, while the recommended CTG areas were mostly located in the Forest–Grass and Grass zones. These results demonstrated the necessity of considering the climatic conditions when implementing the revegetation program.

4. Discussion

4.1. Environmental impacts of revegetation options

Increases of forest and grass covers on slope lands would reduce the water yield, and the magnitude of this reduction varied depending on the degree of land use conversions [49,50]. Water yield, a proxy of the capacity in supplying water for a catchment, is strongly connected to the regional natural and economic conditions. In comparison with cropland, growing more trees on slope lands would result in more water loss because of its relatively large leaf area and transpiration rate [9], while growing grasses on slope lands would accelerate the evaporation rate from the soil because it cannot protect the soil surface from solar radiation. The sediment yield was predicted to decrease with the increase in forest and grassland coverage on the slope lands. Generally, when cropland is replaced by grass or trees, the land surface roughness and evapotranspiration would be improved, resulting in reduced water yield and sediment yield as well [16,45]. For soil water, this study showed that the increase in forest cover on slope lands may have slight effects on the soil water content, and this can be attributable to the original lower water retention potentials on steep slopes [51,52]. Qiu et al. [5] also reported that converting croplands on steep slopes (> 25° and 15°) to forest can exert slight effects on soil water content in the Yanhe River Basin. This demonstrated the key role in conserving soil and water of afforestation on slope lands. Compared to forest, grass has a shallow root depth and needs less water for growth, leading to the increase in soil water content in CTG and CTFG. This finding was also supported by the experimental studies. For example, Yu et al. [51] reported the soil moisture in hilly and gully regions of the Loess Plateau would be higher in grassland than that in forest and farmland, especially in the wet seasons. In addition to the land use types, the topographic domains (e.g., slope aspect and elevation) also play a significant role in influencing the soil moisture content, making a complex response of soil water content to land use changes [53,54]. Because forest has relatively large productivity [55], afforestation on slope lands would undoubtedly increase the regional production and enhance the SOC sequestration. In contrast, replacing slope cropland with grassland would lead to a lower production and weak SOC accumulation due to its lower productivity [9].

4.2. Trade-offs and synergies among water availability, soil conservation, and carbon sequestration

Our study revealed significant conflict among water availability, soil conservation, and carbon sequestration across the potential land use conversion scenarios [56–59]. Conflicts between water yield and carbon sequestration were primarily found in CTF options, indicating challenges of managing water, soil, and carbon sustainability concurrently associated with afforestation. The findings were also supported by the experimental results [60,61]. Through analyzing more than 600 observations, Jackson et al. [62] found that plantations decreased streamflow by 227 mm per year globally with biological carbon sequestrations. These findings demonstrated the importance of water resources sustainability when converting cropland to forest for soil retention. Conflicts between soil water and carbon sequestration were primarily found in CTG and CTFG. The phenomenon highlighted that replacing slope cropland with grassland would help improve the soil moisture but at the expense of decreased water yield and carbon sequestration [58,63,64]. Persistent declines in water yield, sediment yield, and NPP occurred through S4 to S9, which are associated with grass plantation on slope lands [65]. The phenomenon highlighted that there are challenges to co-manage and enhance these ecosystem services together when replacing the slope cropland with grassland. Temporally, the water yield, sediment yield, and NPP showed similar changing patterns with time progressing under the baseline and the nine scenarios (Fig. S1 in Appendix A). The water yield and sediment yield decreased first and then diverged with the NPP increasing, indicating the relationships between water and carbon may vary with time. Actually, the similar inter-annual variability of water yield, sediment yield, NPP, and their general positive relationships during 1976–2005 (Fig. S1) could be explained by the precipitation variability, which has been illustrated in our previous study [9]. Positive effects on both soil water content and SOC were found in CTG and CTFG, indicating opportunities to co-manage these two ecosystem services when considering grass plantation in future revegetation. In brief, the above phenomena further demonstrated the trade-offs and synergies among water, soil conservation, and carbon sequestration co-existed in the revegetation.

4.3. Implications for policy

This study has several implications for the coupled water and carbon management associated with revegetation. First, the large spatial variability demonstrates a particular environmental index could either increase or decrease at a given location depending on future revegetation, underscoring the importance of local measures and fine-scale management [47]. Second, our identification of potential areas that are suitable for future land use conversions would help achieve "win–win" target and maximize benefits with optimal land use planning/management. Third, most areas showed improvements in some environmental indices but declines in others (rarely increase for all), indicating the importance of trade-offs [66] and the necessity of appropriate human interventions for minimizing the negative impacts. Moreover, the analyses presented here can also support decision-making associated with the ongoing revegetation in areas beyond but with similar biophysical conditions, for example, the Yanhe River and the Weihe River Basins on the Loess Plateau.

4.4. Limitations and future scope

We admitted that there are limitations in this study. First, even though the land conversion scenarios used in this study included many different combinations, the specific vegetation types (i.e., the forest and grass types involved in conversions) were not explicitly examined. Future research should evaluate the specific effects of different forest or grass types on both water and carbon. Second, in the simulation of hydro-biogeochemical processes, we just focused on land use change without considering other ecological engineering measures (e.g., dam and terrace constructions) which can also influence water, sediment, and carbon dynamics [67]. It is necessary to investigate the effects of the ecological engineering measures in future studies. Third, some elements in our study might be sensitive to climate change, and future studies should also take into account the climate change effects. More importantly, the growing population and economic development will increase the water demand, and thus policy makers must consider the socioeconomic system when implementing the revegetation project. Future studies should link the socioeconomic system with the natural ecosystem to avoid the water conflict on the Loess Plateau.

5. Conclusions

We applied, for the first time, a coupled SWAT-DayCent model to investigate the potential impacts of revegetation-induced land use conversions on water availability, soil conservation, and carbon sequestration. Our results showed that converting cropland with slopes (> 25°, 15°, and 6°) to forest or grassland could reduce both sediment and water yield. Converting cropland with slopes (> 25°, 15°, and 6°) to forest could improve ecosystem productivity with slight influences on soil water content, whereas converting cropland to grassland would lead to a decline of NPP but with a substantial increase in soil water content. Replacing slope cropland with forest and grassland would have positive effects on the SOC. In summary, revegetation could cause conflict between soil conservation, water resources, and carbon sequestration. However, through analyzing the spatial variations of the environmental indices including water, sediment, carbon, and their relationships with land use patterns, we identified the potential areas where conversions can be beneficial to water availability, soil conservation, and carbon sequestration simultaneously. Our results can be valuable for policy makers in optimizing revegetation policies in the JRB and have the potential to be scaled up to inform the coupled water and carbon management associated with revegetation across the Loess Plateau.

Acknowledgments

This study was funded by the National Natural Science Foundation of China (31961143011), the China Postdoctoral Science Foundation (2020M683451), the Strategic Priority Research Program of the Chinese Academy of Sciences (XDB40020205), the Shaanxi Key Research and Development Program of China (2018ZDXM-GY-030), and the National Thousand Youth Talent Program of China. We sincerely thank the editor and two anonymous reviewers for their valuable comments/suggestions on the article. We also thank the high-performance computing cluster (HPCC) Platform in Xi'an Jiaotong University for computing equipment and computer maintenance.

Compliance with ethics guidelines

Fubo Zhao, Yiping Wu, Xiaowei Yin, Georgii Alexandrov, and Linjing Qiu declare that they have no conflict of interest or financial conflicts to disclose.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eng.2020.12.017.

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