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Ecologically asynchronous agricultural practice erodes sustainability of the Loess Plateau of China

Tianming Wang,[1] Jianguo Wu,[1,2,3] Xiaojun Kou,[1] Chadwick Oliver,[4] Pu Mou,[1] and Jianping Ge[1,5]

[1]*State Key Laboratory of Earth Surface Processes and Resource Ecology and Center for Landscape Ecology and Sustainability Science, Beijing Normal University, Beijing 100875 China*
[2]*School of Life Sciences & Global Institute of Sustainability, Arizona State University, Tempe, Arizona 85287 USA*
[3]*Sino-US Center for Conservation, Energy, and Sustainability Science, Inner Mongolia University, Hohhot 010021 China*
[4]*School of Forestry and Environmental Studies, Yale University, New Haven, Connecticut 06511 USA*

Abstract. Sustainability of agricultural landscapes depends largely on land-use practices. As one of the most productive and widespread agricultural soils, loess is often deep and easily eroded, posing grand challenges for environmental sustainability around the world. One prime example is the Loess Plateau of China, which has been cultivated for more than 7500 years. Based on long-term data sets, this study demonstrates that the dominant agricultural practice, winter wheat cropping, continues to be the primary driver for the massive soil erosion and landscape modifications on the Loess Plateau. This traditional farming system is asynchronous with the dynamic rhythm between natural vegetation and climate in the region. In particular, the long summer fallow period for winter wheat fields is concurrent with the heavy-rainstorm season, which greatly accelerates soil erosion. Our finding indicates that common land-use practices that have lasted for thousands of years in China are not environmentally sustainable. Agriculture in this region has relied primarily on the continuous "mining" of the soil for the past several thousand years but does not have a one-thousand-year future because of myriad environmental and socioeconomic factors associated with soil erosion. To contain soil erosion and promote sustainability on the Loess Plateau, therefore, a change in the agricultural regime is needed to make sure that current and future agricultural practices follow the vegetation–climate rhythm. In addition, to achieve environmental, economic, and social sustainability in this region, multifunctional land-use planning is required to increase landscape diversity and functions (e.g., proper arrangement of crop fields, orchards, and protected areas).

Key words: agriculture; LAI; land use; Loess Plateau, China; NDVI; rainfall erosivity; sediment load; soil erosion; summer fallow; sustainability; vegetation–climate rhythm; winter wheat.

Introduction

The Loess Plateau is one of the most environmentally devastated regions in China. It has long been recognized for its fertility and has been an early and long-lasting center of cultivation (Catt 2001, Liu and Ding 2004, Montgomery 2007*a*). Facing the Gobi Desert and the Mongolian Plateau to the north, the loess region extends over 640 000 km^2 in the middle and upper reaches of the Yellow River (Fig. 1). About 50% of this region is covered by loess, with deposits as great as 250 m or more in depth (Burbank and Li 1985, Wintle and Derbyshire 1985, Catt 1988, Shi and Shao 2000, He et al. 2004).

Particularly in the last few centuries, soil erosion has dramatically transformed the landscape, decreasing biodiversity and deteriorating ecosystem services, and resulting in loss of farmlands, villages, and even cities (Shi and Shao 2000, Shi 2001, Liu and Ding 2004). Abundant evidence suggests that soil erosion continues to undermine the environmental sustainability of the Loess Plateau and to degrade the livelihood of 104.2 million people who live there. The Loess Plateau region is still an important source of food, and erosion and concomitant land degradation are major threats to world food security and environmental quality. Food cultivation on the Loess Plateau is exacerbating erosion, sedimentation of the Yellow River, and groundwater recession. Restoring natural vegetation could solve some of these problems, but exacerbate the food supply issue and increase wildfires in the natural vegetation.

It is important to understand how growth of different natural and cultivated crops affects erosion in the loess so that appropriate solutions to the many issues related to the region can be applied. Many studies in the past decades have identified geological features, soil properties, rainstorms, deforestation, land-use, and intensive farming as the main causes of soil erosion on a range of scales in space and time (Shi and Shao 2000, He et al.

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[5] Corresponding author. Present address: College of Life Sciences, Beijing Normal University, 19 Xinjiekou wai Street, Beijing 100875 China. E-mail: gejp@bnu.edu.cn

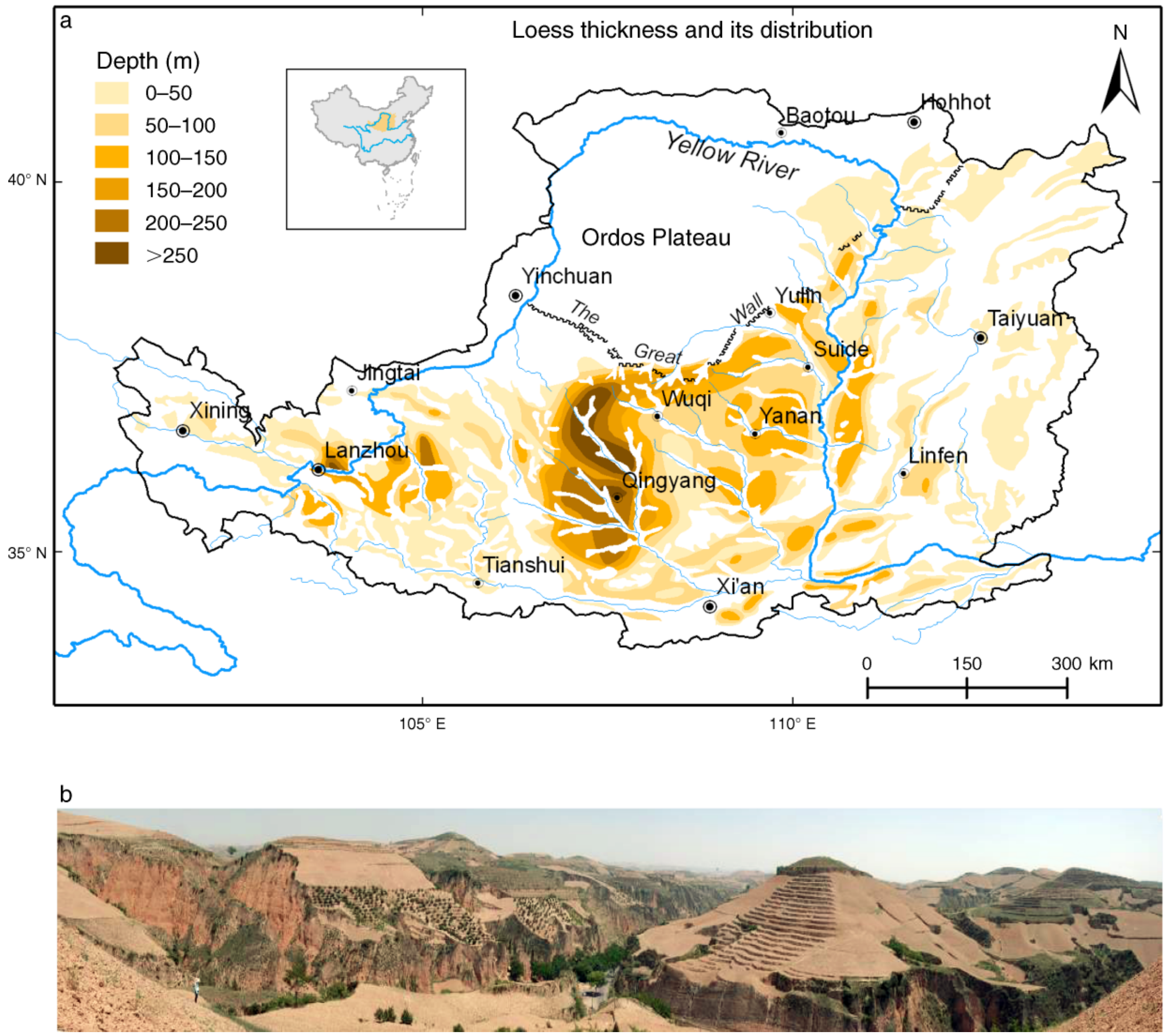

FIG. 1. Geographic distribution of the Loess Plateau of China. (a) Spatial extent and depth of loess deposits (modified from YRCC [1987]). (b) Panoramic view of a highly eroded and rugged landscape near Suide County, typical of what is found across the loess region of China.

2004, Liu and Ding 2004, He et al. 2006, Zheng 2006, Li et al. 2007, Wei et al. 2007). These studies show that agriculture has dramatically increased erosion; however, they do not address details of the causes. For example, was the erosion caused by poor cultivating practices or something innate about the particular crops grown? Other recent studies (Kang et al. 2001, Huang et al. 2006, Wei et al. 2007) discussed the causes but did not assess the seasonal (monthly) relationship among vegetation, climate and soil erosion in depth. Such an assessment could enable a landscape-level understanding and ultimately facilitate the development of ecosystem-management and regional-planning strategies. In particular, the effects of changed vegetation phenology caused by cropfields replacing natural plant communities have not been examined rigorously on a seasonal and landscape scale, although such effects have been reported in other parts of the world (Montgomery 2007*a*, *b*).

The major goal of this study is to fill this knowledge gap by asking three related questions:

1) Have agricultural practices with specific crops severely disrupted the evolved seasonal relationship between vegetative growth and local climate (the natural vegetation-climate rhythm) on the Loess Plateau?

2) If so, could this disruption have been a major cause for the dramatic increase in soil erosion in the recent history of this region?

3) Could other crops or natural vegetation more in synchrony with the native vegetation–climate rhythm reduce erosion on the Loess Plateau?

To address these questions, we quantified the spatial and temporal changes in agricultural and natural land covers, analyzed how these changes are correlated with rainfall erosivity, and compared these results directly with field measurements of soil erosion rates.

Background

Loess Plateau geography and area

Land-use and land-cover patterns and their socioeconomic drivers vary across the Loess Plateau. Two contrasting subregions exist separated by the Great Wall (Figs. 1 and 2). Historically, agricultural activities were restricted almost exclusively to the loess areas found south of the Great Wall; the drylands in the north (desert and desert steppe with an annual precipitation of $<$400 mm) were utilized for nomadic grazing (Liu and Ding 2004). This dichotomous land-use and land-cover pattern, however, began to change between the 1950s and 1970s because government policies encouraged the encroachment of cultivation to the north (Jiang 2004, 2005). Currently, $<$6% of the area north of the Great Wall is cultivated, but intensive grazing is common (Fig. 2). The primary source of sediment loading of the Yellow River has been loess (thus the name of "Yellow" River) (He et al. 2004, Liu and Ding 2004, He et al. 2006, Zheng 2006, Wei et al. 2007). Our present study focuses on the loess areas south of the wall, where agricultural practices have continued for hundreds to thousands of years.

More than 1.6 billion Mg of soil are eroded away annually (Douglas 1989, Shi and Shao 2000), and annual soil erosion rates have been estimated to be 5000–10 000 $Mg \cdot km^{-2} \cdot yr^{-1}$ in hilly areas (He et al. 2004). Soil erosion from the plateau provides approximately 90% of sediment load for the Yellow River, which carries the second largest sediment load in the world (Wang et al. 2007). As a result, the Yellow River is now higher than its surrounding floodplain in its middle and lower reaches, and thus causes frequent flooding downstream (1590 major flood events in the past 2540 years) (Vörösmarty et al. 1998).

Land-use history

The most widely distributed crop on the plateau has been wheat, introduced more than 4650 years ago (Li et al. 2007). In particular, winter wheat (*Triticum aestivum* L.) has been the most dominant variety in the region since early Han Dynasty (206 BC–AD 220), accounting for up to 80% of the total area of wheat fields (Jin 1996, Liu and Ding 2004).

Wheat evolved and was domesticated in the Middle East (Southwest Asia). The rainy winters and dry summers of the Middle East are dramatically different from the climate regime of the Loess Plateau, which has summers with intensive thunderstorms and dry winters. To gain enough water for wheat, farmers in China's loess region grow the wheat in spring and early summer on the previous year's stored soil water. They harvest the wheat in the dry early summer and plow the fields to enable the summer rainfall to remain in the soil of the fallow fields for next spring's growth—without a cover crop to reduce the water through evapotranspiration.

Soil erosion in this region has dramatically accelerated during the past 1000 to 2500 years (Saito et al. 2001, He et al. 2006), and this rapid increase has been attributed primarily to anthropogenic drivers, particularly cultivation, deforestation, and ancient wars (Saito et al. 2001, Liu and Ding 2004, He et al. 2006, Li et al. 2007).

Especially in the past 1000 years, the human population on the Loess Plateau has increased exponentially from a few million to more than 100 million persons (Wang et al. 2006) as a result of immigration and natural population increases. These population pressures have created rapid expansion of cultivation throughout the loess areas in the region, even into steep-sloped hills (Meng 1996, He et al. 2006). The additional soil erosion directly attributable to human activities is estimated to be 45.5% of the total soil erosion caused by all factors (Zhu et al. 2003).

Beginning in the 1980s, many areas of the Loess Plateau have been terraced to reduce gully development caused by surface runoff on steep fields. These terraces have probably helped reduce gully development, but their overall effect is probably overpowered by the increased cultivation and by the erosion caused by sinkholes and landslides in fields bordering gullies (Fig. 1b).

Loess soils and erosivity

Studies have shown that several major factors have been responsible for the large-scale soil erosion on the Loess Plateau, but their relative importance has changed distinctly on a geologic time scale (Saito et al. 2001, Zhu et al. 2003, Liu and Ding 2004, He et al. 2006). The key driving forces for soil erosion shifted from tectonic activities during 11 000–7000 yr BP to climatic factors during 7000–2000 yr BP, and then to a combination of climatic and anthropogenic factors since 2000 yr BP (Zhu et al. 2003).

Loess is the single most abundant Quaternary deposit, covering $>$20% of the earth's land surface and found on every cultivable continent (Catt 1988, 2001). Loess is wind-deposited silt. It is fertile and has an established structure to great depths and so is readily arable even when its surface layer has been removed. Loess soils are loose and porous; however, their infiltration capacities can be exceeded during intensive storms. Then, loess is extremely susceptible to erosion but has an essentially vertical stable angle of repose. Consequently, cultivated slopes can exist adjacent to erosion-created, precipitous canyons. In addition to dramatic erosion gullies and canyons created by overland flow of water, water infiltrating into the loess near these canyons can wash away soil deep beneath the surface and create sink holes and landslides in the fields above; these sink holes further erode into gullies. Cover crops can reduce the soil water saturation, create roughness to the soil surface

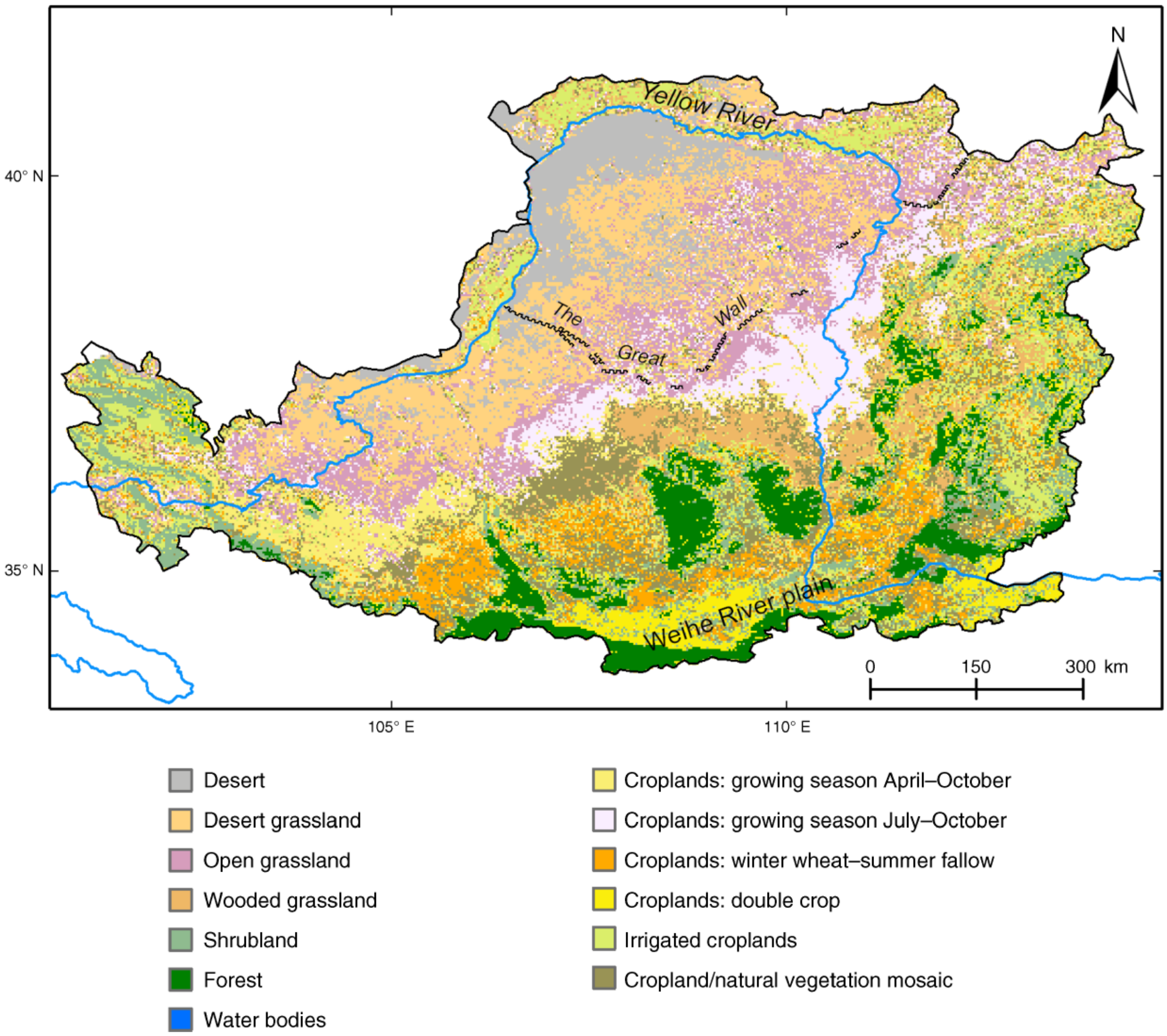

FIG. 2. Land-use and land-cover map of the Loess Plateau in 2001 (based on 250-m MODIS-NDVI [normalized-difference vegetation index] time series of cloud-free composite images).

(Kang et al. 2001), and break the impact of raindrops during high-intensity rainfalls.

Normal soil-erosion prevention practices can be helpful, such as breaking streams of overland flow by contour plowing, terracing, creating berms at slope edges, planting grass strips at intervals along the contours, planting steep slopes with shrubs or trees, maintaining cover crops on the soil, and controlling grazing. In addition, special measures such as reducing the amount of water infiltration into the soil in fields near gullies are needed to prevent sink holes in these fields.

MATERIALS AND METHODS

To determine the seasonal behavior of present and potential natural and cultivated crops relative to the seasonal patterns of precipitation and erosion, data were obtained on the phonological patterns of different land-cover types, the long-term rainfall patterns, and the soil erosion rates.

Data sources

The phenological patterns of different land-cover types in the region were derived from remote-sensing data (MODIS [moderate-resolution imaging spectroradiometer] 250 m NDVI [normalized-difference vegetation index] between 2001 and 2005), obtained from NASA's Land Processes Distributed Active Archive Center (LP DAAC; *available online*).[6] Field measurements of winter wheat and corn leaf-area index (LAI) between 1994 and 2005 were acquired from Qingyang Agricultural Ecology Research Station (Guo et al. 2005). LAI values of natural vegetation types were derived from MODIS data for the period 2001–2005

[6] ⟨https://lpdacc.usgs.gov⟩

(*available online*).[7] Long-term (1961–2005) rainfall data for the Loess Plateau region were obtained from 190 weather stations (China Meteorological Data Sharing Service [CMDSS]; *available online*),[8] from which rainfall erosivity was computed. Actual soil erosion rates were obtained from field measurements at 78 hydrological gauging stations distributed across the region. These stations were designed, and have long been used, for monitoring soil erosion in the Loess Plateau.

Land-cover classification

An unsupervised classification procedure (ISODATA) was used for classification of 2001 MODIS-NDVI 250 m time-series of cloud-free composite images, since it allows identification of all important NDVI phenology cycle groupings. NDVI bands from April to October were used as input to the iterative ISODATA clustering algorithm. Validation of the classification was done by using field-survey data. The final land cover for the Loess Plateau is illustrated in Fig. 2. Accuracy estimates for the classification indicate that the overall accuracy of the classification is 89%. We generated the phenology index profiles for each thematic class using 2001–2005 MODIS NDVI time-series data based on 2001 ground-truth classification image.

Rainfall-runoff erosivity factor, R

Rainfall erosivity, commonly used to indicate potential erosion risks with the revised universal soil loess equation (RUSLE), is calculated as the product of total storm kinetic energy (E) and the maximum 30-min intensity (I_{30}) during a storm (Wischmeier and Smith 1958, 1978, Wischmeier 1959). Data for calculating rainfall erosivity in this study were from 10 hydrological gauging stations that had the rainfall intensity (pluviographic) data. These 10 stations covered a broad south–north climatic gradient across the Loess Plateau region. Rainfall erosivity was calculated in SI metric units (Foster et al. 1981) for the period 1961–2003 following the standard procedures described in the RUSLE handbook (Renard et al. 1997).

The following equation was used to calculate the unit energy (Brown and Foster 1987, Renard et al. 1997):

$$e = 0.29[1 - 0.72\exp(-0.05i)]$$

where e is the kinetic energy (in $\mathrm{MJ\cdot ha^{-1}\cdot mm^{-1}}$) and i the rain intensity (in mm/h). The sums of EI_{30} values during a month and a year give rise to the values of the monthly and annual rainfall erosivity, respectively.

Because detailed pluviographic data are usually unavailable for all standard meteorological stations in the Loess Plateau, a regression model of mean monthly EI_{30} (dependent) and mean monthly rainfall (independent) for 10 stations was developed and subsequently used to estimate monthly rainfall erosivity for each site:

$$R_i = \alpha\left(P_i^2/P\right)^{\beta}$$

where R_i ($\mathrm{MJ\cdot mm\cdot h^{-1}\cdot ha^{-1}\cdot (month)^{-1}}$) is the monthly rainfall erosivity, P_i (mm/month) is the monthly average precipitation, P (mm/yr) is the annual precipitation, α ($=11.542\ \mathrm{MJ\cdot mm\cdot h^{-1}\cdot ha^{-1}\cdot yr^{-1}}$) and β ($=1$) are empirical coefficients. The estimated and USLE-based R values were in good agreement, which indicates that the model can be used for the Loess Plateau ($R^2 = 0.83$, $P < 0.01$). A map of monthly R values was then generated by interpolation with the ordinary Kriging technique using monthly values from all 190 stations. Monthly R grids show a high quality and the r^2 of cross-validation for interpolation range from 0.60 to 0.95 for the period April to October.

Measurements of actual soil erosion rates

We delineated the boundaries of watersheds of the Loess Plateau based on the digital elevation model (DEM) obtained from the Shuttle Radar Topography Mission (SRTM) by running ArcGIS's hydrologic analysis tools (SRTM; *available online*).[9] The average erosion rates for all watershed units were calculated based on a long-term sediment yield data set collected from 78 hydrological monitoring stations (see Fig. 6). Because the sediment delivery ratio (the ratio of sediment yield to gross erosion) is ~1 in the Loess Plateau (Mou and Meng 1982), the sedimentation rate of the river recorded in gauging stations directly reflects the watershed's erosion rate and thus the intensity of soil erosion.

The vegetation–precipitation coupling index (VPCI)

The value of VPCI for each land-cover type across the region was obtained by correlating monthly mean NDVI (2001–2005) with rainfall erosivity averaged over the period 1963–2003 using the standard Pearson's product-moment correlation (Fig. 3):

$$\mathrm{VPCI} = \frac{\sum_{i=1}^{n}(\mathrm{VI}_i - \overline{\mathrm{VI}})(R_i - \bar{R})}{\sqrt{\sum_{i=1}^{n}(\mathrm{VI}_i - \overline{\mathrm{VI}})^2 \cdot \sum_{i=1}^{n}(R_i - \bar{R})^2}}$$

where VI_i and R_i are the values of NDVI and rainfall erosivity for each 250×250 m grid cell for month i, respectively. $\overline{\mathrm{VI}}$ and $\bar{R}$ are the means of NDVI and rainfall erosivity. The statistical analysis was performed with the software ERDAS Imagine, version 8.7 (ERDAS, Atlanta, Georgia, USA).

Results

The results show that up to 78% of the annual precipitation and 90% of the annual cumulative erosivity

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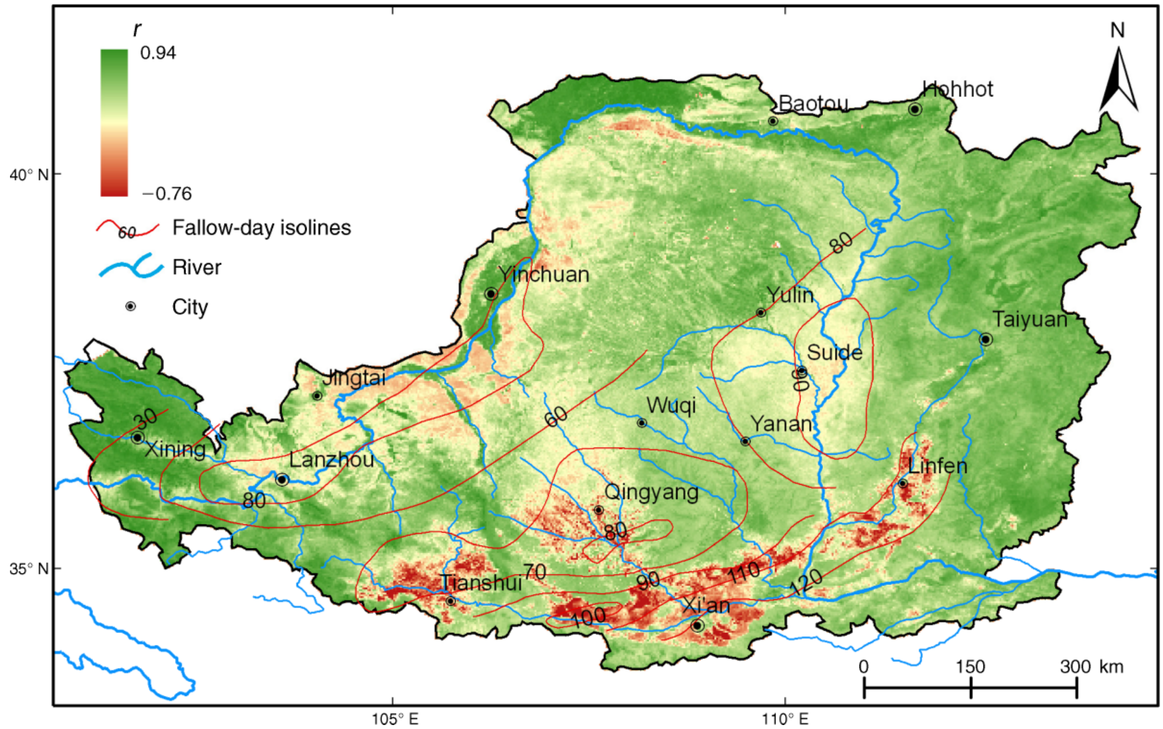

FIG. 3. Spatial pattern of the correlation coefficients (r) between NDVI and rainfall erosivity for different land-cover types on the Loess Plateau. The values represent the linear correlation coefficients between monthly average NDVI (2001–2005) and rainfall erosivity (1963–2003) for each 250×250 m grid cell. The lengths of summer fallow periods for different agricultural areas are indicated by fallow-day isolines (30–120 days).

on the plateau occur between June and September, during which time intense thunderstorms are frequent and crop cover is sparse. The bell-shaped temporal pattern of erosivity is well matched by that of the leaf area index (LAI) of native land-cover types, including forests, shrublands, and grasslands (Fig. 4a). With native plant cover and rainfall erosivity peaking at the same time, this synchronous relationship between vegetation and climate constrains soil erosion.

The temporal pattern of the LAI of winter wheat has a quite different phenological pattern from that of natural vegetation. The LAI of winter wheat reaches its largest value around early May, declines rapidly afterwards, and disappears completely at the harvest time in late June. Traditionally, the fields are plowed deeply after harvesting, and fallowed until September. This summer fallow coincides exactly with the high rainfall erosivity period—a situation that maximizes soil erosion (Fig. 4a).

The above patterns are confirmed by spatial analysis using NDVI, a correlate of vegetation abundance derived from remote-sensing data (Fig. 4b, c). Again, a synchronous relationship between NDVI and rainfall erosivity was found for natural land covers but not for winter wheat and double-cropping fields (consecutively producing corn after winter wheat on the same land in the same year). In addition, we further examined how NDVI and rainfall erosivity were related spatially over the entire region. The correlation coefficient between NDVI and rainfall erosivity—"the vegetation–precipitation coupling index" (VPCI)—measures the degree of synchrony between the dynamics of land-cover types and the natural vegetation–climate rhythm. NDVI and rainfall erosivity are highly positively correlated for all natural land-cover types (i.e., with high values of VPCI values), but negatively correlated for agricultural areas dominated by winter wheat in the southern part of the plateau and for sand dunes and severely degraded desert steppe to the north of the Great Wall (Figs. 2, 3, and 5).

Not all crops show such an asynchronous pattern, however. For example, corn (*Zea mays* L. ssp. *mays*), another major, introduced crop in the region, exhibits a pattern largely in accord with the vegetation–precipitation rhythm. Nevertheless, the time span during which a significant amount of LAI existed is truncated for corn because of its much shorter growing period, implying less capacity for resisting soil erosion on a yearly basis (Fig. 4a).

To examine whether winter wheat fields are indeed more severely eroded, the actual soil erosion rates for the entire region were computed using data from 78 hydrological gauging stations (Fig. 6). All high erosion rates are associated with heavily cultivated areas that have low values of VPCI, except for the Weihe River plain around Xi'an City where the topography is extensively flat. Winter wheat fields generally have

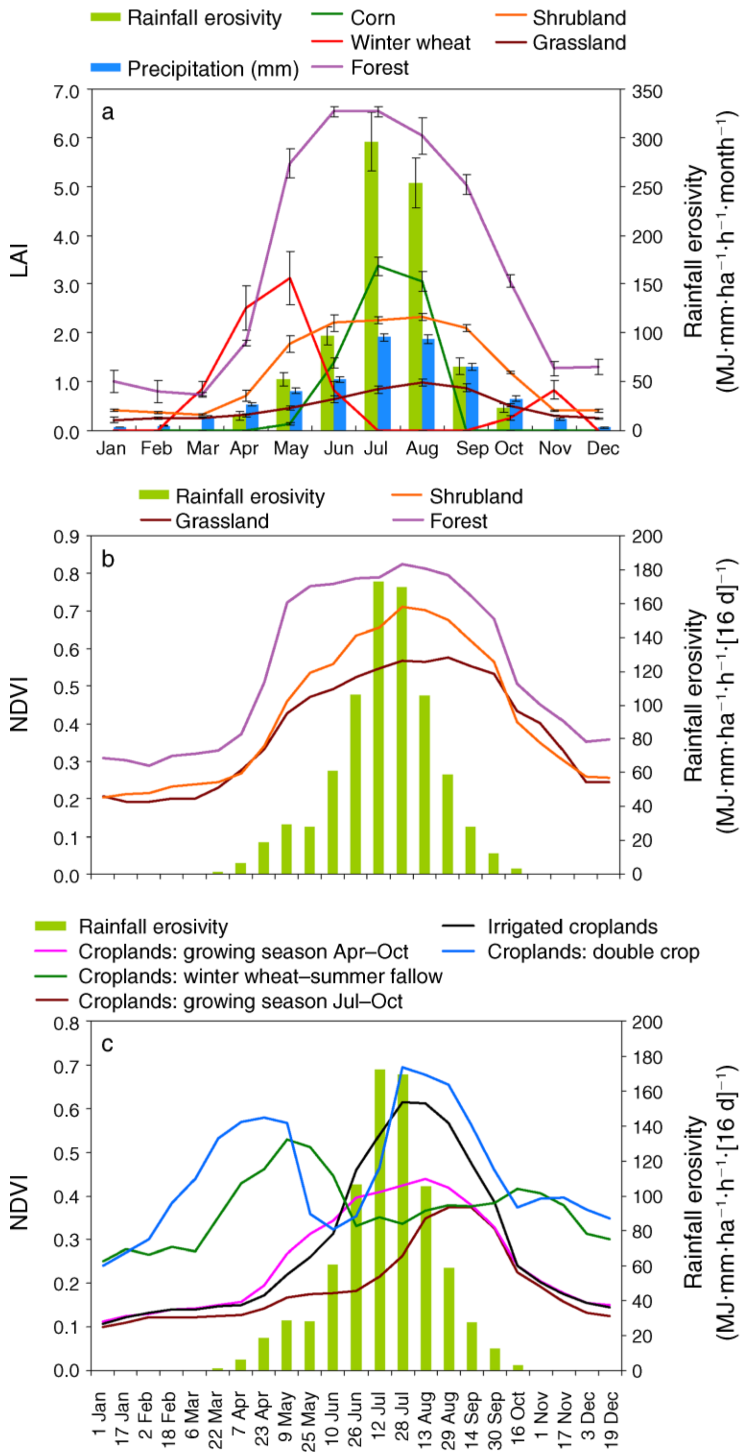

FIG. 4. Temporal patterns of natural and agricultural land covers in relation to changes in precipitation and rainfall erosivity on the Loess Plateau. (a) LAIs (leaf-area indexes) of winter wheat, corn, shrubland, grassland, and forests. Data are means ± SE. (b) NDVI (normalized-difference vegetation index) of forests, shrublands, and grasslands. (c) NDVI of main cropping systems on the Loess Plateau, including winter wheat, corn, and winter wheat–corn double cropping. Dates for panel (b) are the same as panel (c). Keys are provided above each panel.

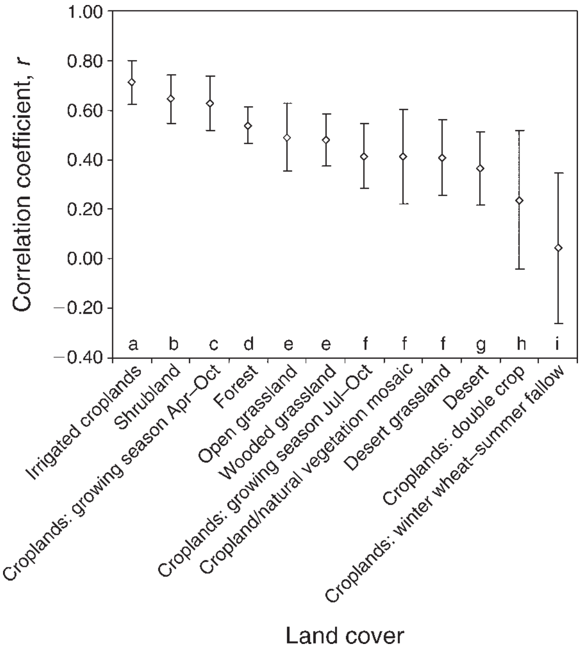

FIG. 5. Correlation coefficients between seasonal variations of NDVI and rainfall erosivity for different land-cover classes in the Loess Plateau. Data are means ± SD. Different lowercase letters above the x-axis indicate statistically significant differences ($P < 0.05$) in r values among land covers.

higher erosion rates than other crops. For example, watersheds 11 and 12 are adjacent to each other and similar in size, landform, and climatic conditions, but 61% of watershed 11 is cultivated primarily with winter wheat, whereas 75% of watershed 12 remains occupied by natural vegetation. The average erosion rate of watershed 11 (8710 $Mg \cdot km^{-2} \cdot yr^{-1}$) is about 5 times that of watershed 12 (1782 $Mg \cdot km^{-2} \cdot yr^{-1}$). Crop fields, with winter wheat accounting for 50–60% of the area, lose at least 5000 $Mg \cdot km^{-2} \cdot yr^{-1}$ more soil to erosion than natural vegetation. This estimate is consistent with earlier reports that natural vegetation is able to decrease soil loss by 58–98% compared to cropland (Huang et al. 2006, Wei et al. 2007). A previous study by Kang et al. (2001) revealed that plowed winter wheat fields had 2–3 times more soil erosion than corn and no-till cropfields between June and August. In addition, field survey observations reveal that gullies, sinkholes, and landslides are much more frequent in winter wheat areas. Overall, the map of VPCI values matched quite well with that of actual soil erosion rates (Figs. 3 and 6).

DISCUSSION

These results are indicative of regime shifts in terms of landscape dynamics (Scheffer et al. 2001). Evidently, agricultural practices in the recent past have approached or exceeded a threshold level in regard to erositivity and sustainability in the Loess Plateau. Our study indicates that, in addition to the spatial extent of the cultivated area, the asynchronous relationship between the crop-

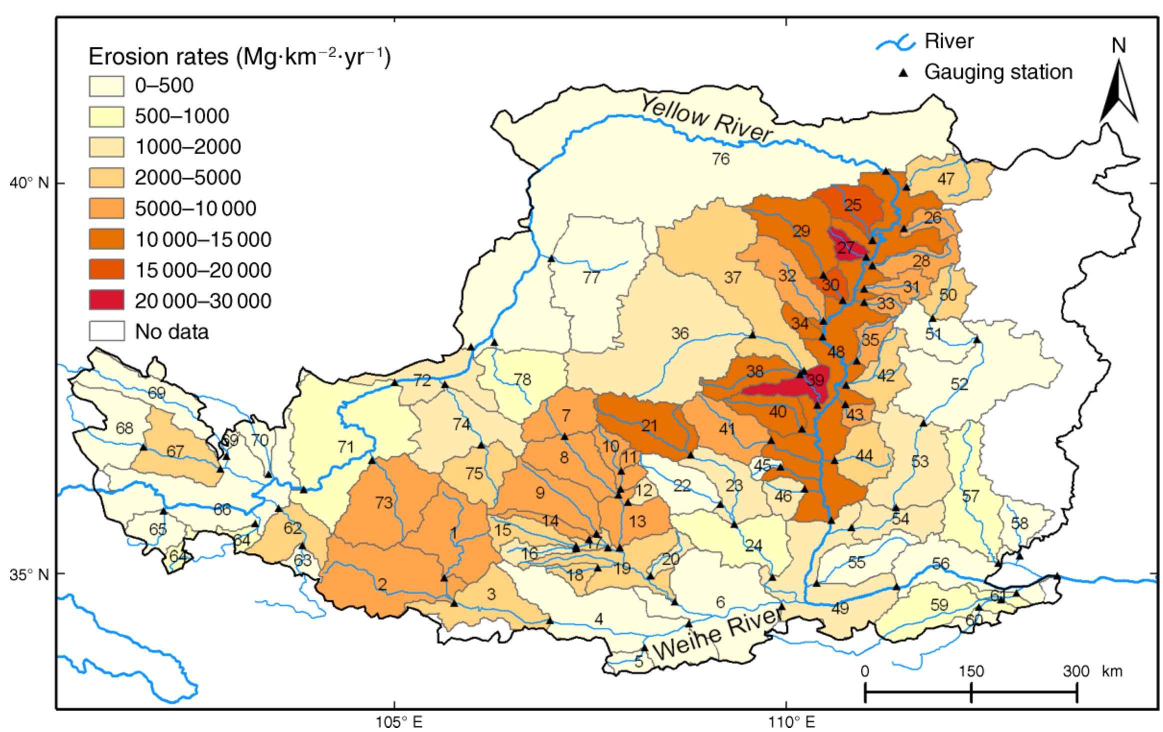

FIG. 6. Soil erosion rates measured at 78 hydrological gauging stations across the Loess Plateau. Numbers in polygons indicate watershed units.

ping system and the natural vegetation–climate rhythm is a key factor responsible for the uncommonly large amount of soil erosion in the loess region. In addition, the localized, violent nature of the summer rainstorms means that some areas are extremely saturated with water every year. In particular, our results show that winter wheat cropping is out of phase with the natural vegetation–climate rhythm, and is chiefly responsible for the soil erosion levels in the Loess Plateau. As the amount of cultivation has dramatically increased, so has soil erosion and loss of land productivity (Kong et al. 2002). The practices of the historic past challenge the current sustainability of the system.

Our findings have several implications for better understanding and controlling the processes that drive soil erosion on the Loess Plateau. First, reduced erosion is likely to follow from the use of crops and cropping practices that are synchronous with the natural vegetation–climate rhythm (such as corn). Avoiding wheat cultivation—and fallow soils during the rainy season near gullies—is important in reducing sinkholes near existing gullies and in steep terrain. Altering the timing and location of cropping activities is one of the key strategies to achieve environmental sustainability in the face of global environmental changes (Howden et al. 2007). Native plants, such as legumes, could be planted during the fallow period to increase ground cover and soil nitrogen (Montgomery 2007*b*). No-till cropping may significantly reduce soil erosion by eliminating plowing.

These measures require radical changes in land-use policy from the central government and stringent implementation by local authorities. A standardized graph of year-round change in vegetation cover against rainfall erosivity, similar to Fig. 4, can be used as a guide to evaluate the potential resilience of a land-cover type or a landscape to soil erosion.

Second, the restoration of natural vegetation in this region is a priority on hillslopes as well as in flat but severely degraded areas. Fairly successful results have been attained by recent "grain-for-green" (returning cultivated land back to natural vegetation) efforts on local scales, but long-term success on a regional scale will likely require sustained subsidies from the Chinese government (Xu et al. 2004, Feng et al. 2005). In addition, the ongoing ecosystem restoration efforts need to be guided by landscape-ecology principles that explicitly consider the interactions among different ecosystems and the spatial optimization of the regional land-use pattern (Naveh 2007, Wu and Hobbs 2007, Nassauer and Opdam 2008). Steep areas could be returned to native vegetation; however, some native plants may lead to wildfires as they grow dense. They also may not provide needed food. Alternatively, fruit trees may provide the erosion-prevention effects of native vegetation, provide food, and be less susceptible to fires than such native species as junipers. Reducing sheep and goat grazing from the gullies and near steep terrain should also allow natural vegetation to grow more vigorous and further help prevent erosion.

Third, to make the above measures effective, a comprehensive, multi-scale framework needs to be developed based on sustainability science (Kates et al. 2001, Clark and Dickson 2003, Turner et al. 2003, Wu 2006). In particular, land-change science may prove useful (Rindfuss et al. 2004, Turner et al. 2007). Such a framework explicitly considers the spatial heterogeneity of vegetation–geography–climate interactions because the impact of agriculture on soil erosion is not uniform across the plateau. For example, the Weihe River plain in the southern part of the Loess Plateau was dominated by extensive irrigated crop fields, but had low erosion rates because its flat topography and low gully density counterbalanced the asynchronous vegetation–precipitation coupling in this region. In the northeastern section of the plateau, the values of VPCI (vegetation–precipitation coupling index) were not the lowest, but soil erosion was highest because of overwhelming influences of human activities, rugged topography, and sparse vegetation. Ecosystem management alone is insufficient. The environmental sustainability of the Loess Plateau cannot be achieved without economic and social considerations.

An appropriate further step would be to model the relationship of erosion rate to slope, distance to gully, rainfall, cover crop, and such agricultural practices as no-till harvesting and/or double cropping. This step would enable quantitative analyses of trade-offs among various management practices, as well as application to other systems and to future climate change scenarios.

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