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Short communication

The role of soil organic matter in maintaining the productivity and yield stability of cereals in China

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ABSTRACT

The role of soil organic matter (SOM) in agricultural systems has been widely studied in conjunction with the potential for greenhouse gas mitigation. However, the link between SOM accumulation in croplands, crop productivity and yield stability has not yet been clearly established. In this paper, we collected data on provincial yearly crop productivity (yields, total cropland area) during 1949–1998 and the average SOM contents in croplands sampled and determined from the National Soil Survey in 1979–1982 of mainland China. The cereal productivity was assessed both with an overall mean of 1949–1998 and with the mean values for different time periods within this overall time, respectively. The yield variability within a single stabilizing stage, and between the fluctuating years, was calculated as a negative measure of yield stability. The correlation between SOM and cereal productivity was very significant for most provinces, but the relationship has become less significant as we approach the present. Moreover, the average yield variability was very significantly and negatively correlated with the cropland SOM level. The findings support our previous hypothesis from case studies, that C sequestration in China's croplands may provide win–win benefits, by enhancing crop productivity and stabilizing yield. This offers a sound basis as a greenhouse gas mitigation strategy by promoting C sequestration in croplands, and enhancing food security in China's agriculture.

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1. Introduction

Soil organic matter (SOM) plays an important role as a pool of terrestrial C, in ecosystem productivity, in the functioning of agro-ecosystems (Loveland and Webb, 2003) and in cropland fertility (Tiessen et al., 1994). While global society is facing the challenge of climate change due to the rapidly increasing CO_2 in the atmosphere, accumulation of SOM and, hence, C sequestration (Schlesinger, 1999, 2000) had been given much attention as a climate change mitigation option at global (FAO, 2001) and regional scales (Smith, 2004) since the late 1990s. However, it is increasingly argued that C sequestration is an important option not only to mitigate climate change but also to enhance soil fertility and the productivity of ecosystems (Dawea et al., 2003; Janzen, 2006; Manlay et al., 2007). While stating the significance of C sequestration in soils in climate change mitigation, Lal (2004) stressed the "win–win" benefits from soil C accumulation in that crop yield is also increased, thereby helping to enhance global food security. Nevertheless, it is difficult to quantify the role of SOM (C in organic forms) in enhancing cropland productivity, and in ensuring the stability of agricultural production.

Food security for the large and ever increasing population of China has been a great issue in recent decades (Brown, 1995), with the problem being exacerbated this year by high food prices on the world market (Zhang, 2008). China is currently facing the double challenge of climate change mitigation of its rapidly increasing emissions, and the increasing food requirements of the largest population of any country, with decreasing availability of arable lands (Pan and Zhao, 2005). In previous studies, the increasing trend of soil organic C over the last two decades was demonstrated both at national (Xu, 2008) and province scale (Liao et al., 2008), and particularly for paddy soils (Pan et al., 2003). Pan and Zhao (2005) and Pan et al. (2006), showed that soil organic carbon sequestration could play a significant role in increasing and stabilizing rice productivity, as well as in sequestering C for CO_2 mitigation in paddy soils from South China. Recently, an overall potential for cropland soil C sequestration in climate change

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mitigation in agriculture was assessed for a better climate policy in China's agriculture (Pan, 2008). Understanding the controls of SOM on productivity and yield stability would provide a sound scientific basis for undertaking C sequestration measures in agriculture. The purpose of this paper is to demonstrate the importance of organic C sequestration for food production, by linking SOM levels to cereal production and yield stability at province level using the 50-year statistical data of 1949–1998 available from a dataset of China's Statistics Bureau.

2. Data and methods

Data on SOM content was collected from the dataset of SSSC (1996). In this dataset, average values of SOM, both for dry croplands and for rice paddy, were organized in categories associated with the cropland area for each province of mainland China. The samples for the measurement of organic matter content were collected from topsoil (0–20 cm depth) at a sampling frequency of 1:66.7 ha. Organic carbon content was determined with wet digestion of H_2SO_4–$K_2Cr_2O_7$ and converted to SOM content by a factor of 1.724 following the technical guideline of the 2nd National Soil Survey (SSSC, 1992) conducted in 1979–1982. The average SOM level was estimated by the weighted mean of the dry croplands and rice paddies by their relative areas, as determined by the soil survey.

Data of provincial cereal production (total production, area of croplands in each year since 1949) was retrieved from the work of OCSNESBS (1999).

3. Data treatment and statistics

Mean cereal productivity (CP) in t ha^{-1} was obtained by dividing total cereal production by the total cropland area for the each year.

Provincial average SOM (SOM_p) level in % was estimated using the following equation:

$$SOM_p = \frac{\sum SOM_i A_i}{A_t} \quad (1)$$

where SOM_i is the average content (%) of category i, A_i is the cropland area (ha) of category i, and A_t is the total cropland area (ha) reported in the 2nd National Soil Survey.

The stability index of cereal production is evaluated by the variability of yield, either of a period of years with normal production, or a period of years with large inter-year fluctuations. The mean production variability was thus estimated for each province by averaging the variability values obtained by both approaches. The production variability (PV_i, %) for a given province in a given period i is calculated as follows:

$$PV_i\,(\%) = \frac{\text{standard deviation of yield}}{\text{mean yield in a period } i} \quad (2)$$

Thus, the average of the production variability (PV_i, %) of all the periods was used as the estimation of the mean production variability index (PVI, %) for a given province.

$$PVI\ (\%) = \text{average}(PV_i,\ i = 1, 2, 3, \ldots n) \quad (3)$$

Here, the periods included three stages of largely stable production in 1949–1958, 1965–1974, and 1984–1992, and three stages of sharply fluctuating production in 1959–1962, 1978–1983, and 1993–1998, respectively, according to the general pattern of cereal production for the whole of China (see below).

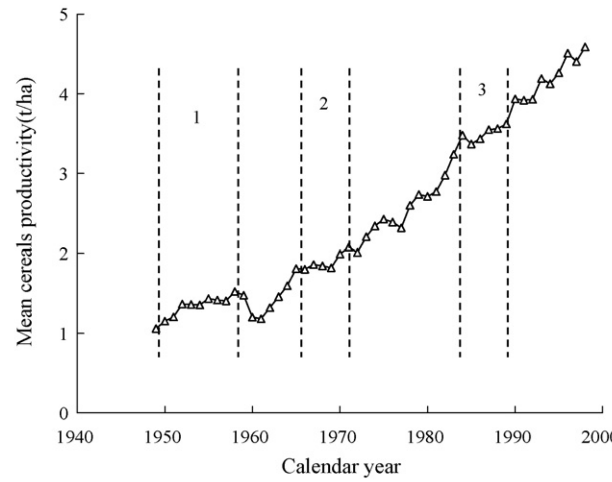

Fig. 1. General pattern of the change in cereals productivity of China during 1949–1998 (showing the stages of stabilizing and those of sharp fluctuating in between).

4. Results and discussions

4.1. SOM and cereal productivity

The evolution of cereal production in China has experienced several stages of development, which has been well discussed in detail previously, with varying contributions from technology and management innovation for cereal production since 1949 (Hu, 2001; Dai, 2001). The overall trend of cereal production for all China is shown in Fig. 1, showing three stages of largely stable production in 1949–1958, 1965–1974, 1984–1992, and three stages of sharply fluctuating production in 1959–1962, 1978–1983, and 1993–1998, respectively. Thus, the provincial mean cereal productivity was evaluated for these different periods, and for the overall average over 1949–1998, while the variability of productivity was assessed by the mean variability of all the above-mentioned periods. As shown in Table 1, there existed much difference in SOM content and average yields across the provinces and the different periods, though the variability of mean yields became smaller towards present.

Different blocks of provinces showed different patterns of correlation between SOM and cereal production. Fig. 2 shows a positive correlation of mean cereal production with the average cropland SOM level for most of the China's provinces. A small number of provinces (Yunnan, Guizhou, Tibet, Jilin, Inner Mongolia and Heilongjiang) with marginal climate and severe land degradation constraints (Zhai and Zhong, 1999) showed no correlation between mean cereal production and the average

Table 1
SOM (%) and yield (t ha^{-1}) variability across provinces of mainland China.

SOM and yield		Mean (plus standard deviation)	Variability across provinces (%)
SOM (%)		2.09 ± 0.77	36.88
Overall mean yield	1949–1998	2.53 ± 1.11	28.84
Yield of stabilizing stages	1949–1959	1.37 ± 0.47	33.95
	1965–1977	2.08 ± 0.68	32.44
	1984–1992	3.64 ± 1.03	28.18
Yield of fluctuating stages	1959–1962	1.30 ± 0.52	39.63
	1978–1983	2.84 ± 0.91	31.90
	1993–1998	4.35 ± 1.04	23.87

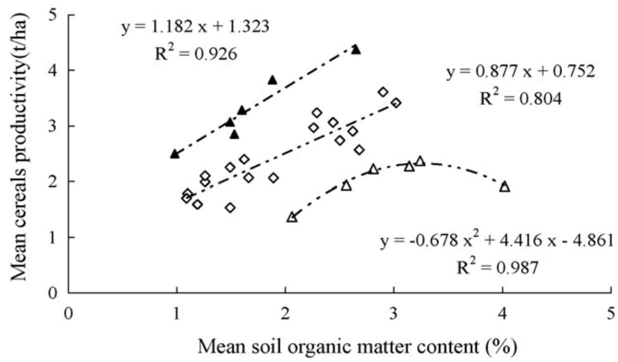

Fig. 2. Mean cereal productivity 1949–1998 correlated with mean cropland soil organic matter content for different blocks of provinces of China (▲, provinces of Beijing, Jiangsu, Shanghai, Shandong, Liaoning, and Sichuan with well managed agricultural systems; ◇, most mid China and South China provinces with normal agriculture; Δ, provinces of Guizhou, Yunnan, Xizang (Tibet), Inner Mongolia, Qinghai and Heilongjiang).

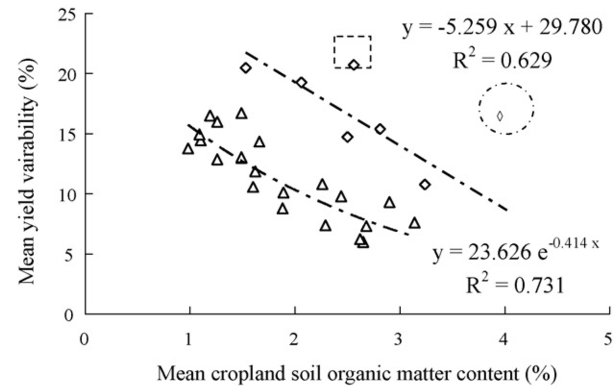

Fig. 4. Mean cereal yield variability (%) 1949–1998 against mean cropland soil organic matter content (%) of provinces of China (Δ, provinces with normal climate region; ◇, provinces of Yunnan, Guizhou, Xizang, Qinghai, Jilin, Inner Mongolia, and Heilongjiang (in dash-circle) and Tibet (in dash-square) with marginal climate).

cropland SOM level. A greater correlation between SOM and mean cereal yield was found for Beijing, Tianjing, Jiangsu, Shanghai, Sichuan, and Shandong than for other provinces, most of which were from Eastern China with good agricultural management (Zhai and Zhong, 1999).

Further evidence is provided by comparing yield and SOM levels in provinces within the same climatic region. Table 2 shows the mean yield (1949–1998) and SOM content for provinces in different eco-regions in China. It shows that in most eco-climate zones, where the climatic drivers of yield are similar, the provinces with higher SOM also tend to have a statistically higher yield. Causality cannot be firmly attributed as a high yield is associated with higher plant production, potentially higher carbon inputs to the soil and therefore higher levels of SOM over time. Nevertheless, within regions with similar current climatic growing conditions, which should give similar yields if climate is the over-riding factor determining current yield, those provinces with higher SOM tend to have higher yield. This supports the argument that higher SOM levels improve yields in areas that, climatically, one would expect similar yields.

The correlation between SOM and productivity also varied with the periods assessed. Fig. 3 shows that, for most provinces except those with marginal climate and severe land degradation, the extent that SOM affected cereal productivity tended to increase since 1949, as the slope increased from 0.67 in 1949–1955 to 0.963 in 1984–1992 despite the background productivity increasing from 0.14 t ha^{-1} 1949–1955 to 2.12 t ha^{-1} in 1984–1992. However, this correlation became weaker towards the present (R^2 decreased from 0.771 in 1949–1959 to 0.364 in 1984–1992), possibly due to the increasing contribution of technological development, which masks the underlying correlation with SOM. The fact that SOM and yield were still significantly correlated, even in 1984–1994 when high rates of fertilization and high yielding cultivars were prevalent in China's agriculture, suggests that SOM is important in underpinning crop productivity in agriculture.

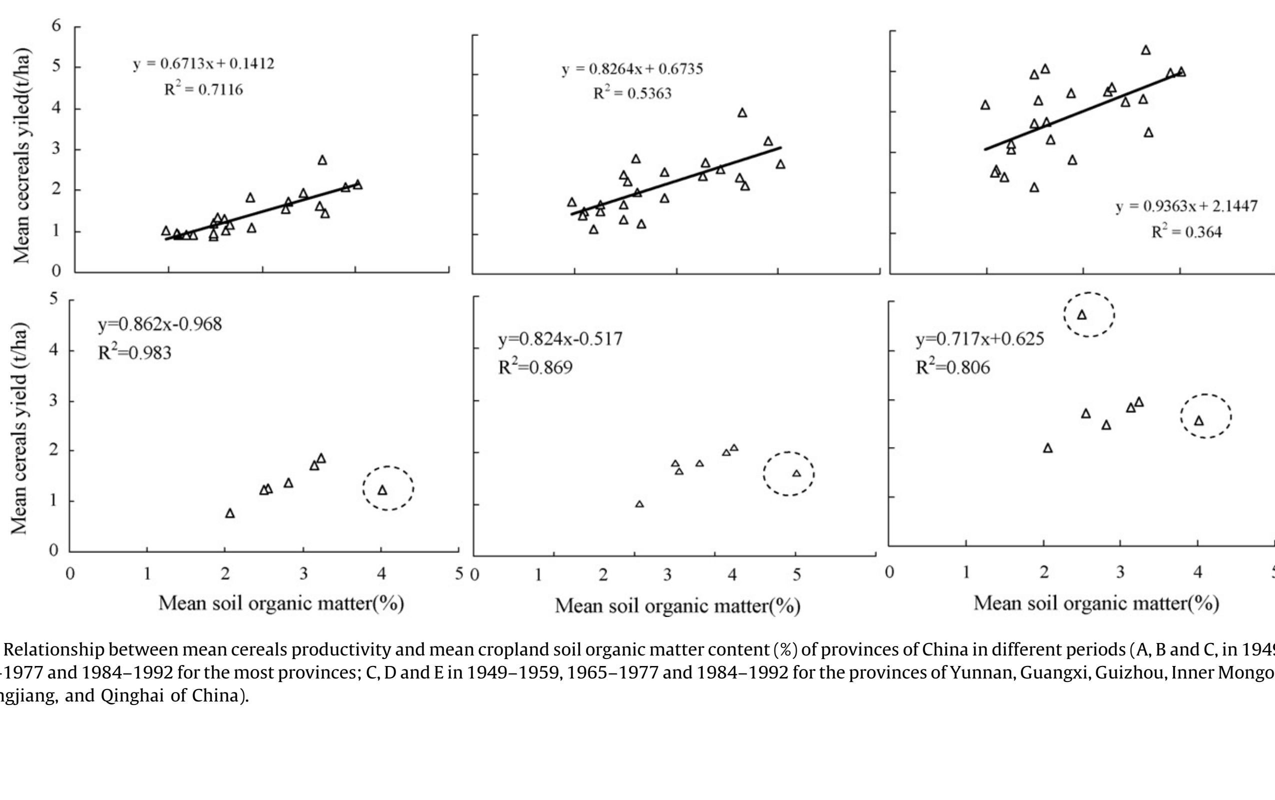

Fig. 3. Relationship between mean cereals productivity and mean cropland soil organic matter content (%) of provinces of China in different periods (A, B and C, in 1949–1959, 1965–1977 and 1984–1992 for the most provinces; C, D and E in 1949–1959, 1965–1977 and 1984–1992 for the provinces of Yunnan, Guangxi, Guizhou, Inner Mongolia, Jilin, Heilongjiang, and Qinghai of China).

Table 2
Difference in average crop yield (t ha^{-1}) of 1949–1998 between provinces with different contents of SOM (%) and similar climate conditions in a same eco-region from China.

Eco-climate	Huang-Huai-Hai plain Temperate Zone			Central East Subtropical Zone		Central South Subtropical Zone		Northwest Arid Zone		Southwest Alpine Zone	
Provinces	Tianjin	Hubei	Henan	Jiangsu	Zhejiang	Jiangxi	Hunan	Xinjiang	Ninxia	Yunnan	Guizhou
SOM	1.49	1.26	1.26	1.60	2.90	1.26	3.02	1.66	1.49	2.28	2.37
Yield	2.25 ± 1.34A	1.99 ± 1.04B	2.10 ± 1.16B	3.29 ± 1.66B	3.61 ± 1.21A	2.10 ± 1.19B	3.41 ± 1.36A	2.07 ± 1.32A	1.59 ± 0.81B	3.14 ± 0.59B	3.24 ± 0.62A

Different capital letters means significant difference between provinces in a same eco-region at $p < 0.01$.

4.2. SOM and the yearly variability of cereal productivity

Yearly variability of mean provincial yield in relation to the average SOM level is shown in Fig. 4. The variability followed an exponentially decreasing trend, and a weaker linearly decreasing trend with the average cropland SOM content for most provinces, and for provinces with marginal climate, respectively. An exponential regression of cereal yield stability against adverse disturbance with average SOM level occurred in 73% of the provinces, apart from those with marginal climate and severe land degradation. From this regression, an increase of the average SOM content from 1% to 3% would be expected to decrease yield variability by 10%. Given that the total production for these provinces amounted to 416.4 Mt of cereals in 1998 (OCSNESBS, 1999), the 10% decrease in yield variability could represent a yearly increase of over 40 Mt of cereal food per year. This finding supports the suggestion by Lal (2004) that C carbon sequestration helps to enhance crop productivity in agricultural soils, and confirms our previous finding from paddy soils in South China that carbon sequestration in soils also produces more stable rice yields (Pan et al., 2006; Pan and Zhao, 2005).

Using these relationships, a 1% increase in SOM on average would lead to an increase in total cereal productivity of 0.43 t ha^{-1}, and a decrease of yield variability against disturbance by 3.5%. As the total cropland area, and the total cereal yield of China in 2006 were 140 Mha and 490 Mt, respectively (Anonymous, 2006), total cereal production would be increased by 77 Mt per year if an overall mean increase in SOM content of 1% in all China's croplands could be achieved. This increase in total cereal production could potentially meet the food requirement of about 2 million people at consumption rates of 370–380 kg per capita for the year 2000 (NOSCPRC, 1996). The more significant correlation between SOM and the stability of cereal production, than with yield suggests that enhancement of SOM in cropland soils may help greatly to diminish the uncertainty of yearly cereal productivity in China, which is an issue of considerable concern for the nation with largest population in the world (NOSCPRC, 1996). Therefore, C sequestration can be accepted as a reliable option both for enhancing food security, and for mitigating greenhouse gases in the croplands of China.

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References

Anonymous, 2006. Yearbook of Statistics of China. China Statistics Press, Beijing (in Chinese).
Brown, J.L., 1995. Who Will Feed China? Wake-up Call for a Small Planet. W.W. Norton & Company, New York.
Dai, Y.X., 2001. Mathematical analysis on grain yield changes in China in the past 50 years. J. Inner Mong. Agric. Univ. 22 (3), 109–112. (in Chinese).
Dawea, D., Dobermannb, A., Ladhaa, J.K., 2003. Do organic amendments improve yield trends and profitability in intensive rice systems? Field Crops Res. 83, 191–213.
FAO, 2001. Soil carbon sequestration for improved land management. World Soil Resources Reports, 2001, No 96, Food & Agric. Organization, Rome, Italy, ISSN 0532-0488.
Hu, Y.M., 2001. A analysis of periodical fluctuation of China's food production. Jianghan Tribune 6, 32–34 (in Chinese).
Janzen, H.H., 2006. The soil carbon dilema: Shall we hoard it or use it? Soil. Biol. Biochem. 38, 419–424.
Lal, R., 2004. Soil C sequestration impacts on Global Climatic Change and Food Security. Science 11/06 (304), 1623–1627.

Liao, Q.L., Zhang, X.H., Li, Z.P., Pan, G.X., Wu, X.M., 2008. Increase in soil organic carbon stock over the last two decades in China's Jiangsu Province. Glob. Change Biol., in press.
Loveland, P., Webb, J., 2003. Is there a critical level of organic matter in the agricultural soils of temperate regions: a review. Soil Tillage Res. 70, 1–18.
Manlay, R.J., Feller, C., Swift, M.J., 2007. Historical evolution of soil organic matter concepts and their relationships with the fertility and sustainability of cropping systems. Agric Ecosys Environ 119, 217–233.
News Office, State Council of Peoples' Republic of China (NOSCPRC), 1996. White-Book of China's Food Supply. Released at: www.chinagate.com.cn 2007 – 02–13 (in Chinese).
Office of Comprehensive Statistics of National Economy State Bureau of Statistics (OCSNESBS), 1999. An Atlas of 50-yr Statistical Data of the State since 1949. China Statistics Press, Beijing (in Chinese).
Pan, G.X., Li, L.Q., Wu, L.S., 2003. Storage and sequestration potential of topsoil organic carbon in China's paddy soils. Glob. Change Biol. 10, 79–92.
Pan, G.X., Zhao, Q.G., 2005. Study on evolution of organic carbon stock in agricultural soils of China: facing the challenge of global change and food security. Adv. Earth Sci. 20, 384–393 (in Chinese with English summary).
Pan, G.X., Zhou, P., Zhang, X.H., Qiu, D.S., Chu, Q.H., 2006. Effect of different fertilization practices on crop carbon assimilation and soil carbon sequestration: a case study of a paddy under a long term fertilization trial from the Tai Lake region, China. Acta Ecol. Sin. 26 (11), 3704–3710 (in Chinese with English summary).
Pan, G.X., 2008. Soil C stock, dynamics of China's croplands and climate change mitigation. Adv. Clim. Change Res. 4 (5), 277–284 (in Chinese with English summary).
Schlesinger, W.H., 1999. Carbon sequestration in soils. Science 284, 2095.
Schlesinger, W.H., 2000. Carbon sequestration in soils: some cautions amidst optimism. Agric. Ecosys. Environ. 82, 121–127.
Smith, P., 2004. Carbon sequestration in croplands: the potential in Europe and the global context. Eur. J. Agron. 20, 29–236.
State Soil Survey Service of China (SSSC), 1996. Dataset of National Soil Survey of China. China Agriculture Press, Beijing, pp. 103–122 (in Chinese).
State Soil Survey Service of China (SSSC), 1992. Technical Report of the National Soil Survey of China. China Agriculture Press, Beijing, pp. 4–41 (in Chinese).
Tiessen, H., Cuevas, E., Chacon, P., 1994. The role of soil organic matter in sustaining soil fertility. Nature 371, 783–785.
Xu, X.W. 2008. Distribution and dynamics of soil organic carbon of croplands at different space scales of China. A Ph D dissertation,Graduate School, Nanjing Agric. University, Nanjing, pp 54–81 (in Chinese).
Zhang, X.W., 2008. Issue of food supply of China and suggestions for the countermeasures. http://www.rednet.cn. 2008-6-10. 14:40:52 (in Chinese).
Zhai, H.Q., Zhong, F.N. (Eds.), 1999. Introduction to Agriculture. China Higher Education Press, Beijing, (in Chinese), pp. 198–221.