Effects of long-term cultivation practices and nitrogen fertilization rates on carbon stock in a calcareous soil on the Chinese Loess Plateau (Postprint)

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Abstract

Soil organic carbon (SOC) and soil inorganic carbon (SIC) are important C pools in the Loess Plateau of Northwest China, however, variations of SOC and SIC stocks under different cultivation practices and nitrogen (N) fertilization rates are not clear in this area. A long-term field experiment started in June 2003 was conducted to investigate the SOC and SIC stocks in a calcareous soil of the Chinese Loess Plateau under four cultivation practices, i.e., fallow (FA), conventional cultivation (CC), straw mulch (SM), and plastic film-mulched ridge and straw-mulched furrow (RF), in combination with three N fertilization rates, i.e., 0 (N0), 120 (N120), and 240 (N240) kg N/hm2. Results indicate that the crop straw addition treatments (SM and RF) increased the contents of soil microbial biomass C (SMBC) and SOC, and the SOC stock increased by 10.1%-13.3% at the upper 20 cm soil depth in comparison to the 8-year fallow (FA) treatment. Meanwhile, SIC stock significantly increased by 19% at the entire tested soil depth range (0–100 cm) under all crop cultivation practices in comparison to that of soil exposed to the long-term fallow treatment, particularly at the upper 60 cm soil depth. Furthermore, moderate N fertilizer application (120 kg N/hm2) increased SOC stock at the upper 40 cm soil depth, whereas SIC stock decreased as the N fertilization rate increased. We conclude that the combined application of crop organic residues and moderate N fertilization rate could facilitate the sequestrations of SOC and SIC in the calcareous soil.

Full Text

Preamble

Effects of Long-term Cultivation Practices and Nitrogen Fertilization Rates on Carbon Stock in a Calcareous Soil on the Chinese Loess

Plateau

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Abstract

Soil organic carbon (SOC) and soil inorganic carbon (SIC) represent important carbon pools in the Loess Plateau of Northwest China, yet variations in SOC and SIC stocks under different cultivation practices and nitrogen (N) fertilization rates remain unclear in this region. A long-term field experiment initiated in June 2003 was conducted to investigate SOC and SIC stocks in a calcareous soil of the Chinese Loess Plateau under four cultivation practices—fallow (FA), conventional cultivation (CC), straw mulch (SM), and plastic film-mulched ridge and straw-mulched furrow (RF)—in combination with three N fertilization rates: 0 (N0), 120 (N120), and 240 (N240) kg N/hm^2. Results indicate that crop straw addition treatments (SM and RF) increased soil microbial biomass C (SMBC) and SOC contents, with SOC stock increasing by 10.1%-13.3% in the upper 20 cm soil depth compared to the 8-year fallow treatment. Meanwhile, SIC stock significantly increased by 19% across the entire tested soil depth range (0-100 cm) under all crop cultivation practices compared to the long-term fallow treatment, particularly in the upper 60 cm soil depth. Furthermore, moderate N fertilizer application (120 kg N/hm^2) increased SOC stock in the upper 40 cm soil depth, whereas SIC stock decreased as N fertilization rate increased. We conclude that the combined application of crop organic residues and moderate N fertilization rates could facilitate the sequestration of both SOC and SIC in calcareous soils.

Keywords: calcareous soil; cultivation practices; N application rate; soil C stock; Loess Plateau

1 Introduction

Soil contains approximately 75% of the terrestrial carbon pool in the form of soil organic carbon (SOC) and soil inorganic carbon (SIC). Changes in soil C stock may exert significant effects on the global carbon budget and atmospheric CO mitigation (Lal, 2004). Increasing the soil C pool by 1 Pg is equivalent to reducing atmospheric CO concentration by 0.47 ppm, and vice versa (Lal, 2007).

Globally, the estimated SOC stock ranges from 1200 to 1600 Pg in the top 1 m soil depth, containing more than twice the quantity of carbon present in vegetation or the atmosphere (Eswaran et al., 1993; Sombroek et al., 1993; Batjes, 1996). However, SIC represents the dominant form of carbon in arid and semi-arid areas covering one-third of Earth’ s land surface. Estimates of the global SIC pool in the top 1 m soil depth vary widely from 695 to 1738 Pg (Batjes, 1996; Zhang et al., 2015), indicating the need for further investigation to reduce this uncertainty.

Soil and crop management practices such as tillage, mulching, and fertilization can significantly alter above- and below-ground crop biomass production, thereby modifying carbon accumulation in soil (Gwenzi et al., 2008; Liang et al., 2012; Li et al., 2013). For example, mulching with crop organic residues exerts numerous beneficial influences on soil characteristics (Sainju et al., 2005; Lal, 2007), while removing crop residues from fields reduces carbon input and accumulation (Lemke et al., 2010). Additionally, plastic film mulch is widely used to conserve soil moisture and maintain temperature in rain-fed farmland; however, film mulching has been shown to decrease SOC stock by accelerating soil carbon mineralization (Song et al., 2002). The effect of N fertilization on the SOC pool has also been extensively studied. While N fertilizer application can increase SOC stock, this increase typically occurs only when crop organic residues are returned to the field (Alvarez, 2005). The influence of N addition on SOC sequestration remains controversial, with reported effects ranging from positive (Regmi et al., 2002) to negligible (Khan et al., 2007) and even negative impacts (Körner and Arnone, 1992).

In contrast to SOC, SIC is often considered much more stable and less sensitive to agricultural practices. However, growing evidence indicates that agricultural practices can fundamentally alter the inorganic carbon cycle in soil (Mikhailova and Post, 2006; Chang et al., 2012; Hurisso et al., 2013). The total loss of SIC in China caused by extensive human activities has been estimated at approximately 1.6 Pg C, with the most significant SIC loss observed in expansive cultivated areas in eastern northern China dominated by dry farmland and irrigated paddy fields. In contrast, SIC stock has increased by approximately 10% in irrigated areas of northwestern China (Wu et al., 2009). Reports indicate that SIC stock can change at rates similar to or greater than SOC stock (Sanderman, 2012). However, the processes underlying SIC accumulation and loss differ from those governing SOC and have seldom been investigated. Therefore, the effect of human activity on the SIC pool warrants further study.

SOC and SIC represent important carbon pools in the Loess Plateau of Northwest China. Significant erosion has resulted in extensive SOC removal, and the density and stock of SIC in Loess Plateau soils are approximately 2.2 and 2.1 times greater, respectively, than those of SOC (Tan et al., 2014). The southern Loess Plateau constitutes one of the birthplaces of Chinese agriculture; carbonized grain discovered in Banpo Village, Xi’ an City, has been dated to 5600-6080 years old (Gong et al., 1999). Farmers in this region have used fertilizer containing loess mixed with manure to improve soil fertility for millennia, forming an anthropogenic surface layer designated as Lou soil (Terric Anthrosols) over the zonal soil (Cinnamon soil) layer (Zhu, 1964) and increasing SOC and SIC contents in topsoil (Dong et al., 2013). The amount of N fertilizer applied in Chinese agriculture has increased rapidly over the past 30 years (Cui et al., 2013), resulting in environmental problems including soil acidification, groundwater pollution, widespread eutrophication, and nitrous oxide emissions (Khan et al., 2007; Ju et al., 2009; Guo et al., 2010; Zhang et al., 2013). Similar situations prevail in northern China, including the Loess Plateau. In northern China, soil pH under cereals and cash crops decreased by 0.27 and 0.58, respectively, from the 1980s to the 2000s (Guo et al., 2010), which may affect SIC stabilization. However, studies on the effects of long-term N application on SIC stock in calcareous soils remain scarce. Therefore, the objective of this study was to determine the effects of cultivation practices and N fertilization rates on SOC and SIC stocks in a calcareous soil of the Chinese Loess Plateau.

2.1 Study Area

A long-term crop rotation experiment was initiated in June 2003 at Northwest A&F University, Yangling, Shaanxi Province, on the southern edge of the Loess Plateau, China (34°17 56 N, 108°04 07 E). The experimental site features a temperate, semi-humid climate at an elevation of 523 m, with an annual mean temperature of 13°C, annual potential evaporation of 1400 mm, and annual precipitation of 600–650 mm, with approximately 60% of precipitation occurring between July and September. The calcareous, clay loam soil at the site is known locally as "Lou soil" and is classified as Terric Anthrosol in the World Reference Base (WRB) for Soil Resources. The main chemical properties of the surface soil (0–20 cm) prior to planting in 2003 were: pH, 8.25; organic C, 8.83 g/kg; total N, 0.67 g/kg; Olsen-P (phosphorus), 17.2 mg/kg; and NH OAc-K (potassium), 169.4 mg/kg.

2.2 Experimental Design

The study employed a completely randomized split-block design. The three main treatments were (1) conventional cultivation (CC), (2) straw mulch (SM), and (3) plastic film-mulched ridge and straw-mulched furrow (RF). The sub-plot treatments were three N fertilization rates: 0 (N0), 120 (N120), and 240 (N240) kg N/hm^2. Each treatment was replicated four times. One fallow (FA) plot was included as a control. Plot size was 4.0 m × 4.5 m. A cropping rotation system comprising winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.) was used.

The CC treatment received no straw or plastic film mulch. Wheat under CC received 40 mm of flood irrigation in winter. Maize was irrigated at the early growing stage after planting to promote plant growth; the amount of irrigation water varied annually (from 0 to 60 mm) depending on rainfall. During reproductive stages, maize depended entirely on rainfall to meet water requirements. For SM and RF treatments, wheat received no irrigation, whereas maize received half the irrigation rate of CC maize. The SM treatment was mulched with 4500 kg/hm^2 of air-dried crop residues. Wheat straw was used to mulch both wheat and maize from 2003 to 2007. Since 2008, wheat crops were mulched with maize residue, while maize crops were mulched with wheat straw. Residues were cut into pieces (approximately 5 cm in length) and applied 60 days after seedling emergence. The RF treatment consisted of alternating ridges (30 cm wide and 15 cm high) and furrows (30 cm wide); furrows were mulched with 2250 kg/hm^2 of air-dried crop residues.

Wheat was sown in mid-October and harvested in mid-June of the following year. Nitrogen was applied as urea (46% N), while P fertilizer (80 kg P O /hm^2) was applied as superphosphate. No K fertilizer was applied. All fertilizers were spread uniformly across the soil surface and ploughed into the upper 15 cm soil depth before wheat sowing. Maize was planted by hand immediately after wheat harvest (without tilling the soil) and harvested in October. One-third of the added N fertilizer was applied at the seedling stage, while the remaining two-thirds were applied at the booting stage. A hoe was used to incorporate N fertilizer into the soil near seedlings. No P fertilizer was applied to maize-growing soil. Weeds were controlled with herbicides and removed by hand periodically (Zhou et al., 2011).

2.3 Soil Sampling

After maize harvest in October 2011, soil samples were collected at 20-cm intervals to a depth of 100 cm using a soil auger (5 cm in diameter). One core was collected from each plot in the CC, SM, and RF treatments, while four cores were collected from the FA plot as replicates. Coarse roots were removed from each soil sample. Subsamples were stored at 4°C for determination of soil microbial biomass C (SMBC) and soluble organic C (SSOC). Residual soil samples were air-dried and passed through a 0.15-mm sieve.

2.4 Analytical Methods

Gravimetric soil water content was determined by drying soil at 105°C for 12 h. SOC content was determined by the potassium dichromate wet oxidation method (Walkley and Black, 1934). Soil carbonate content was determined using a Chittick apparatus (Dreimanis, 1962). In the study region, soil carbonates were dominated by CaCO ; therefore, a factor of 0.12 (the ratio of the atomic mass of C to the molar mass of CaCO) was used to convert soil CaCO to soil inorganic C (Yang et al., 2012). SMBC content was determined by the chloroform fumigation extraction method (Vance et al., 1987). Fumigated and non-fumigated fresh soil samples were extracted with 0.5 mol/L K SO and shaken at 220 rpm for 30 min. Aliquots from the non-fumigated filtrates were used to determine SSOC. Soil pH was determined in a soil:water suspension (1:1).

2.5 Data Analysis

Soil C stock (TSC, Mg/hm²) at the 0-100 cm soil depth was calculated using the following equation:

$$SC = \sum_{i=1}^{n} SC_i \times B_i \times D_i \times 10^{-1}$$

where SC_i is the SOC or SIC content of the ith layer (g/kg); B_i is the soil bulk density of the ith layer (g/cm³); D_i is the thickness of the ith layer (cm) (e.g., 20 cm); 10^{-1} is the correction factor (m²/hm²); and n is the number of soil layers. Soil bulk densities at 0-20, 20-40, 40-60, 60-80, and 80-100 cm depths were 1.34, 1.57, 1.57, 1.52, and 1.50 g/cm³, respectively.

Cultivation practice and N fertilizer rate were analyzed together using split-plot ANOVA. Mean differences were compared by Duncan's test at $P < 0.05$. All statistical analyses were conducted using SAS version 8.1 for Windows. According to ANOVA results, no significant interactive effect existed between cultivation practice and N fertilization rate; therefore, interactive effects of these two factors on soil pH, SMBC, SSOC, SOC content, and SIC content were not analyzed or discussed.

3.1 Soil pH

The highest pH value occurred at the 40-60 cm depth, while the lowest pH value was observed at the 0-20 cm soil depth (Fig. 1 [Figure 1: see original paper]). Soil pH values did not vary significantly among CC, SM, and RF treatments, whereas FA treatment significantly decreased soil pH compared to CC treatment at the 60-80 cm soil depth. Over the 0-100 cm depth, the lowest pH value was found in soil subjected to the N240 treatment.

3.2 Soil Microbial Biomass C (SMBC) and Soil Soluble Organic C (SSOC)

SMBC and SSOC contents decreased with soil depth (Fig. 2 [Figure 2: see original paper]). SMBC content at 0-60 cm depth under SM and RF treatments was significantly higher than that in FA soil. SMBC content did not significantly differ among soil samples subjected to CC, SM, and RF treatments, except at the 0-20 cm depth. SSOC content in soil samples subjected to CC, SM, and RF treatments was greater than that in FA soil. N fertilization rates showed no distinct effect on SMBC or SSOC content at 0-60 cm soil depth. A significant positive correlation was found between SMBC and SSOC ($y = 0.176x + 0.064$, $P < 0.01$).

3.3 SOC and SIC Stocks

Approximately 50% of SOC stock accumulated in the upper 40 cm depth (Fig. 3a [Figure 3: see original paper]). At 0-20 cm depth, SOC stock increased by 3.4%, 13.3%, and 10.1% in soil samples subjected to CC, SM, and RF treatments, respectively, compared to FA soil. Similar to SOC stock, SIC stock at 0-40 cm depth accounted for 75.9%-78.8% of total SIC stock (Fig. 3b). Average SIC stock significantly increased by 7.6%-9.9% at 0-20 cm depth, 19.1%-24.6% at 20-40 cm depth, and 38.2%-39.6% at 40-60 cm depth in soil samples subjected to CC, SM, and RF treatments, respectively, compared to FA soil.

SOC stocks at 0-100 cm depth under different N application rates followed this decreasing order: N120 (86.3 Mg/hm^2) > N0 (85.3 Mg/hm^2) > N240 (84.3 Mg/hm^2) (Fig. 3c). Conversely, SIC stock decreased as N addition rate increased (Fig. 3d). At 0-100 cm depth, SOC stocks ranged from 83.7 to 85.8 Mg/hm^2 and did not significantly differ among fallow and tested cultivation treatments. SIC stocks ranged from 58.8 to 70.0 Mg/hm^2 among soil samples. SIC stock was significantly increased by 18.7% in soil samples subjected to crop cultivation treatments compared to FA soil (Fig. 4a [Figure 4: see original paper]). N fertilization rates did not affect SOC, SIC, or total carbon (TC) stock for the entire 0-100 cm soil depth (Fig. 4b). SOC content accounted for 54.3%-59.0% of TC within the 0-100 cm soil depth, whereas SIC content accounted for 41.0%-45.7%.

4.1 Effects of Cultivation Practices on Soil C Stocks

These findings agree with previous reports that SOC stock is primarily improved in the upper 15-30 cm soil layer by management practices such as crop rotation, N fertilization, and conservation tillage, whereas SOC accumulation in subsoil remains unaffected (Chen et al., 2009; Hernandez-Ramirez et al., 2009). As shown in Figures 3a and 4a, conventional crop cultivation slightly increased SOC stock compared to long-term fallow soil, especially at 0-20 cm depth, because more than 60% of crop root biomass was distributed in the upper 20 cm depth (Pausch et al., 2013a); additionally, more crop organic residue remained in the field as stubble under crop cultivation. Generally, organic residue constitutes the main source of soil organic carbon accumulation (Sainju et al., 1998). However, labile carbon exuded from roots can stimulate decomposition of recalcitrant soil organic materials (i.e., a priming effect), which counteracts the positive effects of roots on SOC sequestration (Prescott, 2010; Pausch et al., 2013b). Consequently, no distinct difference in SOC stock was found when comparing FA and CC treatments.

In contrast, straw mulch significantly increased SOC stock at 0–20 cm depth compared to both fallow and conventionally cultivated soil. Similar effects of crop residue return on SOC sequestration have been reported in other long-term experiments (Rasmussen et al., 1980; Lemke et al., 2010; Ghimire et al., 2012; Smith et al., 2012). For example, crop residue removal reduced cumulative carbon input from straw and roots by 13% over a 50-year experiment (Lemke et al., 2010). Therefore, maintaining crop residue on farmland represents an effective approach to sustain and improve soil organic matter input.

Under RF treatment, plastic film on ridges captures rainfall and directs runoff to furrows where crops are sown. Thus, plastic film mulching maximizes water efficiency while reducing soil evaporation and increasing soil temperature, advantages that have led to widespread use of plastic film mulching in Northwest China during the past 15 years (Li and Gong, 2002; Wang et al., 2005). However, some researchers have reported that SOC content decreased under plastic film mulching, particularly in the topsoil layer, because significantly increased soil temperature and moisture content accelerated organic carbon decomposition (Li et al., 2007; Bu et al., 2010). In this study, plastic film mulching improved SOC stock by 6.3% at 0–20 cm depth compared to conventional crop planting. Two explanations may account for this increase. First, for soil under plastic film mulching, crop straw was returned to furrows during each crop season at 2250 kg/hm², serving as an important source of soil organic matter. Second, wheat and maize yields increased under plastic film mulching (Li et al., 2007; Bu et al., 2010; Zhou et al., 2011), resulting in higher above- and below-ground biomass, which in turn increased soil organic matter. These results suggest that the combination of plastic film-mulched ridge and straw-mulched furrow could increase crop yield while conserving or increasing SOC stock.

In this study, more than 70% of SIC was distributed in the uppermost 40 cm soil depth (Fig. 3b). Compared to SIC stock in fallow soil, SIC stock at 0–100 cm depth significantly increased by 18.7% under crop cultivation treatments, with particularly significant increases in the upper 60 cm soil depth. These results align with previous reports (Entry et al., 2004; Wang et al., 2013). For example, monocropping or rotation of different crops increased SIC stock by 20%–26% compared to soil left fallow for 23 years (Li et al., 2010). SIC consists of two major components: lithogenic inorganic carbon (LIC) and pedogenic inorganic carbon (PIC). LIC represents inherited carbonate from soil parent material such as limestone, marl, and loess, while PIC forms through dissolution and precipitation of carbonate parent material without accompanying change in SIC stock (Schlesinger, 1985). In loess, carbonate is redistributed during pedogenic processes at the levels of soil aggregates, soil profiles, or landscapes, while formation of pedogenic inorganic carbonates depends on precipitation and dissolution of carbonates governed by the CO -H O-CaCO balance (Gocke et al., 2012; Sanderman, 2012). Two explanations are offered for the observed SIC stock increase induced by crop cultivation. First, bicarbonate ions formed from active biological respiration (including root and microbial respiration) during crop cultivation. Carbonate precipitation generally acts as a net sink for CO (Schlesinger, 1982) through the reaction SOC → CO (g) → CO (aq) → HCO → CaCO (s). In arid and semi-arid areas, 5%-10% of pedogenic carbonates derive from CO released by organic matter decomposition (Capo and Chadwick, 1999), and soil CO from microbial and root respiration represents the main factor controlling dissolution of primary carbonates and formation of secondary carbonates (Kuzyakov et al., 2006). Second, irrigation contributes to carbon sequestration in arid and semi-arid areas (Entry et al., 2004). In this study, irrigation was applied to crop cultivation plots every season but never to the fallow plot. Soil CO produced from plant biomass and microbial activity due to irrigation could serve as an important source for carbonate exchange. However, Ca^{2} and CO^{2} in irrigation water, along with high water pH, increase the dissolved HCO rate of carbonate recrystallization. Moreover, application of chemical fertilizer superphosphate to crop cultivation plots facilitated carbonate formation. A previous study showed that soil carbonate content increased by 27% after 40 years of irrigation compared to non-irrigated soil (Magaritz and Amiel, 1981). Another study showed that irrigation improved SIC stock slightly in loess soil in northwestern China (10% increase in the upper 0–30 cm depth) (Zhang et al., 2015).

4.2 Effects of N Fertilizer Rates on Soil C Stocks

SOC stock at 0–100 cm depth did not significantly differ among soils subjected to different N application rates (Fig. 4b), consistent with other studies (Barber, 1979; Neff et al., 2002; Holeplass et al., 2004). However, N addition either had limited effect on SOC stock or increased SOC stock in cropland soils in North America (Christopher and Lal, 2007). Maintenance and improvement of SOC stock relate to the amount of crop residues returned to the field, which is directly related to N application. N fertilizer significantly accelerated decomposition of light soil carbon fractions while further stabilizing carbon compounds in heavier, mineral-associated fractions, yet no significantly detectable change in total soil carbon bulk was observed (Neff et al., 2002). In tropical regions, N fertilizer resulted in no additional carbon sequestration, while in temperate regions it appeared to increase net carbon sequestration (Alvarez, 2005). In this study, total SOC stock within 0–100 cm depth was greatest under the 120 kg N/hm^2 treatment (86.3 Mg/hm^2), followed by the 0 kg N/hm^2 treatment (85.3 Mg/hm^2), while soil under 240 kg N/hm^2 contained the least SOC (84.3 Mg/hm^2) (Fig. 3c). However, these differences were not significant. Thus, we suggest that N fertilizer application in agricultural ecosystems should be adequate but not excessive to maximize economic profitability and ecological safety while minimizing negative effects on SOC accumulation.

SIC stock showed a decreasing trend as N application amount increased (Fig. 4b). In irrigated calcareous desert soil, 18 years of fertilization with manure and chemical fertilizers reduced SIC stock at 0–30 cm depth in a wheat-maize system (Zeng et al., 2008). This decreasing trend in SIC stock corresponded with decreased soil pH caused by N application. The lowest pH value in this study was measured in soil under 240 kg N/hm^2, demonstrating soil acidification driven by N fertilization (Fig. 1b). Although agricultural fields in northern China resist acidification due to relatively higher CaCO content (5%–10%), these fields were significantly acidified under cereals and cash crops (pH decreases of 0.27 and 0.58, respectively) (Guo et al., 2010). Previous research found that approximately 500 kg CaCO /hm^2 was required to neutralize each 50 kg/hm^2 of added ammonium-N (Blake and Goulding, 2002). The soil alkalization process is accompanied by carbonate dissolution and CO release to the atmosphere. Therefore, developing optimal N management strategies has become an urgent requirement for sustainable agriculture and carbon sequestration.

5 Conclusions

Compared with long-term fallow soil and soil under conventional crop cultivation, we found that soil with organic residue return showed a 10% increase in SOC stock in the upper 20 cm depth, along with increased content of labile carbon (SMBC and SSOC). Crop cultivation practices (CC, SM, and RF) also increased SIC stock by 19% compared to fallow soil across the entire 100 cm soil depth; this increase might be attributed to exchange and/or formation of pedogenic carbonates due to organic matter decomposition. Compared to soil without N fertilization, soil fertilized with 120 and 240 kg N/hm^2 showed no significant changes in SOC or SIC stock within the 100 cm soil profile. However, the reduction in soil pH across the entire 100 cm profile under the 240 kg N/hm^2 treatment implies that more attention should be paid to the effect of excessive N addition on soil acidification and inorganic carbon stock loss. We conclude that the combination of crop residue return and appropriate N fertilization could enhance SOC sequestration and SIC stabilization in calcareous soils of the Chinese Loess Plateau.

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Note: Figure translations are in progress. See original paper for figures.