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Spatial Variability of Soil Erosion and Soil Quality on Hillslopes in the Chinese Loess Plateau

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ABSTRACT

Soil erosion rates and soil quality indicators were measured along two hillslope transects in the Loess Plateau near Yan'an, China. The objectives were to: (a) quantify spatial patterns and controlling processes of soil redistribution due to water and tillage erosion, and (b) correlate soil quality parameters with soil redistribution along the hillslope transects for different land use management systems. Water erosion data were derived from ^{137}Cs measurements and tillage erosion from the simulation of a Mass Balance Model along the hillslope transects.

Soil quality measurements, i.e. soil organic matter, bulk density and available nutrients were made at the same sampling locations as the ^{137}Cs measurements. Results were compared at the individual site locations and along the hillslope transect through statistical and applied time series analysis. The results showed that soil loss due to water erosion and soil deposition from tillage are the dominant soil redistribution processes in range of 23-40 m, and soil deposition by water erosion and soil loss by tillage are dominant processes occurring in range of more than 80 m within the cultivated landscape. However, land use change associated with vegetation cover can significantly change both the magnitudes and scale of these spatial patterns within the hillslope landscapes. There is a strong interaction between the spatial patterns of soil erosion processes and soil quality. It was concluded that soil loss by water erosion and deposition by tillage are the main cause for the occurrence of significant scale dependency of spatial variability of soil quality along hillslope transects.

Keywords: Soil erosion. Soil quality. Cesium-137. Spatial variability. Loess Plateau.

INTRODUCTION

The spatial variability patterns of soil erosion and their impacts on soil quality within the landscape is being considered as a basis for making management decisions for sustainable cropping systems in China. Early estimation of the suspended sediment indicates that soil erosion in the Yellow River Basin, China causes considerable losses of N, P and other soil nutrients. However, a serious gap in knowledge about the spatial relationship between erosion and soil quality exists for the "homogenous loess soil" within changing landscape structure and vegetation cover

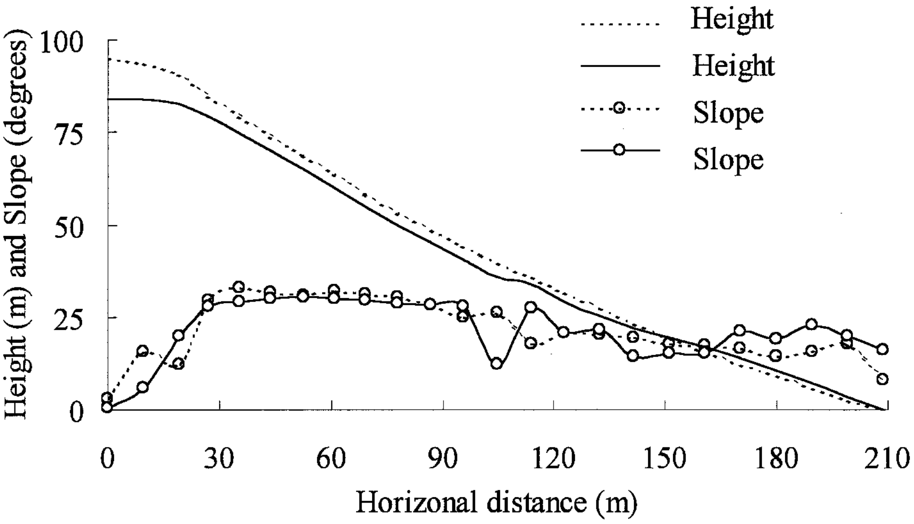

Figure 1. Height and slope characteristics of the two studied treatments with cultivated hillslope (dash line) and mixed land use hillslope (solid line).

in the Loess Plateau. Therefore, soil quality management has been neglected for soil conservation strategies and land use planning decisions in this region. This has mainly been due to the difficulty of obtaining the detailed spatial erosion data and linking these data to soil quality parameters within hilly landscapes with different land use.

^{137}Cs technique allows the assessment of both spatial patterns and rates of soil redistribution in the landscape (Ritchie and McHenry, 1990; Walling and Quine, 1993; Quine et al., 1994). But erosion data derived from ^{137}Cs and soil quality parameters can not explain much of the variability identified in complex soil landscapes (Montgomery et al., 1997).

Geostatistical techniques and time series analysis show promise for developing new insights into soil-landscape patterns and processes (Nielsen et al., 1983; Wendroth et al. 1997; Zhang, 1998) Numerous applications of geostatistics in soil investigation in the past 10 years are mainly focused on interpolation of soil attributes across the landscapes. However, less attention has been paid to the underlying spatial processes of soil erosion within the landscapes. We believe that ^{137}Cs integrated with time series provide great potential for determining the similarities of spatial variability patterns and the scale of dependent variability in soil redistribution processes from landscape scale to a regional scale and for linking them to soil quality for a large heterogeneous basin. To meet this need, an investigation was conducted on two similar hillslopes with different land use in the Loess Plateau. The objectives were to: (a) quantify spatial patterns and controlling processes of soil redistribution caused by tillage and water erosion and (b) compare these patterns with the spatial patterns of soil quality parameters such as soil organic matter, bulk density and available nutrients across the landscape.

MATERIALS AND METHODS

Study Area

The field sampling and investigation were conducted in the Yangjuangou dam reservoir catchment (Li et al., 1997). The catchment has an area of 2.02 km^2, 1025-1250 m above mean sea level, located near Yan'an city, northern Shaanxi province in China (36° 42' N, 109° 31' E). It is a second tributary of the Yanhe River. Soil erosion is the result of runoff scouring, irrational activities of human reclaiming natural vegetation or cultivating on steep slopes up to 40° and the extremely high erodibility of loess when lacking vegetation cover (Li, 1995). This study area is typical of China loess plateau with long-term cultivation history.

Field Sampling and Survey

Soil samples for the determination of spatial patterns in ^{137}Cs were collected from different landscape positions over the full hillslope range in April 1997. Two downslope transects were established on similar topographic features,

Table 1. Main characteristics of the two contrasting hillslopes.

	Top	Upper	Middle	Lower	Foot
Slope I					
Slope aspect			Southwest-facing		
Slope length (m)	30	50	60	50	50
Slope angle (degrees)					
Range	3-12	29-33	18-31	17-21	8-17
Mean	10	31	27	19	15
Height change (m)	4.5	27.1	27.8	20.1	15.7
Soil type			Typical loessial soil		
Plant cover (%)	20	< 5	10	30	30
Land use	cultivated	cultivated	cultivated	cultivated	cultivated
Slope II					
Slope aspect			Southwest-facing		
Length (m)	40	40	60	50	50
Slope angle (degrees)					
Range	1-28	28-30	12-30	14-28	15-23
Mean	14	29	30	21	21
Height change (m)	4.5	19.6	26.3	16.9	16.7
Soil type			Typical loessial soil		
Plant cover (%)	80	90	80	50	70
Land use	Grassland	Forest	Forest	cultivated	cultivated

one hillslope was cultivated and the other had a mixed land use, over a length of 240 m (Figure 1 and Table 1). Both hillslopes were located on southwest facing slope.

Samples were collected using a 9.95 cm diameter hand-operated core sampler at 10 m intervals along each transect. Two to four cores were collected at each sampling point to a depth of 40 cm. Reference sites for determining the ^{137}Cs fall-out in the study area were established in the catchment at undisturbed, uneroded, level terraced fields constructed in 1954 and uncultivated grassland. A reference value of 2390 Bq m^{-2} was determined. For the soil quality parameters, bulk density was determined over the 40 cm sampling depth, while available nitrogen (N), phosphorus (P), and organic matter (OM) were for the surface 10 cm.

^{137}Cs analysis

All samples were air-dried and passed through a 2 mm sieve and weighed. Measurements of ^{137}Cs concentration were conducted on a sub-sample of 1000-1300 g of the finer fraction (<2 mm) of each sample using a hyperpure coaxial Ge detector coupled to a multichannel analyser. ^{137}Cs content of samples were detected at 662 keV and counting time, which were 80 000(86 400 s, provided an analytical precision of ±6 percent for ^{137}Cs. The amount of ^{137}Cs can be expressed per unit mass as the activity (mBq g^{-1}) or per unit area as the inventory (mBq cm^{-2}).

Calculations of soil redistribution rates

Soil redistribution for cultivated land was derived from ^{137}Cs measurements using ^{137}Cs Mass Balance Model incorporating soil movement by tillage (Walling and He, 1999):

$$R = R_t + R_w \qquad [1]$$

where R (t ha^{-1} yr^{-1}) is the net soil redistribution rate due to tillage R_t (kg m^{-2} yr^{-1}) and water R_w (kg m^{-2} yr^{-1}). For a given point along a flow line, the tillage-derived soil re-

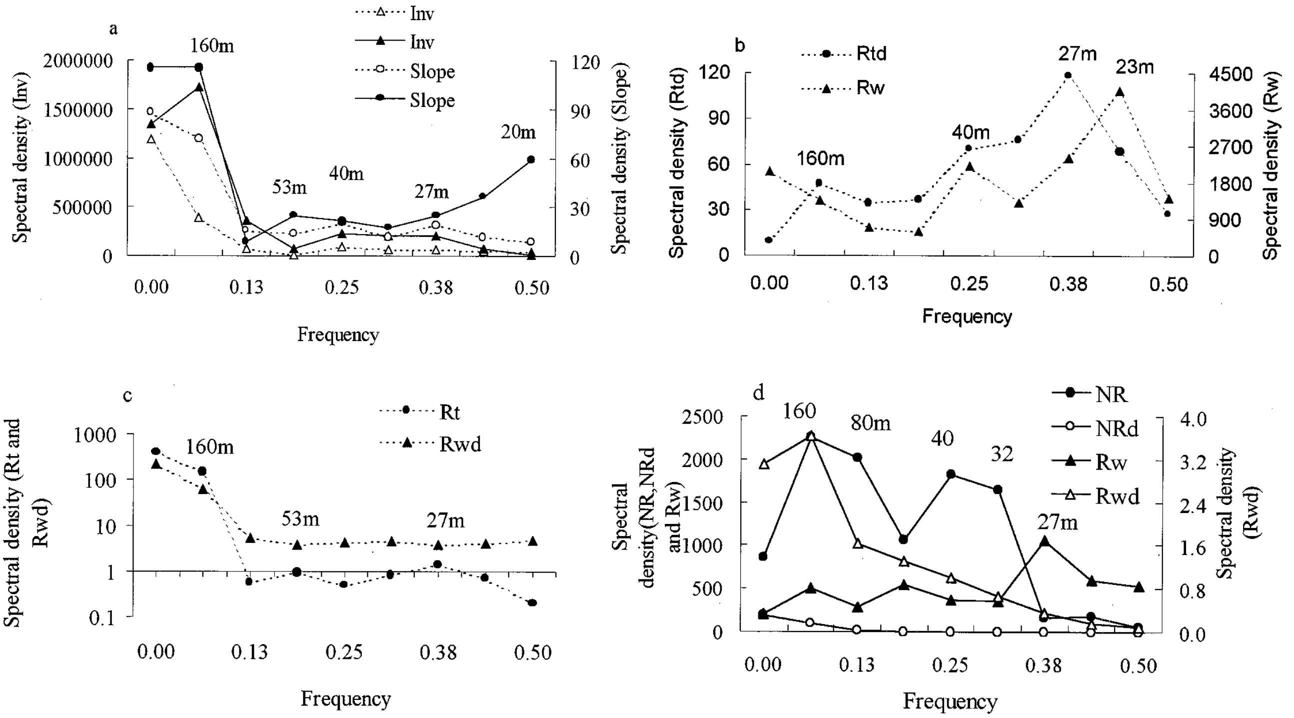

Figure 2. Power spectrum of soil redistribution rates and slope angles over the cultivated hillslope (dash line) and mixed land use hillslope (solid line): (a) 137Cs inventories (Inv) and slope angles (Slope); (b) soil loss by water (Rw) and soil deposition by tillage (Rtd); (c) soil loss by tillage (Rt) and soil deposition by water (Rwd); (d) net soil loss (NR), net soil deposition (NRd), Rw and Rwd.

distribution rates Rt (kg m-2 yr-1) can be calculated using the following equation (Govers et al., 1994, 1996):

$$Rt=(F_{Q,\,out}-F_{Q,\,in})/L_i = \Phi(\sin\beta_i-\sin\beta_{i-1})/L_i = R_{t,out,i}-R_{t,in,i} \qquad [2]$$

where $F_{Q,\,out}$ and $F_{Q,\,in}$ are the downslope sediment output or input flux (kg m^{-1} yr^{-1}) from the contour slope length L_i (m) of the ith segment, and Φ (kg m^{-1} yr^{-1}) is a constant related to the tillage practice involved, βi and βi-1 are the slope angles (degrees) of the ith and (i -1)th segments, and $R_{t,out,i}$ and $R_{t,in,i}$ (kg m^{-2} yr^{-1}) are he downslope sediment fluxes output or input of the ith slope segment due to tillage erosion. Values of the parameter Φ in Eq. [2] may be estimated from the erosion rate R_1 (kg m^{-2} yr^{-1}) for an eroding point from the first slope segment at the top of the slope (with length L_1 and slope angle β1, assuming that water erosion is significant due to the limited slope length and that there is no tillage input to this point):

$$\Phi = R_1\, L_1/\sin\beta_1 \qquad [3]$$

For a point along a flow line, the water-induced erosion (Rw, kg m^{-2} yr^{-1}) can be estimated by solving the Eq. [4] numerically (Walling and He, 1999):

$$dA(t)/dt = (1-\Gamma)I(t) - (\lambda + P\, R_w/d)A(t) \qquad [4]$$

where: A(t)= cumulative ^{137}Cs activity per unit area (Bq m^{-2}); R= erosion rate (kg m^{-2} yr^{-1}); d= cumulative mass depth representing the average plough depth (kg m^{-2}); λ= decay constant for ^{137}Cs (yr-1); I(t)= annual ^{137}Cs deposition flux (Bq m^{-2} yr^{-1}); Γ= percentage of the freshly deposited ^{137}Cs fallout removed by erosion before being mixed into the plough layer; P= particle size correction factor.

The annual soil loss (t ha^{-1} yr^{-1}) for the eroding point on uncultivated land was estimated using a Profile Distribution Model as the following (Walling and Quine, 1999):

$$Y=\frac{10}{(t-1963)P}\ \ln\left(1-\frac{X}{100}\right)h_0 \qquad [5]$$

where: X = percentage ^{137}Cs loss in total inventory in respect to the local ^{137}Cs reference value (Bq m^{-2}) (defined as $(A_{ref}-A_u)/A_{ref}$); h_0 = coefficient describing profile shape (kg m^{-2}); t = year of sample collection (yr); P = particle size correction factor.

For a depositional location, the deposition rate R' can be estimated from the excess ^{137}Cs inventory Aex(t)

(Bq m^{-2}) (defined as differences in the values between measured total ^{137}Cs inventory in the sampling point A_u and reference inventory A_{ref}) and the ^{137}Cs concentration of deposited sediment C_d (Bq kg^{-1}) (Walling and He, 1999):

$$R' = \frac{A_{ex}}{\int_{t_0}^{t} C_d(t')e^{-\lambda(t'-t')}dt'} = \frac{A_u - A_{ref}}{\frac{P'}{\int_s RdS}\int_s A_{ref}(1-e^{-R/h_0})dS} \qquad [6]$$

Evaluation of Spatial Variability

Usually when a variable is sampled in the field, the mean and the variance are determined to reflect the sampled population, assuming that sampling occurred randomly and representatively (i.e. classic statistics - observations are independent of each other and, in general, are normally distributed). Most soil properties, however, occur with a regular pattern across the landscape. Moreover, these patterns develop spatially, temporally, or in both domains (Wendroth et al., 1997), which can not be described using classic statistics. Using standard correlation methods, Kachanoski et al. (1985) found that micotopography and A-horizon parameters were not related. However, considering the sampling coordinates of the parameters, and applied cospectral and spectral analysis techniques, Kachanoski et al found that spatio-periodical relations did exist. We are assuming that the changes in the scale dependence of the spatial variability of soil redistribution due to tillage and water erosion may be in the

Table 2. Descriptive statistics for soil redistribution rates and soil quality parameters studied.

Variables	Max.	Min.	Average	SD	CV
Cultivated hillslope (n=24)					
^{137}Cs (Inv, Bq m^{-2})	4321	349	965	960.8	99.6
Soil loss by tillage (Rt, t ha^{-1}yr^{-1})	94	0	6	18.7	325.4
Soil deposition by tillage (Rtd, t ha^{-1}yr^{-1})	27	0	5	7.8	158.7
Soil loss by water (Rw, t ha^{-1}yr^{-1})	165	0	54	41.1	75.8
Soil deposition by water (Rwd, t ha^{-1}yr^{-1})	63	0	4	14.9	364.2
Net soil loss (NR, t ha^{-1}yr^{-1})	161	0	56	41.5	73.6
Net soil deposition (NRd,t ha^{-1}yr^{-1})	76	0	5	19.1	361.1
Slope (degree)	32.8	4.7	20.2	8.0	39.4
Available phosphorus (P, mg kg^{-1})	2.43	1.01	1.71	0.3	18.9
Organic matter (OM,%)	0.75	0.25	0.40	0.1	25.2
Available nitrogen (N, mg kg^{-1})	26.15	9.56	16.68	3.2	19.0
Bulk density (BD, g cm^{-3})	1.33	1.10	1.24	0.1	4.8
Mixed land use hillslope (n=24)					
137Cs (Inv, Bq m^{-2})	3011	363	1601	735.1	45.9
Net soil loss (NR,t ha^{-1}yr^{-1})	124	0	25	36.2	143.2
Net soil deposition (NRd, t ha^{-1}yr^{-1})	40	0	4	9.5	218.3
Soil loss by water (Rw, t ha^{-1}yr^{-1})	124	0	21	29.8	144.9
Soil deposition by water (Rwd, t ha^{-1}yr^{-1})	9	0	1	2.6	339.1
Slope (degree)	30.2	0.5	21.4	8.1	37.8
Available phosphorus (P, mg kg^{-1})	3.78	1.20	1.97	0.6	32.5
Organic matter (OM,%)	1.98	0.39	1.05	0.5	45.5
Available nitrogen (N, mg kg^{-1})	74.49	17.46	38.15	14.8	38.8
Bulk density (BD, g cm^{-3})	1.28	1.01	1.18	0.1	5.2

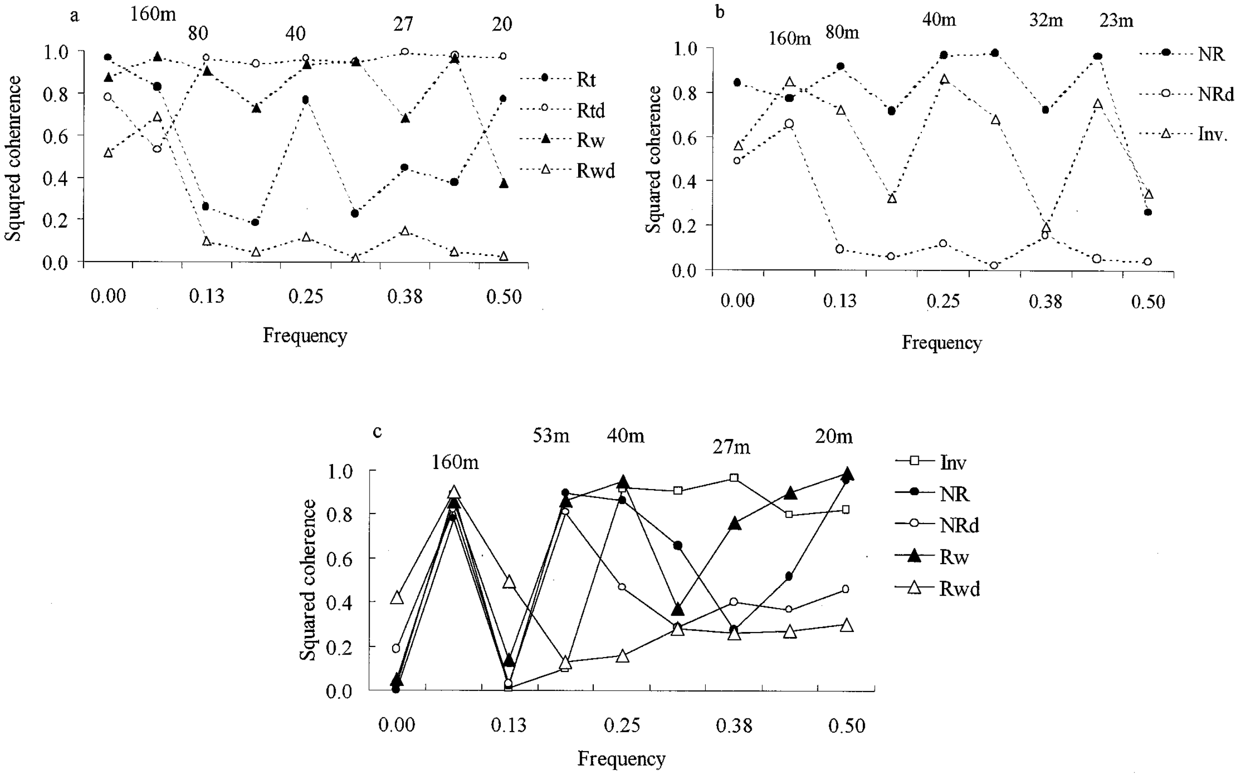

Figure 3. Squared coherence of ^{137}Cs inventories and soil redistribution rates vs slope angles on the cultivated hllslope (dash line, Figures 3a and 3b) and mixed land use hillslope (solid line, Figure 3c).

frequency domain, as quantified using the spectral analysis such as power spectrum and squared coherency (Nielsen, personal communication, 1998).

The power spectrum $f(\lambda)$ of the process x_i as a function of wave length (λ distance dependence) is obtained using Fourier transformation (Wendroth et al., 1997):

$$f(\lambda)=\sum_{-\infty}^{\infty} C(h)exp[-2\pi i\lambda h] \qquad [7]$$

where $i^2=-1$. Power spectrum separates the variation or fluctuation of a series of observations into periodical components, and reflects the amplitude and frequency regardless of phase or distance shift. Therefore it may be useful for quantifying the dominant spatial processes and detecting the effects due to the regular pattern of agricultural operations and changes in landscape structure and land use.

To better understand the erosion impacts on soil quality, we compared the squared coherence variations of soil redistribution and slope angles with the selected soil quality parameters using spectral coherency analysis (Wendroth et al., 1997). The squared coherence $K_{yx}(\lambda)$, as a measure of frequency dependent correlation, can be determined for the two series of observations according to:

$$K_{yx}(\lambda)=\frac{[f_{yx}(\lambda)]^2}{f_x(\lambda)\, f_y(\lambda)} \qquad [8]$$

where $f_{yx}(\lambda)$ is the cross spectrum (Shumway, 1988). $K_{yx}(\lambda)$ is analogous to the coefficient of determination with values between 0 and 1. It equals 1 at all frequencies (1/wave lengths) if one series is an exact linear correlation with another series. Therefore, spectral coherency reflects the quality of regression at the frequency domain between two series of variables.

RESULTS AND DISCUSSION

Spatial variability Patterns of Soil Redistribution

To quantify the spatial variability patterns of soil redistribution processes and their scale of dependent on slope angle and land use changes, comparisons in two

Table 3. Correlation coefficients between soil redistribution rates and slope angle and soil quality variables.

	Rt	Rtd	Rw	Rwd	NR	NRd	Slope	Inv
Cultivated hillslope (n=24)								
Slope	-0.41	-0.37	0.61^b	-0.40	0.44^a	-0.41	1^c	-0.48^a
P	-0.12	0.52^a	-0.34	0.43^a	-0.44^a	0.42^a	-0.46^a	0.41
OM	0.09	0.53^a	-0.47^a	0.65^c	-0.43^a	0.68^c	-0.51^a	0.72^c
N	0.22	0.38	-0.53^a	0.66^c	-0.42^a	0.68^c	-0.64^b	0.70^c
BD	0.23	-0.03	0.23	-0.08	0.31	-0.12	0.32	-0.23
Mixed land use hillslope (n=24)								
Slope	-	-	<0.03	<0.03	<0.03	<0.03	1^c	0.26
Available P	-	-	0.03	-0.01	0.47^a	-0.18	-0.12	-0.40
OM	-	-	-0.29	0.47^a	-0.49^a	0.07	0.16	0.61
Available N	-	-	-0.23	0.28	-0.43^a	-0.05	0.08	0.39
BD	-	-	0.27	-0.41	0.22	-0.53	-0.01	-0.41

[a] Significant at 5 % level, [b] Significant at 1 % level, [c] Significant at 0.1 % level

contrasting hillslopes with different land use are made here using basic statistical properties and power spectrum analysis (Table 2 and Figure 2).

The inventories in ^{137}Cs, net soil loss and deposition rates varied greatly for the two contrasting hillslopes with different land use, while slope angle means are similar between the two slopes. Over the two hillslopes, soil redistribution resulted in heterogeneous soil properties due to soil loss and/or deposition from tillage and water erosion as indicated by CV value >75% even though slope angles were homogenous (CV < 40%) (Table 2). This provides clear evidence that vegetation cover (grass and forest) has been effective in reducing soil loss in the study area. However, this does not quantify the effects of conservation practices (grass and forest) to the scale of variability patterns of the erosion processes. This prompted the study to determine if the spatial variability patterns of soil redistribution are consistent in the two contrasting hillslopes by power spectrum analysis (Figure 2).

There are three peaks that occur at wave lengths (1/Frequency) of about 27-40m and 160m in the power spectrum for ^{137}Cs inventories that are related to erosion processes on the two contrasting hillslopes (Figure 2a), when compared to slope angles at wavelengths of 20-27m, 40-53m and 160m. Peaks in power spectrum for net soil loss occur at wavelengths of 32-40m and 80-160m for the hillslope with mixed land use (Figure 2d) and at wavelengths of 23m, 40m and more than 160m for the cultivated hillslope. These peaks appear at approximate frequencies indicating land use change does not obviously change the overall spatial patterns of soil redistribution by water erosion in the study area (Quine et al., 1997; Zhang et al., 1997). On the contrary, land use change has significant role in the scale of spatial patterns of net soil export within the landscapes (Table 2, Figures 2b and 2d).

Spatial patterns of soil redistribution by tillage operations can be described at wavelengths of 27m, 40m and 160m for soil deposition (Figure 2b) with wavelength patterns of 27m, 53m and 160m for soil loss (Figure 2c), respectively. Evidently, soil loss by water erosion and deposition by tillage are dominant soil redistribution processes in range of 23-40m, and soil deposition by water erosion and soil loss by tillage are dominant processes occurring in range of more than 80m within the landscape. This is closely related to the changes in field boundary due to tillage and slope location. Moreover, the similar spatial patterns of water and tillage erosion reflect their strong spatial interaction for accelerating soil loss thus decreasing soil quality on cultivated slopes of the study area.

Effects of Landscape Structure and Land Use Change on Spatial Variability. Patterns of Soil Redistribution

To further determine whether the spatial variability patterns of soil redistribution coincide with that of the

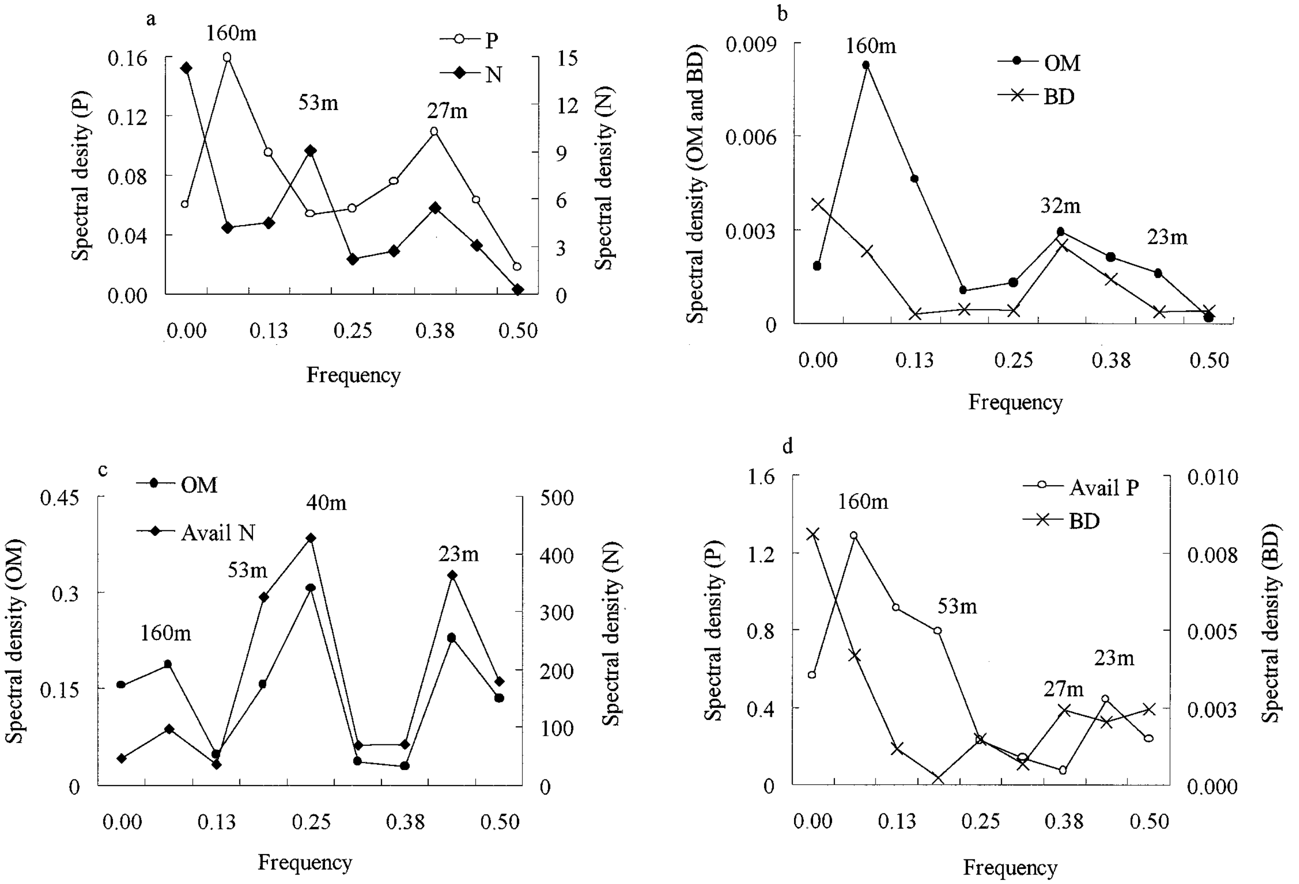

Figure 4. Power spectrum of soil quality parameters on the cultivated hillslope (Figures 4a and 4b) and mixed land use hillslope (Figures 4c and 4d): available phosphorus (P), available nitrogen (N), organic matter (OM) and bulk density (BD).

slope angle and land use change, a systematic analysis of correlation coefficients and squared coherence of two series of variables were made for the two contrasting hillslopes (Table 3 and Figure 3).

Soil redistribution rates by tillage and water erosion shows a significant correlation with slope angle ($r = 0.40$; $p < 0.05$) over the cultivated hillslope, but not significant for the hillslope with mixed land use (Table 3). The spectrum of squared coherence of erosion processes over the cultivated hillslope (Figure 3a) shows a strong coherency at wavelengths of 20 to 80m for soil deposition by tillage and at wavelengths of 23 to 160m for soil loss by water erosion. Strong coherence peaks in the spectrum for soil loss by tillage appear at wavelengths of 20m, 40m and 160m and only one strong peak for soil deposition by water erosion at the wavelength of more than 160m. These indicate similarities in the spatial variability patterns of soil deposition by tillage (Rtd) and loss by water erosion (Rw) vs. slope angle and differences of soil loss by tillage (Rt) and deposition by water erosion (Rwd) vs. slope angle across the cultivated hillslope landscape (Table 3a). For the mixed land use hillslope, strong squared coherence of soil loss rate by water vs slope angle occur at wavelengths of 20-27m, 40-53m and 160m, but not as strong at those wavelengths as that the cultivated hillslope (Figure 3c).

These spatial relationships can be further confirmed by squared coherence of ^{137}Cs inventory, net soil loss and deposition vs. slope angle, as is shown in Figures 3b and 3c. This quantitatively explains why net soil loss rates do not increase with slope length of more than 60m or elevation alone (Bussaca et al., 1993; Montgomery et al., 1997; Martz and deJong, 1987; Zhang et al., 1997). However, changes in conservation practices or the changes in slope angle curvature strongly affect soil redistribution processes by both tillage (Lindstrom et al., 1992) and water erosion (Young and Mutchler, 1969).

Contributions of Soil Redistribution to Spatial Patterns of Soil Quality

There exist significant differences in averages of organic matter and available N and bulk density between two contrasting hillslopes (Table 2). When compared the correlation coefficients of soil quality parameters with net soil loss, significant negative correlation at $\alpha = 0.05$ level for all nutrient variables (Table 3). These indicate that removal of soil indigenous nutrients by erosion have resulted in serious lowering of soil quality within the cultivated hillslope.

However, quantifying the spatial patterns of soil erosion impacts on soil quality is much more challenging, especially in the soil landscape with "homogenous loess materials". Moreover, there is no initial information about the quantification of spatial patterns of soil nutrients in this region. We suggest as a solution to this problem, construction of the spectral density functions of soil quality patterns and comparison with soil erosion processes using squared coherence analysis (Wendroth et al., 1997).

Typical strong peaks occur at long wavelength of 160m (or >160m) in the power spectrum for available nitrogen and available phosphorus, organic matter on the cultivated hillslope (Figures 4a and 4b) even though several weak peaks at short wavelengths of 27-53m. But typical strong peaks in the power spectrum occur at short wavelengths of 23m and 40-53m for available nitrogen and organic matter and 53-160m for available phosphorus on the mixed land use hillslope (Figure 4c and 4d). Peaks in power spectrum of bulk density occur at short wavelengths of 20-32m and more than 160m on the two slopes (Figures 4b and 4d). These reflect variability patterns and scale of soil erosion impacts on soil quality due to field boundary, land use and landscape location.

The spatial patterns of erosion impacts on soil quality may be further quantified by the squared coherence of soil quality variables vs. ^{137}Cs inventories, as shown in Figure 5. High squared coherence for cultivated hillslope occurs at long wavelength of more than 80m and specially at short wavelength about 20-40m, corresponding to the scale of variability patterns of soil deposition by tillage and soil loss by water (Figure 5a and Figure 2b). This provides evidence that soil loss by water and soil deposition by tillage are the main reason for the occurrence of significant scale dependency of spatial variability of soil quality on the cultivated hillslope. For the hillslope with different land use, the spectrum of squared coherence between ^{137}Cs inventories and soil quality variables shows different patterns as that for cultivated hillslope and strong coherence for several short wavelengths but especially for long wavelengths of more than 80m (Figure 5b). This provides some evidence that soil conservation practice (grass and forest) can greatly affect the spatial variability patterns and its scale dependency of soil erosion on soil indigenous fertility, thus increase soil quality.

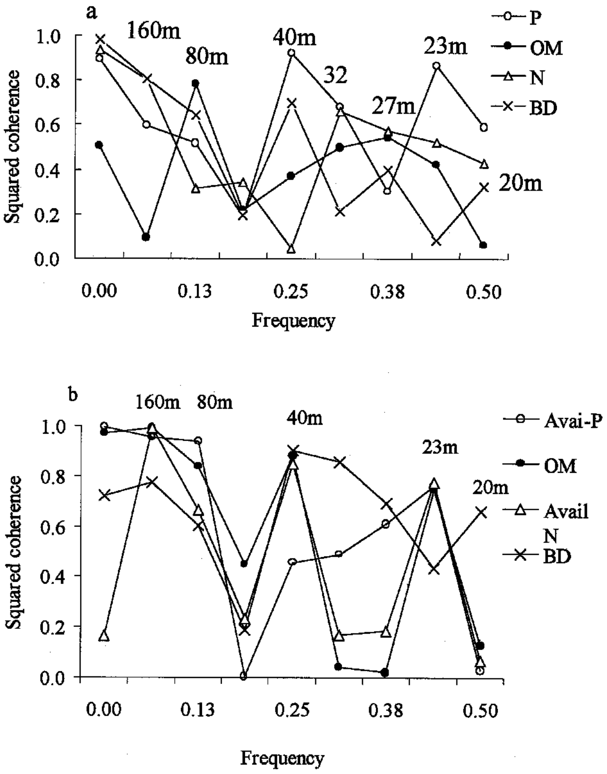

Figure 5. Squared coherence of soil quality parameters vs ^{137}Cs inventories on the cultivated hllslope (Figure 5a) and mixed land use hillslope (Figure 5b).

CONCLUSIONS

We have demonstrated a conjunctive method of ^{137}Cs technique integrated with time series analysis for determining the similarity and variability of soil erosion and soil quality and quantifying the scale of dependent variability between them within landscape with different land use. This method has shown promise for quantifying spatial patterns of soil redistribution by tillage and water erosion within the landscapes. This method appears to have utility for identifying changes in soil quality indicators that have both predictable spatial patterns and strong coherency with ^{137}Cs measurement.

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