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Estimations of soil organic carbon storage in cropland of China based on DNDC model

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Abstract

Loss of soil organic carbon (SOC) can cause soil degradation, which may not only undermine soil productivity, but may also-affect environmental health. In China, a huge amount of crop residues is regularly removed from the fields, and therefore China's agriculture depends on high levels of chemical fertilizer inputs. This paper aims to estimate the SOC storage in Chinese cropland, identify its changing trends under current cropping systems, and finally put forward some strategies to keep the SOC in balance. A computer simulation model of carbon and nitrogen biogeochemistry in agro-ecosystems (DeNitrification and DeComposition or DNDC) was applied to predict SOC dynamics in the upper (0–30 cm) soil layer of agricultural ecosystems at national scale. Data on climate, soil properties, cropping systems, acreage, and management practices at county scale were collected from various sources and integrated into a GIS database to support the model runs. The model results revealed (1) the total SOC storage in croplands in China is about 3968 Tg C; and (2) SOC is lost at a rate of 78.89 Tg C/year. The highest losses of SOC occur in the northeastern provinces. Chinese cropland soils release 186 Tg C as carbon dioxide into the atmosphere, and receive only 68 Tg C from crop residues annually. Considering the potential of global warming, SOC loss in cropland could be a serious contributor. Strategies to reduce the loss of SOC in Chinese cropland are proposed based on DNDC model runs for a number of scenarios under different management practices.

Keywords: Soil carbon storage; DNDC model; Cropland; China

1. Introduction

Agriculture is the foundation of China's economic development. As a large country, China owns a very large percentage of the world's cropland and rural population. The social and economic stability of the nation largely depends on agricultural development.

Soil organic carbon (SOC) is one of the key factors that affect agricultural production, nutrient availability, soil stability and the flux of greenhouse gases between land surface and atmosphere. It represents a major pool of carbon within the biosphere and acts both as a source and a sink for carbon and nutrients. Loss of SOC may cause soil degradation, which does not only undermine sustainable agricultural development but also affects

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environmental health. In the last 20 years a lot of biogeochemical models (Smith et al., 1997) have been designed for estimating soil organic carbon storage and loss from cropland under global warming scenarios. These models include ROTHC (Jenkinson et al., 1987), DNDC (Li et al., 1992a,b), CENTURY (Parton et al., 1996), CANDY (Franko, 1996), DAISY (Mueller et al., 1996), and NCSOIL (Molina et al., 1983).

The DNDC (*De**N*itrification and *De**C*omposition) model, simulating carbon and nitrogen biogeochemistry in agro-ecosystems, is used to study the agricultural soils of China. The DNDC model has been validated throughout the world by using long-term and short-term experimental data, testing the modeling behavior and sensitivity of the carbon biogeochemical process in agricultural soils (Li et al., 1994, 1997, 2000). It was also evaluated against data relevant to the main environments and crops in China (Xu et al., 1999; Li et al., 2002; Qiu et al., 2003a,b, 2004). DNDC was reported to be one of the good performance models by using seven long-term experiments which were selected from GCTE SOMNET and represented three different land-uses, a range of climatic conditions within the temperate region, and different treatments (Smith et al., 1997).

Chinese agriculture is under enormous pressure to meet the demands of the huge population having limited cropland. Consequently, a high multi-cropping index, manifested by lack of mechanization and short growing intervals between crops, is the main characteristic of Chinese cropping systems. As a result, a large amount of crop residues cannot be returned back to soil (only about 15% of non-grain aboveground crop biomass for national average, reported in 1997 by Ministry Of Agriculture in P.R. China), and high inputs of chemical fertilizers are required. This paper aims to (1) estimate the SOC storage in Chinese cropland; (2) identify its changing trends under current cropping systems; and (3) formulate policy options and strategies to balance the SOC.

2. Materials and methods

2.1. DNDC model

The DNDC model is a process-oriented simulation tool of soil carbon and nitrogen based on biogeochemistry that has been discussed in detail elsewhere (Li et al., 1992a,b, 1994, 1996; Li, 2000). The model contains six interacting sub-models: (1) Soil climate and thermal-hydraulic sub-models.

These sub-models use soil physical properties, air temperature, and precipitation data to calculate soil temperature and moisture profiles and soil water fluxes through time. The results of the calculations are input to the other sub-models. (2) Nitrification and denitrification sub-models.

These calculate hourly denitrification rates and N_2O, NO, NH_3 and N_2 production during periods when the soil water filled pore space exceeds 40%.

(3) Decomposition sub-model.

This sub-model simulates decomposition of each SOC pool, i.e., calculates daily decomposition, nitrification, ammonia volatilization processes, and CO_2 production from soil microbial respiration.

(4) The plant growth sub-model calculates daily root respiration, N uptake by plants, and plant growth.

(5) The fermentation sub-model calculates daily methane (CH_4) production.

In the DNDC model, SOC resides in four major pools: plant residues or litter, microbial biomass, humads, and active humus. Each pool consists of one or more sub-pools with different properties. The daily decomposition rate for each sub-pool is regulated by pool size, its specific decomposition rate (SDR) or fraction lost per day, soil clay content, N availability, soil temperature and moisture, and effective depth of the soil profile. The effects of cropping practices on C and N dynamics are also considered in the model (Li et al., 1994).

2.2. Data input

A major challenge in applying an ecosystem model at national scale is assembling adequate data sets needed to initialize and run the model. Applying the DNDC model to estimate the soil organic carbon storage in cropland in China requires spatial databases of soil properties, daily weather data, cropping and other data of agricultural management practices. County-scale data sets were developed to represent the status of the agricultural production in 1998 from maps, agricultural census data, and ground investigations. County-level agricultural census data and typical agricultural management practices for China in 1998 were prepared from two sources: (1) the Agricultural Economic Database (unpublished) of the Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences; and (2) field investigations of typical cropping areas. The database contains county statistics on crop acreage for major crops, acreage of total cropland, sown area, irrigated upland - area, nitrogen fertilizer use, and livestock and human population. These data are available for 2473 counties in China, excluding Taiwan, Hongkong, Macao, and the numerous small islands in the South China Sea (Xisha Qundao, Nansha Qundao, Zhongsha Qundao).

Table 1
Model results of alternative scenarios in cropland of mainland China

Scenarios	Baseline	50% res. returned	No-tillage	No-manure	No-fertilizer	+2 °C	+4 °C
SOC storage	3968	4027	4006	3946	3957	3953	3916
dSOC	−78.89	−24.3	−41.4	−101.3	−93.6	−97.5	−109.3

50% res. returned: 50% of non-grain aboveground crop biomass returned to soil.

Harvesting two or three crops from a single plot in a single year (multi-cropping) is most common in China, while single cropping is generally practiced in the northwestern and northeastern areas. The cropland area data reflect the actual cropland area, while the sown area data count double (or triple) the land that is multi-cropped. As such, the total crop sown area for mainland China in this database is 56% greater than the total cropland area. To solve this, we estimated single-cropped areas in each of 29 categories (as well as fallow), double-cropped areas in each of 24 categories and triple-cropped areas in 6 categories (according to the ground investigations, such as winter wheat/rice, rice/rice, rice/rice/hay etc.) based on the difference between total cropland and total crop sown areas, and the areas of each crop for each county. For this estimation, we prioritized crops in their own orders according to the cropping systems in 5 ecological regions. So we developed new maps showing the distribution of cropland in China by combining remote sensing and ground census data (Qiu et al., 2003a,b). The calculated areas agree with the total cropland, sown area and individual crop area (single plus double cropped plus triple cropped).

Maps of soil pH, soil texture, and soil organic matter, were digitized from 1 : 14,000,000 maps (ISS, 1986). Daily weather data for 1998 needed to run the model (precipitation, maximum and minimum air temperature) were acquired for 600 weather stations in China and each county was assigned to the nearest weather station.

2.3. Methods for process-model simulation

We used the DNDC model to simulate county scale SOC storage and its change for each crop/management scenario at county level (e.g., winter wheat / rice rotation). Previous work with the DNDC model has shown that the SOC storage is most sensitive to soil organic carbon content (Li et al., 1994; Qiu et al., 2004). Therefore we developed an estimation of the likely range of SOC storage and dSOC (value of SOC at the end of cropping season minus the previous value) for each crop by simulating one calendar year (1998) for each rotation in each county using both the high and low soil organic matter content values. In this paper we present the mean results (average of high and low estimates). County SOC (Tg[1]C) and dSOC (Tg C/year) were calculated by multiplying the mean SOC and dSOC for each crop rotation scenario with the area of each crop rotation in each county, and summing these totals for all crop rotations in a county. County totals were then summed to get a national total.

To explore the consequences of different management and climate scenarios, 6 additional sets of simulations were run. Results from these alternative scenarios will be discussed below. A set of simulations was run with no tillage (all other factors unchanged) to estimate the 'tillage-induced' SOC and dSOC as the difference between the baseline run and the 'no-tillage' run. Similarly, 'zero-N fertilizer', 'zero-manure', 'high residue returned', 'warmer temperature' sets of simulations were used to estimate respectively, the effects of 'fertilizer-induced', 'manure-induced', 'high residue induced', and 'warmer temperature induced' SOC and dSOC (Table 1).

Some important assumptions within the model runs are given below:

(1) Fertilizermix assumption: 40% urea, 40% NH_4HCO_3, 20% $NH_4H_2PO_3$;
(2) Animal and human populations were used to calculate manure additions to croplands. Baseline scenario assumptions were: 20% of livestock and 10% of human manure added to soil. Manure N production rates were set at 50 (cattle), 40 (horses, donkeys, camels), 12 (sheep, goats), 16 (swine) and 4 (humans) kg N/head/year;
(3) Tillage assumptions: 20 cm deep on planting day; 10 cm deep one day after harvest; and
(4) Base case scenario assumption was 15% of non-grain aboveground crop biomass returned to soil.

3. Results and discussion

3.1. Modeled SOC storage

According to the model simulation, the total SOC storage in the 0.968×10^8 ha croplands (0–30 cm

[1] Tg = 10^{12} g.

Table 2
Model estimated SOC storage and its changes in cropland of each province of mainland China in 1998

Provinces	SOC storage (Tg C)	dSOC (Tg C/year)	Rate %	Provinces	SOC storage (Tg C)	dSOC (Tg C/year)	Rate %
Beijing	6.84	−0.08	0.10	Henna	160.77	−4.91	6.22
Tianjing	6.75	−0.13	0.16	Hubei	90.63	−1.25	1.58
Hebei	155.02	−3.09	3.92	Hunan	101.32	2.23	−2.83
Shanxi	108.62	−2.75	3.49	Guangdong	84.51	−0.68	0.86
Inn Mongolia	466.22	−13.35	16.92	Guangxi	134.65	−2.59	3.28
Liaoning	200.64	−4.77	6.05	Sicuan	217.30	−2.94	3.73
Jilin	317.56	−8.22	10.42	Guizhou	75.48	−0.57	0.72
Heilongjiang	725.27	−18.92	23.99	Yunnan	120.03	−1.73	2.19
Shanghai	8.30	−0.06	0.08	Xizhang	20.00	−0.05	0.06
Jiangsu	132.99	−2.43	3.08	Shanxxi	87.76	−2.56	3.25
Zhejiang	51.11	0.64	−0.81	Gansu	101.26	−2.17	2.75
Anhui	102.20	−0.43	0.55	Ningxia	27.30	−0.08	0.10
Fujian	38.94	0.01	−0.01	Qinghai	30.73	−0.41	0.52
Jiangxi	70.98	0.78	−0.99	Xingjiang	139.83	−3.22	4.08
Shandong	156.53	−4.47	5.67	Hainan	24.44	−0.69	0.87
National total					3968	−78.89	100.00

SOC storage: the total soil organic carbon storage throughout 0–30 cm soil layer.
dSOC: the variations of SOC — during the cropping season, i.e., dSOC = endSOC − iniSOC.
Rate (%): is the rate of each dSOC to total national dSOC.

soil layer) in China is about 3968 Tg C, averaging 40.99×10^6g C per hectare cropland. The SOC rich areas are located in the northeastern four provinces, Jilin, Liaoning, Heilongjiang, and Inner Mongolia, where the SOC storage amounts to 317.56 Tg C, 200.64 Tg C, 725.27 Tg C, and 466.22 Tg C, respectively (Table 2). Expressed in percentages from the national total, it amounts to 8.0%, 5.1%, 18.3% and 11.7%, respectively. The total SOC storage in these four provinces comprise 43.1% of the national total of SOC in agricultural soils, while the total cropland area (0.228×10^8 ha) occupies only 23.6% of the national total. The average SOC storage is 74.99×10^6g C per hectare of cropland and exceeds the national average value by one time. The SOC storage is reasonably high because these northeastern areas have dominantly fertile soils with high organic matter content.

3.2. The situation of net C balance

The SOC in China cropland is at a situation of net loss currently, losing SOC at a rate of 78.89 Tg C/year (Fig. 1), or 1.95% per year. Most of the provinces were losing SOC in their own croplands, especially in the northeastern provinces (Inner Mongolia, Jilin, Liaoning and Heilongjiang) where the most fertile soils of the country are located. The loss of SOC in these provinces accounted for nearly 60% of the total national loss (Table 2). China's arable soils released 186.5 Tg C as carbon dioxide (CO_2) into the atmosphere, emitted 3.6 Tg C, leached 3.5 Tg C, and incorporated into the soil only 68.2 Tg C as crop residue and 37.6 Tg C as manure annually. The minimal return of crop residue to the soil was one of the major reasons that caused the net loss of SOC.

3.3. Implications and policies from alternative simulations

Since the equilibration time was longer for increasing SOC than for decreasing SOC content (Li et al., 1994), the efforts to enhance carbon sequestration in cropland soils would do well to focus on those specific areas and agricultural practices that have the greatest potential for increasing soil carbon content (Table 1).

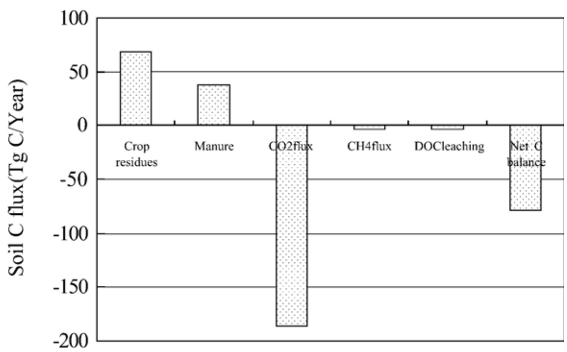

Fig. 1. Model estimated soil C fluxes and net C balance in cropland of mainland China in 1998. Total area of cropland in China is about 0.968×10^8 ha in 1998, on which 2172.6×10^4 tons of fertilizer with pure nitrogen were applied annually.

The most promising practices to enhance soil C equilibration include:

(1) Increasing the crop residue returned back to the field.

Crop residues are the main source of organic matter in the soil. Results of running the model using alternative scenarios with high residue returned to field revealed that if the rate was increased from the current 15% to 50% (aboveground parts), the national total dSOC would decrease from −78.89 Tg C to −24.3 Tg C, and the loss of SOC would significantly decrease to 69.2%. Correspondingly the SOC value would increase by 1.49%.

(2) Advocating protective cultivation by decreasing tillage.

Running the model using a no-tillage scenario revealed that the national total dSOC would decrease from −78.89 Tg C to −41.4 Tg C, and the loss of SOC would decrease by 47.5%. Correspondingly the SOC value would increase by 0.96%.

(3) Increasing manure application (both animal and human) and any other organic fertilizer.

Results of the alternative scenarios with zero manure applied to the field revealed that the national total dSOC would increase from −78.89Tg C to −101.3 Tg C and the SOC losses would increase by 28.4%. Correspondingly the SOC value would decrease by 0.55%.

(4) Application of chemical fertilizer at a rational level.

Results of the alternative scenario with no-chemical fertilizer revealed that the national total dSOC would increase from −78.89Tg C to −93.6 Tg C and the SOC losses would increase by 18.6%. Correspondingly the SOC value would decrease by 0.28%. So a decrease of application of chemical fertilizers to a more rational level will not cause a decline in SOC, i.e., the SOC response to applied N is not linear but rather reaches a plateau.

Global warming has a negative impact on SOC. Model runs of an alternative scenario revealed that if air temperature increases by 2 °C, the national total dSOC would increase from −78.89 Tg C to −97.5 Tg C, and the SOC losses would also increase by 23.6%. Correspondingly the SOC value would decrease by 0.38%. If the air temperature increases by 4 °C, the SOC losses would increase by 38.5%. Correspondingly the SOC value would decrease by 1.3%.

3.4. Uncertainty analyses and discussions

A significant uncertainty in the national inventory estimates of SOC storage made with DNDC is the actual cropland area. China's 1998 cropland area in our database is within 1% of the national total provided by China's State Statistical Bureau (SSB) in their annual report (e.g., SSB, 1999). However, the SSB states that 'figures for the cultivated areas are underestimated and must be further verified'. Consequently, also the surface areas in our database are probably underestimated (Qiu et al., 2003a,b, 2004). Recent estimates using remote sensing data, report an actual cropland area of 1.3×10^8 ha (Ministry of National Land Resources, 2001) which exceeds our data by 25.5%.

In the DNDC analysis, working with this smaller cropland area would probably lead to an underestimation of the total SOC storage. It would also increase synthetic fertilizer and manure application rates (the same amounts applied to smaller land area). However, the datasets at county level used in this study are the best ones currently available.

Organic matter content and other soil hydraulic characteristics significantly affect the simulation of the C and N biogeochemical cycle. In our GIS dataset, the initial organic matter content was derived from information reported in 1986, which can't exactly represent the current situation. In this study, we report a mean value of SOC storage of 3968 Tg C (ranging from 1958 Tg C to 5968 Tg C), which is derived from running both the high and low soil organic matter content value simulation, because the range of soil organic matter content in one place would be relatively stable. Therefore the estimated results are reliable.

The identification of a few important parameters, such as the rate of residue returned back to the field and rate of manure application, will also significantly affect the modeled results. The rate of 15% of non-grain aboveground residue returned to field used in this simulation was the national average derived from the Agricultural Ministry. Using the individual county rate would give better results.

CH_4 estimation is one of the important terms among the C balance. Since CH_4 is one of the principal greenhouse gases related to rice cultivation, the monitoring and estimations of its emission are often reported. The annual CH_4 emission from mainland China ranges from 3.35 to 8.64 Tg C/year (Matthews et al., 2000). Their "best estimate" of national CH_4 emission value is 3.73Tg C/year. The estimated national total of CH_4 in this paper is 3.6 Tg C/year.

As for keeping SOC in balance, most attention should be drawn to the specific area. The land in the northeast is rich and fertile. One of the most famous belts of black earth is found in the northeast of China. Only in Heilongjiang province, the acreages of black earth, Chernozem and meadow soil, occupy 67.6% of the provincial total areas of cropland. Since large areas of black earth were brought under cultivation, the soil organic matter decreased annually due to the unreasonable cultivation with less manuring and less crop residue returned to the field. Since the original reclamation-, the organic matter in black earth and Chernozem soil decreased from 6–8% to 1–3%, while the humus layer thickness dropped from 60–70 to 20 cm. At the actual annual loss of the thickness of black earth in hilly cropland, being 0.1to 0.5cm, the black soil in the reclaimed land will be disappeared within 40–100 years. The same results have been derived from our model estimates, so it's urgent to adopt countermeasures to mitigate the carbon loss in these areas.

4. Conclusions

Based on the simulations made by the processed model DNDC, the total SOC storage in croplands (0–30 cm soil layer) in China is about 3968 Tg C. The SOC in China croplands was at a situation of net loss, loosing SOC at a rate of 78.89 Tg C/year, mainly in the northeastern provinces (Inner Mongolia, Jilin, Liaoning and Heilongjiang) where the most fertile soils of the country are located. The loss of SOC in these provinces represented about 60% of total national loss. China's arable soils release 186 Tg C as carbon dioxide (CO_2) into the atmosphere, and only 68 Tg C as crop residue is returned to the soil annually. The lack of residue return of crop residue is one of the major reasons that cause the net loss of SOC.

The DNDC model tested several alternative management practices, such as land cover changes, conservative tillage and increased percentage of crop residue returned back to the field after harvest. Increasing the rate of crop residue return to field from the current level of 15% to 50%, decreased the loss of SOC by about 70%. Other countermeasures such as no tillage, increasing the returning rate of livestock and human waste, are also able to effectively increase SOC in the cropland in China. China needs a long-term policy based on scientific analysis to protect her soil resources to maintain soil fertility, sustainable yield, and environment safety.

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References

Franko, U., 1996. Modeling approaches of soil organic carbon turnover within the CANDY system. In: Powlson, D., Smith, P., Smith, J.U. (Eds.), Evaluation of Soil Organic Matter Models Using Existing Long-term Datasets. NATO ASI Series I, vol. 38. Springer-Verlag, Heidelberg, pp. 247–254.

Jenkinson, D.S., Hart, P.B.S., Rayner, J.H., Parry, L.C., 1987. Modeling the turnover of organic matter in long-term experiments. INTECOL Bull. 15, 1–8.

Li, C., 2000. Modeling trace gas emissions from agricultural ecosystems. Nutr. Cycl. Agroecosyst. 58, 259–276.

Li, C., Frolking, S., Frolking, T.A., 1992a. A model of nitrous oxide evolution from soil driven by rainfall events: I. Model structure and sensitivity. J. Geophys. Res. 97, 9759–9776.

Li, C., Frolking, S., Frolking, T.A., 1992b. A model of nitrous oxide evolution from soil driven by rainfall events: II. Model applications. J. Geophys. Res. 97, 9777–9783.

Li, C., Frolking, S., Harriss, R., 1994. Modeling carbon biogeochemistry in agricultural soils. Glob. Biogeochem. Cycles 8, 237–254.

Li, C., Narayanan, V., Harriss, R., 1996. Nitrous oxide emission in 1990 from agriculture lands in the United States. Glob. Biogeochem. Cycles 10, 297–306.

Li, C., Frolking, S., Crocker, G.J., Grace, P.R., Klír, J., Körchens, M., Poulton, P.R., 1997. Simulating trends in soil organic carbon in long-term experiments using the DNDC model. Geoderma 81 (1–2), 45–60.

Li, C., Qiu, J., Frolking, S., Xiao, X., Salas, W., Moore III, B., Boles, S., Huang, Y., Sass, R., 2002. Reduced methane emissions from large scale changes in water management of China's rice paddies during 1980–2000. Geophys. Res. Lett. 29 (20). doi:10.1029/2002GL015370.

Matthews, R.B., Wassmann, R., Arah, J., 2000. Using a crop/soil simulation model and GIS techniques to assess methane emissions from rice fields in Asia: IV. Upscaling to national levels. Nutr. Cycl. Agroecosyst. 58, 201–217.

Molina, J.A.E., Clapp, C.E., Shaffer, M.J., Chichester, F.W., Larson, W.E., 1983. NCSOIL, a model of nitrogen and carbon transformations in soil: description, calibration and behavior. Soil Sci. Soc. Am. J. 47 (1), 85–91.

Mueller, T., Jensen, L.S., Hansen, S., Nielsen, N.E., 1996. Simulating soil carbon and nitrogen dynamics with the soil–plant–atmosphere system model DAISY. In: Powlson, D., Smith, P., Smith, J.U. (Eds.), Evaluation of Soil Organic Matter Models Using Existing Long-term Datasets. NATO ASI Series I, vol. 38. Springer-Verlag, Heidelberg, pp. 275–282.

Parton, W.J., Mosier, A.R., Ojima, D.S., 1996. Generalized model for N_2 and N_2O production from nitrification and denification. Glob. Biogeochem. Cycles 10, 401–412.

Qiu, J., Frolking, S., Boles, S., McGill, W.B., Arah, J.R.M., Chertov, O.G., Coleman, K., Franko, U., Frolking, S., Jenkinson, D.S., 2003a. Combining remote sensing and ground census data to develop new maps of the distribution of cropland in China. Geocarto Int. 18 (2), 3–13.

Qiu, J., Tang, H., Li, C., 2003b. Study on the situation of soil organic carbon storage in ecotone between agriculture and animal husbandry: an Inner Mongolia case study. Chin. J. Eco-Agric. 11 (4), 86–88 (in Chinese).

Qiu, J., Wang, L., Tang, H., Li, H., Li, C., 2004. Studies on the situation of soil organic carbon storage in croplands in northeast of China. Chin. Agric. Sci. 37 (8), 1166–1171 (in Chinese).

Smith, P., Smith, J.U., Powlson, D.S., 1997. A comparison of the performance of nine soil organic matter models using datasets from seven long-term experiments. Geoderma 81, 153–225.

Xu, W.B., Hong, Y.T., Chen, X.H., Li, C.S., 1999. Study on the emission of N_2O in agricultural land — a case of Guizhou Province. China Sci. (D) 29 (5), 450–456 (in Chinese).