Effects of Vegetation Restoration on Soil Conservation and Sediment Loads in China: A Critical Review

LISHAN RAN, XIXI LU AND JIANCHU XU

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Q5. Au: Please provide more specific URL for State Forestry Administration reference.

TABLE OF CONTENTS LISTING

The table of contents for the journal will list your paper exactly as it appears below:

Effects of Vegetation Restoration on Soil Conservation and Sediment Loads in China: A Critical Review
Lishan Ran, Xixi Lu and Jianchu Xu
Effects of Vegetation Restoration on Soil Conservation and Sediment Loads in China: A Critical Review

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China has been one of the countries suffering from the most serious soil erosion, which has severely degraded soil productivity and water quality, thus affecting agricultural activities and hindering economic and social development. During the past few decades, a large amount of effort has been made to combat soil erosion. Vegetation restoration as a major strategy is given equal importance compared to engineering measures. Although a measure of success has been achieved, many uncertainties remain unanswered such as to what extent the vegetation restoration has reduced soil erosion and sediment loads especially in large river systems. This paper first analyzes the impacts of vegetation restoration on soil erosion and sediment loads in terms of vegetation cover and vegetation species. Then, the spatial scale effect of soil erosion reduction benefit resulting from vegetation restoration is elaborated. Soil erosion reduction benefit decreases with increased vegetation planting area. In addition, a comprehensive discussion about the disputes between vegetation restoration and engineering measures is made by integrating published studies spanning large spatial and temporal scales. Finally, future research needs regarding vegetation restoration efforts are given. In order to evaluate the effects of vegetation restoration programs on soil erosion, assessments in shorter time interval and larger spatial scale should be undertaken. Further, the present assessment system mainly based on simple statistical methods has to be improved. Specific areas demanding immediate...
attention, including the western China in general and the upper Yangtze River basin in particular, are highlighted as well.

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KEY WORDS: China, sediment load, soil and water conservation, soil erosion reduction benefit, vegetation restoration

1. INTRODUCTION

Soil erosion, as a direct response of natural environment to human activities, is second only to population growth as the biggest environmental and public health problem, causing direct economic loss of around USD$400 billion per year in the world (Pimentel, 2006). As one of the most severely affected countries in the world, China has undergone soil erosion for quite a long time. Given the increasing demands to support rapid population expansion, vast tracts of land have been reclaimed for grain production since 2000 years ago. Consequently, soil erosion has become extremely serious owing to inadequate consideration of nature’s bearing capacity (Chen et al., 2007).

Accelerated by anthropogenic perturbations, soil erosion rates are more rapid than natural soil forming rates, resulting in a net loss of soil productivity (Lal, 2003; Pimentel et al., 1995). The agents of the accelerated erosion are water and wind, each contributing variably to the total soil loss within the world depending on climatic conditions. In this review, we will mainly focus on the water-borne accelerated erosion, which is the detachment and transport processes of soil from the land by water, including rainfall and runoff (Ward and Elliot, 1995).

With the establishment of the People’s Republic of China, massive economic reconstruction was launched. Owing to blind pursuit of economic development and weak environmental protection awareness, the accelerated soil erosion due to anthropogenic perturbations became much more severe in the first few decades. According to Wang (2001) and Dai et al. (2009), the total soil erosion area with soil erosion modulus exceeding 200 t/km²/a has increased to $1.16 \times 10^6$ km² in the early 1950s and further to $1.79 \times 10^6$ km² in 1985. The soil erosion modulus is defined as the eroded soil volume normalized by drainage area in units of t/km²/a. Spatially, soil erosion is mainly distributed in the upper and middle reaches of large river basins, such as the Yangtze, Yellow, and Pearl rivers. Taking the Yangtze River basin as an example, the soil erosion area was about $36.4 \times 10^4$ km² in the 1950s, accounting for 20.2% of its total drainage area (1.8 million km²). In the 1980s, it increased to $56.2 \times 10^4$ km², representing more
Effects of Vegetation Restoration

FIGURE 1. Map showing the location of several major soil conservation programs (Color figure available online)

than 30% of the total drainage area (Zhang and Guo, 1999). The second national soil survey shows its soil erosion area has further increased to 63.7 × 10^4 km^2 in 2001 (Ministry of Water Resources of China, 2001). Totally, China is currently suffering from soil erosion 30–40 times faster than the natural replenishment rate as a result of unwise land development strategies and management practices (Ehrenberg, 2008; Pimentel, 2006).

In response, widespread efforts have been undertaken to fight soil erosion, and numerous soil conservation programs have been implemented on multiple scales (Figure 1). The most commonly used soil conservation measures in China are reforestation, grass planting, terracing and silt check dams (Figure 2). Generally, the former two measures are called vegetation measures while the latter two engineering measures (Huang and Zhang, 2004). The reforestation strategy includes planting trees and shrubs on hillslopes, and the selected species varies greatly depending on local climatic conditions. Grass plantation is primarily encouraged in north China due to the dry climate and the attempts to alleviate increasing grazing pressure. Terraces are constructed on eroding slopes with gradient less than 25° to reduce runoff by altering the slope gradient and thus provide temporary water storage for agricultural production. Because of the dual advantages in reducing soil erosion and promoting agriculture, they have been widely constructed on the Loess Plateau (Figure 2). Silt check dams built on gully channels are a permanent structure and could bring immediate benefits in intercepting water and sediment (Chen et al., 2007; Wang and Ran, 2008). Up to 2003, approximately 11.35 × 10^4 silt check dams had been constructed in the middle
FIGURE 2. Soil conservation measures being implemented in China (Color figure available online)

Yellow River basin and have trapped sediment of 21 Gt, representing a great contribution to the reduced sediment loads measured in its lower reach (Li, 2003).

From a hydrological point of view, the planted vegetation controls soil erosion through the following processes: (a) protect the soil from direct raindrop impact by intercepting raindrops and reducing their energy for soil splash through plant canopies and litter; (b) reduce surface runoff velocity by providing additional surface roughness; (c) enhance infiltration due to the presence of roots, plant residue, and increased biological activity; (d) accelerate transpiration rates of soil water due to changed soil structure as well as the need for plant growth; and (e) hold soil particles in place by physically binding soil particles together and by acting as mechanical barriers to soil and water movement (Pimentel et al., 1995; Woo et al., 1997). These effects vary considerably because of the differences in influencing factors such as species, climate, soil properties and degree of maturity (Ward and Elliot, 1995). In contrast, the engineering measures can take effect quickly. However, disputes have arisen since the beginning as they could interfere with ecological functionality and stability (Chen et al., 2007). In comparison, the vegetation restoration measures would not significantly affect the ecosystem while reducing soil erosion in the long term. That is quite different from the engineering measures as the silt check dams have to be abandoned once filled up (Linda et al, 1995). More importantly, unlike the engineering measures, vegetation itself is an indispensable component of the nature (Gao et al., 2002; Hongo et al., 1995).
Effects of Vegetation Restoration

TABLE 1. Major vegetation restoration projects implemented in China in recent decades

<table>
<thead>
<tr>
<th>Name</th>
<th>Start</th>
<th>End</th>
<th>Planted/managed area (km²)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yellow River Conservation Project</td>
<td>1999</td>
<td>2005</td>
<td>6.27 × 10⁴</td>
<td>Liu, 2005</td>
</tr>
<tr>
<td>Yangtze Conservation Project</td>
<td>1989</td>
<td>2008</td>
<td>9.6 × 10⁴</td>
<td>Liu, 2010</td>
</tr>
<tr>
<td>Three-North Shelterbelt Program</td>
<td>1978</td>
<td>2009</td>
<td>2.446 × 10⁵ (Vegetation cover increase: 30%)</td>
<td>State Forestry Administration, 2010</td>
</tr>
<tr>
<td>National Key Project of Soil and Water Conservation</td>
<td>1983</td>
<td>2009</td>
<td>(Vegetation cover increase: 24%)</td>
<td>Xu, 2009</td>
</tr>
<tr>
<td>Grain-for-Green Project</td>
<td>1999</td>
<td>2010</td>
<td>1.467 × 10⁵</td>
<td>Cao, 2011</td>
</tr>
<tr>
<td>National Natural Forest Protection Project</td>
<td>2000</td>
<td>2010</td>
<td>6.82 × 10⁵</td>
<td>State Forestry Administration, 2010</td>
</tr>
<tr>
<td>Sand Control Program</td>
<td>2001</td>
<td>2010</td>
<td>5.2 × 10⁴</td>
<td>Cao et al., 2011</td>
</tr>
<tr>
<td>Soil Conservation Project of Dark Soil in NE China</td>
<td>2008</td>
<td>2010</td>
<td>(Vegetation cover increase: 20%)</td>
<td>Liu, 2011</td>
</tr>
<tr>
<td>Upper Pearl River Conservation Project</td>
<td>2004</td>
<td>2020</td>
<td>1.85 × 10⁴ (Estimated)</td>
<td>Pearl River Water Commission, 2005</td>
</tr>
</tbody>
</table>

Since the 1970s, a number of vegetation restoration programs have been implemented in quick succession (Table 1). For instance, to mitigate soil erosion in the northwest, the north and the northeast China (Figure 1), the Three-North Shelterbelt Program aims to increase forest cover to 15% by 2050 and a total of 35.6 million ha of plantation is expected to be established (Zhu et al., 2004). According to a report by the State Forestry Administration (2010), the program has already doubled the forest cover of the total to-be-treated area from 5.1% in 1977 to 10.5% in 2008, and more than 40% soil erosion area has been effectively controlled by forest ecosystems. Another national program, the Grain-for-Green Project, initiated in western China in 1999, has set aside more than 1.4 × 10⁵ km² of cropland for forest and grassland by the end of 2010 through compensating farmers with in-kind grain allocations and cash payments. On the whole, up to 2008 the total area of vegetation restoration has increased to 7.2 × 10⁵ km², and it is still increasing at a rate of about 2 × 10⁴ km² per year (Ministry of Water Resources of China,
In particular, as a region suffering from the severest soil erosion, the achievement of vegetation restoration in the Yellow River basin is quite tremendous. The total forest and grassland area have reached $8.87 \times 10^4$ km$^2$ and $2.67 \times 10^4$ km$^2$, respectively (Ran, 2006).

Though it has been widely accepted that vegetation cover can strongly affect overland runoff and soil erosion processes (Li, 1983), the relation between vegetation cover and soil erosion is extremely complicated and remains poorly constrained (Cao, 2008; Cao et al., 2010). One example is that, except for linear simulation advanced by the Universal Soil Loss Equation (Wischmeier, 1959), some others have adopted an exponential relationship (Thornes, 1990). Rogers and Schumm (1991) even contended that neither a linear nor an exponential equation could accurately deal with this issue. It is believed that these uncertainties will continue to confuse soil conservation scientists in the foreseeable future. As for the soil conservation measures being implemented in China, disputes also exist over which kind of measures (engineering vs. vegetation) should be given priority and what combination of measures is optimal. In addition, most previous evaluations of soil erosion reduction resulting from restored vegetation focused exclusively on individual case studies and an integrated analysis involving spatial and climatic variability is lacking. Since the 1950s, supported by the Chinese government (mainly the Ministry of Water Resources) and international organizations, a huge amount of financial aid has been allocated to alleviate soil erosion (Chen et al., 2007). Tremendous achievements have thus been attained; however, a comprehensive and systematic evaluation of vegetation restoration’s impacts on soil erosion reduction at a national level has never been reported. For these reasons, it is clear that a timely evaluation of previous work is necessary for future soil conservation endeavors.

The objective of this article, therefore, was to review the impacts of vegetation restoration on soil conservation and sediment loads. Particular attention will be paid to benefit differences in soil erosion reduction caused by vegetation cover change over a wide range of spatial scales. Furthermore, with the available studies consisting of engineering and vegetation measures, a comparison analysis of soil and water reduction benefits resulting from different conservation measures is made. We conclude with several problems as to what we perceive as the most urgent research needs in vegetation restoration assessment.

2. DATA DESCRIPTION AND RELIABILITY

With the implementation of soil conservation programs at different levels and on-site observations at numerous experimental watersheds scattered across China, quite a large number of research progresses have been publically reported. Based on field measurement data, these studies have tried to analyze
vegetation's effects on soil conservation in several topics, including erosional mechanism, environmental and economic costs, and ecological disturbances (e.g., Cao, 2011; Hao, 1993; Li and Shao, 2006). For experimental watersheds or plots, with slope area generally less than 10 km², the measurements were carried out at the outlet located at the foot of the slopes. Particularly, the plots were usually bounded and trenched around to lead away upslope runoff water, and runoff and eroded soil were drained into troughs and then into larger containers for weighing. For the watersheds with gullies included, the measurements were usually conducted at hydrological stations near the outlet (Luo et al., 1996; Shi and Guo, 2006; Wang and Ran, 2008; Xu, 2004a).

To precisely evaluate the restored vegetation's soil conservation benefits, the planting area of various vegetation measures were first calculated, as were the sediment detention volume in silt-check dams and the area of terraces. After a certain time period, the treated watersheds were compared with untreated background watersheds, which are mostly situated nearby with similar natural conditions and human perturbations. Through comparison with the background watersheds, the changes in soil/sediment loads and runoff could be quantified and attributed to different measures according to their contributions.

Two conventional approaches used in reduction benefit evaluation are hydrologic statistics method and soil conservation method (Zhang and Guo, 1999). By establishing an empirical sediment-runoff model based on measured data in a baseline period, the hydrologic statistics method could estimate the sediment loads under assumed unchanged underlying surface using the measured runoff after soil conservation measures. The difference of sediment loads between the estimated and the measured represents the reduction benefit produced by soil control work. On the other hand, for the soil conservation method, the area of planted vegetation and the storage capacity of engineering measures in a specific study area are first calculated. Then, a percentage (index) indicating to what extent these measures could reduce soil/sediment loads will be assigned to each measure. Consequently, the total reduced sediment loads could be quantified easily. It can be seen that the soil conservation method does not need long-term on-site measurement, and the indexes are somewhat subjective, whereas a long-term on-site measurement is required for the hydrologic statistics method. Further, the developed sediment-runoff relation could never be regarded as general given its complexity. For example, for storms with same precipitation volume, the higher intensity storm events usually could cause much severer soil erosion than the lower intensity ones.

In this review, more than 95% case studies have adopted the hydrologic statistics method. Therefore, it is believed that, although spatially scattered, they can be combined together to evaluate the effects of vegetation on soil erosion control and sediment loads changes at a wide range of spatial and temporal scales.
3. SOIL EROSION CONTROL BY VEGETATION RESTORATION

3.1 Effects of Vegetation Cover

The major objective of vegetation restoration regarding soil erosion is to change soil structure and thus make soil particles less vulnerable to erosion. This is especially true for the bare Loess Plateau (Figure 1), where loosely cemented loess particles are readily susceptible to movement and are the culprit for downstream channel aggradation. Furthermore, as plant roots have the ability to bind soil particles, enhance infiltration of surface runoff, and to provide additional surface roughness, the resultant soil erosion reduction from vegetation rehabilitation is positively correlated with vegetation cover percentage. To analyze the complex relation and evaluate to what extent the effect is, we collected data from several studies based on a broad spectrum of natural conditions within China and the fitted regressions are displayed in Figure 3 (more information refers to the Supplementary Information). The data used are a collection of several studies carried out in different regions representing a variety of climates, spanning from the cold and wet northeastern region via arid and semiarid loess region in the north China to humid subtropical climate in the south, thereby representing spatial generality of such relation. In addition, these studies were based on plot measurements for at least one hydrological year, and more than 94% of the obtained results have been compared with previous reports where similar measurements had been taken. There is a strong nonlinear relationship between soil erosion reduction benefit (SERB) and vegetation cover. Here, SERB is the ratio of the

\[ y = 101.5209e^{0.260912x - 0.912088} \]

\[ R^2 = 0.62 \]

**FIGURE 3.** Relation between SERB and vegetation cover percentage (data sources: Chen et al., 2006; Gao et al., 1995; Wang and Cai, 1999; Xiong et al., 1996; Yang et al., 2006) (Color figure available online).
Effects of Vegetation Restoration

reduced soil volume resulting from vegetation restoration to the total eroded soil from sizeable bare land.

When the vegetation cover is below 60%, the SERB increases sharply with vegetation cover; in comparison, the vegetation restoration strategy could reduce soil erosion by at least 80% once it exceeds 60% (Figure 3). The marginal SERB decreases with increasing vegetation cover, implying that vegetation restoration programs should probably aim for partial vegetation plantation as the SERB is not linearly correlated with vegetation cover changes. Based on individual catchments at various spatial scales, this critical percentage (~60%) referring to substantial soil erosion reduction has also been validated and proposed as a guideline for vegetation plantation programs (Chen et al., 2006; Hou and Cao, 1990; Xu and Sun, 2006). Furthermore, it is clear that, in most cases, the soil erosion could be greatly reduced once the vegetation cover percentage reaches 80%, which is consistent with the result of computer modeling that 78% vegetation cover can effectively control soil erosion (Zhou et al., 2008).

In the attempts to evaluate the effects of vegetation restoration on soil erosion, one unavoidable fact is that the eventually calculated SERB percentages based on various study areas are highly variable. That is because every individual area has its own characteristics in terms of geographical background, vegetation species, forest/grass ratio, growth age, and management scheme. To remove the differences caused by these external factors as much as possible, 69 catchments in the coarse sediment producing area (Xu and Yan, 2005) are selected exclusively to examine the effects of vegetation cover (mainly reforestation measures). They all are located in a semiarid climate zone with a mean annual precipitation of 300–500 mm. The spatial area varies from less than 0.1 km² to larger than 1000 km². The compiled data and fitted results are shown in Figure 4. As can be seen, the soil erosion modulus after reforestation shows an exponential decay with increasing vegetation cover. Once the forest cover exceeds 80% approximately, the trend line of soil erosion modulus becomes quite gentle and most of the points are below 1000 t/km²/a, a widely pursued soil conservation objective given the vulnerability of loess particles to erosion. On the other hand, the spread of the data points highlights the large variability of SERB under different environmental backgrounds, indicating that minor vegetation rehabilitation may not necessarily bring traceable soil erosion alleviation.

As stated previously, several empirical relations have been advanced between the two variables with various explanations. However, it should be noted that they are confined to small individual catchments or based on artificial simulation record. Thus, they could not be generalized arbitrarily to other places with probably completely different backgrounds. For instance, in comparison to the exponential relation, Wang (2004) and Xu (2005) suggested that a parabolic function, rising at first and then falling, could better explain the coupling of soil erosion modulus and vegetation cover change.
FIGURE 4. Relation between forest cover and soil erosion modulus in the coarse sediment source of the Yellow River (data sources: Duan, 2009; Wang, 2004; Yang et al., 2006) (Color figure available online).

The rule states that the vegetation measures can predominate the erosion process and reduce soil loss only if its cover percentage exceeds a threshold, around 20–30%, for example (Gao et al., 2011; Wang, 2004). In fact, even with the same vegetation cover percentage, the extent of soil erosion reduction, reflected through decreased erosion modulus, in different areas would be quite variable due to the differences in canopy density and plant litter amount. Not to mention the fact that the yield and intensity of soil erosion are related not only to vegetation cover, but also to other factors such as soil type, slope gradient, rainfall erosion, and rate of mulch application (Gao, 2008; Zheng, 2006). Overall, the finally obtained SERB based on any study area is the integrated result of various influencing factors. More efforts should be taken to improve our understanding of the complex response processes.

Although vegetation cover could prevent soil on hill slopes from being eroded away by surface flow, it could not completely solve the soil erosion for catchments with gullies. That is because a considerable part of the sediment measured at given outlets is supplied from the gullies, while only a small portion comes from the areas between the gullies (∼30–40%; Xu and Sun, 2006). For soil erosion in the gullies, engineering measures such as silt check dam, is commonly adopted to trap the eroded soil. Therefore, in view of sediment source, the effect of vegetation restoration on soil erosion is limited and its potential maximum reduction benefit will be the percentage of the soil coming from hill slopes to the total measured sediment flux. In addition, for any individual vegetation measure, its SERB could not increase
Effects of Vegetation Restoration

FIGURE 5. Relation between SERB and the area of reforestation (a) and grassland (b) in Wuding River basin (drainage area: 30261 km²; from Xu and Sun, 2006). The broken lines are drawn by eye.

monotonically without an upper limit. But rather, the marginal SERB resulting from vegetation restoration diminishes with an increase in the restored area (Figure 5).

As illustrated by the broken lines, the left lines have a steeper slope; while the right ones are nearly parallel to the horizontal axis. That is, either for forest or for grassland, with increasing vegetation cover area, the increasing rate of SERB changes from positive value (at the rising stage) to nearly zero (at the stable stage). The potential maximum SERB lies in the intersection point of the two lines. At the rising stage, the SERB increases with changing vegetation restoration area. In contrast, at the stable stage, it remains roughly unchanged although the vegetation restoration area continues to increase. Therefore, the vegetation restoration area size (or percentage) the intersection point refers to could be regarded as a critical vegetation cover percentage, which coincides with the earlier mentioned threshold. However, while vegetation cover gets up to ∼60% and can exert an apparent controlling effect on soil erosion, it does not necessarily imply that a general realization has been achieved. Using satellite data and measured soil erosion record in the middle Yellow River basin, Wang (2004) concluded that soil erosion would decline significantly as long as the mixed vegetation cover, including trees, shrubs and grass, on the slopes reaches 24%.

In general, there is a critical vegetation cover percentage referring to the substantial soil erosion reduction. But it should be careful to apply such critical percentage to other places. Because apart from the vegetation cover itself, the critical vegetation cover percentage would be influenced by other factors like rainfall characteristics, soil texture, and topography. For instance, even with the same vegetation cover percentage, an abrupt increase in soil erosion reduction is expected when the slope is higher than 25° (Li et al., 2009). In addition, the spatial distribution of vegetation plantation also plays
a significant role in affecting the critical vegetation cover percentage (Rey, 2003). One example is that the gully activity is only correlated with the vegetation cover percentage on the gully floors. Unfortunately, similar studies have not received adequate attention in China.

3.2 Effects of Vegetation Type

Vegetation development and its distribution are strictly affected by natural conditions, such as climate, soil properties, and hydrological regime (Li and Shao, 2006). On the other hand, vegetation growth can change the local natural conditions to varying degrees. China is characterized by great landform varieties exhibiting diverse environment and climate zones, which indicates the vegetation species adapting to different natural conditions are also diverse. For the to-be-selected species, they should thus be diverse as well. For example, in the semiarid north China, in most cases only grass and few tree species that do not consume large amounts of water are preferred. In contrast, in the relatively humid south regions, tree planting is usually a preferable option, in particular the species that could quickly bring economic benefits.

Table 2 shows the SERB resulting from several species planted throughout China. Generally, soil erosion could be effectively reduced or controlled through the enforcement of vegetation restoration measures. The afforestation option, including tree and shrub plantations, appears to be more effective than the grassland. For instance, the SERB for the *Hippophae rhamnoides* planted in Gansu and for the *Acacia dealbata* planted in Yunnan is 92% and 98.9%, respectively. By contrast, mostly it is around 80% for grass plantation. Another point is that the SERB is positively related to the degree of maturity of vegetation species planted. One example is that it increases gradually with the age of the *Robinia pseudoacacia* (Table 2). It even reaches 98.9% as the trees reach 15 years of age, indicating higher performance of complex root systems in preventing soil movement (Hou and Cao, 1990). The positive correlation between SERB and the restored vegetation's age highlights the importance of ecological succession (Bonet, 2004), and it is essential to preserve the older species from clearance, particularly in arid areas where planted vegetation is struggling for survival.

Comparing with single species planting shows a mix of different species performs more effective in reducing soil erosion in most cases (Gyssels et al., 2005). That is because the plants connect with each other underground, and the microorganisms that live in association with them produce tiny threads that would ramify through the soil layers, thus coiling around soil particles and holding them in place (Chen et al., 2004). As the Table 2 illustrates, the SERB for a mix of *Astragalus adsurgens* and *Caragana korshinskii* is 87.1% while that for the single species is only 83.9% and 74.8%, respectively. Nevertheless, not all the mixed compositions could perform more effectively than the single species. One exception is that the mix forest of *Onobrychis*
### Effects of Vegetation Restoration

**TABLE 2.** Soil erosion reduction benefit by different vegetation species

<table>
<thead>
<tr>
<th>Species</th>
<th>Site</th>
<th>SERB (%)</th>
<th>Maturity</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Robinia pseudoacacia</em></td>
<td>Suide, Shaanxi</td>
<td>70.2</td>
<td>3~4 years</td>
</tr>
<tr>
<td><em>Robinia pseudoacacia</em></td>
<td>Suide, Shaanxi</td>
<td>89.3</td>
<td>5~6 years</td>
</tr>
<tr>
<td><em>Robinia pseudoacacia</em></td>
<td>Suide, Shaanxi</td>
<td>91</td>
<td>7~8 years</td>
</tr>
<tr>
<td><em>Robinia pseudoacacia</em></td>
<td>Ansai (Nan Valley), Shaanxi</td>
<td>76.9</td>
<td>1~6 years</td>
</tr>
<tr>
<td><em>Robinia pseudoacacia</em></td>
<td>Ansai (Nan Valley), Shaanxi</td>
<td>98.9</td>
<td>7~15 years</td>
</tr>
<tr>
<td><em>Robinia pseudoacacia</em> + <em>Elm</em></td>
<td>Yan’an, Shaanxi</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td><em>Medicago sativa</em></td>
<td>Lishi, Shanxi</td>
<td>95.3</td>
<td></td>
</tr>
<tr>
<td><em>Melilotus suaveolens</em></td>
<td>Suide, Shanxi</td>
<td>69.5</td>
<td></td>
</tr>
<tr>
<td><em>Melilotus suaveolens</em></td>
<td>Ansai, Shaanxi</td>
<td>66.8</td>
<td>4 years</td>
</tr>
<tr>
<td><em>Astragalus adsurgens</em></td>
<td>Jungar, Inner Mongolia</td>
<td>88.7</td>
<td></td>
</tr>
<tr>
<td><em>Astragalus adsurgens</em></td>
<td>Ansai (Nan Valley), Shaanxi</td>
<td>97.8</td>
<td>2~8 years</td>
</tr>
<tr>
<td><em>Caragana korshinskii</em></td>
<td>Ansai</td>
<td>83.9</td>
<td></td>
</tr>
<tr>
<td><em>Caragana korshinskii</em></td>
<td>Ansai (Nan Valley), Shaanxi</td>
<td>99.8</td>
<td>32 years</td>
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<td>Ansai</td>
<td>74.8</td>
<td></td>
</tr>
<tr>
<td><em>Medicago sativa</em></td>
<td>Ansai (Nan Valley), Shaanxi</td>
<td>37.5</td>
<td>1~5 years</td>
</tr>
<tr>
<td><em>Medicago sativa</em></td>
<td>Ansai, Shaanxi</td>
<td>78.7</td>
<td></td>
</tr>
<tr>
<td><em>Onobrychis viciifolia</em></td>
<td>Ansai, Shaanxi</td>
<td>74.7</td>
<td></td>
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<td><em>Melilotus suaveolens</em></td>
<td>Ansai, Shaanxi</td>
<td>68.4</td>
<td>3 years</td>
</tr>
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<td><em>Melilotus suaveolens</em> + <em>Caragana korshinskii</em></td>
<td>Ansai, Shaanxi</td>
<td>69.9</td>
<td>3 years</td>
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<td>80</td>
<td>4 years</td>
</tr>
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<td><em>Astragalus adsurgens</em> + <em>Caragana korshinskii</em></td>
<td>Ansai, Shaanxi</td>
<td>87.1</td>
<td></td>
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<tr>
<td><em>Amorpha fruticosa</em></td>
<td>Zhangjiakou, Hebei</td>
<td>72.2</td>
<td>2 years</td>
</tr>
<tr>
<td><em>Vetiveria zizanioides</em></td>
<td>Zigui, Hubei</td>
<td>98.1</td>
<td>1 year</td>
</tr>
<tr>
<td><em>Pinus tabulaeformis</em></td>
<td>Dingxi, Gansu</td>
<td>95</td>
<td>14 years</td>
</tr>
<tr>
<td><em>Hippophae rhamnoides</em></td>
<td>Dingxi, Gansu</td>
<td>92</td>
<td>14 years</td>
</tr>
<tr>
<td><em>Acacia dealbata</em></td>
<td>Toutang, Yunnan</td>
<td>98.9</td>
<td>6 years</td>
</tr>
</tbody>
</table>

viciifolia and Caragana korshinskii could only reduce soil erosion by 69.9%; whereas the SERB for each single species is 74.7% and 74.8%, respectively. It is evident that composition of different vegetation species contributes to soil erosion variably. The optimal species composition could be worked out only if the interactions between vegetation species’ root systems and soil properties and between vegetation species themselves are fully realized.

In southwest China, due to loose soil structure and high intensity rainfall with long duration, as well as strong anthropogenic disturbances, soil erosion is considerably severe (Lu and Higgitt, 2000). Since the implementation of returning slope lands to forest and grassland, by means of plot experiments and statistical methods, a few studies have analyzed the sediment and water yield controlling effects of different vegetation species under subtropical monsoon climate (Deng et al., 2005). One representative example is the study conducted in the famous dry-hot valley in Jinsha River basin, where lithologic property is the crucial factor regulating soil moisture and vegetation types (Xiong et al., 2005). Through impact comparison analysis of different vegetation species, several researchers have put forward the optimal vegetation restoration suggestions for slopes with different soil structure in association with moisture dynamics (Cui et al., 2009).

It is well known that vegetation’s root systems play an essential role in preventing the movement of soil particles down the slope (Gyssels et al., 2005), yet their efficiency varies considerably among different species. However, similar study on the impacts of plant roots in reducing soil erosion based on vegetation restoration strategy in China is quite lacking (Liu et al., 1996). For the few progresses reported, most were conducted solely on the loess regions, while corresponding study in other regions, such as the humid south China, is scarce.

In recent years, absolute economic growth index such as GDP has become the most important indicator of performance appraisal for almost all levels of local government in China. Other issues such as environmental sustainability have largely been neglected, though the top policymakers have taken it as a basic policy. Consequently, a variety of problems have occurred accompanying the implementation of soil conservation measures. For example, the Eucalyptus trees were first introduced into south China as ornamentals in around 1890; they have been extensively planted to boost local economy and control soil erosion since 1950s (Stone, 2009). While the effects in promoting economic development are pronounced, few reports have seriously concerned their negative impacts on soil conservation (Zhou et al., 2002). As their major purpose is for providing timber and fuel wood, frequent planting and clearance would therefore cause severe soil erosion (Kosmas et al., 1997). Therefore, the measured SERB in reality will be offset partially. Being called a despot tree, the Eucalyptus has been criticized as a hidden cause of the severest drought in southwest China in 2010 (Chen, ...
Effects of Vegetation Restoration

2010; Qiu, 2010), where the fast-growing trees are widely distributed. Because the exotic Eucalyptus trees could create adverse conditions for the growth of indigenous species, the soil with Eucalyptus cover remains almost bare and undergoes even stronger erosion as compared with soils left under natural vegetation (Kosmas et al., 1997). Similar soil erosion mitigation failures caused by plantation of unsuitable tree species, such as Populus tremula, have also been reported in arid north China (Cao et al., 2011). Given the huge knowledge gap in our present understanding, special attention is needed regarding the potential negative impacts on soil conservation.

For each vegetation species, its growth requirements for water, soil texture, and illumination intensity need to be considered. Without full consideration of a specific species’ water requirement, for example, arbitrary plantation in unsuitable places would only enhance evapotranspiration and thus reduce water storage volume in soil (Cao, 2008). That will in turn lead the planted trees or grasses to die soon, further accelerating soil erosion. Heterogeneity in geographical backgrounds implies the species testified effective in one place would be ineffective in other places. To find out appropriate vegetation species for specific sites demands long-term field observation and experimental modeling analyses. Thus, understanding the differences of various species is vital to selecting suitable vegetation species. Comparative analysis between the mix of different species and a single species should also be explored.

3.3 Effects of Spatial Scale

Spatial scale effect has been an important theoretical issue in earth sciences studies (Church, et al., 1999; Smets et al., 2008; Yan et al., 2011). Focusing on the impacts of vegetation cover on soil erosion, Braud et al. (2001) found the impacts vary on three different scales after a long-term field investigation in the Andes region. It is difficult to use an exclusive model in relating soil erosion reduction to the average vegetation cover. For example, in their study the obtained relationship based on 3 m × 10 m plots could not be reproduced to larger subcatchments (2–4.5 ha). In China, although several research reports based on small plots or catchments have also been published in recent years (e.g., Xu and Yan, 2005; Zheng et al., 2007), the impact analysis of vegetation restoration on soil erosion concerning larger spatial scales has yet to be investigated. Given the enormous spatial heterogeneities, the effects of vegetation restoration under larger spatial scales would not necessarily, if not totally, be the same as that under smaller ones (Smets et al., 2008). Therefore, it is crucial to examine the spatial scale effects of vegetation restoration in reducing soil erosion.

To analyze the spatial scale effects as much as possible, we present 25 studies carried out in different climatic zones covering the major river
FIGURE 6. Spatial variations of SERB resulted from vegetation restoration, where P, SC, MC, and LC represent plot, small catchment, medium catchment, and large catchment, respectively (data sources: Chen et al., 2003; Chen et al., 2004; Chen et al., 2006; Deng et al., 2005; Ding et al., 1995; Fu et al., 2009; Li et al., 2005; Meng et al., 2000; Tang, 2002; Wang and Cai, 1999; Wang et al., 2006; Zeng, 1992; Zhang et al., 2005).

basins from the subtropical Pearl River to the cold Heilongjiang River in northeast China (Figures 1 and 6). The area ranges from several m² to more than 10000 km². The smaller plots with a few square meters in size were usually conducted on hill slopes without gully included, while the larger areas mostly consist of hill slopes and gullies, or even channels. The spatial scale is classified into four groups, namely plot, small catchment, medium catchment, and large catchment. Spatially, the plot group is defined as area <1 km², the small catchment from 1 to 1000 km², the medium catchment from 1000 to 10000 km², and finally the large catchment >10000 km².

The SERB shows a downward trend (Figure 6). With increasing spatial scale, the SERB decreases gradually when the area is <10000 km², followed by a significant decline after that. With respect to the plot cluster, the data points distribute dispersedly and are with substantial fluctuation range, indicating the discrepancies of SERB among plot studies. Despite the huge differences, however, most SERBs are larger than 70%, except the two points in the shaded circle obtained from experimental plots with extremely harsh natural conditions. The scattered points demonstrate the difficulties in generalizing the SERB. As regards the small catchment cluster, generally the SERB is larger than 60%, even reaches 95% in four case studies. Possibly, a main reason is that the eroded soil beyond vegetation interception ability is deposited in gully channels, resulting in a reduced soil amount measured at the outlet and an increased SERB accordingly. As the increased SERB is
largely attributed to soil conservation work, thus it presents significantly high
treatment efficiency.

With spatial scale larger than 10,000 km² (large catchment), the SERB decl-
ines substantially, especially for the drainage basins. According to (Zheng et al., 2007) and many others, principally three factors are responsible for
this decreasing trend. First, due to the tremendous spatial heterogeneities
in larger river basins, the sediment fixed by vegetation restoration measures
on hill slopes would be supplied from gully erosion and/or channel ero-
sion. Initially stored sediment within channel is likely to be remobilized by
enhanced sediment carrying capacity and increased sediment delivery ratio.

At that point, the sediment loads would remain relatively constant although
soil conservation measures have already been implemented on the slopes
and started to work (Trimble, 1997, 1999). Second, for the larger drainage
basins, such as the Three-Gorge Reservoir Area (51,000 km²), it is impossible
to implement soil conservation work at the same pace everywhere. Conse-
sequently, the proportion of the catchment controlled by restored vegetation
will generally decrease as the catchment size increases. The positive impact
of vegetation restoration would be offset partially or even completely by in-
creased sediment loads from other places. This is especially true for regions
with extensive human activities such as civil construction. Last, it usually
takes a much longer time for the restored vegetation to be effective, partic-
ularly for the regions with strong gravitational erosion where a short-term
vegetation cover could not generate immediate soil erosion reduction. Gen-
erally, despite the complex soil-vegetation interaction and fluvial sediment
transport processes, these factors could explain the decreasing trend to
some extent.

Reduced soil erosion on hill slopes is expected to cause channel sedi-
ment transport decline as most sediment comes from the hill slopes. How-
ever, how the channel sediment load reduction can be precisely ascribed to
soil conservation measures has not yet been clearly understood. Except for
the soil conservation measures conducted on hill slopes or gully floors, nor-
mally the constructed reservoirs and other hydraulic projects along channels
also play a significant role in trapping sediment, especially in south China
where hydropower resources are considerably rich and a large number of
hydroelectric projects have been built. In the Three-Gorge Reservoir Area,
Xiong et al. (2009) concluded that the soil conservation measures, includ-
ing vegetation and engineering, contributed 12.1–13.9% sediment reduction.
Thus, the contribution from vegetation restoration should be less than 10%
in most instances. For the whole Yangtze River basin during 1956–2002, the
sediment load reduction is mainly caused by dams (88%), and only 12% by
soil conservation measures (Yang et al., 2002). In the middle Yellow River
basin, Ran (2006a) analyzed the sediment yield changes during 1970–1996,
and discovered the sediment reduction caused by reservoir impoundment
(1.2 × 10⁸ t/a) represents about 29% of the total reduction (4.5 × 10⁸ t/a). In
addition, the contribution from vegetation restoration and terraces accounts for 35.3% of the total reduction resulted from soil conservation measures. Taking into account the entire Yellow River basin, the soil conservation measures contributed 40% to the total sediment decrease (Xu 2003; Wang et al., 2007). For the third largest Pearl River, Dai et al. (2007) examined the temporal variation of sediment loads and concluded that the decreased sediment loads had little to do with soil conservation measures in the past 20 years. Combine the nine major Chinese river basins together, the sediment reduction resulting from dams and reservoirs during 1959–2007 is 28 Gt, representing 56% of the total sediment reduction, while the contribution from soil conservation measures is only 23% (11.5 Gt; Chu et al., 2009).

It can be found that as the spatial scale increases, the SERB resulting from restored vegetation fluctuates significantly among different drainage basins. Indeed, if dams are believed to have played an extraordinarily dominant role in impounding sediment, then the SERB resulting from all soil conservation measures appears to be negligible (Wolman, 1985), let alone the effects of restored vegetation only. Furthermore, what deserves special attention is that for the large river basins, the aforementioned SERBs are the effects of all soil conservation practices, including vegetation restoration and engineering measures. In the next section we comparatively discuss the impacts between vegetation restoration and engineering measures.

3.4 Vegetation Restoration Versus Engineering Measures

Since the very beginning of soil conservation work in China, both engineering and vegetation measures have been adopted synchronously with equal importance. The former has proved to play a more important role than the latter in retaining soil particles (e.g., Chen et al., 2007; Xu, 2004b). That is because the former could nearly hold up all the inputting sediment by concrete dams or by reducing the flow velocity for terraces. For instance, during the period of implementing engineering measures in the middle Yellow River basin (1980s), the silt check dams accounted for up to 90.7% of the total sediment reduction, and around 70.8% in 1990s as some were abandoned (Xu, 2004a). In contrast, the vegetation restoration strategy reduces soil erosion mainly through shifting soil structure and surface runoff regime, thus mostly it could not completely control soil particle movement. Even so, its achievements in the past decades are also enormous. Just in the Yellow River basin, annually about 0.3 Gt sediment has been reduced owing to the implementation of vegetation restoration programs. In particular, the coarse sediment entering the mainstream has decreased sharply (Shi and Guo, 2006).

However, there has been a long-term dispute over which soil conservation measures should be prioritized (Wang, 2005), because both engineering and vegetation measures have their own strengths and weaknesses. It is arbitrary to claim one is better than the other as each approach is well suited
to specific problems in different areas. While the engineering measures, notably the silt check dams, can only have temporary effects on sediment loads in gullies or stream channels, the vegetation measures are more effective on sloping land and become increasingly remarkable with time. Furthermore, sediment deposition behind the silt check dams will raise the groundwater table, accelerating the risk of valley-side gravitational landslides and flooding in return. On the other hand, hillside terraces, by retaining surficial runoff leading to increased infiltration, would be likely to exacerbate gravitational erosion (Cao et al., 2007). In contrast, for vegetation measures, coupled with the reduced surface runoff due to the foliage cover, the plant roots can considerably lower the possibility of gravitational erosion by increasing the shear strength through a matrix of tensile fibers. Geographically, the engineering measures are more suitable in water-short regions where vegetation is difficult to survive, while the vegetation measures are usually a preferential choice in humid subtropics. From a perspective of cost effectiveness, engineering measures are more expensive in short term and could not bring enormous economic benefits, and vegetation restoration requires long-term investments and has greater potential to promote economic growth.

As water is the transport agent of soil particles, the observed soil erosion reduction should be accompanied with a reduction in surface runoff. To examine the differences between engineering and vegetation measures, the resulting reduction benefits of both soil erosion and water loss spanning a wide range of basin area in size are presented in Table 3. These studies were based on basins with diverse precipitation conditions, but a considerable portion of them were located in north China where annual precipitation was generally low. It can be seen that not all soil erosion and water loss reduction benefits resulting from engineering measures are larger than that from vegetation measures. For a few small catchments, the reduction benefits from the latter are around twice the former, indicating the dominance of vegetation measures.

In addition, generally no inevitable connection could be established between the SERB and the water loss reduction benefit, although Yuan and Lei (2004) have tried to develop a linear relationship. It should be pointed out that their conclusion is only based on an individual catchment and could thus not be extrapolated carelessly. The contribution of vegetation measures to the water loss reduction benefit is not always proportional to its contribution to the SERB. On average, for the water loss reduction benefit, the contribution from the vegetation measures is nearly equivalent to that from the engineering measures (48.9% vs. 51.1%). Nevertheless, with regard to the SERB, the contribution from the former is far less than that from the latter (37.4% vs. 62.6%), which is because sediment mainly comes from the gullies while only a little is supplied from the areas between gullies (Chen and Cai, 2006). Xu (2004a) warned that less than 50% of channel sediment could be reduced if only vegetation measures are enforced. Despite the
TABLE 3. Soil erosion and water loss reduction benefits by various soil conservation measures

<table>
<thead>
<tr>
<th>Source</th>
<th>Area (km²)</th>
<th>Annual precipitation (mm)</th>
<th>Total water loss reduction benefit (%)</th>
<th>Total SERB (%)</th>
<th>Water loss reduction</th>
<th>Soil erosion reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Engineering measure</td>
<td>Vegetation measure</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(%)</td>
<td>(%)</td>
</tr>
<tr>
<td>Gao et al., 1995a</td>
<td>12.01</td>
<td>628.2</td>
<td>24.5</td>
<td>40</td>
<td>35.2</td>
<td>64.8</td>
</tr>
<tr>
<td>Hao, 1993</td>
<td>70.1</td>
<td>508.1</td>
<td>40.7</td>
<td>60.3</td>
<td>29</td>
<td>71</td>
</tr>
<tr>
<td>Tian et al., 1996</td>
<td>1134</td>
<td>402.3</td>
<td>20.9</td>
<td>23.7</td>
<td>66.7</td>
<td>33.3</td>
</tr>
<tr>
<td>Chen et al., 2003a</td>
<td>1272</td>
<td>374.8</td>
<td>16.6</td>
<td>26.7</td>
<td>21.1</td>
<td>78.9</td>
</tr>
<tr>
<td>Chen et al., 2007</td>
<td>4080</td>
<td>497</td>
<td>—</td>
<td>40.8</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Cao et al., 1993</td>
<td>4558</td>
<td>364.4</td>
<td>58.5</td>
<td>78.9</td>
<td>38</td>
<td>62</td>
</tr>
<tr>
<td>Tang et al., 1993</td>
<td>5268</td>
<td>454.6</td>
<td>30.3</td>
<td>65.6</td>
<td>11</td>
<td>89</td>
</tr>
<tr>
<td>Liu et al., 1996</td>
<td>7577</td>
<td>400–500</td>
<td>7.6</td>
<td>10.5</td>
<td>93</td>
<td>7</td>
</tr>
<tr>
<td>Liu et al., 2001</td>
<td>26900</td>
<td>514</td>
<td>24.7</td>
<td>16.4</td>
<td>61.2</td>
<td>38.8</td>
</tr>
<tr>
<td>Zhang et al., 2010</td>
<td>30261</td>
<td>409.1</td>
<td>61.4</td>
<td>78.9</td>
<td>12.6</td>
<td>87.4</td>
</tr>
<tr>
<td>Ran et al., 2001b</td>
<td>45421</td>
<td>550</td>
<td>25.6</td>
<td>88.6</td>
<td>91.9</td>
<td>4.8</td>
</tr>
<tr>
<td>Bai et al., 1999</td>
<td>51322</td>
<td>400–550</td>
<td>29.4</td>
<td>35.3</td>
<td>63.3</td>
<td>36.7</td>
</tr>
<tr>
<td>Liu, 1993</td>
<td>63282</td>
<td>630</td>
<td>28.7</td>
<td>30.9</td>
<td>76.4</td>
<td>23.6</td>
</tr>
<tr>
<td>Ran et al., 1999</td>
<td>113000</td>
<td>423.9</td>
<td>21</td>
<td>28.2</td>
<td>61.1</td>
<td>38.9</td>
</tr>
<tr>
<td>Average</td>
<td>—</td>
<td>—</td>
<td>30</td>
<td>44.6</td>
<td>51.1</td>
<td>48.9</td>
</tr>
</tbody>
</table>

Note. The last four columns of soil erosion and water reduction benefits are calibrated based on combination of different measures and their contributions to the total sediment reduction. More information refers to the Supplementary Information.

aEngineering measure is represented exclusively by terrace;
bOther human activities, such as road construction and mining, lead soil erosion to happen, and thus the sums for both water and soil erosion reductions do not equal 1.
Effects of Vegetation Restoration

fact that the contribution of engineering measures varies spatially from one another, their dominant role in comparison with the vegetation measures is beyond doubt.

It can be concluded that the vegetation measures could not completely replace engineering measures, especially for the larger spatial areas with strong gully or gravitational erosions. Therefore, both vegetation restoration and engineering measures should be adopted synchronously as they tackle soil erosion and water loss in different locations.

4. PROBLEMS, SYNTHESIS AND PERSPECTIVES

Having reviewed the impacts of vegetation restoration on soil erosion in the preceding sections, what are the chief remaining gaps in knowledge impeding a more accurate evaluation of vegetation restoration and its implementation? Answering the question is perhaps not as straightforward as it seems, because each case study has its own unique characteristics in some aspects to be considered. As far as the vegetation restoration efforts being made in China, the following issues should be given more attention and be addressed for better measure selection and benefit assessment.

4.1 Assessment in Shorter Time Intervals

Although the vegetation restoration strategy has proven to play a positive role in reducing soil erosion in various research areas or at different spatial scales, it is important to note currently almost all the reduction benefit results are obtained based on interannual or decadal scale or longer time intervals. In contrast, corresponding temporal dynamics studies in shorter time intervals, including seasonal, monthly, and event-based, are desperately lacking. Consequently, the available studies could not accurately reflect the real situation. Vegetation growth and cover are tightly correlated with seasonal variations, and to what extent it could control soil erosion differs remarkably between dry and wet seasons (Cao, 2008). The resulting SERB will be different accordingly. In addition, infrequent hydrological scenarios, such as extreme rainfall events, can exert disproportionately significant influence on vegetation cover and soil conservation (Chen and Cai, 2006). Especially for the loess regions, the sediment eroded by several extreme rainfalls can account for more than 70% annual sediment flux (Shi and Shao, 2000). In these cases, how much the restored vegetation can retain soil is still unknown.

Vegetation cover in relation to soil erosion control includes canopy interception and plant litter absorption of water. The two factors differ substantially with season. For instance, the planted forest species are normally deciduous in north China while nondeciduous in south China. Thus, the canopy cover varies between different seasons and locations. Besides, in
some under-developed rural areas, plant litter is usually collected as firewood. Increased plant litter clearance will definitely affect the SERB. Therefore, a seasonally-based evaluation analysis involving anthropogenic activities is also needed.

4.2 Assessment Methods

Regarding the reduction benefit calculation method, several critical problems need to be addressed or improved urgently. Previously, because most researchers merely adopted simple statistical methods to evaluate soil conservation work, the calculated reduction benefits are met with a few unavoidable errors and even obvious inconsistencies in some cases (Wang et al., 2006). As discussed previously, both the methods used in reduction benefit evaluations have their respective pros and cons. A future comparative analysis on the two different methods is needed to solve the differences.

Furthermore, the studies using mathematical statistics evaluation have rarely taken into account the impacts of vegetation’s growth age. The degree of maturity could affect the SERB to some extent. Without full consideration, it could even lead to an inverse trend to the generally accepted knowledge. Through a four-year field measurement in 12 small watersheds in the Loess Plateau, Chen and Cai (2006) found an inversely decreasing trend of SERB with vegetation cover percentage, and they attributed the decrease to the immaturity of the planted species. High vegetation cover percentage, if with weak root systems and low canopy density such as the newly planted seedlings, does not necessarily produce high soil conservation benefit. In contrast, having highly developed root system and high canopy density, the watersheds with relatively low vegetation cover could see weak soil erosion. Similar trend between SERB and the growth age of planted species can also be found in Table 2. Therefore, taking vegetation’s maturity degree into account is quite necessary in evaluating vegetation’s soil conservation benefit.

Another important issue is that, since the implementation of soil conservation programs starting from the 1970s, quite a few studies have explored the optimal composition of different soil conservation measures (e.g., Huang et al., 2001). A couple of optical composition schemes have been suggested accordingly (Chen et al., 2006). However, it should be pointed out that the suggested composition schemes are indeed misleading. As the trees, shrubs and grass are planted separately rather than mixed together, it is almost impossible to argue which composition scheme performs best. Future work should focus more on the differences among mixes of trees, shrubs and grass of different species, degree of maturity and planting density. In addition, as has been strengthened by Pimentel et al. (1995), the socioeconomic costs and benefits should be included during the judgment processes to define a realistically optimal composition.
4.3 Larger Spatial-Scale Assessment

From the cited studies, it is easy to find that most previous research was carried out based on plots or small- or medium-sized watersheds. That is because it is comparatively easier to acquire data and conduct field verification in such cases. In contrast, for the large river basins, to get a precise evaluation of the reduction benefit is almost impracticable through field measurement at higher spatial resolution, due to various limits in funding and other logistic guarantees. Yet, in view of the increasing spatial scale of recent soil conservation programs and the central government’s resolve to tackle soil erosion, more national programs are expected to be implemented in the near future. Therefore, to shed light on the planning and implementation of future soil conservation projects, it is highly recommended to get a quantitative evaluation of the programs being undertaken.

An urgent task to be settled is to identify the high-risk soil erosion areas within large river basins and provide detailed background information, thus optimizing the vegetation restoration implementation strategy and consequently enhancing its performance in combating soil erosion. In addition, if data for large river basins (>1 × 10^6 km² in drainage area for example) are collected, what would the trend showed in Figure 6 be? Will it continue to drop or become stable? To answer these questions, advanced monitoring technologies could provide help. Incorporating modern techniques, such as remote sensing and geographic information system (GIS) analysis tools, into the impact assessment has become a new research hotspot around the world (Lin et al., 2004). Some preliminary studies using 3S techniques, namely remote sensing, GIS, and global positioning system, on China’s vegetation cover changes have been reported (Xin and Xu, 2007; Zhou et al., 2008), yet very few has used them in evaluating soil conservation work. These new techniques can be applied to quantify the area of restored species and their temporal attributes (e.g., seasonal variation and maturity degree), especially for studies focusing on larger spatial scales.

In summary, more large river basin–based benefit evaluations are needed. Also, the new technique application should be incorporated as it has the potential to provide a more comprehensive and rapid identification for further investigations, thus facilitating the vegetation restoration’s benefit evaluation.

4.4 Emphasis on Study Areas

An overall review of China’s vegetation restoration efforts has discovered that most of the previous studies were initiated in regions with strong anthropogenic disturbances, such as the fragile Loess Plateau. With the initiation of Western China Development, many originally fragile areas are being developed at an unprecedented pace to boost local economy that has lagged
behind the coastal regions for tens of years. Taking the upper Yangtze River as an example, apart from the newly completed Three Gorges Reservoir, 417 large and medium reservoirs are being constructed or planned (Yang et al., 2007). Along with the construction of hydroelectric projects and the implementation of the Grain-for-Green Project, much soil conservation work has been done to protect the fragile environment and prevent land degradation. However, compared with other regions, corresponding assessment on SERB of previous efforts has not been fully studied. Further evaluations and analyses are needed to provide valuable guidance on future soil conservation initiatives.

Particularly, the most severe drought hit southwest China during 2009–2011, resulting in numerous people short of drinking water and ruined crops due to serious soil degradation. Natural factors like El Niño phenomenon and improper water management strategies have been proposed as possible reasons. Another often cited culprit is the plantation of fast-growing but water-thirsty *Eucalyptus* and rubber trees (Qiu, 2010; Ziegler et al., 2009). In the future, extreme climatic disasters are predicted to happen more frequently than before, therefore, their potential impacts on soil erosion and water loss need to be evaluated as early as possible (they should be regarded as a kind of vegetation restoration effort, though their major purpose is for economic profits). Whatever the extent of soil conservation might be, cautious efforts are strongly demanded to find out a sustainable path, especially when there is a contradiction between economic profit and environmental sustainability.

4.5 Perspectives

With enhanced awareness on the importance of harmony between humans and nature, soil erosion treatment has been speeded up in recent years, increasing from $\sim 2 \times 10^4$ km$^2$ per year in the early 1990s to present $4-5 \times 10^4$ km$^2$ per year (Jia, 2006). Yet, not all local governments have consciously carried out the sustainable development strategy formulated by the central government. A large area of new human-induced soil erosion is emerging beyond the treated areas. It is estimated that the newly appeared soil erosion area is increasing at a rate of about $1.5 \times 10^4$ km$^2$ per year since 1990s, amounting to over 0.3 Gt soil eroded annually (Jia, 2006). Therefore, the actual situation of soil conservation is still far from optimistic. Up to 2006, the total soil erosion area with soil erosion modulus exceeding 200 t/km$^2$/a is $3.56 \times 10^6$ km$^2$, accounting for 37% of the total land area, of which about $2 \times 10^6$ km$^2$ needs to be treated immediately (Zhang et al., 2007).

As an eco-friendly approach to combating soil erosion, the vegetation restoration strategy has been widely undertaken in China long time ago. Especially in the past two decades, huge achievements have been obtained as a result of a vast number of soil conservation projects implemented in
specific regions or in the whole country. Despite these efforts, the SERB varies substantially among different treated sites, time periods and spatial scales due to the diversity feature of natural environment and degree of human disturbances. In brief, the restored vegetation cover plays a positive role in reducing soil erosion.

From this point of view, the vegetation restoration strategy should be adhered to and further deepened in future. Much more attention is badly required regarding its implementation in terms of species selection, composition scheme and management strategy. For any given regions to be treated, a comprehensive vegetation restoration planning based on site-specific consideration is needed, rather than simple duplication from other already successfully treated places. During the implementation process of soil conservation measures, addressing the contradiction between human needs, economic benefit and environmental bearing capacity is a practical issue and will determine to what extent these measures could succeed ultimately.

Currently, to maintain its fast economic growth, numerous projects are being under construction or planned in China, quite a considerable portion of which are located in the western underdeveloped areas, placing huge stress on the already fragile environment. Therefore, controlling soil erosion remains an arduous challenge and needs relentless efforts. Instead of disturbing the nature by introducing artificial engineering facilities, vegetation restoration, as a measure to rehabilitate the original natural environment as much as possible, is an ideal and effective approach.

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