Trade-off between surface runoff and soil erosion during the implementation of ecological restoration programs in semiarid regions: A meta-analysis

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ABSTRACT

The application of ecological restoration programs, related to water resources protection and soil erosion control, may have some undesirable outcomes. An important example is the effect that vegetation restoration may have in reducing surface water resources. After searching peer-reviewed articles, we selected 38 publications from 16 countries in comparable areas - semiarid conditions (aridity index <0.5), surface coverage >50% and fine soil texture - to evaluate the effectiveness of different types of vegetation (i.e., forestland, scrubland and grassland) in regulating runoff and sediment transport. In particular, we used three indices: the runoff reduction effect, the sediment reduction effect and the ratio between runoff and sediment reduction. These indices were calculated from measured data reported in the original articles. Results showed that scrubland had higher runoff reduction effect (59% in gentle slopes; 65% in steep slopes) than in grassland (39% on gentle slopes; 43% on steep slopes) and forestland (33% on gentle slopes; 51% on steep slopes). For the three types of vegetation, the sediment reduction effect was >70%. Concerning the ratios between runoff and sediment reduction, grassland showed the lowest ratios (56% on gentle slopes; 53% on steep slopes) compared to forestland (63% on gentle slopes; 65% on steep slopes) and scrubland (93% on gentle slopes; 81% on steep slopes). Our results indicate that low values of ratios between runoff and sediment reduction are the most suitable because they indicate an effective soil erosion and sediment delivery reduction but maintaining surface runoff. Overall, our study demonstrates that grassland may...
1. Introduction

Soil erosion is one of the most severe and widespread environmental problems worldwide and causes economic loss in terms of agricultural production and gross domestic product (Panagos et al., 2018). Overgrazing, tillage and unsuitable agricultural practices often increase the magnitude of soil erosion processes (Borrelli et al., 2017; Keesstra et al., 2016; Rodrigo-Comino et al., 2018), resulting in a series of on-site and off-site environmental problems, including increased sediment loads in rivers and flood risk, and reduced biodiversity (Jia et al., 2014; Xu and Cheng, 2002).

In order to cope with these threats, many ambitious ecosystem restoration programs have been proposed in the world (Cao et al., 2009; Jia et al., 2014; Yan et al., 2018). For example, the Chinese government implemented the Grain-for-Green program in 1999 to encourage farmers to plant trees or grass on sloping farmland (slope gradient higher than 15°) that is characterized by lower crop yield, by providing subsidies to farmers, including free grain and cash compensation (Ostwald and Chen, 2006; Xu et al., 2006). However, in semiarid areas, water scarcity is common and few rainfall events are recorded per year. Under these water-deficient conditions, surface runoff is the main source of water supply to the river systems, and thus, it is critical to ensure the sustainability of ecological systems (Cao et al., 2010; Liu et al., 2019; Robinson et al., 2003).

Previous studies have shown that there is a trade-off between water provisioning services and soil conservation services, especially between runoff generation and sediment transport (Hu et al., 2017; Jia et al., 2014; Power, 2010). The term ‘trade-off’ refers to the process by which the levels of multiple ecosystem services are adjusted to achieve an optimal overall outcome (Maron and Cockfield, 2008; Raudsepp-Hearne et al., 2010; Rodríguez et al., 2006). Such a trade-off may involve the reduction in the beneficial effects of one ecosystem service in order to increase the environmental benefit of others (Bennett et al., 2009; Zheng et al., 2014).

Ecological restoration programs are meant to prevent desertification, for instance through the use of windbreaks to reduce the entrainment of topsoil. However, conflicts can arise between protection of soil loss and maintenance of water resources. In particular, vegetation restoration may favor a decline in other ecosystem services, such as the decrease in regional agricultural production and surface water yield (Jia et al., 2014; Liu and Diamond, 2005; Rodríguez et al., 2006). Some studies have shown that vegetation restoration has decreased river flow by reducing runoff generation, which affects the health of aquatic ecosystems (Cao et al., 2011; Dang et al., 2018; Farley et al., 2005; Feng et al., 2012). It has been shown that vegetation generally reduces runoff through canopy interception, higher soil permeability, root consumption for plant growth, and evapotranspiration (De Baets et al., 2007; Farley et al., 2005; Gysels and Poesen, 2003). Moreover, many studies have demonstrated that vegetation reduces soil erosion by increasing the above-ground plant parts, litter layers, canopy and ground cover, and the soil binding effects provided by the root systems (Borrelli et al., 2017; López-Vicente et al., 2017; Wei et al., 2007; Zhao et al., 2014). How to achieve the optimum trade-off between water resources protection and soil erosion control remains in need of further study, to support the implementation of ecological restoration programs.

Therefore, a thorough analysis of the available literature data on changes of runoff and sediment yield resulting from re-vegetation practices may help design such restoration programs. In particular, the evaluation of the effects of different vegetation types on runoff and sediment yield 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 soil erosion control.

In this study, we examined published articles to assess the effectiveness of three main re-vegetation types, namely forestland, scrubland and grassland, in maintaining runoff while reducing soil erosion. The findings could help determine the re-vegetation types in the Grain-for-Green program on the Loess Plateau, and supplement the knowledge of the trade-off between soil- and water-related ecosystem services during the implementation of restoration programs in semi-arid regions.

2. Material and methods

2.1. Study area and experimental design

To estimate the effectiveness of different vegetation types on controlling soil erosion on hill slopes, we collected relevant data on runoff and sediment yield by searching peer-reviewed journal articles through the Web of Science and Google Scholar search engines with the keywords “runoff” or “sediment” or “soil erosion” and “semi-arid” or “semiarid”. The criteria for data compilation were: (i) the aridity index, i.e. precipitation (mm)/potential evapotranspiration (mm), in the study site >0.5; (ii) each article compared at least one of the vegetation types (forestland, scrubland and grassland) in relation to a control land use (bare land or farmland); and (iii) at least one of the variables (runoff or sediment) was measured in both the control and vegetated plots. All the available data from each article was extracted directly from the text or tables, or from figures using GetData Graph Digitizer 2.24 software (see in Table S1).

In total, 38 articles were used in this meta-data analysis that included data obtained under simulated or natural rainfall. Among these articles, there were 16 studies in Chinese study areas, and others in Spain, USA and elsewhere (Fig. 1). Our results have a wide geographical coverage and should contain findings relevant to the implementation of the Grain-for-Green program. The spatial scale of the published studies ranged from 0.091 m² to 2.8 ha, but the majority were conducted at a scale smaller than 100 m². The study sites generally had >50% vegetation cover, and some were grazed. The mean annual temperature of the study sites ranged from 5.6 to 18.2 °C. The mean annual rainfall ranged from 180 to 970 mm, and the mean annual evapotranspiration from 785 to 1988 mm. Following Elias et al. (2018), soil textures were divided into five classes from coarse to fine soil, with >50% of the soils belonging to fine soil. Thus, the database was consistent and robust.

2.2. Meta-data analysis

Three indices were employed to compare the efficiencies of the three vegetation types on controlling soil erosion and runoff. These included the runoff reduction effect (RRE, %), the sediment reduction effect (SRE, %) and the ratio between runoff and sediment reduction (RRSR, %). These indices were calculated as follows (Zhao et al., 2014):

\[
RRE = \frac{R_c - R_v}{R_c} \times 100
\]

\[
SRE = \frac{S_c - S_v}{S_c} \times 100
\]

\[
RRSR = \frac{RRE}{SRE} \times 100\%
\]

be 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.
where \( R_v \) and \( R_c \) represent the runoff variables (i.e., runoff amount, runoff coefficient, runoff rate or runoff depth) for the vegetated and control plots, respectively; and \( S_v \) and \( S_c \) represent the sediment variables (i.e., sediment yield, sediment concentration, erosion modulus or soil loss) for the vegetated and control plots, respectively. A high RRE or SRE means that vegetation is effective in reducing runoff or sediment yield regarding the rates observed in the control area (farmland or bare land). The RRSR indicates the relative effectiveness of runoff reduction compared to sediment reduction in the same area. A low RRSR means that the performance of vegetation in reducing sediment is more effective than in reducing runoff. The area of farmland with a slope gradient \( >15^\circ \) on the Loess Plateau is 2.52 M ha, which is the main target of the Grain-for-Green program for vegetation restoration (Chen et al., 2015; Tang et al., 1998). Following this criterion, the selected studies were divided into two groups: gentle slopes (0–15°) and steep slopes (>15°). The map of site distribution was drawn using ArcGIS v.10.2 software. Other figures were drawn using the ggplot package of Revolution R Enterprise 8.0 software (R Core Team, 2014).

3. Results

In this study, the mean RRE of scrubland on gentle slopes (65%, on average) was slightly higher than on steep slopes (59%; Fig. 2). In contrast, forestland and grassland had higher RRE on steep slopes (51% in forestland; 43% in grassland) than on gentle slopes (33% in forestland; 40% in grassland).

The mean SRE of the three vegetation types was similar between them, about 70% on gentle slopes (Fig. 3). On steep slopes, the SRE of the three vegetation types increased slightly, the highest SRE being recorded in forestland (85%, on average), followed by scrubland (75%) and grassland (70%).

The RRSR of the different vegetation types on gentle slopes was ranked in the following order: scrubland (93%, on average) > forestland (63%, on average) > grassland (56%, on average). Similarly, scrubland had the highest RRSR on steep slopes (81%, on average), followed by forestland (65%) and grassland (53%). These results mean that the performance of grassland in maintaining runoff yield and reducing sediment delivery in semi-arid areas was higher than the ability of forestland and scrubland to achieve the same goal (Fig. 4).

4. Discussion

4.1. Effects of re-vegetation types on runoff maintenance and sediment reduction

The contribution of vegetation restoration to ecosystem services generally varies according to the topographic conditions and vegetation types (Bochet et al., 2006; Gyssels et al., 2005; Marques et al., 2007). Vegetation showed relatively higher RRE and SRE on steep slopes than

![Fig. 1. Distribution of the 45 case sites (from 38 articles) examining the effects of re-vegetation types on water resources protection and soil erosion control.](image1)

![Fig. 2. Runoff reduction effect (RRE) for the three vegetation types, on gentle (0–15°) and steep (>15°) slopes. Note: The upper and lower hanging bars denote the maximum and minimum values, respectively. The top and bottom edges of box denote the upper and lower quartile values, respectively. The lines in the middle of the box denote the median values. Black dots denote the outlier values. Blue dots with numbers denote the mean values.](image2)
vegetation were not consistent, possibly due to the different above-ground vegetation and the predominant root systems (Hu et al., 2017; Zheng et al., 2014).

In previous articles, Chen et al. (2015) and Liu et al. (2019) highlighted that the ecological restoration program in China needs to focus on reducing soil erosion and sediment yield, while maintaining runoff, in order to achieve the specific goal of sustainable ecosystem development. The lowest values of RRSR found in grassland indicated that runoff reduction was lower than in forestland and scrubland, whereas soil erosion reduction was similar. This finding is important for maintaining the stability and services of river systems, and thus supports sustainable environmental and economic development. The majority of studies have shown that afforestation reduces runoff (McVicar et al., 2007), the reduction being as high as 99% in some studies (Wang and Wang, 2001). In contrast, grassland has been reported to reduce runoff by about 20% (Meng et al., 2010) but to increase it in other cases (Liu et al., 2019). Soil and water conservation under forestland and scrubland occurs via the dense canopy, litter-humus layer and root system, which effectively intercept rainfall and improve soil permeability, and thus greatly reduces runoff and sediment losses (Anache et al., 2018; Pizarro et al., 2006; Wei et al., 2007). In contrast, grassland restoration favors the presence of abundant fine roots in the topsoil that have a fast turnover rate, which increases soil cohesion and improves soil stability, and thus, promoting soil erosion control (De Baets et al., 2007; Zhang and Wang, 2015).

Although previous studies have reported that the impacts of vegetation restoration on runoff and sediment yield are also affected by other factors, e.g., vegetation coverage, vegetation clearance for wildfire prevention, soil texture and climate conditions (López-Vicente et al., 2011; Li and Fang, 2016; Anache et al., 2018), little attention has been paid to the trade-off between soil erosion control and water resources protection during vegetation restoration. This study has effectively assessed the impacts of re-vegetation types on soil- and water-related ecosystem services. The similar characteristics of the study sites included in this meta-data analysed, namely the fine soil texture, vegetation coverage >50% and semi-arid conditions, minimized the impact of these factors on the final results, and thus, the observed differences were likely due to the different vegetation types.

The effects of vegetation restoration on different kinds of soil erosion (i.e., river bank and gully erosion) might be different. Moreover, the articles involved in this study were mostly conducted in small plots (<100 m²). There are few catchment-scale studies of vegetation restoration in relation to water yield (Farley et al., 2005; Cao et al., 2011; Cheng et al., 2017), but even less on soil erosion. To investigate soil erosion processes at a larger scale is something to consider (Alaoui et al., 2012). Therefore, further studies should focus on analysing the effects of re-vegetation types on overland flow velocity and sediment connectivity, surface water resource protection and soil erosion control at different scales (i.e., landscape, hillslope, geomorphic feature, hydrologic response unit and patch) (Wang et al., 2012; López-Vicente et al., 2014).

4.2. Implications for land management

This study has proved that the contributions of vegetation restoration to ecosystem services depends more on vegetation types than on slope gradient. Grasslands appeared more effective in maintaining runoff and reducing sediment. This finding 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. Moreover, this work can improve the knowledge on the trade-off between soil- and water-related ecosystem services during the implementation of ecological restoration programs in semi-arid regions.

5. Conclusions

The meta-data analysis allowed us to evaluate the specific effectiveness of the three main vegetation types used in ecological restoration
programs, namely forestland, scrubland and grassland, on reducing runoff and sediment yield. These results supported the positive evaluation of the impacts of the Grain-for-Green program on ecosystem services. Namely, we found that (i) vegetation had an obvious ability to reduce runoff, especially scrubland; (ii) the three vegetation types had similar efficiency in sediment reduction; and (iii) grassland showed a higher performance in maintaining runoff yield and reducing sediment delivery compared to forestland and scrubland. Our study revealed that grassland not only reduced sediment and protected soil from erosion but also increased runoff, which has benefits for the sustainability of terrestrial as well as aquatic ecosystems. While forestland and scrubland could both reduce both runoff and sediment, runoff reduction was higher. This study provides some insights for land and water managers on how to achieve the trade-off between surface water protection and soil erosion control related to re-vegetation. In addition, it suggests that grasslands could successfully optimize the trade-off between soil and water-related ecosystem services during the implementation of ecological restoration programs in semi-arid regions.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References


