Quantifying Soil Organic Carbon Sequestration Potential with Modeling Approach

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Abstract: A process-based model, Denitrificaion-Decomposition or DNDC, was utilized in this study to test a hypothesis that the Soil Organic Carbon (SOC) content in a soil, if under constant climate, soil texture and farming management conditions for a centuries-long time span, would approach to a equilibrium level, which is independent on the initial SOC content; and hence the potential of the soil for sequestering the atmospheric carbon can be quantified as the difference between the initial SOC content and the prospective SOC equilibrium content. A crop system with corn and winter wheat rotated, which is typical for North China, was selected for the test. A baseline scenario was composed based on the local climate, soil properties and farming management practices. DNDC was run for 300 years for the selected cropping system with varied initial SOC contents. The modeled results indicated that all the simulated soils tended to have an identical, prospective SOC content during the 300-year simulations. Alternative scenarios were composed by varying the farming practices, climate or soil texture to test their impacts on the prospective SOC equilibrium content. The results indicated that (1) the prospective SOC equilibrium content was substantially elevated by 43 600, 70 100 or 23 600 kg C/ha by increasing the above-ground crop residue incorporation rate from 15% to 80%, applying manure at rate 2 000 kg C/ha, or converting conventional tillage to no-tillage, respectively; and (2) the prospective SOC equilibrium content varied when the climate or soil texture changed. This study demonstrated that the process-based models such as DNDC could serve the C sequestration business by quantifying the soil C sequestration potentials across climatic zones, soil types and management regimes for agroecosystems.

Key words: Carbon sequestration; Soil organic carbon; DNDC

Carbon (C) sequestration is an important approach for mitigating the greenhouse effect on climate by converting the atmospheric CO_2 into biotic or abiotic C sequestered in terrestrial ecosystems, underground reservoirs, the ocean, and as mineral carbonates (Lackner, 2003). As managed systems, agricultural ecosystems are being studied for their potential to sequester C in their soil through management alternatives. For example, replacing conventional tillage with no-tillage generally results in net sequestration of soil organic carbon while maintaining or improving long-term crop yields (Lal *et al.* 1998, Robertson *et al.* 2000). Lackner (2003) estimated global storage capacity of soil carbon at roughly 100 Gt C. The C stored in terrestrial soils mainly exists in organic forms. In most agricultural soils, the SOC pools are highly dynamic driven by both natural factors (e.g., climate, soil properties etc.) and anthropogenic activities. It is clear that any likely scenario for a transition to a low carbon economy will require a national portfolio that includes all options for carbon management. Regional applications of C sequestration strategies can be designed only upon our capacity for quantitatively predicting the C sequestration rates across climatic zones, soil types and management regimes. This paper reports how we utilized a modeling approach to quantify the C sequestration potentials for agricultural soils.

1 Modeling SOC dynamics by tracking litter production and decomposition

Dynamics of the organic carbon pools in agricultural soils is mainly driven by two processes, i. e, gaining C through crop litter incorporation or manure application losing C through SOC decomposition or erosion (Li *et al.* 1994). For most terrestrial ecosystems, litter incorporation is almost the sole source of SOC. During or after plant growing season, the plant litter or residue can be incorporated into the local soils through senescence or harvest/tillage practices. As soon as the fresh litter becomes accessible for the soil microorganisms, the litter C will be utilized as an energy source by the microbes. This is the beginning of the process of decomposition. During the process, the litter C will be converted into the microbial biomass first. After death of the microbes, their remains will join the soil humads pool, a pool consisting of readily decomposable organic matter. Further decomposing processes will turn the humads into humus, a resistant SOC pool. During the decomposing processes from the fresh litter to the inert humus, a part of the SOC will become carbon dioxide (CO_2) or dissolved organic carbon (DOC), which can be lost through emission or leaching. Apparently, size of the SOC pool in a soil is determined by the balance between the C input through fresh litter incorporation and the C loss through CO_2 emission and/or DOC leaching driven by decomposition (Figure 1).

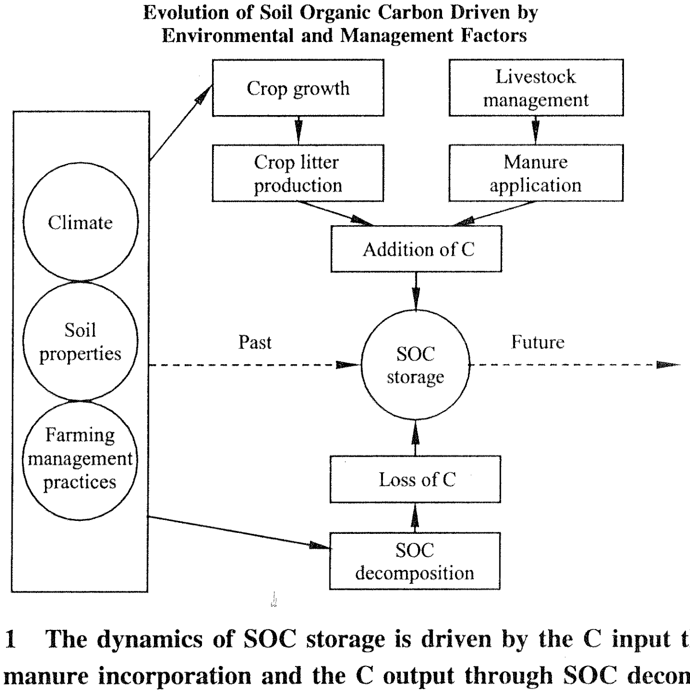

Figure 1 The dynamics of SOC storage is driven by the C input through litter or manure incorporation and the C output through SOC decomposition

During the past decade, a number of process-based models were developed to integrate the relationships among the environmental drivers, litter production, decomposition and SOC dynamics for the terrestrial ecosystems. The Denitrification-Decomposition or DNDC model resulted from one of the modeling efforts (Li *et al.* 1992, 1994, 1997, 2004, 2005; Li 1995, 2000; Zhang *et al.* 2002). The core of DNDC is a soil biogeochemistry model describing C and N transport and transformation driven by a series of soil environmental factors such as temperature, moisture, redox potential (i. e., Eh), pH, and substrate concentration gradients (Figure 2). Basic physical, chemical, and biological laws governing the relevant reactions, as well as empirical equations developed from field and laboratory observations, were utilized to construct the model framework. DNDC is driven by daily meteorological data, soil properties, vegetation status, and anthropogenic activities including farming management. Detailed management measures (e.g., crop rotation, tillage, fertilization, manure amendment, irrigation, weeding, and grazing) have been parameterized and linked to the various biogeochemical processes (e. g., crop growth, litter production, soil water infiltration, decomposition, nitrification, denitrification) embedded in DNDC. DNDC has been tested against numerous field observations regarding SOC dynamics and trace gas emissions in agroecosystems worldwide (Brown *et al.* 2002; Zhang *et al.* 2002; Li 2000; Xiu *et al.* 1999; Frolking *et al.* 1998; Plant *et al.* 1998; Smith *et al.* 1997; Li *et al.* 1997, 1994, 1992; Zhang *et al.* 2006; Jagadeesh Babu *et al.* 2006; Kesik *et al.* 2005).

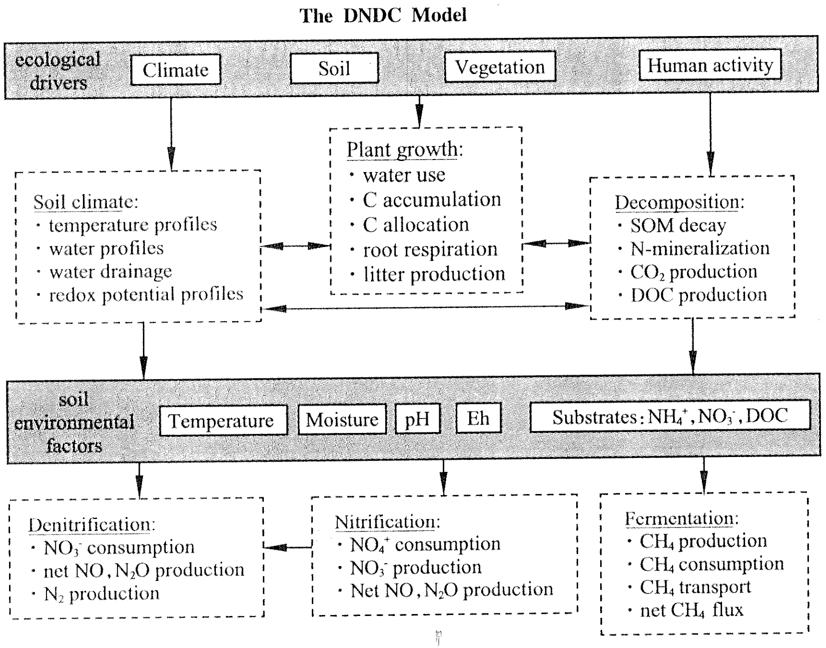

Figure 2 Structure of the DNDC model

DNDC predicts SOC dynamics by tracking litter incorporation and SOC decomposition. The detailed processes parameterized in DNDC for the two features are summarized as follows.

1.1 Modeling crop growth and litter production

The DNDC model predicts litter production by simulating crop growth and biomass partitioning among the plant parts (e. g. , leaf, stem, root and grain). In DNDC, a crop is defined with five major factors, namely optimum yield, thermal degree days (TDD), water requirement, N demand and N fixation index. The optimum yield, in unit kg dry matter/ha, is defined as the yield of the crop growing under the conditions without any temperature, water or N stress. TDD, in unit ℃, is the sum of the daily average air temperatures above 0℃ during the entire growing season from seeding to maturity. The water requirement, in unit kg water/kg dry matter, is the amount of water required for producing a unit of dry matter of the crop yield. The N demand, in unit kg N/ha, is the amount of N required by the crop during the entire growing season under stress-less conditions. The N demand for a crop is determined by the crop optimum yield, the partitioning of crop biomass among the leaf, stem, root and grain sectors, and the C/N ratios of the crop sectors. The N fixation index is defined as a ratio of the total plant N/the plant N taken from soil. The specific values of the above-mentioned parameters for each crop were collected from various literatures and stored in a series of library files included in the DNDC package. The current version of DNDC simulates about fifty crop types with the default parameter values for each of the crops. Most of the default values stored in DNDC were collected from various sources published in U. S. or Europe. To make the modifications with the crop parameters routine and convenient, a special tool named "Crop Creator" has been developed in DNDC to allow the users to review and modify the parameters based on their own data (see details in the DNDC User's Guide, available at http: // www. dndc. sr. unh. edu). Since it is crucial for modeling soil biogeochemistry to correctly simulate crop growth, it is recommended to review and modify these parameters before any serious simulations. For example, to apply DNDC for the agricultural studies in China, we thoroughly modified the parameters for all the major crops of China based on a wide range of information from the Chinese publications. The modified parameters for the crops in China are summarized in Table 1.

Table 1 Physiological parameters adopted in DNDC for modeling major crops in China

Crop	Optimum yield (kg dry matter/ha)	Grain C/N	Shoot C/N	Root C/N	Total C/N	Grain fraction	Shoot fraction	Root fraction	Water requirement (kg water/kg)	TDD (℃)
Corn	4 800	35.0	50.0	50.0	43.2	0.37	0.47	0.16	250	2 550
Winter wheat	3 900	18	50	71	33.7	0.3	0.53	0.17	200	2 000
Soybean	1 653	10	45	24	18.8	0.35	0.45	0.20	541	1 500
Hay	22 000	50	50	90	62.5	0.01	0.80	0.19	550	2 500
Spring wheat	3 000	25	60	60	41.0	0.33	0.52	0.15	600	1 400
Sugarcane	64 000	400	400	400	400.0	0.5	0.3	0.2	212	7 250
Barley	2 600	26	57	44	40.0	0.3	0.47	0.23	508	1 000
Oats	3 500	18	51	50	35.8	0.23	0.54	0.23	509	1 650
Alfalfa	8 000	10	10	13	10.7	0.01	0.69	0.3	300	2 000
Sorghum	4 000	20	69	85	37.5	0.35	0.56	0.09	304	2 600
Cotton	1 500	12	30	35	20.6	0.32	0.52	0.16	646	1 200

continued

Crop	Optimum yield (kg dry matter/ha)	Grain C/N	Shoot C/N	Root C/N	Total C/N	Grain fraction	Shoot fraction	Root fraction	Water requirement (kg water/kg)	TDD (℃)
Rye	2 134	20	50	50	35.2	0.28	0.47	0.25	551	2 000
Vegetables	6 000	30	30	50	30.6	0.65	0.3	0.05	800	1 400
Potato	14 000	40	40	60	40.7	0.7	0.25	0.05	415	2 100
Beets	21 000	58	50	80	56.6	0.75	0.2	0.05	318	2 550
Wetland rice	6 400	27	43	45	34.8	0.4	0.53	0.07	508	2 200
Peanuts	2 650	25	40	50	34.1	0.35	0.47	0.18	554	2 900
Upland rice	3 375	35	55	40	39.4	0.37	0.43	0.2	400	2 250
Rapeseeds	1 600	12	45	52	46.7	0.23	0.69	0.08	450	700
Tobacco	1 800	15	15	40	15.7	0.45	0.48	0.07	700	3 400
Millet	1 900	20	40	50	37.9	0.32	0.52	0.16	331	1 750
Sunflower	1 500	10	45	50	22.0	0.3	0.67	0.03	495	1 500
Beans	1 500	9.2	33	35	17.2	0.36	0.46	0.18	300	1 900

During the simulated growing season, daily N demand is calculated based on the total N demand, daily temperature and TDD. Daily water demand is calculated based on the daily N demand, daily potential biomass growth and water requirement. If there is no enough water or N to meet the demand, water stress or N stress will occur that will reduce the daily biomass production. The increase in crop biomass will be partitioned into the shoot (i. e., leaf and stem), root and grain pools of the crop at a daily time step. Root exudation is calculated as a fraction of the daily root growth rate. Senescence is defined as a fraction of the shoot biomass when the crop approaches to maturity. At harvest, all the roots will be incorporated in the soil, and a user-defined fraction of the above-ground crop residue will be left as stub in the field. The stub will be incorporated into the soil by the following tilling practice. The incorporation of the roots and the above-ground residue will constitute the fresh input for the SOC pool. In many ecosystems, the litter incorporation is the sole source to add fresh litter into the SOC pools. So it is crucial for modeling SOC dynamics to accurately simulate crop growth and hence litter production and incorporation.

1.2 Modeling SOC decomposition

Soil organic carbon (SOC) is the sum of all the organic components including living microorganisms and abiotic organic compounds existing in the soil. In DNDC, these organic components are divided into four major SOC pools, namely litter, microbial biomass, humads and humus. The litter pool contains all the plant residues in different degree of decomposition. The microbial biomass pool includes the living microorganisms from fungi to bacteria. The humads pool stands for the dead microorganisms or other decomposable humus. The humus pool is defined for the passive humus, which is relatively resistant and can stay for decades to centuries in the soil. Each of the litter, microbes and humads pools consists of two or three sub-pools representing the relatively labile and resistant fractions of the pool (Figure 3). As soon as the fresh litter is incorporated in the soil, the litter will be partitioned into three sub-litter pools (i. e., very labile, labile and resistant litter pools) based on the bulk C/N ratio of the fresh litter. The higher the bulk C/N ratio the more litter mass will be partitioned into the resistant pool (Figure 4). The very labile, labile and resistant litter pools have specific decomposition rates 0.25, 0.074 and 0.02 per day, respectively. The litter decomposition rates are also affected by the soil temperature, moisture, clay content and tilling disturbance (Li *et al.* 1992, 1994).

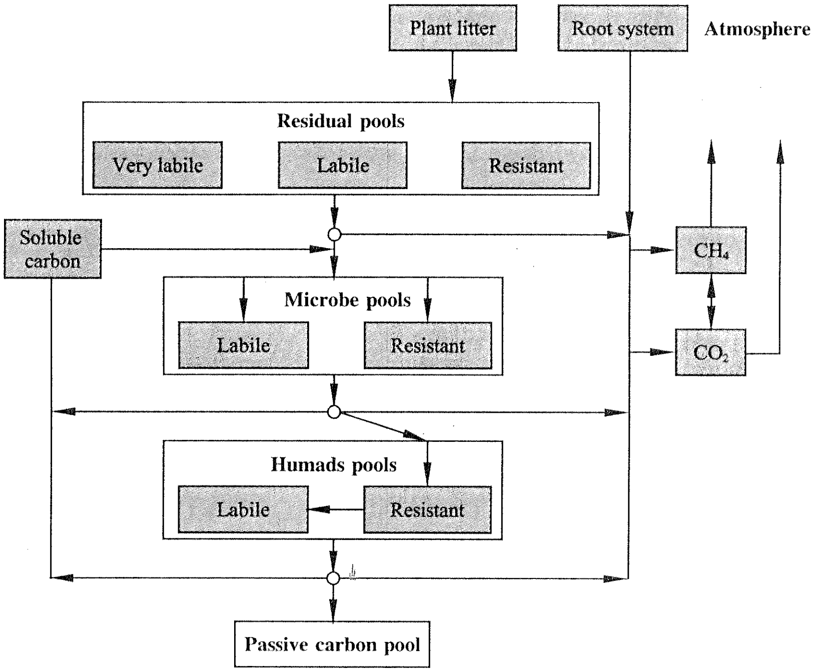

Figure 3 Soil C pools and fluxes simulated in the DNDC model

During the decomposition of litter, a part of the litter C is used as the energy source by the soil microbes and hence becomes carbon dioxide (CO_2) emitted into the atmosphere, and the rest part of the litter C is turned into the microbial biomass. After the death of the microbes, their remains will be transferred into the humads pool. The SOC in the humads pool can further decompose into passive humus through the soil microbial activity. During the sequential decomposing processes, a fraction of the SOC will become dissolved organic carbon (DOC), which can be readily utilized by the soil microbes or leached with the soil water flow. The C outputs through CO_2 emission and DOC leaching compose the major SOC losses simulated by DNDC. DNDC doesn't simulate soil erosion, so that the SOC loss through the wind or water erosion is not counted in the simulations.

By precisely simulating the litter production and SOC decomposition, DNDC is capable of tracking the SOC dynamics based on the balance of the C inputs and outputs for a specific ecosystem. For agroecosystems, manure application provides an additional input of SOC. In

DNDC, manure is defined as a combination of water, urine, dung, humads and/or litter. Based on the manure types (e. g., farmyard manure, slurry animal waste, compost, straw etc.), the applied manure will be partitioned into the soil water, C or N pools, and then subjected to the corresponding biogeochemical processes.

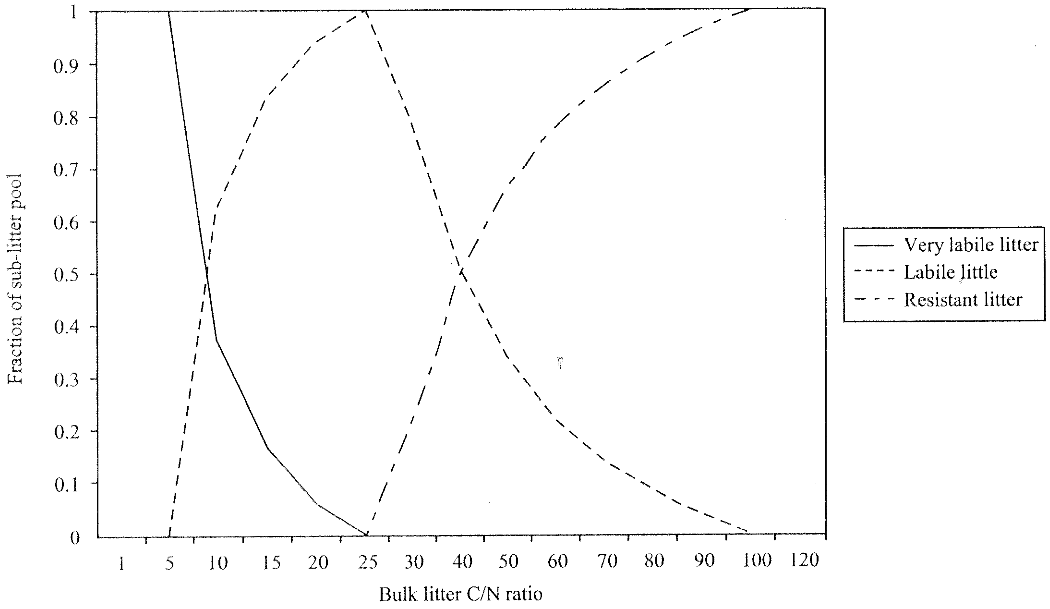

Figure 4 Fresh litter is partitioned into the soil very labile, labile and resistant litter pools based on the bulk C/N ratio of the fresh litter

2 Quantifying SOC sequestration capacity

If climate, soil texture and management conditions are kept constant in a relatively long term (e. g., 300 – 600 years), the SOC content in a soil will gradually approach to an equilibrium level, on which the SOC content won't either increase or decrease any more. In other words, the C input rate through litter incorporation or manure amendment will equal to the C output rate through decomposition after the equilibrium point. The equilibrium level will depend on the climate, soil texture and management conditions but be independent on the initial SOC content (Li *et al.* 1994). The potential of a soil for sequestering more C can be defined as is the difference between the prospective equilibrium SOC content and the initial (or current) SOC content of the soil:

$$CSP = PCEC - ICC \qquad (1)$$

where *CSP* is C sequestration potential, *PCEC* is prospective SOC equilibrium content, and *ICC* is initial SOC content. The unit for the three items is kg C/kg soil or kg C/ha.

To illustrate the relationship among the soil C sequestration potential, the initial SOC content, the prospective equilibrium SOC content and the environmental conditions, we conducted a series of 300-year simulations with DNDC for a typical crop field in North China. The simulated field is located in Quzhou County (latitude 39. 1° N), Hebei Province. The field was planted with rotated corn (June 25 — October 30) and winter wheat (November 1 — June 20) with 120 kg N of urea applied for each of the crops per year. The field was conventionally tilled and adequately irrigated. Fifteen percents of the above-ground crop residue was incorporated in the soil after harvest. No manure was applied. The soil is a silty clay loam with bulk density 1.4 and pH 7.0. The SOC contents ranged between 0.01 and 0.03 kg C/kg within the county scope. The daily weather data of 2004 were obtained from the local climatic station and repeatedly utilized for the 300-year model runs. A baseline scenario was composed based on the above-described climate, soil and management conditions.

By running DNDC with the baseline scenario for five soils which shared the same climate, soil properties and cropping management practices but only with different initial SOC contents (i.e., 0.01, 0.015, 0.025 or 0.03 kg C/kg), we obtained five curves representing the dynamics of the SOC storages in the five soils during the simulated 300 years. All the five curves approached to an identical equilibrium level during the 300-year simulations. The SOC content (0 — 30 cm) at the equilibrium level was about 0.018 kg C/kg or 66 400 kg C/ha (Figure 5). The simulated results indicated that all the soils containing the initial SOC contents lower than 66 400 kg C/ha continuously increased, and all the soils containing the initial SOC contents higher than 66 400 kg C/ha continuously decreased to approach the prospective equilibrium level. The modeled results proved the hypothesis that the SOC content in a soil, if under constant climate, soil texture and farming management conditions for a centuries-long time span, would approach to an equilibrium level, which is independent of the initial SOC content.

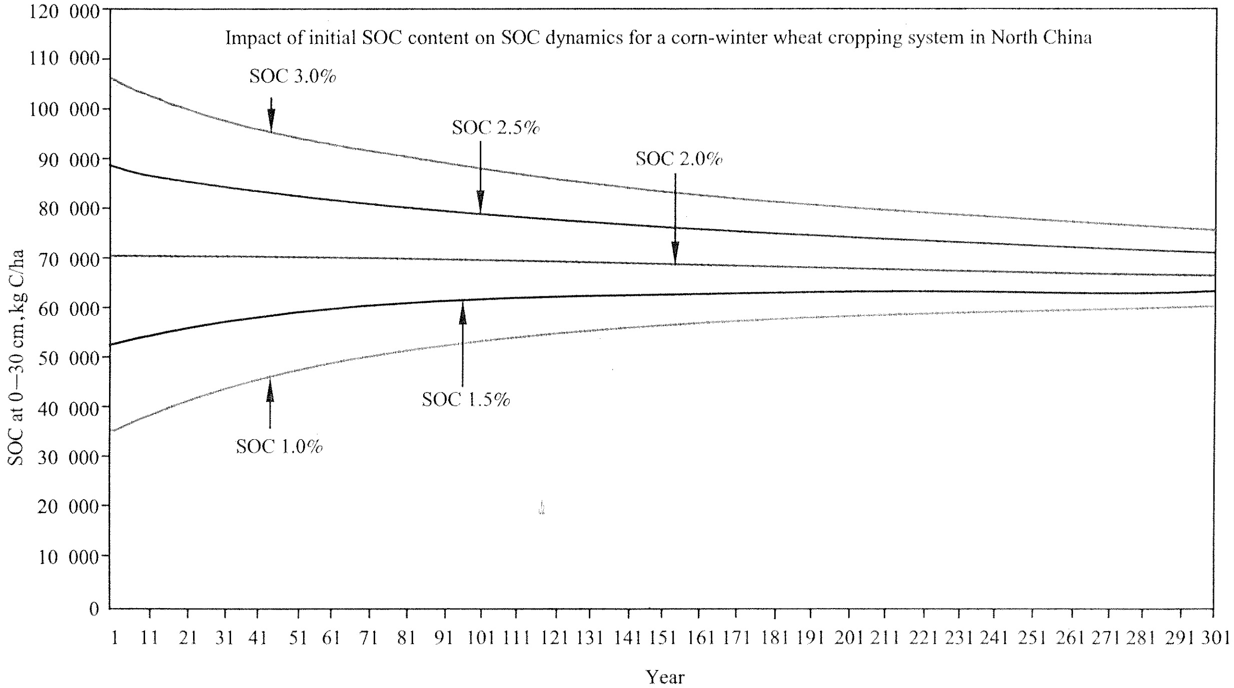

Figure 5 Under constant climate, soil texture and management conditions, the modeled SOC contents approached to an identical equilibrium level, which is independent of the initial SOC contents of the soils

Based on Equation (1), increase in the soil C sequestration potential (CSP) can be realized by increasing the prospective SOC equilibrium content (PCEC), which is collectively determined by the climate, soil texture and farming management practices for a specific cropping system. Since neither climate nor soil texture can be easily manipulated, the only feasible approach for altering the soil C sequestration potential is to change the farming management practices. In this study, three alternative management scenarios were designed by changing the crop residue incorporation rate from the baseline (15%) to 80%, increasing the manure application rate from 0 to 2 000 kg C/ha per year, and converting the baseline conventional tillage to no-tillage, respectively. DNDC was run with the alternative management scenarios for 300 years. The modeled results indicated that all the three tested management practices had significant impacts on the SOC dynamics for the tested cropping system (Figure 6). By applying the alternative residue management, manure use and tillage elevated the prospective SOC equilibrium content from the baseline 66 400 to 110 000, 136 500 and 90 000 kg C/ha, respectively (Table 2).

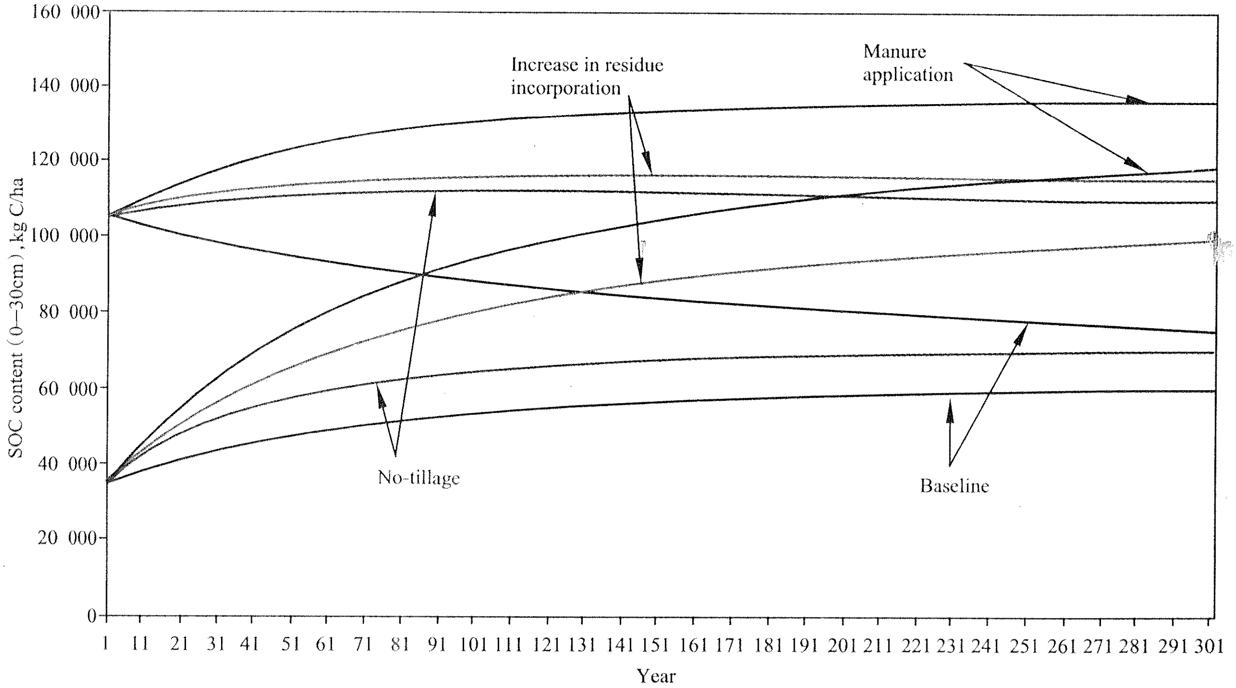

Figure 6 Impacts of alternative farming management practices on SOC dynamics for a corn-winter wheat rotated field in Quzhou County, Hebei Province, China

However, the impacts of the farming management practices on SOC are subject to the local climate and soil conditions. Within the Quzhou County, the annual average air temperature varied with a deviation of ±4℃, and the soil texture ranged from sandy loam to clay. Four additional scenarios were composed by increasing and decreasing the daily air temperatures by 4℃, and shifting the soil texture from the baseline texture (silty clay loam) to sand loam or clay. The modeled results indicated that the prospective SOC equilibrium level changed under the alternative temperature or soil texture conditions. The warm weather decreased the prospective SOC equilibrium content by about 10 000 kg C/ha; and the cooler weather increased the equilibrium

Table 2 DNDC-modeled SOC sequestration potentials under baseline and alternative climate, soil texture and farming management conditions for a corn-winter wheat system in North China

Scenario	Initial SOC concentration in top soil (kg C/kg soil)	Initial SOC content in soil profile (0—30 cm) (kg C/ha)	Prospective SOC equilibrium content (kg C/ha)	SOC sequestration potential (kg C/ha)
Baseline *	0.010	35 431	66 400	30 969
	0.015	53 162	66 400	13 238
	0.020	70 896	66 400	−4 496
	0.025	88 626	66 400	−22 226
	0.030	106 357	66 400	−39 957
Alternative soil texture: Sandy loam	0.010	35 431	44 280	8 849
	0.030	106 357	44 280	−62 077
Alternative soil texture: Clay	0.010	35 431	105 000	69 569
	0.030	106 357	105 000	−1 357
Alternative climate: −4 degree C	0.010	35 431	81 000	45 569
	0.030	106 357	81 000	−25 357
Alternative climate: +4 degree C	0.010	35 431	57 000	21 569
	0.030	106 357	57 000	−49 357
Alternative management: 80% of crop residue incorporation	0.010	35 431	110 000	74 569
	0.030	106357	110 000	3 643
Alternative management: Manure 2 000 kg C/ha	0.010	35 431	136 500	101 069
	0.030	106 357	136 500	30 143
Alternative management: No-tillage	0.010	35 431	90 000	54 569
	0.030	106357	90 000	−16 357

* Baseline scenario: corn-winter wheat rotation, conventional tillage, 120 kg urea-N/ha applied for each crop, no manure amendment, fully irrigated; silty clay loam, pH 7.0, bulk density 1.4, SOC 0.01 —0.03 kg C/kg; annual average temperature 14.1℃, precipitation 353 mm

content by 15 000 kg C/ha (Figure 7). The simulated data showed that the higher temperatures increased the SOC decomposition rates but not significantly elevated the crop litter production. When the soil texture was shifted from silty clay loam to sand loam or clay, the prospective SOC equilibrium content decreased to 44 280 or increased to 105 000 kg C/ha, respectively (Figure 8). In DNDC, clay minerals can adsorb SOC components and hence protect them from decomposition.

As shown in Equation (1), the C sequestration potential (CSP) for a soil can be calculated as the difference between the prospective SOC equilibrium content (PCEC) and the initial or

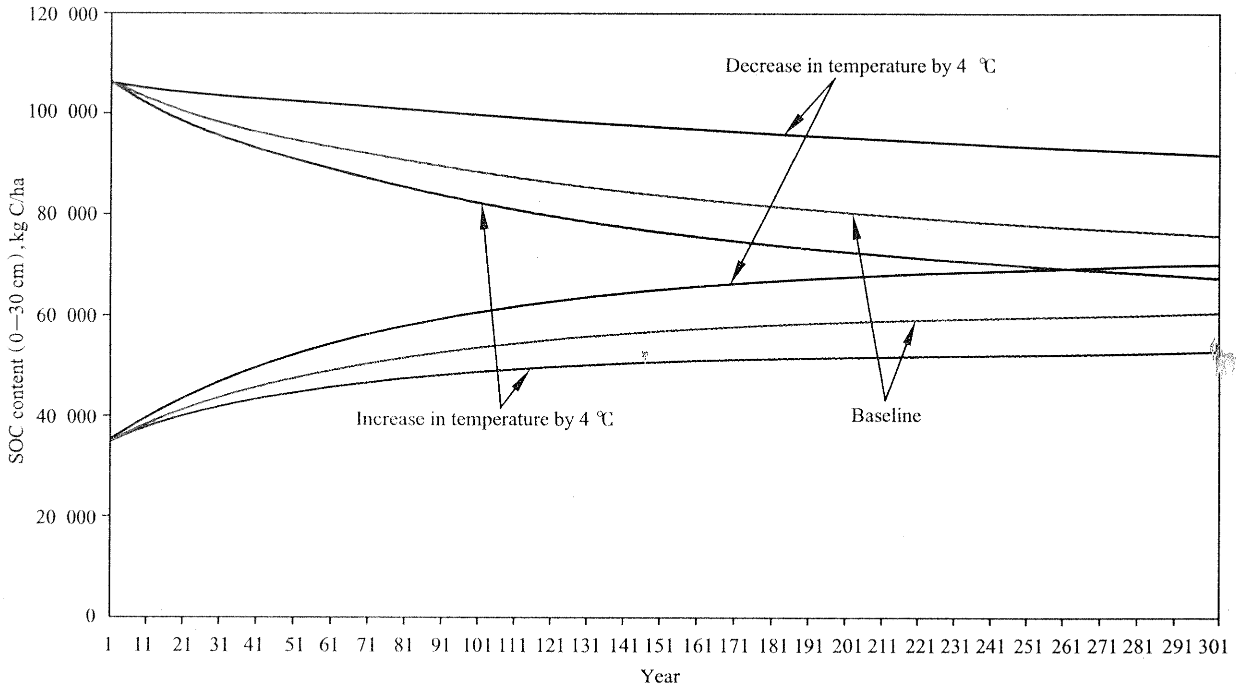

Figure 7 Impact of temperature on SOC dynamics for a corn - winter wheat cropping system in North China

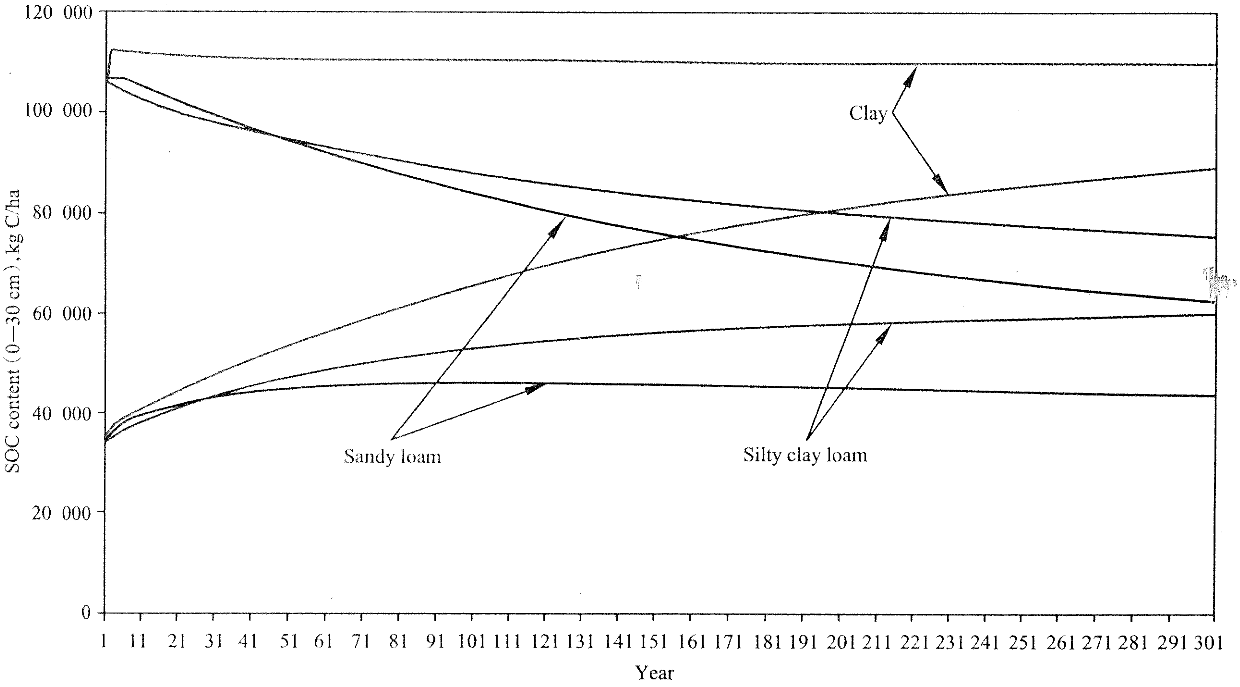

Figure 8 Impact of soil texture on SOC dynamics for a corn - winter wheat cropping system in North China

current SOC content (ICC). If the difference is positive, the soil will gain C; otherwise the soil will lose C. The calculated results for the tested cropping system in the Quzhou County are shown in Table 2. The results indicated that the soil C sequestration potentials of the tested corn-wheat system were highly variable driven by the initial SOC content, the climate, the soil texture and the farming management practices within the county scale. The general conclusions can be summarized as follows:

(1) Under the baseline climate, soil texture and management conditions, the prospective SOC equilibrium content is fixed as a constant, the soil C sequestration potentials for different soils will vary mainly depending on their initial SOC contents. For the tested cropping system in Quzhou, all the soils with the initial SOC concentration lower or higher than 0.02 kg C/kg will gain or lose C, respectively, in the coming 300 – 500 years.

(2) If the temperature increases by 4℃, the SOC sequestration potentials will decrease. For example, the sequestration potential for the soils with current SOC of 0.01 kg C/ha will drop from the baseline 31 000 to 21 600 kg C/ha.

(3) When soil texture is shifted from the baseline (silty clay loam) to a lighter soil texture (e.g., sandy loam) or a heavier texture (e.g., clay), the C sequestration potential of the soil will decrease or increase accordingly. For example, the C sequestration potential of a sandy loam soil with the initial SOC 0.01 kg C/kg will be 22 100 kg C/ha lower than that of a silty clay loam soil with the same initial SOC content.

(4) All the three alternative farming management practices by increasing crop residue incorporation rate, applying manure and converting conventional tillage to no-tillage can effectively increase the soil C sequestration potentials for all the soils with various initial SOC contents. Even the alternative residue and manure practices can convert the soils with high SOC contents (e.g., 0.03kg C/kg) from a source to a sink of the atmospheric C.

3 Discussions

It is essential for estimating terrestrial C sequestration capacity to quantifying soil C dynamics in the various ecosystems. Since SOC dynamics is determined by a complex systems, in which the C input through crop litter or manure incorporation as well the C output through decomposition are collectively and simultaneously controlled by a series of natural and management factors, only field measurements at a limited number of sites may not be able to provide adequate information to quantify the C sequestration capacity at regional or national scale. The study reported in this paper was an attempt to utilize a process-based model to serve the purpose. The results from the modeling tests indicate that (1) a well calibrated and validated biogeochemical model such as DNDC is capable of estimating the prospective SOC equilibrium contents and hence able to quantify the C sequestration potentials for any soils; and (2) the modeled SOC sequestration potentials are heterogeneous driven by the climate, soil and management conditions, so that applying process-based models will help us with the making of the spatially differentiated policies for C sequestration at regional or national scale.

In China, especially in North China, SOC loss used to be a problem threatening the local soil fertility in history. Due to some of the social-economic barriers, the rates of crop residue incorporation or manure application are still low in the regions. The modeled results indicate that the SOC sequestration potential can be substantially elevated if the farmers can increase the crop residue incorporation rate, apply manure fertilizer, or convert the conventional tillage to no-tillage. The modeled results indicate that the highest benefit will be gained if the alternative farming management practices are applied for the poor soils containing low SOC contents with a priority.

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References

Brown L, Syed B, Jarvis S C, *et al.* 2002. Development and application of a mechanistic model to estimate emission of nitrous oxide from UK agriculture. *Atmospheric Environment*, **36**: 917 — 928.

Frolking S E, Mosier A R, Ojima D S, *et al.* 1998. Comparison of N_2O emissions from soils at three temperate agricultural sites: simulations of year-round measurements by four models. *Nutrient Cycling in Agroecosystems*, **52**: 77 — 105.

Jagadeesh Babu Y, Li C, Frolking S, *et al.* 2006. Field validation of DNDC model for methane and nitrous oxide emissions from rice-based production systems of India. *Nutrien Cycling in Agroecosystems*, **74**: 157 — 174. doi: 10. 1007/s10705 - 005 - 6111 - 5.

Kesik M, Ambus P, Baritz R. 2005. Inventories of N_2O and NO emissions from European forest soils. *Biogeosciences*, **2**: 353 — 375. SRef-ID: 1726 — 4189/bg/ 2005 - 2 - 353.

Lackner K S. 2003. Climate change: A guide to CO_2 sequestration. *Science*, **300**: 1677 — 1678. DOI: 10. 1126/science. 1079033.

Lal R, Kimble J M, Follett R F, Cole C V. 1998. *The Potential of U. S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect.* Ann Arbor Press, Chelsea MI. 128 pp.

Li C , Frolking S, Butterbach-Bahl K. 2005, Carbon sequestration in arable soils is likely to increase nitrous oxide emissions, offsetting reductions in climate radiative forcing. *Climatic Change* **72**: 321 — 338. DOI: 10. 1007/s10585 - 005 - 6791 - 5.

Li C. 1995. Impact of agricultural practices on soil C storage and N_2O emissions in 6 states in the US. In: Advances in Soil Science (eds. R. Lai *et al.*), *Soil Management and Greenhouse Effect*, pp. 101 — 112.

Li C. 2000. Modeling trace gas emissions from agricultural ecosystems. *Nutrient Cycling in Agroecosystems*, **58**: 259 — 276.

Li C, Mosier A, Wassmann R, *et al.* 2004. Modeling Greenhouse Gas Emissions from Rice-Based Production Systems: Sensitivity and Upscaling. *Global Biogeochemical Cycles* 18: GB1043, doi: 10. 1019/ 2003GB002045.

Li C, Frolking S, Harriss R C. 1994. Modeling carbon biogeochemistry in agricultural soils. *Global Biogeochemical Cycles*, **8**: 237 — 254.

Li C, Frolking S, Frolking T A. 1992. A model of nitrous oxide evolution from soil driven by rainfall events: 2. Applications. *Journal of Geophysical Research*, **97**: 9777 — 9783.

Li C, Frolking S, Croker G J, *et al.* 1997. Simulating trends in soil organic carbon in long-term experiments using the DNDC model. *Geoderma*, **81**: 45 —60.

Plant R A J. 1998. GIS-based extrapolation of land use related nitrous oxide flux in the Atlantic zone of Costa Rica. *Water Air and Soil Pollution*, **105**: 131 —141.

Robertson G P, Paul E, Harwood R R. 2000. Greenhouse gases in intensive agriculture: Contributions of individual gases to the radiative forcing of the atmosphere. *Science*, **289**: 1922 — 1925.

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

Xiu W B, Hong Y T, Chen X H, *et al.* 1999. Agricultural N_2O emissions at regional scale: A case study in Guizhou, China. *Science in China*, **29**: 5 —17.

Zhang F, Li C, Wang Z, *et al.* 2006. Modeling impacts of management alternatives on soil carbon storage of farmland in Northwest China. *Biogeosciences*, **3**: 451 —466.

Zhang Y, Li C, Zhou X, *et al.* 2002. A simulation model linking crop growth and soil biogeochemistry for sustainable agriculture. *Ecological Modeling*, **151**: 75 —108.

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