THE RELATIVE EFFICIENCY OF FOUR REPRESENTATIVE CROPLAND CONVERSIONS IN REDUCING WATER EROSION: EVIDENCE FROM LONG-TERM PLOTS IN THE LOESS HILLY AREA, CHINA

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ABSTRACT

Large areas of traditional slope cropland were recently converted to other land-use types in the semiarid Loess Plateau of China. In this study, we selected four representative conversion options of slope croplands, i.e., pastureland rotated with cropland (cultivated with *Medicago sativa* L. and rotated with *Triticum aestivum* L.), shrubland and woodland (afforested with *Hippophae rhamnoides* L. and *Pinus tabulaeformis*), and grassland (native herbage *Stipa breviflora*) to study the effect of land-use conversion by comparing with traditional cropland. Compared with slope cropland, the relative effects of different conversion options on surface runoff and soil erosion were assessed over a 14-year measurement period. Observations showed that distinct features and consequences of vegetation succession were found among the conversion options. Plots of shrubland had the highest vegetation coverage with dense undergrowth; natural herbaceous and subshrub species gradually spread into plots of grassland resulting in higher vegetation cover. Neither bushes nor herbs colonized the plots of *Pinus tabulaeformis*, which resulted in a higher percentage of bare soil. Significant differences in runoff generation, sediment yield and conservation efficiencies among the selected conversion options were detected through an analyses of variance (ANOVA). Compared with cropland, total runoff and sediment decreased by 65 per cent and 95 per cent in shrubland, 41 per cent and 92.5 per cent in grassland, 18 per cent and 77 per cent in woodland, and 12 per cent and 58 per cent in pastureland, respectively. The ranking of soil and water conservation efficiencies was shrubland > grassland > woodland > pastureland > cropland. Based on the effectiveness of soil and water conservation, shrubland and grassland are highly recommended as promising options for cropland conversion projects. However, pastureland and woodland are not suggested as potential options for slope-cropland conversion because of low soil and water conservation in the long term. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS: runoff; soil erosion; cropland conversion project; land use; vegetation change; soil and water conservation; PR China

INTRODUCTION

Over the last century, owing to deforestation and cultivation of sloping lands as well as adverse climatic conditions, farmland in semiarid loess hilly areas has experienced serious soil erosion and increased land degradation (Fu, 1989; Fu and Gulinck, 1994; Ash and Edmonds, 1998; Shi and Shao, 2000; Yang and Li, 2000). Due to poor vegetation coverage, severely degraded landscapes are relatively dysfunctional in retaining soil particles, nutrients and water. The degradation processes lead to the progressive inability of the vegetation and soil to regenerate. In combating the land degradation, the agrarian policy of the Cropland Conversion Project (CCP) is

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designed to change 14.7 million hectares of low-yield slope cropland to forest and grassland by 2010. The objectives of the project are: (1) large-scale reforestation or re-vegetation; and (2) water erosion control and land rehabilitation by converting cropland on steep slopes to grasslands and woodlands.

With the rapid progress of reforestation and large-scale land conversion in recent years, land use and vegetation can be altered radically within a short period. Therefore, we paid more attention to the development of vegetation coverage and the relevant effects on erosion control. However, the related physical and biological changes affecting the erosion rates (Turner, 1989; Fu *et al.*, 1994) within the soil may operate over a longer period (Martinez-Fernandez *et al.*, 1995). Generally, the effects of land use on soil erosion are closely related to land-use types, management practices, vegetation cover (Bryan and Cambell, 1986; Francis and Thornes, 1990; Kosmas *et al.*, 1997; Bellot *et al.*, 2001), the stability and resilience of the soil and vegetation, and the frequency and severity of disturbances. Furthermore, it has been proved that the soil and water conservation effects of vegetation result from the integrated effects of vegetation at different levels (canopy, undergrowth, and/or litter) (Dunne *et al.*, 1991; Hudson, 1995; Woo *et al.*, 1997). Natural vegetation (mainly perennial) can achieve the best hydrological effects through prolonging the duration of effective vegetation coverage and thus reducing surface runoff.

Although a number of projects aiming at improving vegetation coverage have been launched in China since the 1970s, there is still much controversy on various issues relating to the vegetation recovery process and subsequent complex hydrological effects. Little information exists about the environmental consequences of extensive cropland conversion in semiarid areas, especially from the vegetation regeneration and hydrological point of view. Generally, reliable long-term monitoring data sets consistent with the objectives of the conversion policy are scarce. Information from rainfall simulation experiments or individual rainfall events are discrete and insufficient to trace the temporal dynamic and holistic characteristics of vegetation restoration. Using reference ecosystems is useful and practical (Hobbs and Norton, 1996). The observational results of runoff and soil loss in different stages of vegetation succession provide a powerful baseline in evaluating soil conservation after cropland conversion. Alternative conversion approaches can provide useful information for developing practical and effective rehabilitation strategies.

The objectives of this study were: (1) to examine the dynamics of vegetation change; (2) to compare the differences in runoff and soil erosion among conversion alternatives; and (3) to investigate the possible conservation efficiencies of each option.

MATERIAL AND METHODS

Site Description

The research was conducted at the Soil and Water Conservation Experimental Station in Anjiagou catchment, about 3 km east of Dingxi County, Gansu Province, northwest China (35° 33' 02" N, 104° 38' 13" E) from 1986 to 1999. The catchment covers 10.09 km² with elevations varying from 1900 m to 2250 m (Figure 1).

The study site has a semiarid continental climate with a hot and wet season from May to September. The annual mean precipitation is 420 mm with great interannual variations. Over 60 per cent of the precipitation falls from July to September, and most occurs as rainstorms. The mean annual air temperature is 6.3 degrees with 141 days frost free. The average annual potential evaporation is 1510 mm.

The soils in the study area have developed on wind-accumulated loess parent material. According to the FAO-UNESCO Soil Classification System, the soil type of the experimental plots is Calcic Cambisol. At the experimental area, soil bulk densities (from 0 to 200 cm soil depth) of the five treatments range from 1.09 to 1.36 g cm⁻³, while organic matter varies from 0.37 to 1.34 per cent.

The natural vegetation, classified as semiarid prairie, consists of grasses (*Stipa breviflora*, and *S. bungeana*), herbs (*Thymus mongolicus*) and small bushes (*Caragana tibetica* and *C. opulens*), appears in only restricted patches. Artificial plantations are of Chinese pine (*Pinus tabulaeformis*), oriental arborvitae (*Platycladus orientalis*), little-leaf peashrub (*Caragana microphylla*), and sea buckthorn (*Hippophae rhamnoides* L.). Much of the sloping area was used for annual crops such as spring wheat (*Triticum aestivum* L.), beans (*Phaseolus*

Figure 1. The location and topography of the experimental plots in Anjiagou catchment, China.

vulgaris), potatoes (*Solanum tuberosum* L.), millet (*Panicum miliaceum*), sorghum (*Sorghum* spp.) and purple alfalfa (*Medicago sativa*).

Methods

The experimental plots were located on the slope between 15 degrees and 30 degrees (average 20 degrees), where rain-fed crops (wheat, potatoes, beans and millet) were planted. The experiment was conducted from March 1986 to September 1999. These plots are similar in topography and soil type, and the initial conditions were slope cropland. Five treatments were arranged in a randomized plot design with three replicates.

- (1) Cropland (spring wheat). Field-management practices were identical to those used by local farmers; the seeds were sown in the plots in April and harvested manually at the end of July or early August. Then a fallow period follows from August to March of the next year. Straw residue was retained on the plots.
- (2) Conversion to pastureland (alfalfa). Alfalfa is a perennial herbaceous legume and an important rotation forage crop in semiarid loess hilly areas. Alfalfa, one of the major forage species used in sown pastures, is planted for hay. The seed is usually drilled or broadcast in April and harvested in early August. It was not permissible to graze in either fenced plots or open fields of alfalfa. Because the continuous alfalfa cultivation periods were 7–8 years in general, the farmers shift to a new crop when levels of forage productivity fall. Alfalfa was replanted annually due to low yield from 1993 to 1999.
- (3) Conversion to shrubland (sea buckthorn). Sea buckthorn, a deciduous, perennial shrub, can form thick shrub–grass communities (Ruan and Li, 2002) considered to be drought resistant (Lu, 1992) and an ideal pioneer plant species for vegetation restoration (Li and Schroeder, 1996; Schroeder *et al.*, 1996; Li, 1999; Lu, 2003). Having a significant role in the course of soil-conservation schemes and land reclamation (Li, 1999; Meng *et al.*, 2002), 60 000 hm² have been planted annually since 1985 (Guo *et al.*, 2003), resulting in the present coverage of more than 200 000 hectares (500 000 acres) in the Loess Plateau. Saplings of sea buckthorn were planted in 1.0 m by 1.0 m spacing in March, 1986. During the experiment, the litter remained on the plots. The annual and perennial grasses and thick litter formed densely covered patches on the ground (Figure 2a).
- (4) Conversion to woodland (Chinese pine). Saplings of Chinese pine were planted in rows spaced at 3.0 m and columns spaced at 1.5 m in March, 1986; The retained litter in the plot was subsequently left to dry and then

Figure 2. The situation of plots for shrubland (a), woodland (b) and grassland (c).

removed from the plots partly by wind and surface flow. By the end of the experiment, no grasses and bushes were visible on the ground (Figure 2b).

- (5) Conversion to grassland (natural needlegrass communities). As a predominant native species of experimental site, natural *Stipa breviflora* was left for succession without cutting, grazing or other management practices (Figure 2c).

Data Collection

The field monitoring was conducted over a period of 14 years. The plots were situated in an upper-slope position (Figure 1). Each plot of shrubland and woodland was 10 m (across slope) $\times$ 10 m (down slope). Plots of cropland, pastureland and grassland were 5 m (across slope) $\times$ 10 m (down slope). Cement berms (30 cm above ground) were constructed around each plot to direct all surface runoff through a H-flume at the down slope of plots where a 1 m² $\times$ 2 m size pond were arranged for collecting runoff and sediment. Volumes of collected water were measured with calibrated buckets, which could be cleaned out for use next time. The samples of sediments were oven-dried and weighed. A meteorological station was located at about 50 m from the experimental plots. Data-logging rain gauges were established in each block and the meteorological station to record the amount and intensity of rainfall.

The evolution (in terms of coverage) of vegetation after cropland conversion was surveyed. The herbaceous coverage was estimated in the maximum growth period by 5 quadrats of 1 m $\times$ 1 m within each plot; height, ground-line diameter (GLD) and canopy width of shrub (sea buckthorn) and tree (Chinese pine) species were measured on a yearly basis. The coverage of shrub and tree in each plot was calculated by means of the measured values of canopy width. Estimates were made for each layer separately and for the plant community as a whole. The thickness of the litter layer on the ground surface of shrubland plots was measured in 1995, and the soil characteristics were measured annually throughout the period of the experiment.

Data Analysis

The cumulative values of runoff and soil erosion were calculated as follows:

$$CR = \sum_{i=1}^T R_i \quad (1)$$

$$CE = \sum_{i=1}^T E_i \quad (2)$$

The cropland was considered as baseline to evaluate soil and water conservation efficiencies of the different conversion options. The reduction ratios of runoff (RRR) and erosion (RRE) for each option were calculated as one minus the ratios of the runoff and erosion values of the conversion options to those of the cropland.

$$RRR = \left(1 - \frac{CR_{T(O)}}{CR_{T(C)}} \right) \times 100\% \quad (3)$$

$$RRE = \left(1 - \frac{CE_{T(O)}}{CE_{T(C)}} \right) \times 100\% \quad (4)$$

Where, *CR* and *CE* refer to cumulative runoff and erosion, *RRR* and *RRE* refer to reduction ratios of runoff and erosion; the '*T*' refers to the year(s) of calculation; the subscripts (O; C) refer to each option and cropland (control), respectively.

Statistical analysis of variance (ANOVA) was performed to ascertain if differences in runoff and sediment yield existed among the conversion options. The ANOVA was performed separately on a yearly basis with the

consideration of the whole observation period. Pairwise multiple comparisons were used to test the differences between each pair of options using the least significant difference (LSD) method at an alpha level of 0.05. All the analyses were conducted with SPSS 11.0®.

RESULTS AND DISCUSSION

The Change of Vegetation

The vegetation coverage of cropland and pastureland, at a minimum shortly after seed sowing in April, increased slowly during the initial stage of seedling growth in May, and then reached their peak value in June, which persisted until late July, and was then followed by a rapid decline after harvest. The highest coverage of crops was normally less than 50 per cent. Seasonal changes of coverage in the other plants (grasses, shrubs and trees) were different from those of the crops. Average coverage of shrubland, woodland and grassland from March to October was higher than that of cropland and pastureland. The vegetation characteristics strongly varied from season to season because of the monthly variation in rainfall. Chronic water deficits often occurred in April and May. Especially for crops and pasture, the characteristics of vegetation cover depended on the degree to which plant water requirements were met at the critical period (seed germination and seedling growth).

Detailed surveys showed the variation of vegetation coverage of plots over 1–14 years of each treatment (Figure 3). In the first 3 years, the coverage of shrubland increased from 40 to 95 per cent, however, it remained at 15 to 37 per cent in the woodland (Figure 3). Over the experiment, steady increases of coverage were observed in shrubland (up to 100 per cent) and woodland (up to 85 per cent) despite the fact that the increases in woodland remained slow. Herbaceous plants prevailed in the first three years, resulting in an increasing coverage in plots of grassland (95 per cent), then the density decreased slightly (85 per cent) and bare soil occurred occasionally. In the first three years, coverage of pastureland decreased from 90 to 75 per cent, and after three years, it varied from 35 to 50 per cent. It is possible to separate fluctuations from directional trends of vegetation coverage with long-term observation. Coverage is a parameter that can reflect the characteristics of both plant communities and the

Figure 3. The vegetation coverage of conversion options and cropland.

environment. It is certain that the plant communities and environments provided by shrubland and grassland are better than those provided by woodland in semiarid loess plateau.

Observations showed that there were distinct features and consequences of vegetation evolution amongst the conversion options (Figures 2 and 3). During the study period, the highest percentage of coverage was found in shrubland (Figure 3), characterized with canopy cover, undergrowth layer and litter cover. Natural herbaceous species germinated under the canopy of *Hippophae rhamnoides*. (Figure 2a). However, neither herbaceous plants nor bushes successfully colonized the plots of *Pinus tabulaeformis*, resulting in lower vegetation coverage and higher bare-soil percentage (Figures 3 and 2b). With the successful invasion and gradual colonization of natural herbaceous and subshrub species (e.g., *Caragana opulens* and *C. tibetica*) in grassland (Figure 2c), a *Stipa* community was formed with a dense grass cover of *Stipa breviflora* (Figure 3). According to the survey results of the ten-year reforestation of *Hippophae rhamnoides* and *Pinus tabulaeformis*, the thickness and density of the litter layers are 4.5 cm and 7.6 kg m⁻², and 0.5 cm and 200 g m⁻², respectively. By contrast, organic matter horizons in soil under plots with sea buckthorn were generally thicker than those under Chinese pine plots.

The difference in vegetation became distinct, which indicated that the direction and pace of vegetation evolution had been strongly influenced by land use. Natural herbaceous species appeared in plots of *Stipa breviflora* and *Hippophae rhamnoides*, with an increasing diversity as the result of the strong germination capability and dominance of *Stipa breviflora*, *S. bungeana* and *Thymus mongolicus*. The habitat changes in shrub communities provide a suitable growing environment for undergrowth species. Under Chinese pine, the density of grass gradually increased and then quickly vanished, which implied that the development of soil microcrust and low moisture content inhibit the colonization of plant species (Bochet *et al.*, 1998). At the same time, communities with extreme environmental conditions do not always undergo sequential replacement of plant species (Whisenant, 1999).

Some indigenous shrub (*Hippophae rhamnoides* and *Caragana opulens*) and herb species (e.g., *Stipa breviflora*, *Thymus mongolicus* and *Stipa bungeana*) have been proved to have long-term climatic adaptabilities due to their ease of establishment and persistence under arid and semiarid conditions. With higher rates of colonization and proliferation, they can coexist with other native plant species in constructing viable plant communities, which is suitable for achieving the CCP's objectives of vegetation rehabilitation and erosion control.

The Runoff and Sediment rate

Total annual runoff and soil sediment loss are shown in Tables I and II for the whole period of observation. Results from the ANOVA test revealed significant differences in yearly runoff (Table I; except in 1996, 1997) and soil erosion (Table II; except in 1994, 1996) among the five treatments ($p < 0.01$). The order of runoff and soil sediment production is cropland > pastureland > woodland > grassland > shrubland.

Annual runoff measurements indicate that cropland and pastureland had a higher contribution on runoff yield without a clear trend, whilst shrubland had a lower contribution on runoff production with a progressive decline trend. Shrubs showed little fluctuation (annual values ranged from 1.0 to 6.0 mm) in their low runoff production levels, which was significantly lower than other options ($p < 0.01$) throughout the course of the study (Table I). Total annual amounts of runoff remained high (5–29 mm) from woodland, which was closer in absolute terms to pastureland than grassland (Table I). Compared to cropland, mean runoff levels (1986–1999) decreased by 12 per cent in pastureland, 18 per cent in woodland, 41 per cent in grassland, and 65 per cent in shrubland, respectively. Mean runoff levels in shrubland and grassland have proved to be significantly lower than those in woodland and pastureland. No significant differences were detected between pastureland and cropland or woodland (LSD, $p < 0.05$; Table I).

The difference in erosion rates between the conversion options is broadly consistent with the observed trends in runoff production. Sediment yields are significantly lower in the three non-cultivated options than those in cropland and pastureland (Table II; $p < 0.01$). Compared with cropland, mean yield of total sediment (1986–1999) is decreased 95 per cent in shrubland, 92.5 per cent in grassland, 77 per cent in woodland, and 58 per cent in pastureland, respectively.

Table I. The annual runoff (mm m^{-2}) of the cropland and conversion options at the experimental plots (1986–1999) with standard errors in parentheses ($n = 3$)^a

Cropland			Cropland conversion options				Significance level				
			Pastureland	Woodland	Grassland	Shrubland					
1986	33 (7)	a	22 (4)	ac	11 (1)	c	18 (2)	bc	24 (5)	ab	**
1987	28 (1)	a	13 (3)	b	18 (1)	c	19 (1)	c	11 (2)	b	***
1988	22 (1)	a	17 (3)	b	21 (1)	a	5 (0)	c	6 (0)	c	***
1989	29 (1)	b	22 (1)	b	29 (8)	b	6 (0)	a	6 (1)	a	***
1990	9 (0)	b	9 (1)	b	8 (1)	bc	6 (0)	ac	5 (0)	a	**
1991	6 (0)	b	7 (1)	b	5 (1)	c	2 (0)	a	2 (1)	a	***
1992	20 (5)	a	11 (2)	b	7 (1)	bc	2 (0)	c	4 (0)	bc	***
1993	12 (1)	b	11 (1)	b	10 (1)	bc	7 (1)	ac	4 (0)	a	***
1994	12 (2)	ab	19 (6)	ac	11 (2)	ab	8 (1)	bc	2 (0)	b	**
1995	24 (4)	bc	34 (6)	b	17 (3)	c	15 (3)	c	3 (0)	a	***
1996	10 (2)	bc	10 (4)	b	8 (1)	bc	8 (1)	bc	1 (0)	a	(n.s.)
1997	12 (3)	a	12 (2)	ac	11 (1)	ab	13 (3)	ac	4 (0)	b	(n.s.)
1998	8 (0)	b	8 (0)	bc	11 (1)	c	9 (1)	bc	4 (0)	a	***
1999	18 (5)	bc	17 (4)	b	23 (1)	bc	17 (1)	bc	6 (1)	a	**
Mean	17 (1)	a	15 (1)	ac	14 (1)	c	10 (1)	d	6 (1)	b	***

^aSame letter(s) on the same rows indicates non-significant differences ($p < 0.05$, LSD).** $p < 0.05$; *** $p < 0.01$.Table II. The annual erosion (g m^{-2}) of the cropland and conversion options at the experimental plots (1986–1999) with standard errors in parentheses ($n = 3$)^a

Cropland			Cropland conversion options							Significance level	
			Pastureland		Woodland		Grassland		Shrubland		
1986	150 (14)	a	72 (17)	b	41 (3)	c	34 (4)	c	76 (9)	b	***
1987	681 (100)	a	77 (6)	b	389 (30)	ab	76 (6)	b	134 (6)	b	**
1988	503 (88)	a	101 (24)	bc	221 (53)	c	15 (2)	b	30 (3)	b	***
1989	1544 (631)	a	624 (266)	ab	485 (89)	b	9 (2)	b	34 (28)	b	**
1990	164 (58)	a	31 (2)	b	25 (5)	b	19 (8)	b	6 (1)	b	***
1991	23 (5)	a	42 (12)	b	7 (1)	ac	1 (0)	c	1 (0)	c	***
1992	619 (312)	a	86 (19)	b	11 (3)	b	8 (1)	b	2 (0)	b	**
1993	194 (65)	a	148 (50)	a	12 (4)	b	13 (2)	b	0	b	**
1994	357 (178)	ab	388 (184)	a	18 (7)	b	18 (5)	b	0	b	(n.s.)
1995	417 (212)	a	269 (48)	ab	17 (8)	b	32 (12)	b	0	b	**
1996	292 (215)	a	64 (38)	a	16 (8)	a	36 (8)	a	0	a	(n.s.)
1997	386 (147)	a	284 (44)	ac	21 (6)	b	124 (4)	bc	0	b	**
1998	57 (24)	a	41 (15)	ac	6 (2)	bc	10 (1)	bc	1 (1)	b	**
1999	193 (61)	a	122 (50)	ac	35 (8)	bc	23 (1)	bc	1 (1)	b	**
Mean	399 (75)	a	168 (32)	b	93 (24)	bc	30 (5)	c	20 (6)	c	***

^aSame letter(s) on the same rows indicates non-significant differences ($p < 0.05$, LSD).** $p < 0.05$; *** $p < 0.01$.

The Variation of Water and Soil Loss

The trends of soil erosion were similar to runoff production from 1986 to 1989. Annual soil erosion ranged from 150 to 1544 g m^{-2} in the cropland, 72 to 624 g m^{-2} in pastureland, 41 to 485 g m^{-2} in woodland, 30 to 134 g m^{-2} in shrubland, and 9 to 76 g m^{-2} in grassland. The greatest production of soil sediments in woodland, shrubland

and grassland correlated with lower vegetation coverage and higher bare soil percentage especially in the initial stages of conversion. However, during the period of 1990–1999, annual erosion varied between 0 and 6 g m^{-2} in shrubland, 7 and 35 g m^{-2} in woodland (Table II) owing to the evolution of both soil and vegetation characteristics. Conversion effects on runoff and soil-sediment losses may be beneficial or detrimental over both short and long term depending on soil conditions and the vegetation recovery. Variation in erosion and erodibility of soils at short and long term occurs due to changes in physical soil properties (Misra and Teixeira, 2001; Catt, 2001). However, high-intensity rainfall immediately after conversion may be the most relevant factor severely affecting runoff and soil losses (e.g., 1986–1989). Observation of the five treatments allowed us to conclude that vegetation dynamics presented a critical threshold in the initial stages of conversion. The coexistence of shrub and herb species can capture more resources with strong seed germination, initiating a positive feedback loop of autogenic rehabilitation.

The runoff and sediment production mechanism under different vegetation cover and land use may be distinct (Peugeot *et al.*, 1997; Puigdefábregas *et al.*, 1998) even within the same rainfall event. In field studies of cropland and pastureland, variation in soil erosion with time can be explained reasonably well in cases where there was a change in cropping or tillage (Paningbatan *et al.*, 1995; Presbitero *et al.*, 1995) as well as the formation and development of soil crust (Luk and Cai, 1990; Zhu *et al.*, 1997). Plots of shrubland and grassland, accelerating the formation of new plant cover with favourable conditions for plant sprouting and seed germination, are effective in soil erosion control.

Considerable year-to-year variation in soil losses from cropland and pastureland are consistent with the consequence of variation in the cultivation regime and coverage of soil. Plots cultivated with crops and the forage legume alfalfa typically remain almost bare during early summer and autumn due to drought and removal of annual vegetation (Kosmas *et al.*, 1997). The plots of cropland ploughed and with lower coverage suffered more intense erosion than soil of the pastureland plots. As the available data suggested, cultivated or newly reforested fields created conditions most favourable for water runoff and sediment loss. This was the case especially in the plots of alfalfa as well as Chinese pine. However, the runoff does not always decrease proportionally to sediment yield.

The Cumulative Runoff and Sediment Losses

The cumulative results from May 1986 to September 1999 indicated that water and soil losses could be reduced by cropland conversions (Figures 4a, 4b) at different magnitudes. The effects of different options on runoff and sediment yield at various intervals were quantified by ANOVA (Table III). The difference of *CR* and *CE* amongst the options varied with cumulative years (Figures 4a, 4b), however, results of an ANOVA revealed significant differences ($p < 0.05$) in runoff and sediment loss between conversion options and the cropland control at three periods of study. From 1986 to 1988 and 1993, no significant differences in cumulative runoff were observed between pastureland and woodland or between grassland and shrubland (Table III; $p < 0.05$, LSD). The annual runoff was larger in pastureland and grassland than in woodland and shrubland (Table I; Figure 3a). *CR* and *CE* of shrubland and grassland were lower than those of pastureland and woodland in short, medium, and long term (3, 8 and 14 years). A reduction in the vegetation cover of woodland may impede either the formation of soil organic matter or the establishment of plant species, thus favouring the intensification of erosion processes.

The cumulative curves indicate that *CE* of pastureland is smaller and bigger than that of woodland during the 1-to-8-year period and the 9-to-14-year period, respectively. The coverage increase of Chinese pine (varied from less than 20 per cent to 75 per cent) had no significant effects on runoff generation. It was observed that the surface soil inhabited by *P. tabulaeformis* was compacted and presented a higher bulk density at a depth of 0–5 cm. Consequently, surface runoff increased and sediment production declined, which is consistent with the other studies (Roth, 1997; Luk and Cai, 1990).

Soil properties and surrounding vegetation before conversions were the same, whereas soil and vegetation were different between the five treatments according to the age and type of conversion. The succession of vegetation resulted in the changes of vegetation coverage, the amount of litter layer, and soil physical characteristics (Caravaca *et al.*, 2004) leading to a shift in hydrological functioning (Misra and Teixeira, 2001). Figure 4b

Figure 4. The cumulative runoff and erosion of different conversion options during 1–14 years after conversion. *Note:* The comparison of cumulative runoff (a) and soil erosion (b) amongst five treatments respond to the various temporal periods (1–14 year or years) of accumulation. The curves indicate that the distinct patterns of cumulative rate respond to the annual runoff and soil erosion yield between the five treatments.

confirms the differences between the four options already discussed above. Soil losses from shrubland and grassland were kept at a low level from 4 to 14 years after conversion (Figure 4b) due to the presence of annual vegetation and plant residues on the soil surface, which were favourable conditions for the prevention of further land degradation by severe soil erosion.

The Changes of Conservation Efficiency

Results of an ANOVA (Table III, $p < 0.01$) indicated that the mean annual runoff and sediment of cropland was significantly higher than the conversion options over the short, medium and long term ($p < 0.05$, LSD) (Table III). The reduction ratios of runoff (RRR) and erosion (RRE) of pastureland gradually declined from the highest level (39 percent and 81 percent) to the lowest level (12 percent and 58 percent). Whereas, those of shrubland increased from the lowest level (50 percent and 82 percent) to the highest level (65 percent and 95 percent). However, RRR and RRE of woodland changed in the opposite direction from 39 percent down to 18 percent and 51 percent up to 77 percent, respectively. The RRE of shrubland and grassland increased to 90 percent in the first three years, and remained at a higher level (95 percent) in the medium/long term.

Table III. The mean annual runoff ($\text{mm m}^{-2} \text{a}^{-1}$) and erosion ($\text{g m}^{-2} \text{a}^{-1}$) of cropland and conversion options at short, medium and long term since conversion with standard errors in parentheses

Factor	Interval	Cropland		Cropland conversion options								Significance level
				Pastureland		Woodland		Grassland		Shrubland		
Runoff	1986–1988	28 (3)	a	17 (2)	b	17 (2)	b	14 (2)	b	14 (3)	b	***
	1986–1993	20 (2)	a	14 (1)	c	14 (2)	c	8 (1)	b	8 (2)	b	***
	1986–1999	17 (1)	a	15 (1)	ac	14 (1)	c	10 (1)	d	6 (1)	b	***
Erosion	1986–1988	445 (87)	b	83 (10)	a	217 (53)	c	41 (9)	a	80 (15)	a	***
	1986–1993	485 (121)	b	148 (48)	a	149 (39)	a	22 (5)	a	35 (10)	a	***
	1986–1999	399 (75)	a	168 (32)	b	93 (24)	bc	30 (5)	c	20 (6)	c	***

Same letter(s) on the same rows indicates non-significant differences ($p < 0.05$, LSD).

*** $p < 0.01$.

Although the RRE of pastureland is higher than or comparable to woodland due to higher coverage of soil as well as no tillage during the period 1986–1993. RRR (–19 per cent) and RRE (31 per cent) of pastureland were lower than those of woodland from 1994 to 1999, which may have resulted from lower coverage and regular cultivation of pastureland. This showed that vegetation exerted an important hydrological control (Morgan *et al.*, 1997) over different land-use types. These results suggested that growing alfalfa could help soil erosion control in the short term with higher vegetation cover and non-tillage. Before sowing and after harvesting, ground surfaces of cropland and pastureland were bare and suffered a high risk of erosion due to rainstorms (Liu, 1999). This can result in the deterioration of soil-surface properties. These effects related to changes in vegetation cover and/or soil caused by agricultural practices (Vanacker *et al.*, 2003).

It has been proved that vegetation cover associates negatively with erosion and runoff coefficients (Morgan *et al.*, 1997; Calvo-Cases *et al.*, 2003). The temporal changes of runoff and erosion reported in our study are consistent with previous studies that vegetation and land-use changes are important factors in controlling yields of runoff and erosion (see also Bryan and Campbell, 1986; Mitchell, 1990; Romero-Díaz *et al.*, 1999). The protective effects of plant cover related to its capability in dissipating the kinetic energy of raindrops (Thornes, 1990), intercepting rainfall and transforming rainfall characteristics as well as affecting the infiltration capacity of the soil (Bellot and Escarré, 1998; Gonzalez-Hidalgo and Bellot, 1997), thus limiting runoff and eventual soil erosion (Woo *et al.*, 1997).

The Effects of Land Use

Significant differences in runoff and erosion were also observed especially between non-cultivated and cultivated options (Table I; Table II). The runoff and erosion values were very low for the non-cultivated land-use types with natural vegetation (grassland) and semi-natural vegetation (woodland and shrubland), nevertheless, those for agricultural fields (cropland and pastureland) were high. The changes in runoff and erosion with land use showed by our results are consistent with many other studies (e.g., Lasanta *et al.*, 2000; Caravaca *et al.*, 2002; Kosmas *et al.*, 2000; McDonald *et al.*, 2002).

The results indicated that cultivation of cropland, pastureland, and subsequent tillage practices resulted in progressive water and soil loss, which can be confirmed by previous studies in the loess area of China (Zhu *et al.*, 1997). Tillage practices influence soil movement (Quine *et al.*, 1999) and the development of soil crusting and sealing (Pagliai *et al.*, 2004; de Rouw and Rajot, 2004) in agricultural areas. The amount of soil loss occurring in an individual storm appeared to be dependent on the supply of loose material on the soil surface that could be transported by surface water flow (Morgan *et al.*, 1997).

Generally, the differences in runoff and soil erosion between cultivated and non-cultivated land-use types may be amplified by the variation of vegetation covers, soil characteristics, and hydrological processes. Poor land cover, cultivation disturbance, and concentrated rainfall in autumn lead to severe soil erosion on cultivated lands.

CONCLUSIONS

Over 14 years of observation, the results on vegetation change and conservation efficiencies provide useful information for the decision making of future cropland conversion projects in the loess hilly area.

Some native species, including shrubs (*Caragana opulens*, *Hippophae rhamnoides*) and herbs (*Stipa breviflora*, *S. bungeana* and *Thymus mongolicus*), are well adapted to semiarid conditions. They can spread into surrounding plant communities to coexist with other species. These plants capture still more resources and initiate a positive feedback loop of autogenic ecological rehabilitation.

Under natural conditions, it was confirmed that cropland conversion can be used as an effective conservation management practice, and severe soil erosion can be alleviated accordingly. The options exhibited increasing conservation efficiencies on runoff and soil in the following order: pastureland < woodland < grassland < shrubland.

In terms of vegetation rehabilitation and conservation efficiencies, either shrubland or grassland meets the general objectives of CCP. However, afforestation with *Pinus tabulaeformis* is not a rational choice for the lower conservation efficiency resulted from the poor vegetation cover and litter layer on the ground. Pastureland exhibits significant positive conservation effects only when there is no ploughing and a dense vegetation cover. It is likely that much of the converted cropland, in particular pastureland and woodland, is uncertain and questionable concerning the degree to which it meets the goals of the CCP in the semiarid loess area.

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REFERENCES

- Ash RF, Edmonds RL. 1998. China's land resources, environment and agricultural production. *The China Quarterly* **156**: 836–879.
- Bellot J, Bonet A, Sanchez JR, Chirino E. 2001. Likely effects of land use change on the runoff and aquifer recharge in a semiarid landscape using a hydrological model. *Landscape & Urban Planning* **55**: 41–53.
- Bellot J, Escarré A. 1998. Stemflow and throughfall determination in a resprouted Mediterranean holm-oak forest. *Annals of Forest Science* **55**: 847–865.
- Bochet E, Rubio JL, Poesen J. 1998. Relative efficiency of three representative matorral species in reducing water erosion at the microscale in a semi-arid climate (Valencia, Spain). *Geomorphology* **23**: 139–150.
- Bryan RB, Campbell IA. 1986. Runoff and sediment discharge in a semi-arid drainage basin. *Zeitschrift für Geomorphologie* **58**: 121–143.
- Calvo Cases A, Boix-Fayos C, Ineson AC. 2003. Runoff generation, sediment movement and soil water behavior on calcareous (limestone) slopes of some Mediterranean environments in southeast Spain. *Geomorphology* **50**: 269–291.
- Caravaca F, Lax A, Albaladejo J. 2004. Aggregate stability and carbon characteristics of particle-size fractions in cultivated and forested soils of semiarid Spain. *Soil & Tillage Research* **78**: 83–90.
- Caravaca F, Masciandaro G, Ceccanti B. 2002. Land use in relation to soil chemical and biochemical properties in a semiarid Mediterranean environment. *Soil & Tillage Research* **68**: 23–30.
- Catt JA. 2001. The agricultural importance of loess. *Earth-Science Reviews* **54**: 213–229.
- De Rouw A, Rajot R. 2004. Soil organic matter, surface crusting and erosion in Sahelian farming systems based on manuring or fallowing. *Agriculture, Ecosystems & Environment* **104**: 263–276.
- Dunne T, Zhang W, Aubby BF. 1991. Effects of rainfall, vegetation, and microtopography on infiltration and runoff. *Water Resources Research* **27**: 2271–2285.
- Francis CF, Thornes JB. 1990. Runoff hydrographs from three Mediterranean vegetation cover types. In *Vegetation and Erosion, Processes and Environments*, Thornes JB (ed.). Wiley: Chichester; 363–384.
- Fu B. 1989. Soil erosion risk and its control in the loess plateau of China. *Soil Use & Management* **5**: 76–82.
- Fu B, Gulinck H. 1994. Land evaluation in an area of severe erosion: the loess plateau of China. *Land Degradation & Rehabilitation* **5**: 33–40.
- Fu B, Gulinck H, Masum MZ. 1994. Loess erosion in relation to land-use changes in the Ganspoel catchment, central Belgium. *Land Degradation & Rehabilitation* **5**: 261–270.
- Gonzalez-Hidalgo JC, Bellot J. 1997. Soil moisture changes under shrub plant cover (*Rosmarinus officinalis*) and cleared shrub as response to precipitation in a semi-arid environment: stemflow effects. *Arid Soil Research and Rehabilitation* **11**: 187–199.
- Guo W, Li B, Huang Y, Zhao H, Zhang X. 2003. Effects of different water stresses on eco-physiological characteristics of *Hippophae rhamnoides* seedlings. *Acta Botanica Sinica* **45**: 1238–1244.

- Hobbs RJ, Norton DA. 1996. Towards a conceptual framework for restoration ecology. *Restoration Ecology* **4**: 93–110.
- Hudson N. 1995. *Soil Conservation*. Iowa State University Press: Ames, IO.
- Kosmas C, Danalatos N, Cammeraat LH, Chabart M, *et al.* 1997. The effect of land use on runoff and soil erosion rates under Mediterranean conditions. *Catena* **29**: 45–59.
- Kosmas C, Gerontidis S, Marathianou M. 2000. The effect of land use change on soils and vegetation over various lithological formations on Lesvos (Greece). *Catena* **40**: 51–68.
- Lasanta T, Garcia-Ruiz JM, Perez-Rontome C, Sancho-Marcen C. 2000. Runoff and sediment yield in a semi-arid environment: the effect of land management after farmland abandonment. *Catena* **38**: 265–278.
- Li TSC. 1999. Sea buckthorn: New crop opportunity. In *Perspectives on New Crops and New Uses*, Janick J (ed.). ASHS Press: Alexandria, VA; 335–337.
- Li TSC, Schroeder WR. 1996. Sea buckthorn (*Hippophae rhamnoides*): a multipurpose plant. *Horticultural Technology* **6**: 370–378.
- Liu G. 1999. Soil conservation and sustainable agriculture on the Loess Plateau: Challenges and prospects. *Ambio* **XXVIII**: 663–668.
- Lu R. 1992. *Sea Buckthorn: A Multipurpose Plant Species for Fragile Mountains*. ICIMOD Publication Unit: Katmandu.
- Lu R. 2003. The role of sea buckthorn in improving degraded environment of west China. *Hippophae* **16**: 3–7.
- Luk SH, Cai QG. 1990. Laboratory experiments on crust development and rainsplash erosion of loess soils, China. *Catena* **17**: 261–276.
- Martinez-Fernandez J, Lopez-Bermudez F, Romero-Diaz A. 1995. Land use and soil–vegetation relationships in a Mediterranean ecosystem: El Ardal, Murcia, Spain. *Catena* **25**: 153–167.
- McDonald MA, Healey JR, Stevens PA. 2002. The effects of secondary forest clearance and subsequent land-use on erosion losses and soil properties in the Blue Mountains of Jamaica. *Agriculture Ecosystems and Environment* **92**: 1–19.
- Meng Q, Fu B, Qiu Y, Zhao W. 2002. Land use effects on soil erosion and phosphorus loss in the hilly area of the Loess Plateau, China. *Proceedings of 12th ISCO Conference*, Beijing, China.
- Misra RK, Teixeira PC. 2001. The sensitivity of erosion and erodibility of forest soils to structure and strength. *Soil & Tillage Research* **59**: 81–93.
- Mitchell DJ. 1990. The use of vegetation and land use parameters in modelling catchment sediment yields. In *Vegetation and Erosion, Processes and Environments*, Thornes JB (ed.). Wiley: Chichester; 289–314.
- Morgan RPC, McIntyre K, Vickers AW, Quinton JN, Rickson RJ. 1997. A rainfall simulation study of soil erosion on rangeland in Swaziland. *Soil Technology* **11**: 291–299.
- Pagliai M, Vignozzi N, Pellegrini S. 2004. Soil structure and the effect of management practices. *Soil & Tillage Research* **79**: 131–143.
- Panigbatan EP, Ciesiolka CA, Coughlan KJ, Rose CW. 1995. Alley cropping for managing soil erosion of hilly lands in the Philippines. *Soil Technology* **8**: 193–204.
- Peugeot C, Esteves M, Galle S, Rajot JL, Vandervaere JP. 1997. Runoff generation processes: results and analysis of field data collected at the East Central Supersite of the HAPEX-Sahel experiment. *Journal of Hydrology* **188–189**: 179–202.
- Presbitero AL, Escalante MC, Rose CW, Coughlan KJ, Ciesiolka CA. 1995. Erodibility evaluation and the effect of land management practices on soil erosion from steep slopes in Leyte, the Philippines. *Soil Technology* **8**: 205–213.
- Puigdefábregas J, Del Barrio G, Boer M, Gutiérrez L, Solé A. 1998. Differential responses of hillslope and channel elements to rainfall events in a semi-arid area. *Geomorphology* **23**: 337–351.
- Quine TA, Walling DE, Chakela QK, Mandiringana OT, Zhang X. 1999. Rates and patterns of tillage and water erosion on terraces and contour strips: Evidence from caesium-137 measurements. *Catena* **36**: 115–142.
- Romero-Díaz A, Cammeraat LH, Vacca A, Kosmas C. 1999. Soil erosion at three experimental sites in the Mediterranean. *Earth Surface Process Landforms* **24**: 1243–1256.
- Roth CH. 1997. Bulk density of surface crusts: depth functions and relationships to texture. *Catena* **29**: 223–237.
- Ruan C, Li D. 2002. Function and Benefit of *Hippophae rhamnoides* L. Improving Eco- Environment of Loess Plateau of China. *Proceedings of 12th ISCO Conference*, Beijing, China.
- Schroeder WR, Li TSC, Walker DS. 1996. *Indian-Summer Sea Buckthorn*. Agriculture and Agri-Food Canada, PFRA Shelterbelt Centre: Supplementary Report, Indian Head, SK.
- Shi H, Shao M. 2000. Soil and water loss from the Loess Plateau in China. *Journal of Arid Environments* **45**: 9–20.
- Thornes JB. (ed.). 1990. *Vegetation and Erosion: Processes and Environments*. Wiley: Chichester; 518.
- Turner MG. 1989. Landscape ecology: the effect of pattern on process. *Annual Review of Ecology and Systematics* **20**: 171–197.
- Vanacker V, Govers G, Poesen J, Deckers J, Dercon G, Loaiza G. 2003. The impact of environmental change on the intensity and spatial pattern of water erosion in a semi-arid mountainous Andean environment. *Catena* **51**: 329–347.
- Whisenant ST. 1999. *Repairing Damaged Wildlands: A Process-Oriented, Landscape-Scale Approach*. Cambridge University Press: Cambridge.
- Woo M, Fang G, diCenzo PD. 1997. The role of vegetation in the retardation of rill erosion. *Catena* **29**: 145–159.
- Yang H, Li X. 2000. Cultivated land and food supply in China. *Land Use Policy* **17**: 73–88.
- Zhu TX, Cai QG, Zeng BQ. 1997. Runoff generation on a semi-arid agricultural catchment: Field and experimental studies. *Journal of Hydrology* **196**: 99–118.