Effects of fallow or planting wheat (*Triticum aestivum* L.) and fertilizing P or fertilizing P and N practices on soil carbon and nitrogen in a low-organic-matter soil

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1. Introduction

Soil organic matter (SOM) has many important functions, such as promoting crop growth, providing nutrients, retaining water, connecting pore spaces and nourishing organisms (Magdoff and Weil 2004). Various agricultural soil management regimes, including reducing tillage (Dalal et al. 2011), using a winter cover crop (Sainju et al. 2002), or altering soil inputs (e.g., fertilizers) (Rudrappa et al. 2006; Verma and Sharma 2007; Gong et al. 2009; Liang et al. 2011), can change the SOM concentration, influencing soil organic carbon (SOC) and soil organic nitrogen (SON) concentrations. For example, SOC has been shown to be sequestered by inorganic fertilizer nitrogen (N) input (Rudrappa et al. 2006; Verma and Sharma 2007; Gong et al. 2009; Liang et al. 2011). However, some studies have shown that inorganic N fertilizers have no effects on SOC content and its fractions (Sainju et al. 2002; Ogunwole 2005; Huang et al. 2010; Gentile et al. 2011).

The management of fallow, including bare fallow (BF; kept free of vegetation and organic amendments) and natural fallow (NF; vegetation is maintained and it grows naturally), also affects the SOC concentration. For example, BF significantly reduced the SOC fraction concentrations in the 0–7.5 cm soil depth compared with a no-fallow treatment during a 17-year field experiment in Brazil (Diekow et al. 2005), as well as decreasing the final total SOC concentrations compared with the initial values in six long-duration (> 30 years) BF experiments conducted in Europe (Barré et al. 2010). In contrast, management using NF has been shown to increase SOC concentrations in some soils (Diekow et al. 2005; Yang et al. 2012).

The light fraction (LF) of SOM represents a pool of SOM intermediate between labile pools of fresh crop residues and recalcitrant pools of humic materials. The size of the LF pool is considered to be a useful early indicator of SOM changes because of different management regimes (Gregorich and Ellert 1993), and it has been used to describe the effects of different agricultural practices, such as fertilization and fallowing, on SOM (Sainju et al. 2002; Liang et al. 2011;
Andruschkewitsch et al. 2013; Li et al. 2014). For example, light fraction carbon (LFC) at 0–15 cm soil depth increased by 84% in a Canadian long-term fertilized system, where the increase in light fraction nitrogen (LFN) was 100% (Campbell et al. 2001). The soil LFC was reported to be reduced by a 17-year BF in a sandy clay loam acrisol in Brazil (Diekow et al. 2005).

Soil microbial biomass is involved in the decomposition of organic materials and in nutrient cycling in soils. Soil microbial biomass carbon (MBC) accounts for only 1–3% of total soil carbon (C), while soil microbial biomass nitrogen (MBN) is only approximately 5% of total soil nitrogen (N). However, they are the most labile C and N pools in soils (Friedel et al. 1996), and, similar to the LF pool, they are frequently used as early indicators of changes in chemical and physical properties resulting from different soil management regimes (Moore et al. 2000; Devi and Yadava 2006; Liang et al. 2011).

The Loess Plateau is located in the upper and middle reaches of the Yellow River in China, covering approximately 640,000 km². The soil in this region is highly susceptible to soil erosion and is low in SOC. In most cases, a small quantity of or even no manure is applied to crop fields, and crop straw is removed from the fields for use as animal food or fuel. Thus, the average SOM concentration in this region’s agricultural soils is only 1.07%, which is much lower than that in the Southwest (4.66%) and Northeast (3.93%) of China (Wu and Cai 2006). Considering such conditions and based on previous studies, different agricultural management regimes, such as fallowing and fertilization, are expected to alter the SOM quality, influencing present and future soil fertility. Some field trials (Wu et al. 2004; Fan et al. 2008; Liang et al. 2011; Zhou et al. 2013) and studies (Han et al. 2010; Liu et al. 2011) have characterized SOM levels in this region, but most of them have focused on fertilization and did not consider the effects of either bare or natural fallowing on soil C and N fractions. Therefore, understanding the effects of soil management regimes on organic C and N in a low-SOM soil demands careful interpretations of changes in organic C and N fractions after different long-term treatments. Based on an 8-year trial, the objectives of the present study were (1) to evaluate the effects of four soil management regimes on different SOC and SON fractions, and soil inorganic C and N (nitrate- and ammonium-N); and (2) to provide suggestions for soil C and N management in dryland soils on the Loess Plateau and in similar areas worldwide.

2. Materials and methods

2.1. Experiment design

A field trial (2004–2012) was conducted using the typical management regimes employed by local farmers at the research farm of Northwest A&F University (34°17′59″N, 108°4′12″E), Yangling, Shaanxi Province, China. This area is located on the southern Loess Plateau at an elevation of approximately 520 m. The geomorphology is the third-level terrace of the Wei River (the biggest tributary of the Yellow River), and the field is a flat land with no water erosion. The subhumid and drought-prone climate makes this a typical rain-fed area in China, and winter wheat (Triticum aestivum L.) is one of the dominant cereal crops. The monthly temperature and rainfall during the experiment are shown in Fig. 1. The average annual rainfall is 550 mm, approximately 60% of which occurs in July, August and September, and the average annual temperature is 13°C. The soil type is classified as Eum-OOrthic Anthrosol (Food and Agriculture Organization of the United Nations (FAO); loess parent material) (Cooperative Research Group on Chinese Soil Taxonomy 2001; Gong et al. 2003). Some soil properties at the beginning of the experiment (September 2004) at a depth of 0–0.2 m are shown in Table 1. Prior to the experiment, the land was cultivated with winter wheat by a local farmer using N and phosphorus (P) fertilizers without irrigation.

The experiment was established in September 2004 and comprised four management treatments with a complete randomized block design using four replicates. The plot size was
**Table 1. Properties of the Eum-Orthic anthrosol (0–20 cm) prior to the experiment.**

| Property                        | Value   |
|---------------------------------|---------|
| Soil organic carbon (g kg⁻¹)    | 7.96    |
| Total nitrogen (g kg⁻¹)         | 1.07    |
| Available phosphorus (Olsen phosphorus; mg kg⁻¹) | 15.0 |
| Available potassium (NH₄Ac extraction; mg kg⁻¹) | 182.4 |
| Bulk density (kg m⁻³)           | 1120    |
| pH (soil:water = 1:2)           | 8.25    |
| Clay (< 0.002 mm; %)            | 26.7    |
| Silt (0.02–0.002 mm; %)         | 40.8    |
| Sand (2–0.02 mm; %)             | 32.5    |

40 m² (4 × 10 m) with a buffer zone of 1 m between plots and 2 m between blocks. The four treatments were (1) winter wheat cultivation with P fertilizer application (WP, 100 kg P₂O₅ ha⁻¹ year⁻¹), (2) winter wheat cultivation with N and P fertilizer application [WNP, 160 kg N ha⁻¹ year⁻¹ (a recommended rate) plus 100 kg P₂O₅ ha⁻¹ year⁻¹, i.e., the fertilization practice used by local farmers], (3) NF (natural fallow) without fertilization or wheat cultivation, and (4) BF (bare fallow) without fertilization or wheat cultivation. Further, urea was used as the N fertilizer, and ordinary superphosphate (a mixture of calcium phosphate and calcium sulfate containing about 20% P₂O₅ and 12% sulfur) was used as the P fertilizer. Both were broadcast on the soil and incorporated into the topsoil (0–15 cm) by rotary tilling as basal fertilizers prior to wheat sowing. Winter wheat (Triticum aestivum L. cv. Xiaoyan 22) was sown with a seeder machine at 135 kg seed ha⁻¹ with a row spacing of 0.2 m during early October and was harvested early in June during the following year. The wheat was grown in rain-fed conditions and was the only crop grown each year. The wheat straw was incorporated into the soil after wheat harvesting, and the weeds that grew in wheat plots were manually removed. The period between the harvest of the preceding winter wheat and the sowing of the following winter wheat was the season of summer fallow, and the field was tilled 2 times by deep plowing (0–25 cm) 1 week after wheat harvest and by rotary tilling 1 week before wheat sowing. No human disturbance, including fertilization and tillage, was applied in the NF treatment, allowing the vegetation to grow naturally throughout the period. In the BF treatment, vegetation was manually removed to ensure a vegetation-free land, and it was also kept free of fertilizer amendments throughout the period, but the tillage management was the same as that used in the WP and WNP treatments.

### 2.2. Sampling and preparation

Wheat samples from four different points of each plot and shoots were harvested by hand using a frame of 1 × 1 m. The heads of samples were cut and then grains were separated from heads by rubbing to determine the wheat yield. Straw (including leaves, stem, glumes and rachis) production was calculated by subtracting grain yield from shoot yield. The grain yield and straw production for each plot was expressed in dry weight.

Soil samples were randomly collected from four points in each plot at two depths (0–20 and 20–40 cm) using a 5-cm-diameter auger on 15 June 2012 (after the wheat harvest). Soil samples collected from the same depth with four cores in each plot were mixed to obtain one sample. Field-moist soil samples (average soil water content = 13.2%) were divided into two subsamples: one subsample was stored at 4°C for no more than 1 week for MBC, MBN and inorganic N (nitrate N (NO₃⁻N) and ammonium N (NH₄⁺N)) analyses; the other subsample was air-dried and passed through 0.25-mm or 2-mm sieves for analysis.

### 2.3. Soil analysis methods

Total SOC and SON: Total SOC was calculated from inorganic and total C, which were determined using finely ground (< 0.25 mm), air-dried soil samples with a total organic carbon analyzer (Shimadzu TOC-VCPH, Japan) and the solid sample module for a TOC-V series total organic carbon analyzer (SSM-5000A, Japan) according to the user manuals. The inorganic C content comprised the C measured based on carbon dioxide (CO₂) evolved during acid (phosphoric acid) treatment in the soil at a temperature of 200°C, and total C was the C measured based on CO₂ evolved from the soil at a temperature of 900°C. Total soil N was determined by the Kjeldahl method (Bremner and Mulvaney 1982), and total SON was estimated by subtracting inorganic N from total N. Inorganic N (NO₃⁻N and NH₄⁺N) was extracted with 1 mol L⁻¹ potassium chloride using field-moist soil (2-mm sieve), and it was determined with an injection pump analyzer (AA3, Bran + Luebbe, Germany) (ISO 2005).

Soil MBC and MBN: MBC and MBN were measured using the chloroform fumigation–extraction method (Brookes et al. 1985; Vance et al. 1987). Fresh soil equivalent to 25 g oven-dry weight was weighed in 250 mL glass bottles. The unfumigated samples were immediately extracted with 100 mL 0.5 mol L⁻¹ potassium sulfate (K₂SO₄) on a rotary shaker at 200 rpm for 30 min and then filtered. The remaining samples were fumigated with alcohol-free chloroform for 24 h at 25°C in the dark. Excess chloroform was then removed by repeated evaporation, and the samples were extracted and filtered. Organic C in the filtrate was determined with a total organic carbon analyzer (Shimadzu TOC-VCPH) (Wu et al. 1990). Total N in the filtrate was treated by alkaline persulfate oxidation and measured with dual-wavelength ultraviolet spectrophotometry (Cabrera and Beare 1993). A Kᵥ of 0.45 and Kᵥ of 0.54 were used to convert the differences between organic C and N extracted from chloroform-fumigated and unfumigated soil samples into MBC and MBN, respectively (Wu et al. 1990).

Soil LFC, heavy fraction carbon (HFC), LFN, and heavy fraction nitrogen (HFN): Density fractions were extracted from the soil using the procedure described by Murage et al. (2007). In brief, an air-dried bulk soil sample of approximately 20 g was weighed into a 100-mL centrifuge tube, followed by the addition of 80 mL of sodium iodide at a density of 1.70 g cm⁻³. The liquid in the tube was then manually swirled for 30 s, and the contents were dispersed using a probe-type sonic disruptor for 1 min. After deposition for 30 min, the solution was centrifuged at 2000 rpm for 30 min. Further, the floating LF was retained on a filter (0.45-μm Millipore HA filter paper, 50 mm
diameter) in a Büchner funnel. This process was repeated 2 times in order to completely separate LF and heavy fractions (HF). The material retained at the bottom of the tube (HF) was added with 50 mL of 0.01 mol L$^{-1}$ calcium chloride ($\text{CaCl}_2$) and deionized water, shaken and centrifuged 3 times to completely wash it. LF was also thoroughly washed 3 times with 50 mL of 0.01 mol L$^{-1}$ CaCl$_2$ and deionized water. Both LF and HF were dried at 55°C for 48 h, weighed, and ground with an agate mortar and pestle. Further, C and N concentrations in LF and HF were determined using a total organic carbon analyzer (Shimadzu TOC-VCPH) and the Kjeldahl method (Bremner and Mulvaney 1982), respectively. To obtain sufficient LFs for analyses, three subsamples were used from each soil sample.

2.4. Statistical analysis

Prior to analysis of variance (ANOVA), the Brown and Forsythe (1974) test ($p < 0.05$) was used to evaluate the homogeneity and homoscedasticity of the data. The one-factorial ANOVA procedure in SAS (v. 8.0, SAS Institute Inc., USA) was used for data analysis, and the F-protected least significant differences test at $p < 0.05$ was employed to assess the differences in the means of four replicates for each soil depth.

3. Results

3.1. Wheat grain yield and straw production

Wheat grain yield in the WP treatment was significantly lower (2657 kg ha$^{-1}$) than that in the WNP treatment (5812 kg ha$^{-1}$) from the years 2006 to 2012 (Table 2), but there was no difference in the first year of the field trial (2005). The straw production was similar to that observed for the grain yield. The ratio of wheat straw to grain was 1.49 and 1.30 in WP and WNP treatments, respectively.

3.2. Total soil organic C and N

Compared with WNP, total SOC concentration significantly ($p < 0.05$) decreased in the BF treatment at 0–20 cm and 20–40 cm soil depths (Fig. 2A) by 35.0% and 33.0%, respectively; however, total SOC was not significantly different in WP and NF treatments at either soil depth.

Compared with WNP, BF treatment significantly ($p < 0.05$) decreased total SON concentration by 14.6% only at 0–20 cm depth (Fig. 2B), and WP treatment decreased total SON by 36.8% and 28.9% at 0–20 cm and 20–40 cm depths, respectively; however, NF treatment did not affect total SON at either soil depth.

3.3. Soil heavy fraction C and N and light fraction C and N

Similar to what was observed for total SOC, soil HFC concentration was also significantly reduced in the BF treatment (Fig. 2C), by 35.9% and 33.0% at 0–20 cm and 20–40 cm depths, respectively; however HFC concentrations were not significantly different in WP and NF treatments. Soil HFN concentration in the four treatments was similar to that observed for total SON (Fig. 2D).

Compared with WNP, LFC concentration was significantly ($p < 0.05$) decreased in the NF and BF treatments (Fig. 2E), by 17.0% and 26.5% at 0–20 cm depth, respectively, but there was no significant difference in WP treatment at either soil depth.

There were also significant differences ($p < 0.05$) in soil LFN concentration among the four treatments (Fig. 2F). Compared with WNP, WP and BF treatments significantly decreased LFN concentration (by 39.4% and 31.9%, respectively) at 0–20 cm soil depth, and BF treatment significantly decreased LFN concentration (by 38.1%) at 20–40 cm depth; however, NF treatment did not change LFN concentration at either soil depth.

3.4. Soil microbial biomass C and N

Soil MBC did not significantly differ among the four management regimes, with averages of 232 and 176 mg C kg$^{-1}$ (Fig. 2G) at 0–20 and 20–40 cm depths, respectively. However, MBN was significantly influenced by the four treatments (Fig. 2H). Compared with WNP, MBN was reduced by BF (62.1%), NF (24.8%) and WP (35.6%) treatments at 0–20 cm depth, and decreased by BF (69.9%), NF (71.2%) and WP (61.1%) treatments at 20–40 cm depth.

3.5. Soil inorganic C and N

Soil management regimes had different effects on soil inorganic C (Fig. 3A). Compared to WNP treatment, the NF treatment decreased soil inorganic C by 29.1% and 23.8% at 0–20 and 20–40 cm depths, respectively, whereas WP treatment correspondingly increased it by 11.0% and 20.8%, and the BF treatment showed no obvious effects.

Ammonium N content was very low (0.19–0.51 mg kg$^{-1}$; Fig. 3B) and did not differ among the four treatments. However, nitrate-N concentration was high and different among the four treatments at 0–20 cm depth (Fig. 3C). But, compared to the WNP treatment, there was no significant difference of the nitrate at 0–20 and 20–40 cm depths among the NF, BF and WP treatments.

### Table 2. Winter wheat (*Triticum aestivum* L.) grain and straw production during the experimental period (2004–2012).

| Experiment year | Grain yield (kg ha$^{-1}$) | Straw production (kg ha$^{-1}$) |
|-----------------|---------------------------|---------------------------------|
|                 | WP | WNP | WP | WNP |
| 2004–2005       | 4414(566) a | 6114(227) a | 6216(815) a | 8114(394) a |
| 2005–2006       | 1886(132) b | 2471(249) a | 391(239) b | 6505(313) a |
| 2006–2007       | 2391(166) b | 3132(354) a | 391(239) b | 6505(313) a |
| 2007–2008       | 1980(44) b | 6331(377) a | 310(76) b | 7063(332) a |
| 2008–2009       | 1988(67) b | 5481(110) a | 296(10) b | 7268(195) a |
| 2009–2010       | 2330(179) b | 6441(262) a | 3793(322) b | 7150(96) a |
| 2010–2011       | 2763(239) b | 6325(557) a | 2728(269) b | 6438(583) a |
| 2011–2012       | 3501(242) b | 6406(271) a | 4986(360) b | 7371(192) a |
| Mean            | 2657(388) b | 5812(342) a | 3956(508) b | 7582(606) a |

The data in brackets denote the standard error of the mean ($n = 4$). WP, winter wheat cultivation with P fertilization; WNP, winter wheat cultivation with N and P fertilization; NF, natural fallow without fertilization or wheat cultivation; BF, bare fallow without fertilization or wheat cultivation. Different letters in the same row mean significant difference at $p < 0.05$. 


4. Discussion

4.1. Effects of soil management regimes on soil organic carbon fractions

SOC in agricultural soils positively contributes to soil fertility and crop production (Reeves 1997), and it is affected by agricultural management regimes, including fallowing and fertilization. Substantial amounts of SOC can be sequestered by inorganic fertilizer N inputs (Gong et al. 2009; Srinivasarao et al. 2011). However, in the present study, 8-year N fertilization did not affect total SOC (Fig. 2A), although the wheat grain yield and straw production differed with the two treatments (Table 2), which is similar to what was reported in other studies (Sainju et al. 2002; Huang et al. 2010; Gentile et al. 2011). These different results may be associated with the different SOC concentrations in the soils at the start of these experiments, i.e., the soils with SOC increases have low SOC concentration (4.4 g C kg\(^{-1}\) (Gong et al. 2009) and 3.1 g C kg\(^{-1}\) (Srinivasarao et al. 2011)), but the soils without SOC changes have intermediate or high SOC concentrations (8.0 g C kg\(^{-1}\) (present study, Table 1), 8.6 g C kg\(^{-1}\) (Sainju et al. 2002) and 29.3 g C kg\(^{-1}\) (Gentile et al. 2011)). Nitrogen fertilization also did not influence the concentration of SOC fractions—i.e., HFC (Fig. 2C), LFC (Fig. 2E) and MBC (Fig. 2G)—thereby agreeing with the results obtained by Chen et al. (2002). Moreover, soil C fractions had no significant relationships with wheat yield or biomass (Table 3). These results indicate that SOC fractions make little contribution to the increase of wheat production and are not affected by N fertilization in a low-SOM soil in northwest China.

In contrast to N fertilization management, fallowing affected SOC fractions, particularly bare fallowing. The BF treatment significantly decreased SOC, HFC and LFC fraction concentrations (Figs. 2A, C, E), thereby agreeing with the findings by Barré et al. (2010). They revealed that BF decreased the final SOC concentration compared with the initial values in six long-duration experiments (> 30 years). One of the main reasons for the decrease in SOC in the BF treatment was a lack of organic C input, but in the other

Figure 2. Effects of different soil management regimes on (A) total soil organic carbon (SOC), (B) soil organic nitrogen (SON), (C) heavy fraction carbon (HFC), (D) heavy fraction nitrogen (HFN), (E) light fraction carbon (LFC), (F) light fraction nitrogen (LFN), (G) microbial biomass carbon (MBC) and (H) microbial biomass nitrogen (MBN). WP, winter wheat cultivation with P fertilization; WNP, winter wheat cultivation with N and P fertilization; NF, natural fallow without fertilization or wheat cultivation; BF, bare fallow without fertilization or wheat cultivation. Bars labeled with different lowercase letters indicate significant differences between treatments (\(p < 0.05\), ANOVA followed by LSD test) in the same soil depth. Error bars represent ± standard errors of the mean (\(n = 4\)).
Effects of different soil management regimes on (A) soil inorganic carbon (C), (B) ammonium-nitrogen (N) and (C) nitrate-nitrogen (N). WP, winter wheat cultivation with P fertilization; WNP, winter wheat cultivation with N and P fertilization; NF, natural fallow without fertilization or wheat cultivation; BF, bare fallow without fertilization or wheat cultivation. Bars labeled with different lowercase letters indicate significant differences between treatments (p < 0.05, ANOVA followed by LSD test) in the same soil depth. Error bars represent ± standard errors of the mean (n = 4).

Table 3. The Pearson correlation coefficient between soil carbon and nitrogen fractions and wheat yield or aboveground biomass (grain yield plus straw production).

| Fractions                  | Wheat biomass | Wheat yield |
|----------------------------|---------------|-------------|
| SON (soil organic nitrogen)| 0.956**       | 0.972**     |
| HFN (heavy fraction nitrogen)| 0.948**       | 0.965**     |
| LFN (light fraction nitrogen) | 0.838**       | 0.879**     |
| MBN (microbial biomass nitrogen) | 0.819**       | 0.892**     |
| SOC (soil organic carbon)  | 0.601         | 0.460       |
| HFC (heavy fraction carbon) | 0.597         | 0.448       |
| LFC (light fraction carbon) | 0.296         | 0.362       |
| MBC (microbial biomass carbon) | 0.359         | 0.235       |

**p < 0.01.

three treatments, vegetation or wheat was grown and organic materials were placed into the soil each year (Table 2). Moreover, the NF treatment did not affect total SOC, HFC and MBC, which is similar to the results described by Diekow et al. (2005), and NF treatment only decreased LFC concentration at 0–20 cm depth. These results indicate that only bare fallow treatment has led to SOC losses in dryland soil in Loess Plateau of China.

4.2. Effects of soil managements on soil organic nitrogen fractions

SON is associated with SOC, and it plays a key role in building soil fertility. Agricultural management regimes are the primary factors affecting SON, particularly fertilization (Magdoff and Weil 2004). In the present study, the N fertilization treatment (WNP) significantly increased total SON concentration at 0–20 cm soil depth compared with the WP treatment (Fig. 2B). Similar results were obtained in a sandy loam soil in Georgia, USA, where total SON accumulation in the treatment with 180 kg N ha$^{-1}$ was significantly higher than that with 90 kg N ha$^{-1}$ (Sainju et al. 2002). Furthermore, the N fertilization treatment (WNP) significantly increased SON fractions (HFN, LFN and MBN; Figs. 2D, F, H). Similar results were also obtained in a winter wheat and summer maize cropping system in Loess Plateau of China, where MBN concentration significantly increased after 17 years of N fertilization, i.e., from 49 mg kg$^{-1}$ with no fertilization to 62 mg N kg$^{-1}$ with N fertilization (165 kg N ha$^{-1}$ year$^{-1}$) at 0–10 cm soil depth (Liang et al. 2011). However, in Typic Hapludoll and Aquic Hapludoll soil in Iowa, USA, MBN was unaffected by long-term N fertilization (0 or 180 kg N ha$^{-1}$ for 20 and 43 years, respectively; Moore et al. 2000). These differences may be explained by the different SON concentration in the soils. SOC concentration in the Iowa soil was 21.2 and 33.7 g C kg$^{-1}$, whereas that in the loess soils in China were only around 6.33 (Liang et al. 2011) and 8.0 g C kg$^{-1}$ (present study, Table 1). In addition, there was a significantly positive correlation between soil N fractions and wheat yield or biomass (Table 3). These results indicate that N fertilization can increase soil organic N fractions in loess soils with low concentrations of organic matter, and thus increase the wheat yield. It is well known that SOC and SON are positively correlated. However, in our study, the N fertilization treatment (WNP) did not have an effect on SOC (Fig. 2A) but significantly increased SON (Fig. 2A). The reason might be due to the large amount of N input into the soil in the WNP treatment, including N in fertilizer and in wheat residues. The former N can be assimilated by microbes and plants, and then can be returned to the soil. The latter N can also be returned to soil by straw incorporation. For example, in the year 2011, 30.3 kg N ha$^{-1}$ in straw straw in the WNP treatment was returned to soil, but the value was only 7.2 kg N ha$^{-1}$ in the WP treatment (unpublished data). In addition, wheat straw yield in the WNP treatment was much greater than that in the WP treatment; the higher input of organic materials into soil can lead to decomposition of ‘old’ soil carbon (Heimann and Reichstein 2008), which is not beneficial to soil organic C sequestration.

Fallowing is another factor affecting SON. In the present study, NF and BF treatments had different effects on SON fractions, i.e., the NF treatment only decreased MBN concentration, while the BF treatment decreased the concentration of...
all SON fractions (Figs. 2B, D, F, H). However, in other studies, the LFN concentration in a conventional cropped system was lower than that in forest (Tan et al. 2007; Assis et al. 2012), implying that cultivation reduced soil LFN compared with the natural forest. This difference was explained by different land use prior to the experiment. The land use in the studies of Tan et al. (2007) and Assis et al. (2012) was forest, while that in the present study was crop land. Furthermore, compared with NF treatment, BF treatment decreased total SON, HFN and MBN concentration. The same results were obtained in Swift Current, Canada, where MBN was significantly higher in a green manure–wheat system than in a fallow–wheat system (Biederbeck et al. 2005), and partial fallow with the growth of annual legumes as green manure was tested as a soil-conserving and more bioresource-efficient alternative to BF. These results indicate that BF had negative effects on sequestration of SON fractions, whereas NF had little effect on SON in the dryland soil on the Loess Plateau.

### 4.3. Effects of soil managements on soil inorganic C and N

The soil C pool has two principal components: soil organic C and inorganic C. In the present study, the average SOC concentration in the four treatments at 0–20 cm soil depth was 7.5 g kg⁻¹, accounting for about 40% of total C, and our results indicated that soil inorganic C was reduced by the long-term N fertilization (WNP treatment) and native fallowing (NF treatment). Similar results were observed by Mikhailova and Post (2006), who reported that soil inorganic C stocks in the native grassland (107 Mg ha⁻¹) were significantly lower than in the continuous crop field (242 Mg ha⁻¹) at 0–200 cm soil depths. The decreased soil inorganic C may be due to soil pH change (data not shown). The pH at 0–20 cm depth in the NF and WNP treatment was 8.26 and 8.28, respectively, which was lower than that in WP (8.37) and BF treatments (8.33). In the NF treatment, the weeds (mainly of legumes) were grown naturally and they may secrete more organic acids into the soil to decrease soil pH (Graham and Vance 2003). By contrast, in the WNP treatment, soil pH decreased with the inorganic N fertilizer application (Guo et al. 2010).

Inorganic N in most soils is found in the form of ammonium and nitrate, which are the main N pools for plants. In the dryland of the present study, soil ammonium-N was usually low (0.1–0.5 mg kg⁻¹), whereas the nitrate-N level was higher (3.3–12.8 mg kg⁻¹), being the dominant inorganic N form (Fig. 3). At 0–20 cm soil depth, compared with the WNP treatment, WP, NF and BF treatments showed no effect on nitrate-N. However, at 0–300 cm soil depths, nitrate-N accumulation was different from that in the topsoil and was 36.5, 171.0, 80.6 and 85.7 kg N ha⁻¹ for WP, WNP, NF and BF (data not shown), respectively. This indicated that nitrate accumulation in the N fertilization treatment at a rate of 160 kg N ha⁻¹ year⁻¹ (171.0 kg N ha⁻¹) is significantly higher than that in non-N fertilization treatments (WP, NF and BF); however this value is much lower than that in the N fertilization treatments at rates of 320 kg N ha⁻¹ year⁻¹ (727.7 kg N ha⁻¹ at 0–300 cm depths; Dai et al. 2015) and 480 kg N ha⁻¹ year⁻¹ (914.2 kg N ha⁻¹) at 0–200 cm depths; Yuan et al. 2000). Therefore, long-term N fertilization with a recommended rate (160–180 kg N ha⁻¹ year⁻¹ for wheat) may not lead to high risks of environmental pollution and land degradation in this dryland soil.

### 5. Conclusions

The results of this 8-year study with fertilization and fallowing indicate that the lack of N fertilization in the soil decreased N sequestration in an organic form by decreasing LFC, HFN and MBN concentrations. NF decreased soil inorganic C but did not affect SON and SOC fractions, whereas BF reduced SOC and SON concentrations. In order to promote soil C and N stocks and to maintain or increase the soil fertility in dryland soils, adding reasonable N fertilization and avoiding BF are recommended practices.

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