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Soil C, N, and P Stocks Evaluation Under Major Land Uses on China's Loess Plateau[☆]



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ABSTRACT

Loess Plateau covers 640 000 km² in the central northern China. Despite a semiarid environment, harsh winters, and hot summers, agriculture has been practiced in this region for > 5 000 yr, and the food production systems are among China's oldest. The environment is fragile because the loessial soils are prone to erosion. Sound scientific information is therefore required to underpin future land use planning in the region. To this end, total soil organic carbon (SOC), N, and P stocks were measured in Huanxian County of the wider Loess Plateau, representing five major land use categories. Sites were sampled three times over 3 yr. In all, almost 2 800 soil analyses were performed. A feature of these soils is low SOC content in the A horizon but comparatively small decline with soil depth. For example, SOC levels for the 0–20 cm and 70–100 cm soil depths averaged 6.1 and 4.1 Mg ha⁻¹, respectively. Alfalfa and rangeland sites had 5.1 Mg ha⁻¹ (10%) more total than cropland and 7.5 t ha⁻¹ (16%) more total SOC to 100-cm soil depth than the two silvopastoral sites. For total soil N (0- to 100-cm soil depth) the averages of alfalfa and RL sites were 20% and 28%, respectively, higher than the cropland and silvopastoral site group means, although soil C, N, and P levels are very low, relative to those of typical soils elsewhere. When these observations are scaled up to a regional level, it can be calculated that a 5% shift in land use from cropping or silvopastoral systems to alfalfa-based systems could increase soil C sequestration by as many as 20 million t CO₂ per yr, although some caution is needed in making extrapolations, as the present data are from a single locality on the Loess Plateau.

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Introduction

The Loess Plateau is an eco-region of northern China approximately 640 000 km² in area (6% of China's land area) and spanning 7 provinces: Qinghai, Gansu, Henan, Shanxi, Shaanxi, Ningxia, and Inner Mongolia from latitude 34–41°N and longitude 101–114°E (Wang et al., 2009). The Loess Plateau is a complex of alluvial and wind-borne deposits accumulated over millennia, in some places to > 400-m depth, and associated with the upper middle reaches of the Yellow River. The alluvial and loessial beds are frequently dissected by deep river valleys, and in places there are exposed outcrops of underlying sedimentary rocks. Calcaric and Eutric Regosols formed from loess predominate in the region, and most of the production agriculture is concentrated on them (Wang et al., 2009). These soils are often several meters deep with a poorly developed A-horizon and a weakly developed blocky structure. Despite a

harsh climate with long cold winters, hot summers, and precipitation typically only 300–600 mm per yr, the region has historically made a disproportionately high contribution to China's food production (Hou et al., 2008). A range of mainly rain-fed arable cropping or mixed cropping and extensive rangeland grazing systems are practiced (Chen et al., 2010; Hou, 2014). However, over the past 50 yr a combination of internal socioeconomic drivers and central government policy directives has collectively resulted in major population increase and associated overgrazing of the grasslands, to the point that severe degradation is widespread (Kemp et al., 2011). In the context of China's comprehensive and rapid modernization, attention is now focusing on the redevelopment of the farming systems in the region, to improve farmer incomes and reverse environmental degradation (Kemp et al., 2011). Two specific problems are that these loessial soils are fragile and erosion prone and that land holdings are typically small (≈ 2 ha per family), limiting development options available to farmers. In moving toward a solution, grazing of rangeland has now been banned across much of the region by a central government directive (Fan et al., 2015), although it is evident that compliance with the grazing ban is incomplete and some authorities have suggested that livestock are a necessary component of a sustainable farming system in the region (Zhen et al., 2014). Hence, in the context of planning for China's future security of

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food supply it has become clear that significant change will be needed in farming systems on the Loess Plateau and China may be about to experience a rationalization of traditional agriculture systems in some ways similar to that which occurred in Europe in the second half of the 20th century.

As part of the wider quest to develop sustainable global food production systems, there has been a growing tendency internationally to inventory fundamental resources such as soil C, N, and P stocks and their changes under differing land uses to provide a sound scientific basis for planning decisions. Guo and Gifford (2002) reviewed 74 publications (mainly reporting paired site comparisons rather than chronosequences) from various countries reporting change in soil carbon associated with land use change, but they found so much variation in methodology and results that they regarded their findings as working hypotheses that need further testing. Among other points, they found little evidence for increase in soil carbon under forestry, that decline in soil carbon under cropping is confined to the soil surface layer, and that soil C accumulation under pasture extends to below 100-cm soil depth. Another engaging analysis of the global picture with respect to impact of agriculture on soil C, N, and P stocks is that of McLauchlan et al. (2006). These authors note that the soil carbon level is an indicator for soil “quality.” In addition, agriculture-related emissions are estimated to have contributed 55Pg to anthropogenic increases in atmospheric carbon dioxide, but agricultural land may act as either a CO₂ source or sink depending on a number of factors. The clear implication is that accurate information about the impact of particular land uses is highly desirable.

Turning more specifically to China’s Loess Plateau, major land use categories in the region include (in order of areas involved) extensive grazing, mixed crop production, alfalfa for forage, and forestry. Useful information on soil carbon and nutrient stocks for the region already exists. For example, Wang et al. (2009) reported soil organic carbon (SOC), total N, and total P levels in the upper 20 cm of the soil profile from 689 samples collected in Northern Shaanxi province as follows: SOC 1.94–3.30%, total N 0.19–0.47%, and total P 0.33–0.41%. However, in this analysis the results are focused more on the statistical properties of the data than on the impact of land use, and no soil bulk density value for conversion of data to a per-ha basis is apparent. A second study specific to the Loess Plateau is that of Hu et al. (2008). These authors collected samples to 60-cm soil depth with the focus of the study being on comparing soil carbon levels for rangeland with those for forested sites. They reported 30 Mg C ha⁻¹ for 0- to 60-cm soil depth under both grassland and established poplar plantations and 23 Mg C ha⁻¹ under Mongolian pine plantations. Clearly there is scope for further data collection for other major land use categories and to greater soil depth.

With these factors in mind, the present study was set up to provide a substantive data set describing levels of C, N, and P to a depth of 1 m in soil typical of China’s Loess Plateau and for differing farming systems on that soil type, with monitoring spanning a 3-yr time period. Eleven sites were chosen representing major categories of land use in the region: rangeland, mixed cropping, alfalfa (*Medicago sativa* L.) production, tree plantations, and a silvopastoral system. For photos of four of these sites, see Figure SM1 (in the online version at [doi:10.1016/j.rama.2016.10.005]). Although it was realized at the outset that 3 yr is a short time frame in which to detect changes in soil C, N, or P status, it was expected that major trends relevant to land use planning would be detectable within this time frame, with additional information available from comparing soil parameters of sites with different land uses. In all, > 3 000 soil samples were analyzed.

Materials and Methods

Site Characteristics

The research was conducted in Huanxian County, Gansu Province, with the 11 selected sites located near a village named Tianshui (37.1°N, 106.8°E) and dispersed over a distance of approximately 1

km. Mean annual precipitation at this locality is 359 mm, with 1 993 mm annual evaporation. Mean annual temperature is 7.1°C, but there is a long cold winter (frost-free period 125 d) and a hot summer (mean of 3 097°C days above 10°C). The region is notable for the occurrence of sometimes steep-sided river gullies cut 100 m or more into a deep blanket of loess. Over past centuries, many gullies have been terraced to facilitate crop production. Crop production is also carried out on valley floors and gently rolling terrain, and the resulting landscapes are spectacular to view.

Vegetation and Farming Systems

Anecdotal information suggests the region was originally forested with a major land clearance event about 1 000 yr ago (Y. Li personal communication) but for all intents and purposes, the current natural vegetation is a steppe grassland classified as a “typical temperate steppe” under the “comprehensive and sequential classification system of grassland” (Ren et al., 2008). Overgrazing, overpopulation, and improper land reclamation have caused severe rangeland degradation in this area (Hou and Nan, 2006; Hou et al., 2008). The dominant plant species occurring in the rangeland include *Stipa bungeana* Trin, shrubby lespedeza (*Lespedeza bicolor* Turcz.), wormwood (*Artemisia capillaries* Thunb.), flaccid grass (*Pennisetum flaccidum* Griseb.) and green bristle grass (*Setaria viridis* [L.] P. Beauv.). This locality can be regarded as typical of a wide area of the Loess Plateau.

The cropping systems at the study sites are mostly unirrigated, though crop production is often concentrated on the lower slopes, where soil moisture levels are augmented by runoff from higher slopes during rainfall events. Soil moisture stored in this way is an important determinant of crop yields. The common crops planted are winter wheat (*Triticum aestivum* L.), potato (*Solanum tuberosum* L.), and buckwheat (*Fagopyrum esculentum* Moench) in rotation, with yr-to-yr variation in rainfall being a factor influencing sowing date and the rotation sequence. Typical crop husbandry regimes involve spreading of 3 000 kg ha⁻¹ treated animal manure on the surface before harrowing of soil for seed bed preparation and chemical fertilizer application by hand (e.g., 250 kg ha⁻¹ urea for winter wheat, 150 kg ha⁻¹ urea for buckwheat, and 225 kg ha⁻¹ ammonium phosphate for potato crops). After harvest, crop residues are also generally recovered for use as a winter heating fuel or as a part ration for livestock. Alfalfa is widely grown on the Loess Plateau, often in conjunction with the cropping systems (Zhang et al., 2014), and because of its deep tap root and reputed water use efficiency, it has a high tolerance of the severe climate conditions (Bodner et al., 2015).

Agroforestry is another significant land use on the Loess Plateau, a common system being the intercropping of white poplar (*Populus* spp.) with alfalfa (Zeng et al., 2010). This land use has increased since 2003, when the Chinese government launched the “Grain to Green Project” to increase the vegetation coverage on sloping and fragile cropland through planting trees or sowing grasses on former cropland (Chen et al., 2008; Liu et al., 2008).

Finally, silvopastoral systems have been established on former rangeland from the 1970s by planting trees on rangeland with the objective of reducing soil erosion and increasing soil water holding capacity. The main tree species used are white poplar and elm (*Ulmus pumila* L.), and forage under the trees has until recently been used to feed a range of livestock including sheep, goats, cattle, and donkeys. However, the bans on grazing of rangeland mentioned earlier generally now extend to silvopastoral plantations as well.

Site Selection

As a benchmark for our soil inventory, a rangeland (RL) site considered to be typical for the area and also of the greater Loess Plateau was selected as sampling site. To compare soil characteristics of the rangeland with those of cropped land, three separate fields (C1, C2, and C3)

	2006												2007												2008												2009											
	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S
C1	Fallow				Potato				Winter wheat				Winter wheat				Fallow																															
C2	Fallow				Buckwheat				Fallow				Potato				Fallow				Potato																											
C3	Winter wheat				Fallow				Fallow				Potato				Fallow				Buckwheat																											

Figure 1. Crop rotation sequences over the data collection period for the three cropping sites: C1, C2, and C3.

were selected for measurement. The crop rotations for the three fields sampled are shown in Figure 1.

To represent the various common uses of alfalfa on the Loess Plateau, a field of alfalfa was selected (AA), with the field in question having been converted from cropland under the Grain to Green Project in 2003. Over the study period the field was harvested twice each yr in June and September to near ground level for livestock feeding and hay. Also selected for measurement were three alfalfa leys within agroforestry systems involving intercropping of alfalfa and poplar and established in 2002, 2000, and 1998 (AP1, AP2, AP3), converted from former croplands, and one poplar row within one of these systems (AP). Finally, two silvopastoral systems, one using elm and the other using poplar, were also selected for measurement (SE, SP).

For each of the 11 sampling sites described earlier, 3 permanently identified subsites were designated, spaced approximately equidistant across the site, making a total of 33 discrete locations (details later) for sample collection, in each of the 3 yr that data were collected.

Soil Sampling and Analysis

The 3 subsites of the 11 sampling sites described earlier (RL, C1, C2, C3, AA, AP1, AP2, AP3, AP, SE, and SP) were each sampled in August of 2006, 2008, and 2009, except that C1 was not sampled in 2008 nor C2 in 2009, when those 2 paddocks were fallow.

In each case, 5 soil cores from each of the 10 soil depths (10-cm progressive increments to a depth of 100 cm) were collected from core holes arranged in a “Z” pattern (cores at 4 corners and center) with an ≈ 40-m span. Cores so obtained were thoroughly mixed to produce one composite sample for each depth at each of the discrete sampling sites in all 3 yr. The soil samples for laboratory analysis were air-dried and then ground to pass through a 0.2 mm sieve.

Soil bulk density was measured in 2006 at each of the 10 soil depths of each site using volumetric rings (100 cm³). Samples were dried at 105°C > 72 hr, with 3 replicates. SOC was measured by the K₂Cr₂O₇-H₂SO₄ oxidation method of Walkey and Black (Nelson and Sommers, 1982). Briefly, a known weight of soil sample was treated with potassium dichromate in the presence of concentrated sulfuric acid. The

sample was slowly digested at a low temperature, and the excess of potassium dichromate not reduced by the organic matter was titrated back against a standard solution of ferrous sulfate. The soil SOC was then calculated on the basis of the quantity of ferrous sulfate consumed. Total soil Kjeldahl nitrogen (TN) and total soil phosphorus (TP) were analyzed using a FIAstar 5000 flow injection analyzer (Foss Tecator, Högnäs, Sweden). All data were converted to units of Mg ha⁻¹ on the basis of site- and depth-specific soil bulk density values measured in 2006.

Statistical Analysis

The data set has a total of 2 790 observations, and no missing values apart from the samples missed in 2008 and 2009 when C1 and C2 sites, respectively, were fallow. Effects needing to be accounted for in the model for each of the 3 soil parameters (SOC, TN, and TP) were the 11 sites, 3 replicates within sites (each site-replicate sample aggregated from the 5 randomly placed core holes), repeat samplings over 3 yr, and 10 soil depths for each of the soil cores. In the first instance, to overview the data, an analysis of variance (ANOVA) to determine site differences in SOC, TN, and TP to 100-cm soil depth in 2006 was performed. Next, to accommodate the structure of the full data set, data for SOC, TN, and TP were each analyzed using a repeat measures analysis in SAS Proc GLM (SAS Inst. Inc., Cary, NC), with site and replicate within site as classifier variables. The 10 soil depths were taken as the repeat measures provided for in the SAS procedure. Since the repeat measures feature of the SAS GLM repeat measures procedure was already allocated to soil depths, to account for the repeat measurements in successive years at the same site, time (yr of sample collection coded as 0 for 2006, 2 for 2008, and 3 for 2009) was added to the model as a linear regression term. Coefficients representing the linear change over time relative to RL as a benchmark were obtained by entering RL as the last site in the dataset and appending the SAS programming code “/solutions SS3” to the model statement. This code also generates standard errors and significance levels for the coefficients.

After trial analyses examining all 10 soil depths separately for the 3 soil measures (not presented), data were aggregated for parsimony and succinctness of presentation into 4 depth bands of 0–20 cm, 20–40 cm, 40–70 cm, and 70–100 cm (Table 1). These groupings were felt to capture

Table 1

Overview of results of statistical analysis of the full data set of 2 970 observations for total nitrogen (TN) and total phosphorus (TP). A repeat measures model in Proc GLM of SAS was used with data for different soil depths taken as the repeat measures (lower panel of results below). To also cater for repeat measures in time in the same data, the yr of sample collection was included in the model as a linear regression term (upper panel of results below).

Term	SOC	TN	TP
Linear effect of yr (1 df)	NS	NS	NS
Site (10 df)	14.34 (< 0.001)	11.49 (< 0.0001)	11.23 (< 0.0001)
Site × yr (10 df)	7.70 (< 0.0001)	16.83 (< 0.0001)	12.80 (< 0.0001)
Replicates within sites (22 df)	NS	1.81 (0.042)	NS
Error df = 49			
Depth (3 df)	267.9 (< 0.0001)	125.46 (< 0.0001)	3.78 (0.0120)
Depth × yr (3 df)	4.52 (0.0076)	10.76 (< 0.0001)	3.25 (0.0236)
Depth × Site (30 df)	20.89 (< 0.0001)	10.76 (< 0.0001)	4.07 (< 0.0001)
Depth × Site × yr (30 df)	7.39 (< 0.0001)	5.35 (< 0.0001)	4.71 (< 0.0001)
Depth × replicate within site (66 df)	NS	NS	NS
Error df = 147			
R ² 0-20 cm depth	0.881	0.820	0.787
R ² 20-40 cm depth	0.804	0.907	0.884
R ² 40-70 cm depth	0.918	0.907	0.875
R ² 70-100 cm depth	0.950	0.849	0.748
R ² 0-100 cm depth	0.911	0.916	0.865

SOC indicates soil organic carbon; df, degrees of freedom; NS, not significant.

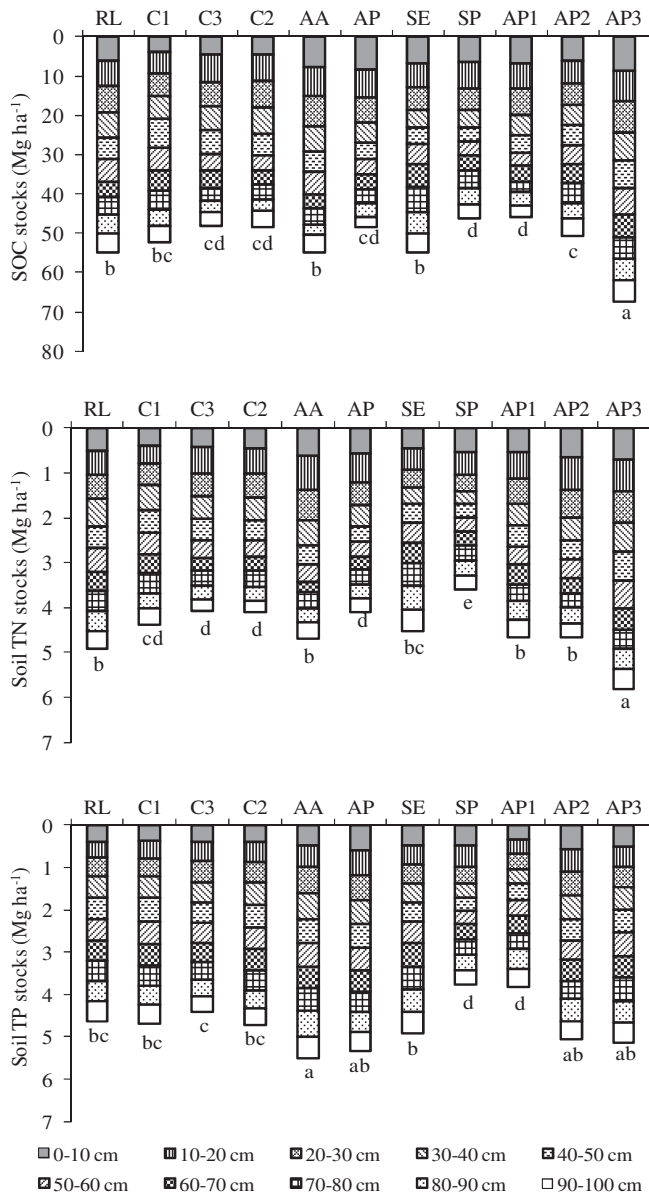


Figure 2. Distribution of soil organic carbon (SOC), total nitrogen (TN), and total phosphorus (TP) in 10-cm soil depth increments to 1 m for the 11 sites described in Section 2.3. These sites were chosen to represent land use categories typical of China's Loess Plateau. Sites with the same letter below do not differ significantly at the 5% probability level for a total of 100-cm soil depth of SOC.

the site \times soil depth interactions for SOC, TN, and TP, which were observed in the full analysis of the 10 soil depths.

To assess associations among SOC, N, and P, data for each site in each yr were summed across the 10 soil depths and correlation coefficients calculated for the 93 data SOC, TN, and TP so obtained. Data were then entered into a principal component analysis (PCA) using the PCA command, and the principal component scores were evaluated for site and yr effects using the GLM command in Minitab version 16.0 (Minitab Inc., State College, PA).

Results and Discussion

Site Totals and SOC, TN, and TP Distribution with Soil Depth in 2006

Caution is required when interpreting these results because site history factors and other local factors besides land use may also have influenced the soil properties at any one site. Even so, results from site comparisons similar to these are commonly reported in the international

literature (Guo and Gifford, 2002), presumably because a controlled experiment would be prohibitively resource intensive and useful information can be extracted from such data.

Soils at the 11 sites when first sampled in 2006 showed variation between sites in total SOC, TN, and TP to 1 m depth, with mean values of 52.4 Mg ha^{-1} , 4.51 Mg ha^{-1} , and 4.99 Mg ha^{-1} for SOC, TN, and TP, respectively, and with lower fertility sites having values about 75–80% of those for higher fertility. For example, C2, C3, and SP sites had low values for all three soil measures, while AA, AP3, and RL sites had high values. Soil bulk density (data not presented) averaged 1.36 Mg m^{-3} and did not change with soil depth for the alfalfa and rangeland sites. However, cropped soils receiving animal manure had an average bulk density of 1.06 Mg m^{-3} in the 0- to 10-cm soil depth and 1.29 Mg m^{-3} in the 10- to 100-cm soil depth, while soils of the SP and SE systems had a bulk density averaging 1.28 Mg m^{-3} in the 0- to 50-cm soil depth and 1.19 Mg m^{-3} in the 50- to 100-cm soil depth.

A feature common to soils at all sites was the value in the surface layer that would be regarded as extremely low when compared with typical soils in most countries, but with a remarkably small decline from the surface to 1-m soil depth (Fig. 2). For example, for 44 soils of the world described by Table 2 of Batjes (1996), total SOC averages 116 Mg ha^{-1} (range 48–293) with on average 60% of the total SOC in the top 30 cm of the soil profile. The comparable figure for the study site (see Fig. 1) is 38% total SOC to 100 cm located in the upper 30 cm.

Statistical Modeling of the Full Data Set

Model *r*-squared values ranged from 0.748 to 0.950 and averaged 0.868 (see Table 1), indicating that the model accounted well for the variation in the data. The upper block of results in Table 1 effectively considers each core as a whole (93 cores), while the second block of results provides the “repeat measures” analysis of variation among the 10 depth segments of each core.

At the whole core level, highly significant site differences as seen in Figure 2 were reconfirmed for all three soil measures. Changes over time were detected, but for all three soil measures, the changes were site-specific as indicated by a nonsignificant linear effect of yr, but a highly significant site \times yr interaction (see Table 1). For the analysis of the soil depth data, the strongest statistical effects were as expected for soil depth, but there were also differences between sites in the depth distributions of SOC, TN, and TP, as reflected by highly significant depth \times site interactions for all three (see Table 1). In addition, there was evidence in the form of significant depth \times site \times yr interactions ($P < 0.0001$) that site-specific changes with time were also localized at particular depths. The agronomic details of these statistical results are elucidated as follows.

Finally, replicate-within-site effects were nonsignificant for SOC and TP and only just achieved significance at $P = 0.042$ for TN, while depth \times replicate-within-site interactions were all nonsignificant (see Table 1). This is an important point because it indicates that the three replicate clusters of five cores collected at each site in each yr gave consistent results.

Agronomic Interpretation of Statistical Results

Site and soil depth effects and the site \times soil depth interactions for SOC, TN, and TP averaged over 3-yr data collection, all indicated as highly statistically significant in Table 1, are reported in Table 2. The full data set confirms conclusions from Figure 2 but adds detail. Salient features are that SOC (0–100 cm) was lower at crop and silvopastoral sites compared with rangeland and alfalfa sites; TN was elevated below 40 cm soil depth in rangeland sites (with accumulation over time of urine deposited by grazing animals possibly a factor) and above 40-cm soil depth at alfalfa sites and was lower at cropping sites (especially 0- to 20-cm soil depth) and forestry sites (especially in the 20- to 70-cm soil depth). TP, compared with a maximum level recorded of $0.54 \text{ Mg TP ha}^{-1}$ in the 10-cm soil depth, which might be taken as “background” because there was depletion in the surface layers of the RL site reducing with depth, a similar but smaller depletion at the alfalfa sites, a depletion at all depths for the cropping sites, and depletion below 20-cm soil depth at the silvopastoral sites.

Table 2

General linear model site means for analysis of soil organic carbon, total nitrogen (TN), and total phosphorus (TP) data collected between 2006 and 2009 at 11 sites representing different land uses in China's Loess Plateau.

Site	Soil organic carbon				Nitrogen					Phosphorus					
	Soil depth (cm)				Soil depth (cm)					Soil depth (cm)					
	0-20	20-40	40-70	70-100	0-100	0-20	20-40	40-70	70-100	0-100	0-20	20-40	40-70	70-100	0-100
AA	7.05	4.8	4.8	3.68	54.7	0.69	0.62	0.35	0.34	4.67	0.5	0.61	0.55	0.64	5.77
AP1 estab. 2002	5.93	3.87	3.87	2.99	45.8	0.6	0.55	0.39	0.34	4.46	0.42	0.46	0.44	0.47	4.48
AP2 estab. 2000	5.32	4.92	4.92	4.53	50.7	0.64	0.54	0.44	0.38	4.79	0.46	0.46	0.44	0.49	4.63
AP3 estab. 1998	7.61	6.43	6.43	5.46	67.3	0.7	0.68	0.58	0.44	5.81	0.49	0.52	0.53	0.56	5.28
C1	5.75	5.97	5.97	4.28	51.5	0.4	0.5	0.46	0.38	4.31	0.4	0.47	0.52	0.44	4.63
C2	6.18	4.87	4.87	3.21	48.2	0.51	0.52	0.38	0.29	4.08	0.42	0.5	0.47	0.44	4.53
C3	6.71	4.23	4.23	3.89	49.4	0.5	0.46	0.37	0.31	3.94	0.44	0.52	0.47	0.38	4.46
AP	5.2	5.03	5.03	5.58	55	0.46	0.39	0.45	0.5	4.53	0.47	0.45	0.5	0.58	5.06
SE	4.81	3.66	3.66	4.08	46.2	0.53	0.32	0.31	0.33	3.6	0.49	0.38	0.32	0.39	3.87
SP	5.68	3.99	3.99	3.21	48.4	0.6	0.5	0.32	0.31	4.09	0.59	0.59	0.53	0.52	5.47
RL	6.65	5.05	5.05	4.7	54.9	0.52	0.59	0.48	0.44	4.96	0.39	0.48	0.5	0.52	4.76
Mean alfalfa	6.47	5.01	5.01	4.17	54.6	0.66	0.6	0.44	0.37	4.93	0.47	0.51	0.49	0.54	5.04
Mean crop	6.22	5.02	5.02	3.79	49.7	0.47	0.49	0.4	0.33	4.11	0.42	0.5	0.49	0.42	4.54
Mean silvopastoral	5.24	3.83	3.83	3.64	47.3	0.56	0.41	0.31	0.32	3.85	0.54	0.48	0.43	0.45	4.67
SE	0.19	0.22	0.13	0.11	1.02	0.02	0.02	0.01	0.02	0.11	0.02	0.01	0.01	0.03	0.12

Values for 0- to 100-cm soil depth are Mg ha^{-1} ; all other values are Mg ha^{-1} in the 10-cm soil depth.

In the SAS GLM procedure used to analyze the data, the coefficient for trend per yr applies to the last site entered, effectively making that site the benchmark for the analysis and the coefficients for the site \times yr effect express the trends at other sites relative to the benchmark site. In this study the RL site was entered last to give that site benchmark status against which to assess SOC, TN, and TP trends at the other sites. No discernible trends for the RL site were detected for any of the three measured parameters (Table 3). Site \times yr effects indicated in Table 1 are elucidated from the coefficients, indicating modeled rate of change ($\text{Mg ha}^{-1} \text{yr}^{-1}$) with time. These varied somewhat between sites within land use categories (Table 4). Coefficients that are statistically significant ($T > 2.01$, 49 degrees of freedom) include those for gain of SOC and TN at some alfalfa sites and loss of SOC and TN at cropping sites and the coefficient for loss of TP at cropping sites. The overall trends for this group of sites averaged for land use categories are for gain of SOC and TN at alfalfa sites and loss at cropping sites with tree sites showing a loss at one measured site and no change at two other measured sites (see Table 4). While it is felt by the authors that these trends are likely real because they are statistically significant at some sites and there is an apparent separation between site categories, further measurement over a longer time frame and a wider range of sites on the Loess Plateau is needed to confirm them. The implications of this data interpretation are briefly explored as follows.

Table 3

Statistical model coefficients and their t values, indicating annual change ($\text{Mg ha}^{-1} \text{yr}^{-1}$) in soil organic carbon (SOC), total nitrogen (TN), and total phosphorus (TP) to 100-cm soil depth.

Soil Measure	Coefficient ($\text{Mg ha}^{-1} \text{yr}^{-1}$)	SE	T statistic
SOC	0.8283	0.8136	1.0181
TN	0.1233	0.0841	1.4660
TP	0.1371	0.0982	1.3963

The T statistic has 49 degrees of freedom and a value of $T > 2.01$ is needed for significance at $P < 0.05$.

Table 4

Coefficients for annual change ($\text{Mg ha}^{-1} \text{yr}^{-1}$) in soil organic carbon (SOC) and total nitrogen (TN) to 100-cm soil depth, relative to the rangeland benchmark.

Land use category	No. of sites	Soil measure	Coefficient range ($\text{Mg ha}^{-1} \text{yr}^{-1}$)	SE	Mean change ($\text{Mg ha}^{-1} \text{yr}^{-1}$)
Alfalfa sites	4	SOC	-0.8379 to +0.9329	1.1506	+0.9982
		TN	+0.1284 to +0.2269	0.1190	+0.3139
Cropped sites	3	SOC	-6.5228 to +0.9367	1.2657	-1.4646
		TN	-0.3750 to -0.6578	0.1309	-0.3830
Tree sites	3	SOC	-5.7483 to +1.0541	1.1506	-0.4342
		TN	-0.0196 to -0.7669	0.1190	-0.1537

Mean change is overall change trend averaged for each land class (statistical significance not available).

The interest in PCA as a tool to analyze the relationship between the soil measures is that points of greatest difference between the data, each uncorrelated with the others, are identified from a series of correlated variables. In this case SOC and TN data aggregated for sites and years were highly correlated ($R = 0.827^{***}$) while SOC-TP and TN-TP correlations were lower though still highly significant ($R = 0.421^{***}$ and 0.436^{***} , respectively). In PCA, the three PCs generated all yielded statistically significant site effects on ANOVA. PC1 ordinated the sites according to higher or lower SOC, TN, and TP with site AP3 ranking highest and site SP ranking lowest (Fig. 2). PC2 had a high coefficient (0.884) for TP and negative coefficients for SOC (-0.343) and TN (-0.318), indicating 2 sites (AA and SP) where TP was higher than expected from SOC and TN values, possibly reflecting P fertilizer use at those sites. PC3 had coefficients indicating a higher N:SOC ratio for alfalfa sites AP1 and AP2 than for the other sites, which may reflect N fixation by the alfalfa crops at those sites. In agreement with the present results, Zhang et al. (2009) found that soil organic carbon and total nitrogen stocks were increased by 71.3% and 87.0% respectively, 10 yr after reed meadow was converted to alfalfa pasture.

However, site history likely also influences site data to some extent. For example, total SOC (0- to 100-cm soil depth) ranged from 45.8 to 67.3 Mg ha^{-1} for the alfalfa sites AP1, AP2, and AP3 and these sites were intentionally chosen to provide a series of different stand ages. AP1 was planted in 2002, AP2 in 2000, and AP3 in 1998. As shown in Table 2, the older stand, AP3, has the highest SOC and TN values and the youngest stand, AP1, the lowest values among this group of sites. For any future studies to reconfirm these findings for other localities on the Loess Plateau, collection of land-use history data that might explain site-to-site variation would therefore be advantageous.

The loss of soil C and N in cropping operations is well known worldwide and the subject of extensive literature. For example, Leifeld and Kögel-Knabner (2005) reported for 0- to 30-cm soil depth in permanent grassland of southeastern Germany 24.6 g SOC kg^{-1} soil compared with

11.7–14.7 g SOC kg⁻¹ soil in arable systems. Corresponding values for TN were 2.4 g kg⁻¹ soil in grassland and 1.4–1.5 g kg⁻¹ in the arable systems. Similarly, Guo and Gifford (2002) found that when cropland was changed to plantation and secondary forest, soil carbon stocks increased by 18% and 53%, respectively, while Chen and Li (2003) found that soil lost about 80% of C and 37% of P when a primary Korean pine forest was converted to potato cropland.

Loss of soil C and N following tree planting is less well known but supported by the literature. For example, Ross et al. (1999) reported 172 g total C kg⁻¹ soil under pasture for 0- to 20-cm soil depth and 136 g total C kg⁻¹ soil under a 19-yr-old pine plantation in New Zealand. In the same study values for soil total N were 10.0 g kg⁻¹ (0- to 20-cm depth) under pasture and 6.8 g kg⁻¹ under pine trees. Similarly, Hu et al. (2008) reported that Mongolian pine (*Pinus sylvestrus* var *mongolica* Litv.) and poplar (*Populus simonii* Carrière) both reduced soil C, often by more than 5 Mg ha⁻¹ (0- to 60-cm soil depth), compared with grassland.

Implications for Policy and Scaling Up to Regional Level

A summary of the data from our study appears to show that rangeland and alfalfa pastures converted from cropland between 1998 and 2002 have increased storage of SOC and N compared with former cropland now converted to silvopastoral or agroforestry and compared with land still being cropped (see Fig. 3). It follows that both rangeland and alfalfa pastures would be expected to lose SOC and N if planted in trees or cropped. The implications for longer-term policy development for restoration of overgrazed rangeland now seen in many parts of the Loess plateau (Kemp et al., 2011) are that the optimal strategy is likely to involve a rotation with periods of alfalfa planting to replenish soil C and N stocks depleted by other land uses. In this case, providing animal

Table 5

Coefficients used in calculations of potential impact of land use change when scaling up present results to regional level.

Calculation entity	Value assumed
Area of less plateau	640 000 km ²
Land use shift to alfalfa	3%
Difference between tree and alfalfa trend (see Table 4)	1.432 Mg ha ⁻¹ yr ⁻¹
Soil organic carbon trend assumed for scaling up purposes	0.5 Mg ha ⁻¹ yr ⁻¹
CO ₂ equivalence factor for soil organic carbon	3.66 kg kg ⁻¹
SOC sequestration potential based on above assumptions	3.51 Tg yr ⁻¹
Grazeable yield of alfalfa	6.0 Mg ha ⁻¹ yr ⁻¹
Annual intake of a sheep	0.75 Mg forage dry weight animal ⁻¹
Annual intake of a dairy cow	5 Mg forage dry weight animal ⁻¹

stocking rates is not so high as to cause depletion of aboveground herbage cover. From a soil conservation perspective, grazing (now banned following widespread overgrazing with resulting erosion damage) would be a viable land use.

Native rangeland conversion into forest in the Loess Plateau of north-western China has been presumed to be beneficial and supported by policy in many districts. Land areas converted over the past 30 yr are quite large. This is a sound policy if the priority is to provide for future requirements for timber. However, if the priority is to provide long-term environmental benefit, the C sequestration and associated animal production opportunities from planting alfalfa might be attractive. The present results need to be interpreted with caution as they are from a single locality within the Loess Plateau. However, if the C sequestration at alfalfa sites in the present study can be confirmed at other localities on the Loess Plateau,

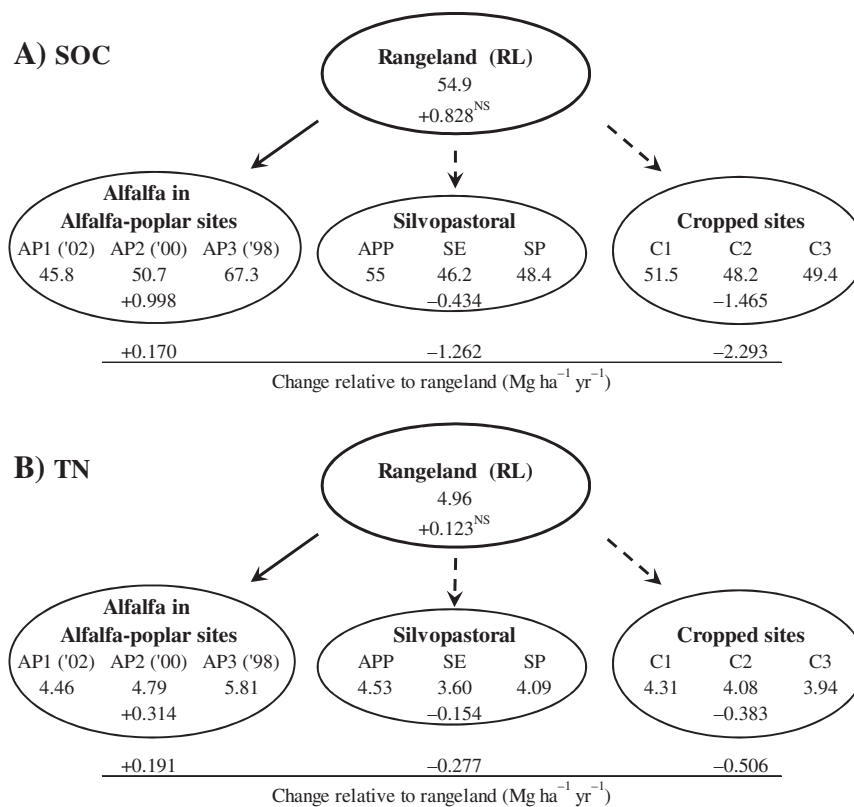


Figure 3. Comparison of (A) soil organic carbon (SOC) and (B) total nitrogen (TN) for 11 sites in this study. SE denotes silvopastoral with elms, and SP indicates silvopastoral with poplars. Ellipses represent a land use category and contain site identifier codes for the sites in that category (with yr established for alfalfa-poplar sites), total SOC or TN for 0- to 100-cm soil depth for each site (Mg ha⁻¹), and the mean trend observed in this study (Mg ha⁻¹ yr⁻¹) for the sites in each land class. For sequestration of SOC and increase in TN, the sites rank as follows: alfalfa (positive) > rangeland > silvopastoral > cropping (negative). Dashed arrows denote a significant trend for reducing soil status during the current study, at least for one site in the indicated category as quantified in Table 4.

then alfalfa planting should enhance C sequestration more than tree planting. Using a conservative value for the potential C sequestration under alfalfa planting and relevant data and coefficients for a simple estimate (see Table 5), it can be calculated that a 3% shift in land use in the Loess Plateau toward alfalfa would provide a C sequestration potential of 3.5×10^6 Tg CO₂ yr⁻¹, enough to offset the CO₂ emissions of a small country like Iceland or Nepal, while the area of alfalfa in question has the potential to support a significant livestock industry likely to enhance food supply security and regional economic development. This information is likely to be relevant for land use planning in other countries in greater Asia.

Conclusion

The agricultural systems of the Loess Plateau have endured for at least a millennium despite extremely low storage of SOC, TN, and TP; however, these systems involve extensive management to preserve the fragile environment.

While caution is needed because data are from a single locality, on the basis of these data, silvopastoral systems are less beneficial to rebuilding depleted soil C, N, and P stocks than previously supposed, whereas well-managed grazing systems based on alfalfa can sequester substantial amounts of C to the soil while also building soil N.

Current ecological policies established over the past 2 decades that place an emphasis on tree planting and a de-emphasis on grazing do create a green landscape but could be reviewed in light of these findings.

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.rama.2016.10.005>.

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