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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 km^2 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 CO_2 per yr, although some caution is needed in making extrapolations, as the present data are from a single locality on the Loess Plateau.

Introduction

The Loess Plateau is an eco-region of northern China approximately 640 000 km^2 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 CO_2 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)