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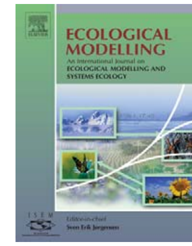

Modeling vegetation coverage and soil erosion in the Loess Plateau Area of China

Z.C. Zhou[a], Z.P. Shangguan[a,*], D. Zhao[b]

[a] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences, Yangling, Shaanxi 712100, P.R. China
[b] Grazinglands Research Laboratory, USDA-ARS, 7207 W. Cheyenne St. El Reno, OK 73036, USA

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ABSTRACT

Soil erosion is still one of major issues limiting agricultural and forestry productivity in Loess Plateau of China. Vegetation plays an important role in controlling soil erosion, but studies on modeling dynamics of vegetation and soil erosion and interaction between them were hardly reported. We hypothesized that changes of vegetation coverage and soil erosion as affected by climate factors and human activities in the Loess Plateau of China might be simulated using appropriate models. In order to test our hypothesis and to better understanding the interaction between vegetation coverage and soil erosion, we conducted a study at watershed of Zhifanggou, a typical region of Loess Plateau. Soil erosion was negative linearly correlated with vegetation coverage ($r = 0.99^{***}$), while vegetation was mainly associated with human activities. Based on climate change, ecological stress factors and human activities, we developed a model to estimate vegetation coverage and soil erosion. Testing the model performance indicated that dynamics of vegetation coverage and soil erosion in the Loess Plateau of China could be precisely simulated. The importance of each factor in the model was also evaluated. The information of this study can be useful for better understanding the relationships between vegetation and soil erosion.

1. Introduction

Loess Plateau accounts for more than 40% of territory in the Northwest region of China. Soil erosion in the Loess Plateau is one of the major issues limiting agricultural and forestry productivity (Wu et al., 1994). Soil erosion caused the decreasing of soil water capacity and soil fertility, which result in vegetation degradation. On the other hand, inappropriate removal of natural vegetation by human activities caused severe soil erosion and leads to problems of ecological environment. Previous studies have indicated that vegetation coverage is one of important factors in controlling soil loss and improving ecological environment (Linda et al., 1995; Zheng and He, 2002; Joseph, 2004; Zhang et al., 2004). The amount of soil erosion decreases dramatically with the increase in vegetation coverage in the Loess Plateau of China (Wang and Wang, 1999).

Plant growth and vegetation development depend on climate factors, soil conditions and land-use types. Natural and non-natural disturbances, such as global climate changes, deforestation, afforestation and other human activities, impact vegetation development (John et al., 2002; Casimiro et al., 2003; Potter, 2004; Li et al., 2006; Ni et al., 2006). Vegetation dynamics, in turn, affects the process of soil erosion. There exists the interaction between vegetation coverage and soil erosion. Previous studies on soil erosion in the Loess Plateau of China mainly focused on erosion initiation, devel-

* *Corresponding author*. Tel.: +86 29 87019107; fax: +86 29 87012210.
E-mail address: shangguan@ms.iswc.ac.cn (Z.P. Shangguan).

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opment and prevention (Zheng and He, 2002; Shangguan et al., 2004). However, little is known about the effect of vegetation evolution on soil erosion and the interaction relationships between vegetation improvement and soil erosion as affected by climate factors and human activities. Lack of knowledge in these aspects directly limits reconstruction of the eco-environment and natural resource conservation policy in the Loess Plateau of China (Zheng and He, 2002).

Although changes in both vegetation and soil erosion are complex processes, we hypothesized that the patterns of vegetation and soil erosion as well as the relationship between vegetation and soil erosion dynamics in the Loess Plateau of China might be predicted using appropriate models. In order to test our hypothesis and to better understand the interaction between vegetation coverage and soil erosion, we conducted this study at watershed of Zhifanggou, a typical region of the Loess Plateau China.

2. Theoretical basis of model

2.1. Equation of vegetation-soil erosion kinetics

Vegetation plays an important role in controlling soil erosion while soil loss by erosion negatively affects plant growth and vegetation development. There exists a complex interaction between vegetation coverage and soil erosion. Thornes (1985) proposed a model of geomorphologic process and used the corresponding differential equations to describe the change rates of vegetation and soil erosion (Eqs. (1) and (2)).

$$\frac{dV}{dt} = (a - bV)V - cE \tag{1}$$

$$\frac{dE}{dt} = dE - fV \tag{2}$$

where a, c, d and f are the functions of the climate, rainfall, soil and topography, respectively, which are constants in a given area and can be determined based on the local existed data; b is vegetation damage due to wild animals; V is vegetation coverage; and E is amount of soil erosion. In our study region, the impact of wild animals on vegetation can be ignored (i.e. $b = 0$) because of intensive human activities.

However, natural disturbance and human activities were not considered in the equations. Wang et al. (2003) investigated effects of several ecological stress factors, human activity, on vegetation evolution and suggested that these ecological factors should be considered when developing a model to describe the relationships between vegetation and soil erosion.

3. Model development

3.1. Vegetation dynamics and ecological stress

Vegetation coverage has been widely used to describe vegetation dynamics in many studies of soil and water conservation. There are considerable differences among vegetation types in controlling soil erosion. In general, arbors and shrubs are superior to herbaceous plants in controlling soil erosion (Zhang et al., 2003). In our study, the vegetation coverage was defined as the percentage of ground covered by all kinds of vegetation (i.e. forest and herbaceous) in the entire land area. Data of vegetation coverage at our study location were obtained from direct survey, remote sensing and other published results.

Vegetation growth and development are directly or indirectly associated with ecological stresses. Atmospheric CO_2 concentration and annual average temperature are two major factors of long-term climate change. We assumed that the responses of vegetation coverage to these two factors are linear. The functional relationships between vegetation coverage dynamics and CO_2 concentration and temperature could be expressed using Eqs. (3) and (4), respectively:

$$\frac{dV}{dt} = K_g\,G_f = K_g\frac{(G - G_a)}{G_a} \tag{3}$$

$$\frac{dV}{dt} = K_t\,T_f = k_t\frac{(T - T_a)}{T_a} \tag{4}$$

where dV/dt is vegetation coverage in a given year or time (t); G_f and T_f are relative changes in CO_2 concentration and temperature (see the last part of Eqs. (3) and (4) for G_f and T_f), respectively; G and T are CO_2 concentration and temperature in the given year, respectively; G_a and T_a are long-term averages of CO_2 concentration and temperature, respectively; and K_g and K_t are constants that can be determined using the investigated vegetation and the global climate change data.

The Loess Plateau of China belongs to semi-arid region and the limited annual precipitation is a major short-term ecological factor influencing vegetation coverage and soil erosion. Changes in vegetation growth and development in the experimental area are closely associated with amount of annual precipitation and drought stress usually limits vegetation development. The response of vegetation coverage (dV/dt) to annual precipitation in a given year t can be expressed using Eq. (5):

$$\frac{dV}{dt} = V_{\text{rain(t)}} = \pm K_p\,P_f = \pm K_p\left[\frac{(P - P_a)}{P_a}\right]^m \tag{5}$$

where $V_{\text{rain(t)}}$ is the change rate of vegetation coverage; K_p and m are constants to be determined based vegetation surrey data; P_f is the relative change in annual precipitation in a given year compared with long-term average; P is annual precipitation in the given year; and P_a is long-term annual precipitation. When P is greater than P_a, $+K_p$ is used; otherwise, $-K_p$ is used in Eq. (5).

An instant ecological stress means the vegetation loss by human activity in a short time period, such as lambing or deforestation. Therefore, change in vegetation coverage (dV/dt) due to the instant stress can be expressed as the following equation (Eq. (6)):

$$\frac{dV}{dt} = -K_{\text{inst}}\varphi \tag{6}$$

where K_{inst} is a constant to be determine and φ is the amount of change in vegetation coverage in a short time period due to an instant ecological stress.

3.2. Changes in land use and vegetation coverage

Since 20 years ago, land use and management policy have been changed to protect ecological environment and to improve agricultural sustainability in China. Recently, trees and grasses have been planted accompanied by a relative reduction in farming lands in the Northwest China, especially the Loess Plateau area. Rapid increase in vegetation coverage positively influences vegetation dynamics and ecological environment in the most regions of the West China. The change pattern of vegetation coverage (dV/dt) with time can be described using the following equation (Eq. (7)):

$$\frac{dV}{dt} = V_R(t) \tag{7}$$

where V_R is percentage of the increase in annual afforestation area in farm land regions and t is the time (or year).

3.3. Model development

Considering all the ecological factors that influence vegetation coverage described above, we integrated Eqs. (3)–(7) and soil erosion (E_R) into Eqs. (1) and (2). Thus, a pair of the following equations (Eqs. (8) and (9)) was developed:

$$\frac{dV}{dt} - aV + cE = K_t T_f + K_g G_f \pm K_p P_f - K_{inst}\varphi + V_R \tag{8}$$

$$\frac{dE}{dt} - dE + fV = E_R \tag{9}$$

The values of V and E can be obtained by solving Eqs. (8) and (9). Details of the solutions could be expressed as following (Eqs. (10) and (11)):

$$V = C_1 e^{r_1 t} + C_2 e^{r_2 t} + e^{r_1 t} \int \times \left[e^{-r_1 t} e^{r_2 t} \int e^{-r_2 t} \left(\frac{dV_m}{dt} - dV_m - cE_m \right) dt \right] dt \tag{10}$$

$$E = C_1 \frac{a - r_1}{c} e^{r_1 t} + C_2 \frac{a - r_2}{c} e^{r_1 t} + e^{r_1 t} \int \times \left[e^{-r_1 t} e^{r_2 t} \int e^{-r_2 t} \left(\frac{dE_m}{dt} - aE_m - fV_m \right) dt \right] dt \tag{11}$$

where

$$r_{1.2} = \frac{1}{2} \left[(a + d) \pm \sqrt{(a + d)^2 - 4(ad - fc)} \right],$$

$$\begin{cases} V_m = K_t T_f + K_g G_f \pm K_p P_f - K_{inst}\varphi + V_R \\ E_m = E_R \end{cases}$$

and C_1 and C_2 are constants that can be determined by the initial conditions of a region. When ecological stresses and soil erosion (E_R) in a particular watershed are known, the quantitative dynamics of both vegetation coverage and soil erosion with time (year) can be estimated.

4. Model calibration and use

Watershed of Zhifanggou (8.27 km^2 with a length of 8.1 km) is a typical region of the Loess Plateau. Long-term annual average temperature is 8.8 °C and average annual precipitation is 549 mm, but more than 61% of total annual precipitation is from July to September. In this watershed, xerophytism shrub and herbs were initially natural vegetation type, but recently the arbor and shrub have become the major vegetation type due to human activities in last 30 years. The major soil type belongs to loess. Water runoff was the major soil erosion in the watershed.

Before 1930s, watershed of Zhifanggou was covered by well-developed forest and soil erosion was not an issue, but the vegetation coverage dropped sharply from 1930s to 1950s because of excessive deforestation and wars. The vegetation coverage was only 0.4% in 1958. Since 1986, vegetation coverage had been kept at a rate of 1.8% per year (i.e. $V_R = 1.8\%$) because of the favorable tree-planting policy. By 1996, about 47% of ground area had been covered by vegetation. In the same period (1987–1996), the soil erosion was reduced from 7700 to 1100 t km^{-2} a^{-1} because of the appropriate soil and water conservation projects (Lu et al., 1997). In addition, the impact of the global climate change on vegetation (V_{gc}) was a constant (i.e. $V_{gc} = 5.143 \times 10^{-5}$ a^{-1}) (Zhou et al., 1997; Jonathan and Samuel, 2004). Based on the impact of the rainfall on vegetation growth (Eq. (5)) and the annual precipitation at watershed of Zhifanggou, the change in the percentage of vegetation coverage was determined (Table 1).

According to the vegetation coverage and soil erosion data before 1975. All parameters were calculated through differential integrating and try-out method. The parameters were adjusted until the simulated result values were agreed with the measured. In addition, when the calculated value of V is >1, V is defined as 1 (i.e. $V = 1$). Similarly, when the calculated value of V is <0, $V = 0$, and when the calculated value of E is <0, $E = 0$. In this study, the values of these constant parameters were: $a = 0.01$ l a^{-1}, $c = 0.000002$ km^2 a^{-1}, $d = 0.02$ l a^{-1}, and

Table 1 – Annual precipitation, relative change in annual precipitation ((P − Pa)/Pa) and vegetation cover variance ($V_{rain(t)}$ (a^{-1})) at Zhifanggou watershed

Year	Precipitation (mm)	(P − Pa)/Pa	$V_{rain(t)}$ (a^{-1})
1986	562.0	0.0236	0.00027
1987	458.3	−0.1653	−0.00190
1988	592.6	0.0792	0.00091
1989	438.0	−0.2024	−0.00233
1990	631.5	0.1500	0.00173
1991	540.7	−0.0152	−0.00018
1992	585.2	0.0657	0.00076
1993	571.3	0.0404	0.00047
1994	455.6	−0.1704	−0.00196
1995	456.5	−0.1687	−0.00284
1996	639.9	0.1654	0.00100
1997	292.8	−0.4668	−0.00737

P: annual precipitation; *Pa* :long-term average of annual precipitation (541.9 mm), and $V_{rain(t)}$ (a^{-1}) = dV/dt in Eq. (3).

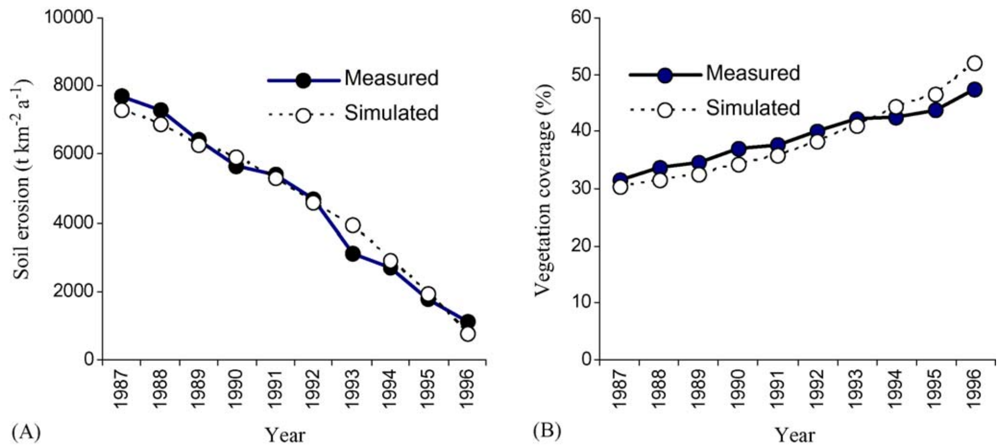

Fig. 1 – Comparison of simulated and measured values of (A) annual soil erosion and (B) vegetation coverage at watershed of Zhifanggou in the Loess Plateau area from 1987 to 1996. The model includes all factors of climate change (CO_2 concentration and temperature), precipitation, and human activities.

$f = 350\,\mathrm{t\,km^{-2}\,a^{-2}}$. The 7-year mean of annual soil erosion from 1975 to 1981 was defined as the initial amount of soil erosion in 1978 (i.e. E_R). Therefore, V_m and E_m can be calculated using the following equations:

$$V_m = V_{m_0(1987)}e^{nt'} + V_{\mathrm{rain}(t)} \qquad (12)$$

$$E_m = E_R e^{n(t-t_0)} \qquad (13)$$

where $V_{m_0} = V_R + V_{gc} = 0.0181514\,a^{-1}$, $E_R = -420\,\mathrm{t\,km^{-2}\,a^{-1}}$, and $n = 0.1$. Integrating Eqs. (12) and (13) into Eqs. (10) and (11), we obtained Eqs. (14) and (15):

$$V = C_1 e^{r_1 t} + C_2 e^{r_2 t} + V_{\mathrm{rain}(t)} + \frac{V_{m_0}(n-d) - cE_R}{(n-a)(n-d) - cf} e^{nt'} \qquad (14)$$

$$E = C_1 \frac{a - r_1}{c} e^{r_1 t} + C_2 \frac{a - r_2}{c} e^{r_2 t} + \frac{-fc + (n-a)E_R}{(n-a)(n-d) - cf} e^{nt'} \qquad (15)$$

where t is the period of time starting from 1978, t' is the period of time starting from 1986, C_1 and C_2 can be determined with the initial conditions, and $V_{\mathrm{rain}(t)}$ is the change rate of vegetation coverage due to precipitation dynamics. The values of $V_{\mathrm{rain}(t)}$ in each year are given in Table 1. The vegetation coverage ranges between zero and one and the soil erosion rate is between zero and infiniteness.

5. Results and discussion

Dynamics of vegetation and soil erosion at watershed of Zhifanggou from 1987 to 1996 are shown in Fig. 1. During this period, vegetation coverage increased linearly with a speed of 1.84% per year and soil erosion decreased by $757\,\mathrm{t\,km^{-2}}$ per year. Amount of soil erosion was closely negative correlated with the degree of vegetation coverage ($r = -0.99^{***}$). Regression of soil erosion with vegetation coverage indicated that a 1% increase in vegetation coverage in an year could decrease soil erosion by $456\,\mathrm{t\,km^{-2}\,a^{-1}}$. When vegetation coverage was about 52%, soil erosion tended to be zero in the study area (data not shown). Based on Eqs. (14) and (15) and the defined constants, the changes in vegetation coverage and soil erosion at watershed of Zhifanggou were simulated (Fig. 1). The simulated amounts of soil erosion in all years were well comparable to their measured values (Fig. 1A). There was no statistical difference between measured and simulated vegetation coverage, although, the model slightly underestimated vegetation coverage in the first 6 years and overestimated in last 3 years (Fig. 1B). Therefore, these equations could be used to simulate the change of vegetation coverage and soil erosion in the Loess Plateau area.

Since the 20th century, atmospheric CO_2 concentration and temperature have increased considerably due to the industrialization and deforestation. In order to determine whether the global climate change, especially CO_2 and temperature, affected dynamics of vegetation coverage and soil erosion or not. We rerun the simulation model without involvement of atmospheric CO_2 concentration and temperature factors (i.e. ignore Eqs. (3) and (4) in the model). The estimated values of both vegetation coverage and soil erosion were similar to the measured values (Fig. 2) even regardless of the effects of CO_2 concentration and temperature. Therefore, under our study area, neither CO_2 concentration nor temperature was the major contributing factor for changes in vegetation coverage and in soil erosion. Our results of the global climate change having little effects on vegetation coverage and soil erosion are in agreement with a recent report by Allen and Joan (2004). Zhou et al. (1997) and Michel et al. (2005) suggested that although the increases in both CO_2 concentration and temperature could stimulate leaf photosynthesis and improve vegetation growth. However, soil moisture or soil water availability would decrease because soil evaporation and plant transpiration increased with the increasing in temperature. Water limitation in arid and semi-arid regions might reduce the positive effects of elevated CO_2 and temperature on vegetation development. In addition, human activities were dominant factors in controlling vegetation coverage and soil erosion. Therefore, the global climate change had little impact

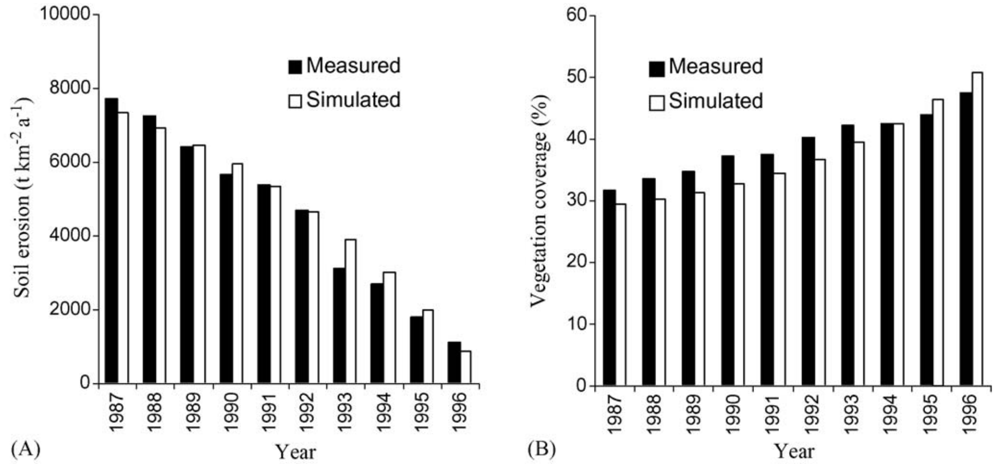

Fig. 2 – Comparison of simulated and measured values of (A) annual soil erosion and (B) vegetation coverage at watershed of Zhifanggou in the Loess Plateau from 1987 to 1996. The model does not include atmospheric CO_2 concentration and temperature.

on vegetation growth and soil erosion in the Loess Plateau area.

In order to determine the effects of afforstation and other conservation measures on improving the eco-environment, vegetation coverage and soil erosion in each year were estimated using the simulation model without involvement of afforestation factor (i.e. Eq. (5)). The estimated soil erosion and vegetation coverage as well as their measured values are shown in Fig. 3. The simulated soil erosion was much higher than measured value in all years and the differences between simulated and measured values increased with the decrease in amount of erosion or with time (Fig. 3A), while simulated vegetation coverage was lower than measured values (Fig. 3B). For instance, the difference between simulated and measured soil erosion was 612 t km^{-2} a^{-1} in 1987, but the differences increased to 1900 t km^{-2} a^{-1} in 1996. The simulated and measured vegetation coverage were 29.9 and 31.6%, respectively, but were 36.4 and 47.4%, respectively, in 1996. These results further suggested that human activities were most important in improving vegetation coverage and controlling soil loss in China Loess Plateau area.

Wang and Cai (1999) suggested that vegetation coverage could significantly reduce sediment yield and afforestation would rapidly increase land coverage, resulting in an effective control of soil erosion. Earlier studies have indicated that soil loss can be reduced by 80–90% when slope lands are turned into terrace lands (i.e. reduction in slope of lands using engineering measures) and appropriate measures of afforestation can reduce soil erosion by 40–60% (Zhou, 1991; van Dijk and Bruijnzeel, 2003). Additionally, other measures of agricultural engineering, such as constructing dams and reservoirs to intercept water and soil runoff, also plaid the certain role in controlling soil erosion. Our results indicated that increase in vegetation coverage could significantly reduce soil loss. Effective controlling soil erosion, in turn, could improve vegetation development and increase land coverage (Wang et al., 2003). There was the interaction between vegetation coverage

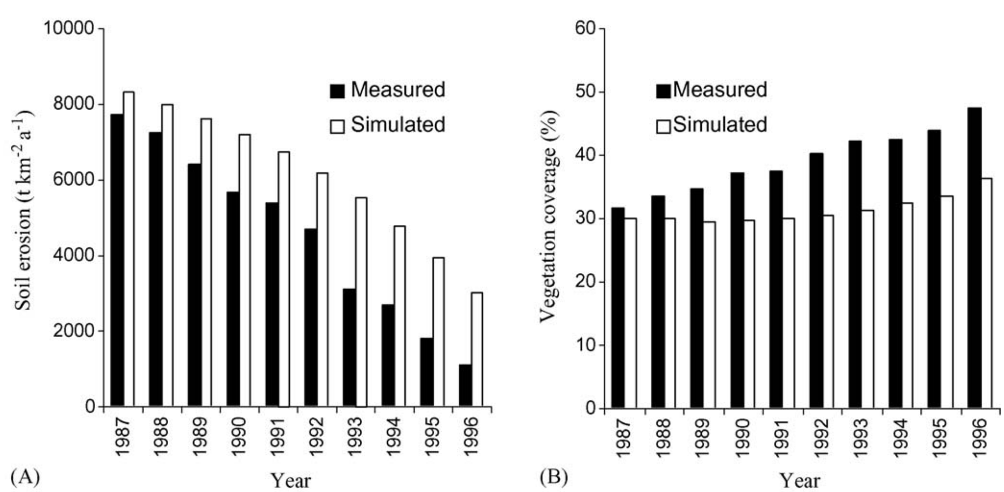

Fig. 3 – Comparison of simulated and measured values of (A) annual soil erosion and (B) vegetation coverage at watershed of Zhifanggou in the Loess Plateau from 1987 to 1996. The model does not include the factor of human activities.

and soil erosion. Therefore, integration of increasing vegetation coverage using agricultural engineering and improving resource management could efficiently reduce soil loss and conserve ecological environment in the Loess Plateau area of China.

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REFERENCES

Allen, G.H., Joan, Q.W., 2004. Climatic influences on Holocene variations in soil erosion rates on a small hill in the Mojave Desert. Geomorphology 58, 263–289.

Casimiro, C., Juan, M.S., Emilio, C., 2003. Patterns of structural complexity and human disturbance of riparian vegetation in agricultural landscapes of a Mediterranean area. Agric., Ecosyst. Environ. 95, 495–507.

John, W., Anna, C., Fred, W., 2002. Effects of sowing and management on vegetation succession during grassland habitat restoration. Agric., Ecosyst. Environ. 93, 393–402.

Jonathan, P.L., Samuel, B.S.C., 2004. Mineral stress: the missing link in understanding how global climate change will affect plants in real world soils. Field Crops Res. 90, 101–115.

Joseph, P.H., 2004. Influence of vegetation cover and crust type on wind-blown sediment in a semi-arid climate. J. Arid Environ. 58, 167–179.

Li, A.N., Wang, A.S., Liang, S.L., Zhou, W.C., 2006. Eco-environmental vulnerability evaluation in mountainous region using remote sensing and GIS, A case study in the upper reaches of Minjing River. Chin. Ecol. Model. 192, 175–187.

Linda, C., Ferdinand, B., Alain, P., 1995. Vegetation indices derived from remote sensing for an estimation of soil protection against water erosion. Ecol. Model. 79, 277–285.

Lu, Z.F., Liang, Y.M., Liu, G.B., 1997. Eco-Agriculture of Chinese Loess Plateau. Xi'an: Shaanxi Sci' Technol' Press (in Chinese).

Michel, C., Richard, A.B., Christopherm, D.H., 2005. Pre-industrial-potential and last glacial maximum global vegetation simulated with a coupled climate-biosphere model: diagnosis of bioclimatic relationships. Glob. Planet. Change 45, 295–312.

Ni, J., Harrison, S.P., Prentice, I.C., Kutzbach, J.E., Stephen, S., 2006. Impact of climate variability on present and Holocene vegetation: A model-based study. Ecol. Model. 191, 469–486.

Potter, C., 2004. Predicting climate change effects on vegetation, soil thermal dynamics, and carbon cycling in ecosystems of interior Alaska. Ecol. Model. 175, 1–24.

Shangguan, Z.P., Shao, M.A., Li, Y.S., Yang, W.Z., 2004. Impacts of forest vegetation on the soil water cycle in Loess Plateau. J. Chin. Soil. Water Conserv. 35, 177–185 (in Chinese with English Abstract).

Thornes, J.B., 1985. Environmental systems-patterns processes and evolution. In: Gregory, K.J., Clark, L. (Eds.), Horizon in Physical Geography. Macmillan, pp. 27–46.

van Dijk, A.I.J.M., Bruijnzeel, L.A., 2003. Terrace erosion and sediment transport model: a new tool for soil conservation planning in bench-terraced steeplands. Environ. Model. Software 18, 839–850.

Wang, X.D., Wang, Z.Y., 1999. Effect of land use change on runoff and sediment yield. Int. J. Sediment Res. 14, 37–44.

Wang, X.L., Cai, Q.G., 1999. Reasons and profits analysis of how the vegetation measure controls slopeland soil erosion. Arid Zone Res. 16, 37–42 (in Chinese with English Abstract).

Wang, Z.Y., Wang, G.Q., Li, C.Z., Wang, F.X., 2003. Research and application of the vegetation- erosion dynamics. Sci. Chin. (Ser. D) 33, 1013–1023 (in Chinese).

Wu, Q.X., Wang, Y.K., Han, B., Wu, R.W., 1994. Forest and grassland resources and vegetation construction in the soil and water loss region of the Loess Plateau. Res. Soil Water Conserv. 1, 2–13 (in Chinese with English Abstract).

Zhang, B., Yang, Y.S., Zepp, H., 2004. Effect of vegetation restoration on soil and water erosion and nutrient losses of a severely eroded clayey Plinthudult in southeastern China. Catena 57, 77–90.

Zhang, Y., Liu, B.Y., Zhang, Q.C., Xie, Y., 2003. Effect of different vegetation types on soil erosion by water. J. Integr. Plant Biol. 45, 1204–1209.

Zheng, F.L., He, X.B., 2002. The effect of vegetation broken and recover on the soil erosion of the Loess Plateau. Soil Water Conserv. Chin. 7, 21 (in Chinese).

Zhou, G.S., Zhang, X.S., Gao, S.H., 1997. Experiment and modeling on the responses of Chinese terrestrial ecosystems to global change. J. Integr. Plant Biol. 39, 879–888.

Zhou, P.H., 1991. Overview of the problem about the reducing sediment benefits of the water and soil conservation in the Loess Plateau. Bull. Soil Water Conserv. 11, 1–3 (in Chinese with English Abstract).