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Increase in soil organic carbon by agricultural intensification in northern China

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Abstract

Agricultural intensification has contributed greatly to the sustained food supply of China's 1.3 billion population over the 30 year period during 1982–2011. Intensification has several and widely recognized negative environmental impacts including depletion of water resources, pollution of water bodies, greenhouse gas emissions and soil acidification. However, there have been few studies over this period on the impacts of intensification on soil organic carbon (SOC) at the regional level. The present study was conducted in Huantai county, a typical intensive farming region in Northern China, to analyze the temporal dynamics of SOC influenced by climate and farming practices. The results indicate that from 1982 to 2011, SOC content and stock in the 0–20 cm layer of the cropland increased from 7.8 ± 1.6 to $11.0 \pm 2.3 \text{ g kg}^{-1}$ (41 %) and 21 ± 4.3 to $33.0 \pm 7.0 \text{ Mg ha}^{-1}$ (54 %), respectively. The SOC stock (0–20 cm) of the farmland for the entire county increased from 0.75 to 1.2 Tg (59 %). Correlation analysis revealed that incorporation of crop residues significantly increased SOC, while increase in the mean annual temperature decreased the SOC level. Therefore, agricultural intensification has increased crop productivity and contributed to SOC sequestration in Northern China. In the near future, more appropriate technologies and practices must be developed and implemented for a maintenance or enhancement of SOC in this region and elsewhere in Northern China, that also reduce non-CO₂ greenhouse gas emissions, since the climate benefit from the additional SOC storage is estimated to be smaller than the negative climate impacts of N₂O from N fertilizer additions.

1 Introduction

Increasing soil organic matter (SOM) storage in arable lands can ensure the sustained supply of nitrogen (N) and other nutrients to crop growth and maintain appropriate soil quality such as aeration, permeability, water-holding capacity and nutrient preserving capacity (Smith et al., 2012). Globally, accumulation of SOM or soil organic carbon

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(SOC) stock in arable lands, which contributes to the mitigation of greenhouse effect and a concomitant improvement in soil fertility (Matson et al., 1997; Sainju et al., 2009), may be achieved by a range of improved farming practices. These practices include adoption of high-yielding crop varieties, balanced fertilization, crop residue incorporation, no-till (NT) or reduced tillage, optimal irrigation, high cropping intensity (Matson et al., 1997; Kucharik et al., 2001). For instance, agricultural soils in US had a carbon sink capacity of 1.3 ~ 21.2 million T C annually from 1982 to 1997, due to land use, NT, higher cropping intensity etc. (Eve et al., 2002; Ogle et al., 2003). The rate of increase in SOC stock in Canada was 5.7 TgCyr⁻¹ during 1991–2001 (Vanden Bygaert et al., 2004). In the Netherlands, the SOC content of arable land increased by about 0.08 g kg⁻¹yr⁻¹ between 1984 and 2004 (Reijneveld et al., 2009). Benbi and Brar (2009) reported that SOC in the Punjab state of India increased from 2.9 to 4.0 g kg⁻¹ (38 %) between 1981 and 2006, largely resulting from irrigation, optimal fertilization, and an increase in crop productivity.

Northern China is one of the most important agricultural regions, producing 60–80 % and 35–40 % of nation's wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.), respectively (NBSC, 2014). Similar to other regions in Northern China, Huantai county has experienced the agricultural intensification process including a high cropping intensity (200 %, winter wheat–summer maize), high fertilizer rate (500 ~ 600 kg N ha⁻¹ yr⁻¹), frequent irrigation and tillage, and an increasing ratio of crop residues incorporation since the 1980s (Shi et al., 2013; Kong et al., 2014). Agricultural intensification increased crop yield within a short period. For example, Huantai county achieved production of > 15 Mg grains (wheat + maize) ha⁻¹ yr⁻¹ for all of its farmland since 1990. While the effect of agricultural intensification on increasing crop yields has been well documented, there have been few studies if any, on SOC content and stock in the region. Most of the research done on SOC sequestration in agricultural soils is confined to long-term plot-scale experiments. However, little information is available at national or region levels (Van Wesemael et al., 2010), especially in Northern China, which is characterized by low levels of SOM.

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We collected three-decades of data of climate, farm management and crop yield from Huantai county, to: (1) analyze the evolution of SOC at the regional level from 1982 to 2011, and (2) establish the cause-effect relationship between the driving forces and SOC change. The results derived from this study may contribute to improved farm management for the long-term sustainable agricultural development in the intensive farming of Northern China and elsewhere.

2 Materials and methods

2.1 Study area

Huantai county, located in Northern China ($36^{\circ}51'50'' \sim 37^{\circ}06'00''$ N latitude and $117^{\circ}50'00'' \sim 118^{\circ}10'40''$ E longitude), is characterized by a warm temperate continental monsoon climate, with annual average temperature of 13.4°C and annual precipitation of 604 mm. The rainfall occurs mainly in June, July and August; with the annual frost-free season of about 198 days. Slope gradient of the landscape is low in northern and high in southern regions, with an average altitude of 6.5–29.5 m, falling gently from southwest to northeast. The main soil types, according to the US soil classification system, include Haplustalfs, Aquents and Vertisols. The household contract responsibility system was implemented in Huantai county in 1980, and land productivity has increased significantly with an increase in fertilizer input, frequent irrigation and adoption of high-yielding varieties. In 1990, Huantai county became the first *Dun Liang County* which achieved high productivity of one Mg of grain per mu for the whole county (1 mu = 1/15 ha) in China. Vegetable production has also been intensified in the county since 1990s.

2.2 Data collection

The soil, climate and farming data were collected between 2011 to 2013 from the sources as described below:

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- *The 2nd National Soil Survey*: the 2nd National Soil Survey in China was conducted during 1981–1983, and was undertaken in 1982 for Huantai county. The survey collected and analyzed soil samples for genesis, physical, chemical and biological properties. The SOM content was tested using the potassium dichromate titrimetric method (Jankauskas et al., 2006). The SOM data in this study was obtained for 258 soil samples (0–20 cm), together with the corresponding GPS location coordinates.
- *Annual Soil Fertility Survey*: the annual SOM data of farmland soil (0–20 cm) were collected from the Soil Fertility Survey, a program undertaken by the county agricultural extension since 1987. Every year, samples from the topsoil layer were collected after the autumn harvest and analyzed for pH, SOM and nutrient contents. Soil sampling in the survey was stratified according to the division of administrative villages. Each village had at least one composite soil sample, representing 6.7 ~ 33.3 ha of farmland. The SOM content was determined by the potassium dichromate titrimetric method (Jankauskas et al., 2006). The data for 1988, 1991, 2000, 2001, 2004, 2005 and 2010 were for each town as the survey was only done at the township level. As there were no data for the period 1983 to 1986, it was assumed that a steady change in SOC occurred during this period. Thus, the average SOC content for the whole county was obtained by interpolation based on the data from 1982 and 1987.
- *Soil Sampling and Measurement Program*: in September 2011, a soil survey was implemented for the whole county. Soil samples were obtained from 0–20 cm depth of the farmland (including cropland and vegetable land), in an evenly distributed 2 km × 2 km grid. Each sample was composited from three collection points. The GPS location was recorded for each sampling point. Soil was ground and passed through a 0.15 mm sieve. For the SOC analysis, 2–3 g of the soil sample was weighed into the beaker, and then 20 mL HCl of 0.5 mol L⁻¹ was added for acidification and removal of carbonates. Samples were then transferred into

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a rotary oscillator (Ronghua, HY-B) to shake for 30 min. After standing for 12 h, deionized water was used to remove the acid from soil samples until neutral pH was obtained. Soil samples were dried in the oven at 60 °C and weighed. The SOC content was determined by a C and N Elemental Analyzer (Thermo EA flash 1112). As acidification led to soil mass loss, the SOC data were corrected using Eq. (1):

$$W_{\text{soc}2} = \frac{m_{\text{soil}1} \times W_{\text{soc}1}}{m_{\text{soil}2}} \quad (1)$$

where, $W_{\text{soc}2}$ is the corrected SOC content, $m_{\text{soil}1}$ is the soil mass after acidification, $W_{\text{soc}1}$ is the SOC content after acidification and $m_{\text{soil}2}$ is the soil mass before acidification. The comparative study of SOC content determined by Elemental Analyzer and potassium dichromate titrimetric method indicated that these two methods are comparable and the differences in between are not significant (Wang et al., 2014).

- *Climate and farm management*: data were obtained for land use (e.g. area under crops, vegetables and urban use), grain and straw yields of wheat and maize, nitrogen fertilizer rate, and the rate of straw incorporation from the Huantai agricultural yearbook of 1982–2011. Climate data for temperature and precipitation were obtained from the China Climatic Data Center, National Meteorological Information Center, CMA (<http://cdc.cma.gov.cn>).
- *Calculation of SOC density and stock*: the Van Bemmelen conversion factor, namely that SOM contains 58 % carbon (Page et al., 1982), was used to compute SOC content in (Eq. 2). The SOC density and stock were computed by Eqs. (3)

and (4), respectively:

$$\text{SOC} = \text{SOM} \times 0.58 \times 10 \quad (2)$$

$$\text{SOCD} = \text{SOC} \times \gamma \times H \times 10^4 \quad (3)$$

$$\text{SOCS} = \text{SOCD} \times S \times 10^{-9} \quad (4)$$

5 where, SOC is the soil organic carbon content (g kg^{-1}), SOM is the soil organic matter content (%), SOCD is the SOC density (kg ha^{-1}), γ is the soil bulk density (BD, g cm^{-3}), H is the thickness (m) of soil layer (0–20 cm), SOCS is the SOC stock (Tg) for the whole county, and S is the farmland area (ha). Soil BD values were interpolated over years from measured values taken in 1982 and 2011. For
10 the calculation of SOCS, we assumed that the SOC content of land for industrial or residential use was maintained at the same level after the farmland was converted.

2.3 Data analysis

15 The Kolmogorov–Smirnov test was used in the SPSS Statistics 17.0 package to determine if SOC content followed a normal distribution. Central tendency, dispersion degree and distribution characteristics of SOC data were calculated. Pearson correlation analysis and/or partial correlation analysis were conducted between SOC content and driving factors including mean annual temperature, mean annual precipitation, grain yield, nitrogen fertilizer rate and straw C incorporation. A multivariate regression model
20 was developed to account for the impact of these factors on temporal SOC change in Huantai county.

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3 Results

3.1 Evolution of SOC content and density between 1982 and 2011

Figure 1 presents the dynamic changes of topsoil SOC content and density for the cropland (winter wheat–summer maize) from 1982 to 2011. The mean increase in cropland from 1982 to 2011 was $7.8 \pm 1.6 \text{ g kg}^{-1}$ to $11.0 \pm 2.3 \text{ g kg}^{-1}$ for SOC content and, $21.4 \pm 4.3 \text{ Mg ha}^{-1}$ to $33.0 \pm 7.0 \text{ Mg ha}^{-1}$ for SOC density, with rates of increase of 41 and 54 %, respectively. The mean SOC content of vegetable land increased similarly as cropland, i.e., from $7.8 \pm 1.6 \text{ g kg}^{-1}$ to $11.0 \pm 2.8 \text{ g kg}^{-1}$ (data not shown). This trend indicates that the rate of increase in SOC content and density of cropland (0–20 cm) in Huantai county since the early 1980s was $0.11 \text{ g kg}^{-1} \text{ yr}^{-1}$ and $0.40 \text{ Mg ha}^{-1} \text{ yr}^{-1}$, respectively. The growth of SOC density was significantly related to increasing SOC content, but also supported by the increase in soil BD in the 0–20 cm layer of the farmland (1.4 g cm^{-3} in 1982 to 1.5 g cm^{-3} in 2011).

3.2 Change of SOC stock in Huantai county from 1982 and 2011

An adjustment in the local agricultural sector altered the land use between 1982 and 2011 in Huantai county. The farmland area in 1982 was 35 204 ha, of which more than 99 % was under winter wheat–summer maize cropping (cropland). Due to the expansion of vegetable production since 1990s, land used for vegetable production increased to about 20 % by the early 2000s, and has remained constant until 2011 at about 6000 ha. The average SOC content of vegetable land is not significant from that of cropland (11.0 vs. 11.0 g kg^{-1} in 2011 for whole county). Some farmland was converted to construction use with the expansion of industry and urban land uses. Of the 31 % reduction of farmland area between 1982 and 2011, 16 % was used for vegetable farming and 15 % converted to construction land.

Although area under cropland decreased from 35 204 ha in 1982 to 24 343 ha in 2011, the SOC stock of cropland (0–20 cm) increased from 0.75 ± 0.15 to $0.80 \pm$

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0.17 TgC (an increase by 6.7%, Fig. 2). When the SOC stock in vegetable land and construction land (converted from cropland and for industrial and residential use. The area increased every year as urbanization took place) was also included, total SOC stock of the farmland in the Huantai county was estimated to be 1.2 TgC in 2011, with a total increase of 59% compared to the 0.75 ± 0.15 TgC in 1982 (Fig. 2).

3.3 The cause-effect relationship governing change in SOC level

Among the natural/climate forces which can influence SOC level, mean air temperature in Huantai county increased within the period of 1982 to 2011, with a relationship represented by the regression equation $y = 0.073x + 12.2$ ($R^2 = 0.67$, $P < 0.0001$, Fig. 3a). However, there was no significant change in precipitation over this period. Nitrogen fertilizer input for farmland was $400 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ in the 1980s and peaked at about $600 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ in 1994, followed by a decline to $500 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ in 2011. There were also significant increases in grain yield over this period ($R^2 = 0.63$, $P < 0.0001$, Fig. 3b). The carbon input between 1982 and 1987 was estimated at about 800 to $1000 \text{ kg C ha}^{-1} \text{ yr}^{-1}$, mainly through roots. However, crop production experienced a rapid growth after 1988, and crop residues (mainly wheat straw) were returned to the soil, leading to a significant increase in the input of biomass-C, especially the above-ground C. As much as 70% of maize straw was also incorporated to the farmland from 2007 onward, leading to a total C input of $> 8000 \text{ kg ha}^{-1} \text{ yr}^{-1}$ ($R^2 = 0.90$, $P < 0.0001$, Fig. 3c).

Correlation and regression analyses were performed between SOC of cropland and driving factors, i.e., temperature, precipitation, crop (wheat and maize) yield, N fertilizer rate and C input from crop residues (Table 1). There was a highly significant correlation ($P < 0.01$) between SOC content and temperature, crop yield, C input from crop residues, with correlation coefficients (r) of 0.55, 0.79 and 0.91, respectively. The correlation between SOC and N fertilizer rate was also significant ($r = 0.38$, $P < 0.05$). However, there was no significant correlation between SOC content and the mean annual precipitation.



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A partial correlation analysis was conducted to determine the relationship between SOC content of cropland with any one major driving factor, as the effect of a set of controlling random variables removed (Table 2). The data indicated a highly significant and positive correlation between SOC content and the C input from crop residues ($r = 0.80$, $P < 0.0001$), but a negative correlation between SOC content and annual mean temperature ($r = -0.42$, $P = 0.03$). The weak positive correlation between SOC content and N fertilizer rate ($r = 0.03$, $P = 0.86$), and weak negative correlation between SOC and crop yield ($r = -0.08$, $P = 0.70$), indicated that N fertilizer and increasing crop yield did not contribute to the augment of SOC in Huantai from 1982 to 2011. As the effect of C input from crop residues was removed during partial correlation, the rising temperature during the past 3 decades significantly decreased the cropland SOC content in Huantai, or promoted the SOC decomposition. In addition to the partial correlation analysis, a multivariate regression model was also developed as follows:

$$Y = 12.0 - 0.31 \text{ Temperature} - 0.0003 \text{ Precipitation} - 0.0006 \text{ Nitrogen} + 0.0005 \text{ C input} - 0.0001 \text{ Yield} \quad (r^2 = 0.88) \quad (5)$$

where, Y is the SOC content in g kg^{-1} . The multi-variate regression analysis also confirmed the positive impact of the input of crop residue carbon and negative impact of the increase in temperature.

4 Discussion

The SOC level of farmland was influenced by climate (mainly temperature and precipitation) and farming practices, including crop residue incorporation, N fertilizer use, crop yield etc. Similar observations have been made elsewhere by Khan et al. (2007) and Ladha et al. (2011).

4.1 Climate factors

Climate warming may increase the rate of SOM decomposition, while the effect of precipitation on SOC is mostly known to be positive because in general SOC increases with increase in precipitation (Post et al., 1982). Whereas air temperature in the Huantai region has significantly increased since the 1980s, the precipitation has not. There is a significant positive correlation between the temperature and SOC content (Table 1), however the partial correlation analysis showed that the correlation was negative ($r = -0.42$, $P = 0.03$, Table 2), indicating that SOC in Huantai county was enhanced by factors other than temperature and precipitation. Indeed, it may take much longer (~ 50 yrs) to observe the effect of climate change on SOC level (De Bruijn et al., 2012), indicating a strong need for long-term research.

4.2 Nitrogen fertilizer

In general, N is the most limiting nutrient in crop production systems (Robertson and Vitousek, 2009). It promotes the production of crop dry matter (and therefore C input to the soil) while chemically stabilizing C in the soil, thereby potentially increasing soil C storage (Paustian et al., 1997). A high input of N fertilizer was a prominent feature of farming in Huantai county, where average N fertilizer rate increased from $400 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ in the 1980s to $600 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ in the 1990s. However, the rate of N fertilizer gradually declined and stabilized at $500 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ in the 2010s. Such a trend is attributed to the increased use of machinery in agriculture and the extension of formula fertilization techniques adopted in the region. The strategy was to balance the N fertilization rate in consideration of the high grain output ($> 15 \text{ Mg grain ha}^{-1} \text{ yr}^{-1}$). However, the rate of SOC increase was still high during this period, as indicated by a weak positive correlation between N fertilizer rate and SOC level over the 30 year period (Table 1). The vegetable production in Huantai county is open-field and there is less organic fertilizer input ($3\text{--}5 \text{ t ha}^{-1} \text{ yr}^{-1}$) compared with other regions like

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Shouguang ($> 15 \text{ t ha}^{-1} \text{ yr}^{-1}$) in China, SOC increase due to organic fertilizers is not significant and at the same level as cropland (11.0 vs. 10.9 g kg^{-1} in 2011).

A few studies (Khan et al., 2007; Mulvaney et al., 2009) have reported that even the long-term input of a massive amount of residue-C and synthetic N fertilizer do not sequester SOC; this was not the case with intensification of cropland in Northern China. A major factor lies in the concentration of the principal parameter (i.e., SOM) which was significantly lower in cropland soils of Northern China than those of the US Corn Belt (9 vs. 25 g kg^{-1} , Ludwig et al., 2011) or countries of the western Europe, because large areas of farmlands in Northern China were affected by saline-alkaline processes prior to 1970s. The initial low crop productivity in the temperate region where N fertilization rate was low resulted in higher SOC level in Northern China with increasing biomass input achieved by higher input of N. Similar trends have been reported by other studies from around the world (Song et al., 2005; Alvarez, 2005). Nonetheless, it is important to point out that any excessive application of mineral N not only increases the production cost, but also exacerbates the negative environment effects, including nitrate contamination of ground and surface waters and N_2O emission to the atmosphere (Triberti et al., 2008). Carbon sequestration effects should be valued in a systematic approach (Wang and Cao, 2011). Indeed, the climate benefit from the additional SOC storage is smaller than the climate damage caused by N_2O from N fertilizer additions (N_2O emissions are estimated (conservatively) to be $\sim 57 \text{ kt CO}_2\text{-eq. yr}^{-1}$, assuming the smallest farmland area of $24\,343 \text{ ha}$ and current stable N application rate of $500 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ using the IPCC Tier 1 default Emission Factor of 0.01 ; soil C storage over the period is equivalent to $54 \text{ kt CO}_2\text{-eq. yr}^{-1}$).

Balanced fertilization should be widely promoted, for optimization of the integrated economic benefits and ecosystem services. It is important to understand that increasing input of N fertilizer increased SOC only when crop residues were returned to the soil. There may have been either no, or only a slight increase in SOC level, if the above-ground crop residues were removed or burnt (Alvarez, 2005) so N fertilization in itself is

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not a suitable strategy to increase SOC, particularly considering the over-riding effects of N₂O emissions from the N fertilizer.

4.3 Grain yield

Grain yield in Huantai county increased from 7200 kg ha⁻¹ yr⁻¹ in 1982 to 16117 kg ha⁻¹ yr⁻¹ in 2011 (an increase of 124%). The highly significant correlation ($r = 0.79$, $P < 0.01$) between SOC content and grain yield indicates the importance of SOM to achieving high crop productivity, and *vice versa* (Pan et al., 2009). Indeed, the interdependence between crop yield and SOM content is widely recognized (Lal, 2002, 2013). Increase in the SOC pool of 1 Mg C ha⁻¹ in the root zone can increase annual food production by 30–50 million Mg in developing countries (Lal, 2013). Meta-analysis indicated that crop yield greatly increased by crop residue retention ($P < 0.001$), particularly in upland China (Liu et al., 2014). Qiu et al. (2009) estimated that for every increase of 1 g C kg⁻¹ of SOC in Huantai county, grain yield could increase by 454 kg ha⁻¹. In Northern China, beneficial effects of crop yield increase will be enhanced as the strategy of returning crop residues is extended to other regions of Northern China.

4.4 Carbon input from crop residues

Carbon input is one of the most efficient factors for the accretion of SOC, which is also confirmed by the highly significant correlation between SOC content and C input from crop residue incorporation ($r = 0.80$, $P < 0.0001$, Table 2). Similar results have also been reported by other scientists (Freibauer et al., 2004). Smith et al. (2005, 2012) reported that input of crop residues could attain the highest rate of C sequestration (0.7 Mg C ha yr⁻¹) in comparison with that of merely 0.2 Mg C ha⁻¹ yr⁻¹ with the input of mineral N fertilizer. In our study, there are two SOC increase stages, one early (1987–1992) and one late (2007–2012), which the early one coincides nicely with increased wheat residue incorporation and the late one with the increased maize residue

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incorporation. Again, it highlights the significance of crop straw input for the building of soil organic matter. In comparison with data from other countries like India ($\sim 1 \text{ MgC ha}^{-1} \text{ yr}^{-1}$, Srinivasarao et al., 2014) or US ($\sim 4.2 \text{ MgC ha}^{-1} \text{ yr}^{-1}$, Johnson et al., 2006), the input of residue-C in Northern China is much higher ($\sim 8 \text{ MgC ha}^{-1} \text{ yr}^{-1}$, Fig. 3c), for maintaining a rapid rate of increase of SOM. Thus, rate of input of residue-C is the principal determinant of the rate of increase of SOM: the annual rate of SOM increase being lower in India, intermediate in the US and high in the North China Plains. Since retention of the entire amount of residues of maize in North China started from 2007/08, the accretion of SOC is projected to continue for another two to three decades until the mid-2040s.

Miao et al. (2011) reported that the significance of N fertilizer and crop residues incorporation to the maintenance and increase of the SOM. Retention of residues (wheat and maize) in conjunction with appropriate rate of N fertilization have been properly implemented in Northern China where the antecedent levels SOM are much lower than those in northern America and western Europe. Therefore, a judicious continuation of these practices will continue to accumulate SOM for a long time to come. However, similar trends may not occur under all situations. For example, Khan et al. (2007) explained that after attaining a steady state, it is unlikely that SOC will continue to increase, and may even decline with continuous use of synthetic N, because of the enhanced activities of heterotrophic soil microorganisms in using crop-derived residues or SOM. In the context of Northern China, therefore, it is likely that the increase in SOC level will continue because of the improved crop productivity and retention of crop residues, but it will eventually attain a new equilibrium. Some other SOC-enhancing practices including application of residue-based animal manure derived from the same land unit, contribute further to SOC sequestration. In addition, higher level of mechanization during the agricultural intensification process may increase the soil BD (about 7% in our study), and this also contributed to the increase of SOC stock and should not be ignored when quantifying of farmland carbon sequestration.

4.5 Comparison of SOC accretion through agricultural intensification in different regions of China

Agriculture in China has grown rapidly over the three decades since 1982, primarily because of the Household Contract Responsibility System and adoption of the open policy. Further, the intensification process achieved some economic and environmental benefits (Firbank et al., 2013). In the case of Northern China, however, there were also problems with increases in soil compaction and water pollution over the period of three decades.

Among all agronomic regions, Northern China registered the highest rate of SOC sequestration. In contrast, however, the SOC level has declined in Northeast China since the 1980s (Table 3). Northeast China, one of the few world regions characterized by the black soil (Phaeozems) and cold climate, has high antecedent SOC content ($\sim 20 \text{ g kg}^{-1}$ in uncultivated soils). Thereafter, cultivation and intensive farming after the 1980s have increased the rate of decomposition of SOM along with a low input of organic materials and biomass-C. The SOC level in Northern China was extremely low ($5 \text{ to } 10 \text{ g kg}^{-1}$) in comparison with the soils of Northeast China and other regions. This trend can be explained by the fact that Northern China has a long history of low crop productivity, long dry season (Stockmann et al., 2013), sandy soil texture and low input of organic amendments. Application of N fertilizer and retention of crop residues has increased the SOC level more in dry lands of Northern China than in those of paddy soils of the lowlands (Liu et al., 2014). Huantai county and other agronomic regions (except Northeast China) in China also witnessed increase in SOC level, mainly attributed to the practices of fertilization (synthetic and organic), increase in crop yield, retention of crop residues, adoption of conservation tillage and use of organic amendments (Table 3). The 0–30 cm layer of soils of cropland in China have gained SOC at the rate of $17\text{--}28 \text{ Tg Cyr}^{-1}$ between 1980 and 2000 (Huang et al., 2010), which is similar to the estimates of $25\text{--}37 \text{ Tg Cyr}^{-1}$ reported by Lal (2002).

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Agricultural intensification in China is an ongoing process, and is progressively evolving over time. For instance, since 2012, maize residues from some cropland have been harvested by Huantai farmers for use as cattle feed and the eventual return of the animal manure to cropland. It is possible that the efficiency of SOM accretion through animal manure is higher than that of returning maize straw (Wilhelm et al., 2007), which may result in yet another period of SOM accretion at the regional level with proper dissemination of this technology (Ladha et al., 2011). Similar to northern China, other important grain production region like Midwest US also experienced the stage of SOC accumulation, although the practices (residue management, non- or reduced tillage and crop rotation) are different (Ogle et al., 2003; Jelinski and Kucharik, 2009). Adoption of conservation agriculture (NT or minimum tillage) may be another option for SOC sequestration. However, its applicability and efficiency need to be validated through long-term research.

5 Conclusions

The study of the impact of agricultural intensification on SOC content and stock was conducted in the Huantai county, which is a representative region in Northern China. The farmland SOC stock of the whole county increased by more than 50 % over three decades from 1982–2011. Among several improved farming practices, retention of crop residues strongly contributed to the restoration of SOC, but there was no synergistic effect between N fertilization rate and crop yield on increase in SOC. The SOC content decreased with increase in mean annual temperature. The temporal change in SOC was significantly influenced by the evolution of the practice of retention of crop residues through implementation of some local farming policies. The data support the conclusion that agricultural intensification may both increase crop productivity and enhance some ecosystem services, such as SOC sequestration in croplands of Northern China. However, current farming practice (e.g., retention of crop residues) may not always linearly increase SOC over time, indicating a strong need for a long-term research. Further-

more, there is also a need to explore other options such as the application of manure through integration of crop and animal production. Research on the use of animal manure within the region is a priority, because of its multiple benefits for grain production, the economy and ecosystem services such as SOC sequestration.

5 *Author contributions.* Fanqiao Meng, Wenliang Wu and Yan Liao designed the experiments and Yan Liao carried them out. Yan Liao and Pete Smith performed the calculations and data analysis. Yan Liao, Fanqiao Meng, Pete Smith and Rattan Lal prepared the manuscript with contributions from all co-authors.

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Table 1. Correlation analysis between SOC content of cropland and driving factors in Huantai county.

	SOC	Temperature	Precipitation	Crop yield	N fertilizer rate	C input from crop residues
SOC	1					
Temperature	0.55 ^a	1				
Precipitation	0.30	0.09	1			
Crop yield	0.79 ^a	0.62 ^a	0.30	1		
N fertilizer rate	0.38 ^b	0.01	0.48 ^a	0.55 ^a	1	
C input from crop residues	0.91 ^a	0.73 ^a	0.35	0.89 ^a	0.43 ^b	1

^a means a highly significant correlation at the level of $P < 0.01$.

^b means a significant correlation at the level of $P < 0.05$.

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Table 2. Partial correlation analysis between SOC content of cropland and driving factors in Huantai county.

Control variables	Partial correlation coefficient between SOC and the driving factor*	
Crop yield, C input from crop residues	SOC vs. Temperature	-0.42 ($P = 0.03$, $df = 26$)
Crop yield, C input from crop residues	SOC vs. N fertilizer rate	0.03 ($P = 0.86$, $df = 26$)
C input from crop residues, N fertilizer rate, Temperature	SOC vs. Crop yield	-0.08 ($P = 0.70$, $df = 25$)
N fertilizer rate, Temperature, Crop yield	SOC vs. C input from crop residues	0.80 ($P < 0.0001$, $df = 25$)

* All of the partial correlation coefficients are 2-tailed.

Table 3. Topsoil (0–20 cm) SOC change from 1980s to 2000s in different agronomic regions of China*.

Region	Site	Soil type (FAO)	Climate	Period	SOC %	SOCD Mg ha ⁻¹ yr ⁻¹	SOCS Tgyr ⁻¹	Literature
Our study					41	0.40	0.15	
North China	Quzhou	Fluvisols	Warm, semi-arid, temperate monsoon	1980–2000	31			Liu et al. (2005)
	Daxing	Fluvisols	Warm, semi-humid, temperate monsoon	1981–2000	33			Hu et al. (2006)
	Hebei	Calcaric Cambisol	Warm, semi-arid, temperate monsoon	1984–2004		0.34	2.2	Xi et al. (2013)
	Henan	Fluvisols	Warm, semi-humid, temperate monsoon	1984–2004		0.32	2.8	Xi et al. (2013)
	Luancheng	Calcaric Cambisol	Warm, semi-arid, temperate monsoon	1979–2000	38			Zhang et al. (2003)
	Hebei	Calcaric Cambisol	Warm, semi-arid, temperate monsoon	1984–2004		0.65		Xi et al. (2013)
Northeast China	Liaoning	Chernozems	Semi-humid, temperate continental monsoon	1984–2004		-0.57	-2.9	Xi et al. (2010)
	Jilin	Albic luvisols	Semi-humid, temperate monsoon	1985–2005		-0.81	-7.2	Xi et al. (2010)
	Heilongjiang	Phaeozems	Cold temperate monsoon	1986–2006		-0.70	-5.5	Xi et al. (2010)
	Heilongjiang	Phaeozems	Cold temperate monsoon	1982–2002	-14			Yu et al. (2003)

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Table 3. Continued.

Region	Site	Soil type (FAO)	Climate	Period	SOC %	SOC _D Mg ha ⁻¹ yr ⁻¹	SOC _S Tgyr ⁻¹	Literature
Northwest China	Yining	Calcicustoll	Arid temperate continental	1981–2001	–9.3			Hou et al. (2003)
	Akesu	Calcaric fluvisols	Arid, warm temperate continental monsoon	1982–2001	10			Li et al. (2002)
	Huangshui	Eutric cambisols	Arid, warm temperate continental monsoon	1981–2001	28			Chen et al. (2003)
	Zhangye	Eutric cambisols	Arid, warm temperate continental monsoon	1982–2003		0.2		Zhang et al. (2009)
East China	Jiangsu	Fluvisols/cambisols	Northern subtropical humid monsoon	1980–2000	34			Yu et al. (2003)
	Jinhua	Haplic alisols	Subtropical humid monsoon	1982–2002	2.6			Xie et al. (2003)
	Xuzhou	Fluvisols	Warm, semi-humid, temperate monsoon	1981–2001		0.1 ~ 0.5		Zhang et al. (2009)

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Table 3. Continued.

Region	Site	Soil type (FAO)	Climate	Period	SOC %	SOCΔ Mg ha ⁻¹ yr ⁻¹	SOCΔ Tgyr ⁻¹	Literature
Central China	Hunan	Haplic alisols	Humid, mid-subtropical monsoon	1984–2004		0.17	0.6	Xi et al. (2013)
	Hubei	Eutric cambisols	Humid, mid-subtropical monsoon	1984–2004		0.31	1.2	Xi et al. (2013)
	Zhengzhou	Fluvisols	Warm, semi-humid, temperate monsoon	1982–2003	35			Fu et al. (2004)
	Taoyuan	Haplic alisols	Humid, mid-subtropical monsoon	1979–2003	32			Liu et al. (2006)
	Jiangnan	Eutric cambisols	Humid, mid-subtropical monsoon	1984–2004		0.62		Xi et al. (2013)
Southern China	Hainan	Ferralic cambisols	Tropical monsoon	1984–2004		−0.16	−0.5	Xi et al. (2013)
	Binyang	Haplic acrisols	Tropical monsoon	1981–2001	19			Liu et al. (2006)
	Pixian	Haplic acrisols	Sub-tropical monsoon	1981–2002	9.0			Wei et al. (2004)
	Yucheng	Haplic acrisols	Sub-tropical monsoon	1981–2002	19			Hu et al. (2004)
	Meitan	Haplic acrisols	Sub-tropical monsoon	1980–2001	67			Ding et al. (2002)

* only the literatures with more than 20 years of experimental interval and more than 30 observation/sampling points were included.

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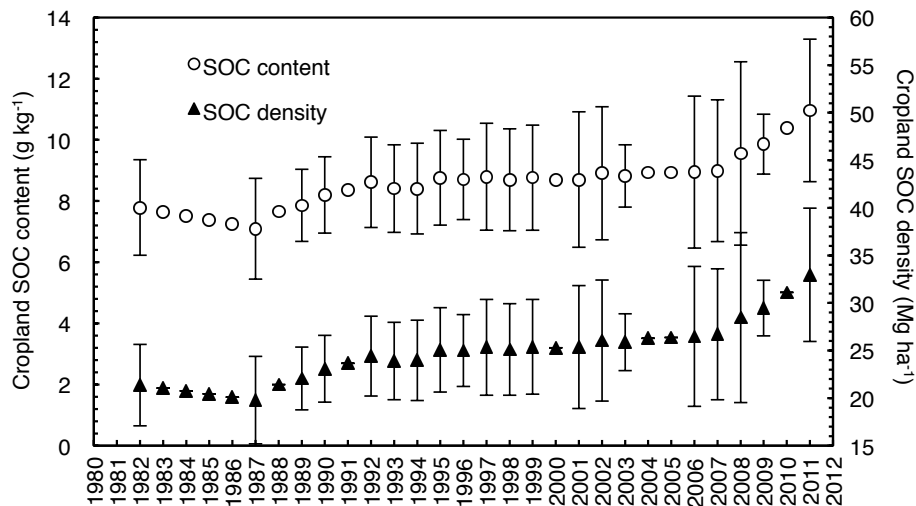


Figure 1. Evolution of SOC content and density for cropland from 1982 to 2011 in Huantai County. Error bars are highlighted only for the years which soil survey is undertaken.

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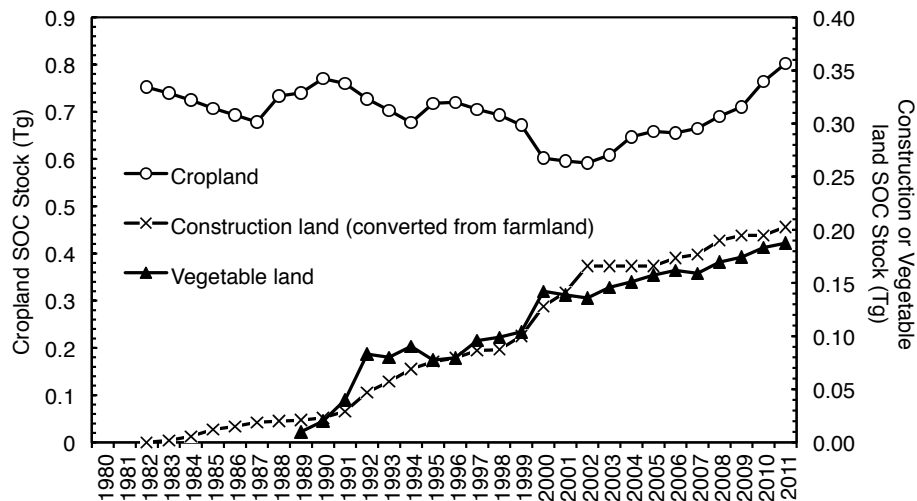


Figure 2. Change of SOC stock for farmland (cropland, vegetable land, farmland converted to construction land) from 1982 to 2011 in Huantai County.

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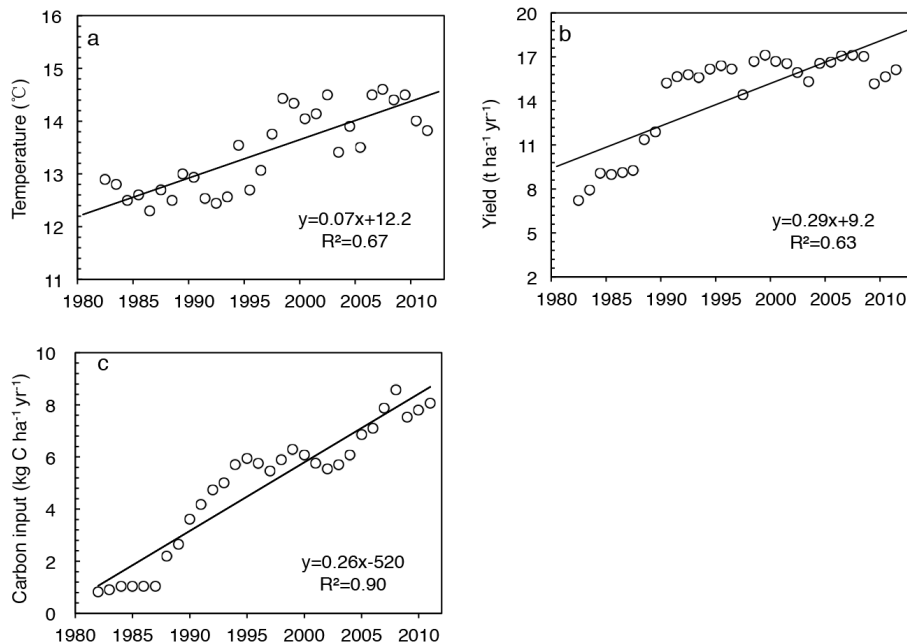


Figure 3. Regression analysis of driving factors with the years in Huantai. **(a)** Temperature vs. year, **(b)** yield vs. year, and **(c)** carbon input vs. year.

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