Manure application increased grain yield and soil organic carbon across China's agricultural land

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Abstract
Application of manures to soil has declined globally due to increased availability of inorganic fertilizers; which have a key role in feeding the growing population. Here we used a combination of long-term field trial data (22-32 years, 20 sites) and both climate change and soil organic carbon (SOC) models to quantify the importance of manure application to grain yield and SOC sequestration across China's agricultural soils (122 M ha). During the past three decades inorganic fertilizers (37-450 kg N ha^{-1} yr^{-1}) have increased grain yield (91-183%) but with little contribution to SOC sequestration (4-17%). In contrast manure (2010 rates; 0.4-4.0 t C ha^{-1} yr^{-1}) when applied with inorganic fertilizer provided a small benefit to grain yield (6-19%) but doubled SOC sequestration (8-41%). Modelling to the end of this century predicted that an additional 0.23 t C ha^{-1} yr^{-1} can be derived from these levels of manure use (manure-C retention coefficient=10%) compared to 0.53 t C ha^{-1} yr^{-1} for inorganic fertilizer only; an average 43% more SOC is sequestered when inorganic fertilizer used in conjunction with manures. We conclude that the use of manures with inorganic fertilizers is essential for soil to maintain the dual functions of increased food production and SOC sequestration.

Keywords: Soil organic carbon sequestration, cropland, manure application, chemical fertilizers, Long-term fertilization, China

Introduction and main objectives

China has 20% of the world population but only 8% of the total arable land and uses more inorganic fertilizer than any other country; accounting for 90% of the global increase in use and consuming 36% of total global production. Between 1980-2010 there was a six-fold increase in inorganic fertilizer use in China (with a co-incident rapid decline in manure application to agricultural land since 1997. While grain yields doubled over this period soil organic carbon (SOC) stocks only changed slightly; with a general decrease in arid/semi-arid regions and increase in humid/semi-humid regions. If China continues to maintain self-sufficiency in food production, then arable lands will need to increase productivity without causing loss of SOC and associated problems of soil degradation and greenhouse gas (GHG) emissions.
Soils in China account for 7 to 12% of the global SOC stock under arable production systems. This SOC stock reflects additions of organic waste to agricultural soils over a period of thousands of years aiding the stabilization of SOC. Use of inorganic fertilizers in the absence of organic amendments can cause losses of SOC with an associated increase in CO2 emissions and nutrient release. This is exemplified in the ancient Loessial soils in China where the decomposition rate of SOC was 21% faster when inorganic fertilizer is applied alone than with manure. As such, our aim was to quantify the contribution of manure application to gain crop yield and SOC sequestration in agricultural soils across China. This was achieved through use of climate and field trial data to measure long-term historical yield and SOC values and to use this date to

calibrate climate change (Hadley Center Global Environmental Mode-Earth System, based on RCP4.5 scenario) and SOC models (Roth-C) to predict the future contribution of manure to SOC stocks by the end of the century.

Methodology

Field trial sites

Our study consisted of 20 long-term experimental trial sites (22-33 years duration) located across China on either upland soils (Wheat or Maize) or on paddy-upland rotation soils (Rice-Wheat rotation). The climate at these sites ranged from arid to semi-humid and from mild temperate to subtropical. Annual mean temperature ranged from 1.5°C in the northeast to 18.3 °C in the southern region, annual precipitation ranged from 131 mm in the northwest to 1653 mm in the southern region, and evaporation was 2-15 times greater than precipitation. Field trial sites represented the major arable land soil types and cropping systems (Since the soil types are complex, just descript in the text, no table to present) within the northeast (Black soil, Dark brown soil), northwest (Grey desert soil, Irrigated desert soil, Dark loessial soil, yellow loessal soil), North China Plain (Fluvo-aquic soil, Loess soil, Shajiang black meadow soil) and southern region (Red soil, Paddy soil, Yellow brown soil, Purple soil) of China.

Experimental design

Field trial treatments consisted of no fertilizer (Control), inorganic fertilizer only (nitrogen (N), phosphorus (P) or/and potassium (K), (NP or NPK), and manure (M) plus inorganic fertilizer (NPM or NPKM). A randomized design was used for all field trial sites (n=20 for field trial location, n=1–4 for within trial plot replicates).

Soil analysis

Composite soil samples (0–20 cm depth) were randomly collected from each plot using push-in soil cores (n=5–10 cores per composite; 5 cm in diameter) during September-October after harvest but before tillage, and then air dried before being sieved (<2 mm) prior to analysis. Soil pH was determined in water (soil:water = 1:1). Soil sub-samples were ground to 0.25 mm for measurements of SOC, total N, total P, and total K. Available N and K were measured following the method of Lu and available P (Olsen-P) by the method of Olsen.

Climate change scenarios

We have previously validated the climate change model for use in Chinese agroecosystems. (There are two climate condition were set: from start year to 2010, the climate parameters (monthly temperature, moisture, and evapotranspiration) used the observed data, from 2011-2099, (1) no climate change, used the average data during experiment of relevant sites; (2) climate change scenario, used the data from climate change model from Hadley Center Global Environmental Mode-Earth System based on RCP4.5 scenario (Representative Concentration Pathway (RCP) 4.5 is a scenario that stabilizes radioactive forcing at 4.5 W m^{-2} in the year 2100 without ever exceeding that value).

RothC model

We used the long-term experimental field trial data sets to validated the accuracy of the Rothamsted carbon (RothC) mode on the sub-set of field trial sites (n=10) where this had not been done previously. The RothC model was able to adequately simulate SOC dynamics in all treatment plots as modeled SOC values fitted well with the observed values during the experimental period. The coefficient of determination (R^2) between observed and modeled SOC contents was 0.92 ($P<0.001$) with a root-mean-square error (RMSE) of 9.71%. Modeled and observed SOC contents showed a declining trend in control plots at most sites. Where plots received inorganic fertilizer only (NP/NPK) modeled SOC values were at steady state or increased slightly, in but obviously increased in plots with organic manure (M, NPM or NPKM, NPM or NPKS). We then used weather files generated from the climate change model scenario as input files to the RothC model to enable future SOC predictions based on climate change.

Manure carbon input scenarios

Since RothC model does not contain the crop-sub model, for plant residues C input, from 2011 to 2099, NPP in NPK and NPKM plots set same as the average of the whole experimental periods. The carbon input scenarios were set as below: (A) under control and NPK plots, from experiment start to 2010, use the original carbon input scenario, from 2011 to 2099, set two C input scenarios: (i) plant residue and manure carbon input were the average one during the experimental period; (ii) plant residue carbon input were the average one during the experimental period and increase the manure C input (NPK+M).(B) Under NPKM plot, from experiment start to 2010, use the original carbon input scenario; from 2011 to 2100, set two C input scenarios: (i) plant residue and manure carbon input were the average one during the experimental period; (ii) plant residue carbon input were the average one during the experimental period and cease the manure C input (NPKM-M).

Statistical analysis

Analysis of variance (ANOVA) and the least-significant-difference (LSD) methods ($P < 0.05$) were applied to compare treatment and manure level on crop yield and SOC sequestration. All statistical analyses were conducted with the software SPSS version 20.0 and Origin profession version 8.5.

Results

The effect of chemical and/or manure fertilizer effect on the grain yield and SOC content

Compared with the control plot, application of inorganic fertilizer with (NPKM) or without (NPK) manure significantly increased gain yield in single-, double-cropping and paddy-upland rotation systems. The manure component also caused a small but significant ($P<0.001$) increase in grain yield during the experimental period; NPKM minus NPK treatments had a mean 10.4, 21.4, 6.0% increase in potential yield in single-cropping, double-cropping and paddy-upland soils, respectively. In contrast to grain yield application of manure significantly increased the SOC in single- (31.1%) and double-cropping system (41.3%) in upland soil, but not in paddy-upland rotation system (7.7%). The interaction effect of chemical fertilizer and manure on SOC improvement in double-cropping system region was higher than that in single-cropping system area.

Maintaining and increasing SOC is a prominent strategy for mitigating atmospheric CO_2 and adapting agriculture to climate change. When applied in combination with inorganic fertilizer the manure component did not contribute appreciably to increased grain yield but caused a large increase in SOC. These findings highlight that a combination of both inorganic fertilizer and organic amendments is required to produce more food from the same available land whilst increasing SOC to enhance soil sustainability, especially in dry land cropping systems.

As expected the amount of C input required maintaining SOC level varied between agro-ecological regions and for cropping system. The amount of C input required to maintain the current SOC level decreased with the annual mean temperature, while there was little effect of annual mean precipitation and evapotranspiration. According to the relationship between SOC change rate and mean annual C input, we estimated the manure required to maintain the current SOC content at each site. The C input required to maintain existing SOC levels was: single-cropping 2.98 t C $ha^{-1}yr^{-1}$, double-cropping 1.01 t C $ha^{-1}yr^{-1}$, and paddy-upland rotation 2.22 t C $ha^{-1}yr^{-1}$. This equated to manure application rates of 17.1, 6.0, and 13.2 t ha^{-1} yr^{-1} in single-, double- and paddy-upland rotation cropping systems, respectively.

Current manure application rates are low (0.4 to 4.0 t C ha^{-1} yr^{-1}) and likely to remain the same unless government policy, focused on use of organic materials to improve soil fertility and GHGs mitigation reverse this trend. The Ministry of Agriculture of People Republic of China have established a new scheme to maintain total inorganic fertilizer use (zero increase) at current levels whilst increasing use of organic materials in agricultural system (i.e. increase the manure application to 40%, straw return to 40%).

The effect of manure application on carbon budget in agricultural system in China

Using current NPP, combined with the no climate change scenario, modelled SOC content to 2099 increased when manure was added with NPK (i.e. NPKM) in all sites; the relative increase of SOC content in 2099 varied from 26% to 150% in single-cropping system area, 39% to 140% in double-cropping system area, and 11% to 61% in paddy-upland rotation system area . It was similar results of the manure effect on SOC content under increased NPP combined with climate change scenario. We estimated that if add locational amount of manure under NPK plot from 2011, there will be 2089.54 Tg and 2493.97 Tg, which accounted for 37% and 27% of the relevant total NPKM SOC can be sequestrated from manure in 2099 under current NPP + no climate change and increased NPP + climate change scenarios, respectively. They were equaled 7661.63 and 9144.56 Tg CO_2 can be mitigated by manure application under these two scenarios in 2099. However, there will be 19584.92 and 19716.43 Tg CO_2 released from the manure application until 2099, which implied that there was 39% and 46% CO_2 released by manure can be sequestrated.

There was no significant relationship between mean annual temperature and precipitation on the annual SOC change during 2011-2099. However, the annual SOC change decreased exponentially with initial SOC concentration and clay content in upland soil and decreased linearly with initial SOC concentration in paddy-upland rotation system area.

In our study, the manure SOC efficiency was ca. 20-30% during the first 18 years (n=20 long-term sites) of field trials. As the capacity of the soil to sequester further C declines so does the manure-C retention coefficient. By 2099 the manure SOC efficiency was not significantly different between the two climate change scenarios and ranged between 8.8-10.3%. Depending on feed-stock and animal species the manure quality varies; material with low C/N ratio have a higher conversion rate to SOC. Here we show that cattle manure had a significantly ($P<0.05$) higher conversion efficiency to SOC that pig and horse manure. This is consistent global data and highlights the preference for cattle manure as a SOC sequestration strategy.

Conclusions

In this study, we qualified that manure when applied combination with inorganic fertilizer, there was little contribution to grain yield (12.6%), but contribute 27.1% to SOC. If we continue use manure with chemical fertilizer at current application rate, there will be increase SOC sequestration of 2493.97 Tg t C, and increase 43% compare to inorganic fertilizer only in the end of this century in arable land in China.