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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 Huaxian 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 main-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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1550-7424/© 2017 The Author(s). Published by Elsevier Inc. on behalf of The Society for Range Management. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).
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 McLaughlan 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 559 Pg 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, >3000 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 1993 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 lespedea (Lespedeza bicolor Turcz.), wormwood (Artemisia capillaries Thumb.), 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 urea 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)
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 agro-forestry 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 and 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 and C3 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 (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, 2003). Over the study period the difference 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 the nature 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

![Figure 1. Crop rotation sequences over the data collection period for the three cropping sites: C1, C2, and C3.](image-url)
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 × 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 × site interactions for all three (see Table 1). In addition, there was evidence in the form of significant depth × site × 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 × 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 × 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 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 RI 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.

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**Results and Discussion**

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

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).

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**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.
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 × 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 4). Site × yr effects indicated in Table 1 are elucidated from the coefficients, indicating modeled rate of change (Mg ha⁻¹ 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 the coefficients indicating a higher N:SOC ratio for alfalfa sites AP1 and AP2 than for the other sites, which may reflect the trends at other sites relative to the benchmark site. 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.

For example, total SOC (0- to 100-cm soil depth) ranged from 45.8 to 63.7 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 34.7 g SOC kg⁻¹ soil prepared with N fertilizer 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.

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### Table 2

<table>
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<tr>
<th>Soil organic carbon</th>
<th>Nitrogen</th>
<th>Phosphorus</th>
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<td>Soil depth (cm)</td>
<td>Soil depth (cm)</td>
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<tr>
<td>Site</td>
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<tr>
<td>AA</td>
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</tr>
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</tr>
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<td>Mean crop</td>
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### Table 3

<table>
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<th>Soil Measure</th>
<th>Coefficient (Mg ha⁻¹ yr⁻¹)</th>
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<th>T statistic</th>
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<td>TN</td>
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<td>TP</td>
<td>0.1371</td>
<td>0.0982</td>
<td>1.3963</td>
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</tbody>
</table>

The T statistic has 40 degrees of freedom and a value of T > 2.01 is needed for significance at P < 0.05.

### Table 4

<table>
<thead>
<tr>
<th>Land use category</th>
<th>No. of sites</th>
<th>Soil measure</th>
<th>Coefficient range (Mg ha⁻¹ yr⁻¹)</th>
<th>SE</th>
<th>Mean change (Mg ha⁻¹ yr⁻¹)</th>
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<tbody>
<tr>
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<td>4</td>
<td>SOC</td>
<td>-0.8379 to +0.9329</td>
<td>1.1506</td>
<td>+0.9982</td>
</tr>
<tr>
<td>Cropped sites</td>
<td>3</td>
<td>TN</td>
<td>+0.1284 to +0.2269</td>
<td>0.1190</td>
<td>+0.3139</td>
</tr>
<tr>
<td>Tree sites</td>
<td>3</td>
<td>TN</td>
<td>-0.3750 to -0.6578</td>
<td>0.1309</td>
<td>-0.3830</td>
</tr>
</tbody>
</table>

Mean change is overall change trend averaged for each land class (statistical significance not available).
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 sylvestris 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. In the present study, we can calculate that the C sequestration potential based on above assumptions would be a viable land use.

Native rangeland conversion into forest in the Loess Plateau of northwestern 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, stocking rates are not so high as to cause depletion of aboveground herbaceous cover. From a soil conservation perspective, grazing (now banned following widespread overgrazing with resulting erosion damage) would be a viable land use.

<table>
<thead>
<tr>
<th>Calculation entity</th>
<th>Value assumed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area of less plateau</td>
<td>640 000 km(^2)</td>
</tr>
<tr>
<td>Land use shift to alfalfa</td>
<td>3%</td>
</tr>
<tr>
<td>Difference between tree and alfalfa trend (see Table 4)</td>
<td>1.432 Mg ha(^{-1}) yr(^{-1})</td>
</tr>
<tr>
<td>Soil organic carbon trend assumed for scaling up purposes</td>
<td>0.5 Mg ha(^{-1}) yr(^{-1})</td>
</tr>
<tr>
<td>CO(_2) equivalence factor for soil organic carbon</td>
<td>3.66 kg (\text{kg}^{-1})</td>
</tr>
<tr>
<td>SOC sequestration potential based on above assumptions</td>
<td>3.51 Tg yr(^{-1})</td>
</tr>
<tr>
<td>Grazable yield of alfalfa</td>
<td>6.0 Mg ha(^{-1}) yr(^{-1})</td>
</tr>
<tr>
<td>Annual intake of a sheep</td>
<td>0.75 Mg forage dry weight animal(^{-1}) yr(^{-1})</td>
</tr>
<tr>
<td>Annual intake of a dairy cow</td>
<td>5 Mg forage dry weight animal(^{-1})</td>
</tr>
</tbody>
</table>

**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 \(3.5 \times 10^6\) Tg CO\(_2\) yr\(^{-1}\), enough to offset the CO\(_2\) 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.

**References**


