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Changes of soil organic carbon in an intensively cultivated agricultural region: A denitrification–decomposition (DNDC) modelling approach

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Abstract

Regional modelling of soil organic carbon (SOC) dynamics is important for predicting large-scale patterns in carbon cycling and for assessing potential responses of soil carbon pools to land-use change. However, data uncertainties related to both spatial heterogeneity and small-scale differences in farming practice related to cropping systems affect the accuracy of regional models. A case study is presented from Quzhou County in the North China Plain, an area characterized by highly intensive farming. For this county, the DNDC model was validated using sampling data from 68 sites around the county under generalized farm practices. Unique modelling units based on soil type, soil texture and crop type were created and then used to model the spatial change of SOC under different farming practices. Considering the main factors affecting SOC sequestration, the results indicate that the DNDC model delivers acceptable modelling results at county level. The results show that there is a great potential for SOC sequestration in Quzhou County in its central, southern and eastern parts. Changes in farming practices show a strong effect on carbon sequestration. A very efficient and environmental friendly sequestration of SOC pools could be achieved even by decreasing nitrogen fertilizer inputs, when the amount of straw returned to the field is greatly increased.

Keywords: DNDC model; Farm management; North China Plain; Regional modeling; Soil organic carbon; Spatially explicit

1. Introduction

Soil organic matter (SOM) does not only contribute strongly to soil fertility, but also plays an important role in global C sequestration (IPCC, 1990; Lal, 2004a). Even very small local changes of the SOM pool may potentially add up to significant changes in large-scale carbon cycling. Furthermore, some fractions of SOM are relatively dynamic and can be greatly influenced by agricultural practices. An intensification of cultivation can result in a significant loss of SOM (JGSSF, 1998; Heenan et al., 2004). This loss may be prevented or reversed by improved agricultural management, including measures

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such as reduced tillage, improved fertilizer management and irrigation as well as increased vegetation cover (Dick et al., 1998; Follett, 2001; Entry et al., 2002; Fortuna et al., 2003; Lal, 2004a). Such improved farming practices can hence be regarded as an important means to achieve both high rates of carbon sequestration in terrestrial ecosystems and sustainable agricultural development (Lal, 2004b; Smith, 2004).

The North China Plain is the main area for the production of wheat and maize in China. Agricultural production in this region constitutes around 37.5% of the total national agricultural production (Xin and Li, 1990). Before the 1970's, about 3.3 Mio ha of the Plain were affected by high levels of soil salinity, making it virtually infertile. After the successful control of soil salt contents following the early 1970's, large areas have been gradually transformed and used for ever more intensive forms of agriculture. The change of soil organic matter contents of these areas is a crucial topic related to both the security of the Chinese food supply and the sustainable management of this environment. According to recent research, the SOC in salinity-transformed areas slightly increased in recent years despite the increased intensity in agricultural management, while increased applications of fertilizer and improved irrigation led to increased production (Liu et al., 2005; Kong et al., 2006; Xu et al., 2006). Unfortunately, the slight increase in SOM was accompanied by numerous environmental problems related to the co-occurring significant overuse of chemical fertilizers (Kong, 2003). The identification of more sustainable farming practices resulting in similar increases of the SOM pool is hence highly desirable.

Recently, more and more concern worldwide is given to the restoration of SOM pools as this has beneficial effects on soil fertility while at the same time mitigating increases in the atmospheric CO_2 concentration. Biogeochemical models offer the possibility to simulate the intricate processes in the soil (Paustian et al., 1992) and evaluate potential effects of changes in agricultural management practices on carbon sequestration by the soils. A spectrum of models has been developed to simulate such changes in SOC. Modelling results at regional level are an important step in assessing response and feedbacks of C cycling to climate change (Paustian et al., 1997). With early reports about the performance of models applied at regional levels widely lacking, the need for model validation became apparent. The most common method was to combine field data from sites differing in soil and climatic conditions (Li et al., 1994; Shevtsova et al., 2003). However, even in small areas, soil properties and vegetation cover, both forming crucial factors with regard to sequestration of SOC, can be highly heterogeneous. Furthermore, differences in the spatial position of areas where the same management practices are applied also lead to differences in carbon sequestration due to the variation of soil properties. Areas where fields are subdivided into very small patches managed by different households, a pattern typically encountered in Quzhou County, may differ with regard to cropping systems and thus to farm practices, showing a high spatial variability also with regard to carbon sequestration. The lack of high-resolution data on the spatial heterogeneity of soil properties, vegetation cover and agricultural management practices proved a considerable obstacles for the evaluation of model performance at regional level and thus caused partly unconstrained results for the regional modelling. The spatial variation of C stocks and their relation to other soil properties was hence a crucial point to generate more accurate modelling results at regional levels (Wang et al., 2002; Ardö and Olsson, 2003; Cerri et al., 2004). Nevertheless, former studies rarely considered additional uncertainties caused by spatial variations in the management practices.

The DNDC (Denitrification–Decomposition) model is a process-oriented model simulating temporal changes in the levels of SOM as well as nitrogen cycling. It consists of two components. The first component includes soil climate-, crop growth-and decomposition sub-models. It predicts soil environmental factors driven by ecological factors like climate, soil, vegetation and anthropogenic activity. The second component utilizes the resulting soil environmental factors as inputs to nitrification-, denitrification- and fermentation sub-models. The DNDC model combines classical findings from physics, chemistry and biology with empirical data generated from laboratory studies and was developed to predict carbon sequestration, trace gas emissions, crop yield, and N leaching in agro-ecosystems (http://www.dndc.sr.unh.edu/model/GuideDNDC89.pdf,1st Sept, 2006). A detailed description of the model development and its structure were published by Li et al. (1992, 2000).

In comparison to other approaches to model changes in soil organic carbon (Smith et al., 1997), the DNDC model shows little model errors. This model has been tested and optimized against numerous field observations with regard to SOC dynamics in agro-ecosystems worldwide (Li et al., 1994, 1997, 2003; Smith et al., 1997). In China, when comparing multi-year simulations with the field data from four agricultural field sites, the model results of the DNDC model again closely resembled the observations (Li et al., 2003).

DNDC is one of the few models developed including both a site-specific mode and a regional mode. In the regional mode, the research region can be divided into small subunits based on the assumption that the attributes in each unit are uniform. The model merges the results from all units to obtain a regional result. To solve the effect of soil heterogeneity on the modelling results, the most sensitive factor (MSF)-method was applied (Li et al., 1996; 2001; 2002; 2004). For this method, each soil factor including texture, SOC content, pH and bulk density, was given a pair of maximum and minimum values for each unit. The soil factors showing the most significant impact on changes in SOC levels through sensitivity analysis at the site scale were then used as basis for the two scenarios (based on respective maximum and minimum values assigned to the soil factors). Then, DNDC was run twice under these two scenarios to produce a maximum and minimum change in SOC levels. The two SOC values generated hence form the range which can be assumed to cover the "real" SOC content with a high probability. Even given this improvement, however, the model still does not consider the spatial distribution of soil properties and changes in crops that relate to different farm management practices.

For the study presented here, the current, thoroughly validated version of the DNDC model which was available for download on the internet (http://www.dndc.sr.unh.edu, V86K, Oct. 2003) was used for the simulation of carbon dynamics in the study area. The main aims of the study were firstly to evaluate the performance of the DNDC model at our study area and to secondly try to improve this performance with consideration to the spatial heterogeneity of soil attributes and cropping patterns, and thirdly to investigate changes in soil organic matter related to different farming practices based on the modelling results of the adjusted DNDC model. The following questions were hence central in our study at Quzhou, which is considered to be an agricultural area well representative for the North China Plain:

1. Can the DNDC model be validated for our study site to produce sound simulations at the regional level?
2. Can the DNDC model be adjusted to predict changes of SOC giving special consideration to the spatial distribution of cropping patterns and soil attributes?
3. Based on the modelling results of the DNDC model, how can the farm management best be adjusted to increase the sequestration of carbon in the form of SOC in the future in the typical, intensively cultivated agricultural area of Quzhou?

2. Study area and database

2.1. Study area

This study was based on sites at Quzhou County, located northeast of Handan in the Hebei Province in the North China Plain. Quzhou County comprises a total area of 67,669 ha, of which 75.3% is arable land. Prior to the 1980's, problems of soil salinity in the region were very serious because of shallow saline groundwater. During the 1980's, soil salt levels were greatly reduced (Xin and Li, 1990). Rotational land use is common in the area. After harvesting of winter wheat, summer crops including maize, millet and soybean are planted. In many cases, cotton is also cultivated as an annual crop, with planting at the end of April and harvesting in November. The total sowing area for winter wheat, summer maize and cotton accounted for an average of 75% of the total sowing area between 1980 and 1999. According to farmer surveys in 1999, chemical fertilizer was commonly used as its application is less laborious than that of manure. Manure applications were widely restricted to vegetable fields and fruit plantations. In the wheat growing season, nitrogen fertilizer was commonly applied before sowing (127–255 kg N/ha) and in the re-greening stage (63–255 kg N/ha). Similar applications of nitrogen fertilizer were used for cotton before sowing and at the budding stage. In the maize growing season, nitrogen fertilizer was commonly applied in the days between node elongation and tasseling (34–255 kg N/ha). Traditional flood irrigation was widespread. Wheat fields were commonly irrigated three to four times, maize fields one or two times, and cotton was commonly irrigated two to three times. In general, only one tillage was applied after the autumn harvest due to time limitations between the summer harvest and the planting of autumn crops.

2.2. Datasets

2.2.1. Soil survey data

During the Second National Soil Survey in 1980, the soil in Handan district, comprising Quzhou County, was sampled, analyzed and mapped. The soil map produced during this period with a scale of 1 to 250,000 was digitized. Bulk density and soil texture of each soil type was recorded during the survey. The soil texture map was derived with help of the attribute descriptions in the accompanying soil survey booklet *Handan soil* (Handan Agricultural Bureau, 1986) (Fig. 2). The soil map of Quzhou was derived by clipping of the respective section from the Handan soil map (Fig. 1). The soil

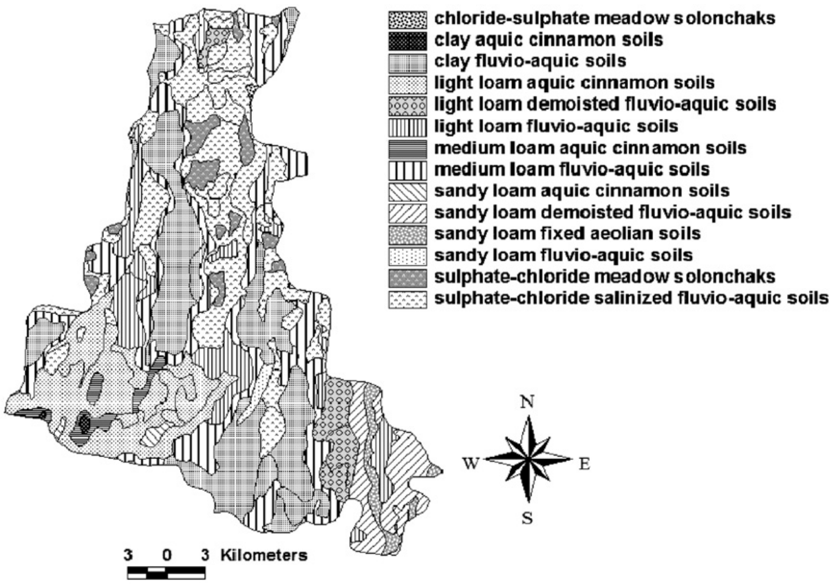

Fig. 1. Soil map of Quzhou County.

classification system taken here is the old Genetic Soil Classification System (Handan Agricultural Bureau, 1986; Cooperative Research Group on Chinese Soil Taxonomy, 2001).

In 1980, soil surface samples were collected from marked locations (Kong et al., 2006). At each site, 3–5 soil samples were collected at 0–20 cm soil depth within a 100 m radius and bulked for analysis. SOM was analyzed using the rapid dichromate oxidation method. The points sampled in 1980 were relocated via GPS measurements and sampled again in spring 1999 using the same sampling technique. These samples were used for measurements of soil parameters including SOC content and pH value.

2.2.2. Farm survey data

In Quzhou County, 210 households in 21 villages were interviewed with regard to their land area, the common farm management of their major cropping systems and their farm inputs and outputs in 1999.

2.2.3. Statistical data

Besides the survey data, statistical data have been obtained for Quzhou County. This data included the sowing area and yields of each crop for the period of 1980 to 1999.

2.2.4. Climate data

The daily climate data, including maximum and minimum temperature as well as precipitation from 1980 to 1999 were collected from climatic stations in the region.

2.2.5. Remote sensing data

Two ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) images, both with a resolution of 15 m in the visible-near infrared spectral, were used for crop classification. One image was taken on the 19th of May 2001, and another on the 9th of July 2002 to allow a sensible classification of the different cropping systems.

3. Modelling approach

3.1. Validation of the DNDC model at county level

Based on data from the soil samples taken at identical sites all around the county in both 1980 and 1999, it was possible to set the data in 1980 as the initial value and compare the simulated output of the DNDC model with the observed value in 1999 to evaluate the model performance.

This led to the problem of data uncertainties with respect to several parameters required by the DNDC model to run precisely. These parameters include information on the crops planted and related farm management practices at each site between 1980 and 1999. Hence, only regional summary information, based on regional statistical data, was used instead of site-specific information for the modelling.

The crops considered in the analysis were the dominant crops in the area; these were a winter wheat/summer maize rotation and cultivation of one season cotton. Farm practice information was generated from the farm survey, local farmer's experience and literature. Information such as the exact date for sowing, harvest, tillage, fertilization and irrigation were derived based on the knowledge of local farmers according to the farmer surveys in 1999. The amount of fertilizer applied in each crop was set according to the literature (Chen et al., 1991a,b; Wang, 1997) and the farmer survey data in 1999 under the assumption that the fertilizer increased evenly between years.

Crop residue management is an important factor affecting the carbon budget in the agro-ecosystem and was also included in the modelling. In the past, crop residues were widely used as fuel and fodder because of limited alternative fuel sources, but the recent economical developments allow farmers to return more residues to their fields (Liu et al., 1998; Niu and Hao, 2001). However, the overall percentage of straw returned to the field is still relatively low because machinery to adequately chop crop residuals is lacking. According to the farmer survey in 1999, a high proportion of wheat straw, but a low proportion of both maize and cotton straw was returned to the field because the latter do not decompose easily. The survey also indicated that farmers, depending on the availability of machinery, returned either none, or all, of the straw to the field.

After the specific local conditions of Quzhou County were transferred into the DNDC model, four different scenarios were generated to further validate and adjust the model according to the effect of different farm management practices on SOC accumulation, starting from conditions given by the soil survey of 1980:

Scenario A In this most simple scenario, all sites were assumed to be cultivated in a wheat/maize rotation from 1980 to 1999, with all straws being taken from the fields.

Scenario B In this more realistic scenario, all sites were again cultivated in a wheat/maize rotation, but the wheat straw was assumed to have been returned to the field only since 1990.

Scenario C This scenario resembles Scenario 2 with the exception that cotton was arbitrarily assumed to have been planted at all the sites from 1988 to 1992, as a profound increase in the cotton sowing area was observed in these years in the statistical data, without considering whether the site was prone to plant cotton or not. Cotton straw was not returned to the field.

Scenario D This scenario resembles Scenarios 2 and 3 with the exception that only the sites classified as cotton fields in the interpretation of the remotely sensed images and sites with soils characterized by sandy loam, a texture most suitable for cotton cultivation, were assumed to have been planted with cotton from 1988 to 1992.

The degree of agreement between simulated and observed SOC values was determined by the R^2 of a regression model between the observed and the simulated data sets.

3.2. Spatially explicit modelling

3.2.1. Crop classification

To obtain spatial distribution information of crops, the two temporal ASTER images were used for crop classification. However, the planting system was very complex. Even in small areas, small neighboring fields were sometimes occupied by three to five different crops as they belonged to different farmers. These small-scale differences were very difficult to detect using a remote sensing-based classification. Nevertheless, since the wheat/maize rotation and cotton account for more than 70% of the sowing area, these crops can be assumed to dominate the carbon cycling dynamics in the county. Hence, only the spatial distribution of the wheat/maize rotation fields and cotton fields were considered for the analysis.

The NDVI (normalized difference vegetation index), which provides a standardized method to compare vegetation chlorophyll contents in satellite images, was used as the basis for crop classifications, which was accomplished in the following steps:

Step 1 Calculation of NDVI values for both images.

Step 2 Setting of a threshold value for the NDVI in both images to distinguish vegetated and non-vegetated area.

Step 3 Overlay of the two maps to establish the spatial distribution of the wheat/maize rotation and cotton fields. According to the cropping calendar, winter wheat is sown in the beginning of October and harvested at the beginning of June. Following the harvest, other summer crops like maize, millet or soybean will be planted. The cotton is planted at end of April and harvested at the middle of November. At the beginning of May, the area under wheat rotation is presented by high NDVI values due to the well-developed wheat plants, whereas the cotton fields are well distinguishable

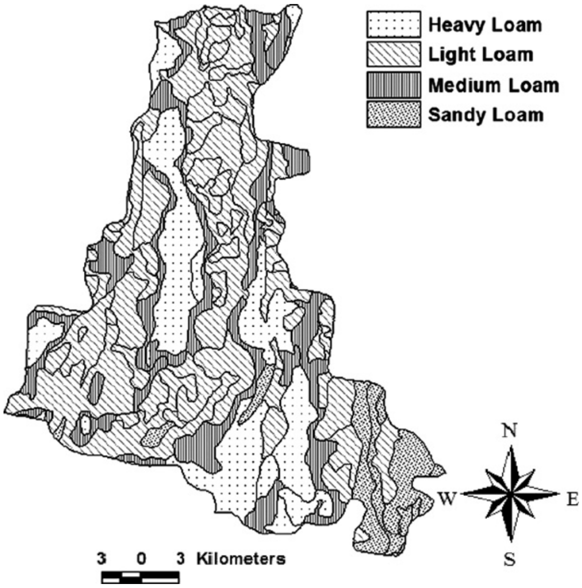

Fig. 2. Soil texture map of Quzhou County.

by their low NDVI values as they are still bare shortly after sowing. On the opposite, fields under wheat rotation are covered in bare soil and represented by low NDVI values, whereas cotton fields are well vegetated, at the beginning of July.

Based on these patterns, four different combinations were identified by overlaying the generated vegetation/non-vegetation maps:

1) Vegetation cover in May and no vegetation cover in July. This area was arbitrarily classified as wheat/maize rotation, as, referring to the statistical data in 2000, wheat/maize rotation occurs at about 85% of the fields under wheat rotation.
2) No vegetation cover in May, vegetation cover in July. These fields were classified as cotton fields.
3) Vegetation cover in both May and July. These areas could either be orchards, vegetable fields, woodlands or even areas covered by ornamental plants. Although they were classified further, these areas will generally not be considered in the further analysis of this study.
4) No vegetation both in May and July. These areas comprised residential areas, industrial areas, and roads, but also water surfaces. Again, they were not considered in the analysis.

3.2.2. Identification of modelling units

To consider soil heterogeneity, spatial distribution of crops and their relations, different modelling units were established each with a unique combination of soil type, soil texture and crops by overlaying the soil map (Fig. 1), the soil texture map (Fig. 2) and the map for the cropping pattern (Fig. 3). A total of 78 modelling units were hence obtained. An area of about 8 km^2 at the southern tip of Quzhou County was not included in this study, as it was not covered by the satellite images (see below).

3.2.3. Modelling approaches

The parameters required by the DNDC model are deduced from the attributes of each modelling unit. SOC contents, bulk density and pH can be assigned according to the soil type. The clay fraction strongly relates to the soil texture type. The range of the above-mentioned parameters for each soil type and texture was based on the soil sampling results from the 1999 survey. Following the regional mode of the DNDC model and the MSF (most sensitive factor) method, we used double runs of the site mode with the two sets of soil parameters set at extremes (maximum and minimum combination of the parameters) for each spatial unit.

To analyze how farm management practices may be adjusted in the future to sequester carbon more efficiently, five different farm management scenarios were again tested in DNDC regional model runs, based on the different modelling units as described above (Table 1). The first scenario models the development in SOC under common farming practices of experienced farmer according to the farmers survey from 1999. In the

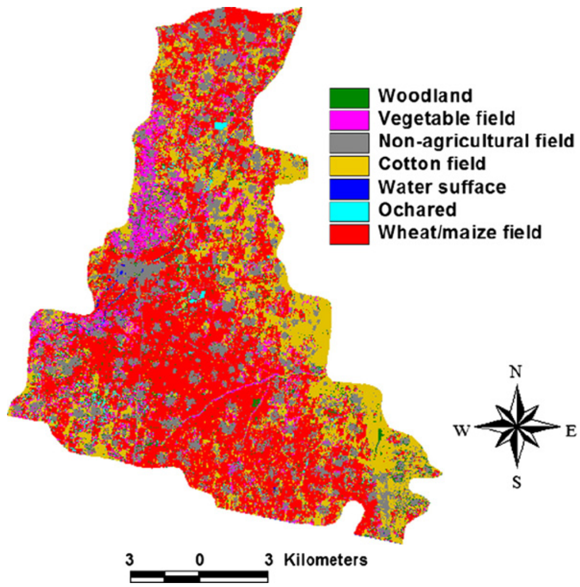

Fig. 3. Map of cropping pattern derived from ASTER images at Quzhou County.

Table 1
Farm management scenarios for the modelling of different land-use scenarios in Quzhou County

Crop	Scenario 1	Scenario 2	Scenarios 3, 4* and 5**
Nitrogen fertilization			
Wheat	2 applications, 170 kg/ha and 127.5 kg/ha	2 applications, 113.3 kg/ha and 85 kg/ha	Same as Scenario 2
Maize	1 application, 170 kg/ha	1 application, 113.3 kg/ha	Same as Scenario 2
Cotton	2 applications, 170 kg/ha and 127.5 kg/ha	2 applications, 113.3 kg/ha and 85 kg/ha	Same as Scenario 2
Percent of straw returned to the field			
Wheat	60	60	100
Maize	30	30	60
Cotton	0	0	30

* In Scenario 4, the whole area was assumed to be planted with a winter wheat/summer maize rotation.
** In Scenario 5, the whole area was assumed to be covered in cotton monocultures.

second scenario, the model was run under conditions of a decrease of nitrogen fertilizer application rates by 1/3 to resemble dosages suggested by fertilizer experts (Chen et al., 2003). For the third scenario, N fertilizer rates were again reduced by 1/3. Additionally, an increased proportion of crop residues was assumed to be returned to the field. In each of the model runs, climatic conditions were taken from the data of the years 1980 to 1999.

Finally, another two scenarios were established based on Scenario 3, but with the whole cropping area being covered in fields under either winter wheat/summer maize rotation (Scenario 4) or the whole cropping area being covered in cotton (Scenario 5).

The simulated average SOC concentration and total SOC content were calculated by the following formula:

$$\mathrm{SOC}_{\mathrm{average}} = \sum_{i=1}^{n} \mathrm{SOC}_i \times \frac{A_i}{A_{total}}$$

$$C_{\mathrm{total}} = \sum_{i}^{n} C_i \times A_i,$$

where $\mathrm{SOC}_{\mathrm{average}}$: average concentration of SOC over the whole study area.

SOC_i	SOC concentration of soil type *i*
A_i	area of soil type *i*

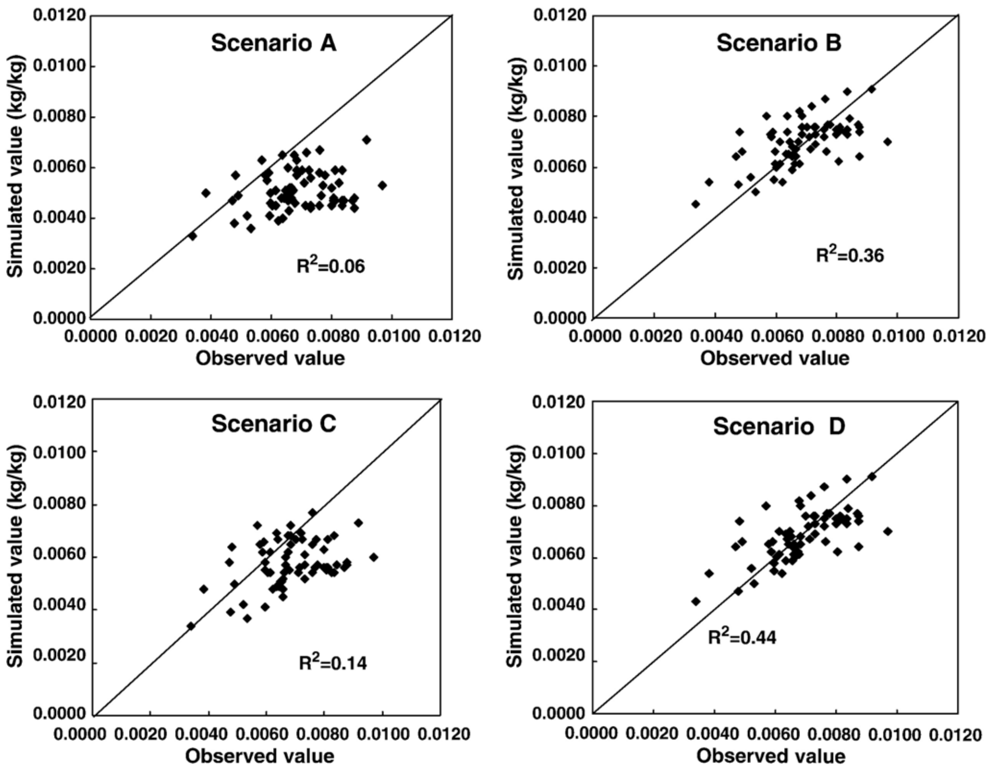

Fig. 4. Comparison of simulated and observed SOC content at each sampling sites (unit: kg/kg).

A_{total} total study area
C_{total} total SOC content of the study area
C_i SOC content of soil type i

4. Results

4.1. Performance of the DNDC model at county level

A total of 68 of the 79 sites where soil survey data was measured both in 1980 and 1999 were included in simulations of the three assumed farm management scenarios in order to test and validate the DNDC model. The remaining 11 sites were excluded from the simulation because they either represented badlands with high levels of salinity or vegetable fields subject to a completely different farm management system. In Fig. 4, results of the comparison between simulated values and observed values in 1999 at each site are illustrated. R^2 values were very low in Scenario A (R^2=0.06), indicating an overall low degree of agreement between simulated and observed SOC values. Moderate values of R^2 were derived under Scenario B (R^2=0.36). Although more realistic than Scenario 2 considering the planting of cotton, Scenario C got worse modelling results (R^2=0.14). However, after considering both cotton planting and its spatial distribution, which strongly relates to soil attributes (Scenario D), the modelling results were greatly improved (R^2=0.44). These results indicated that DNDC can derive sound results at county level only after taking temporal changes in the most common planting systems and their spatial distribution, and even then, many uncertainties still exist.

4.2. Spatially explicit modelling results of different farm management scenarios

The simulated soil organic carbon pool (0–20 cm) ranged between 1.0 and 1.2 Mt C assuming a continuous application of N fertilizers at the levels applied in 1999 (Scenario 1, Table 2). Under a decrease of nitrogen applications by about 1/3 as compared to farming practices in 1999 (Scenario 2), total SOC contents ranged from approximately 0.9 to 1.1 Mt C. Nevertheless, if this decrease in nitrogen fertilizer applications was accompanied by a higher proportion of crop residues returned to the fields (Scenario 3), the total SOC content increased to range from approximately 1.1 to 1.4 Mt C. Finally, when assuming that the whole cropping area was to be covered in fields under winter wheat/summer maize rotation with a reduced fertilizer input and a high proportion of straw being returned to the ground (Scenario 4), the SOC pool reached maximum values, ranging between 1.2 and 1.4 Mt C, whereas the simulation assuming a complete change in cropping pattern to cotton, again assuming a reduced fertilizer input and enhanced straw return (Scenario 5), the SOC pool reached minimum values of 0.7 to 0.8 Mt C. Generally, values of the simulated average SOC concentrations show similar patterns as the simulated soil organic carbon pool when comparing the simulated values of the five different farm management scenarios (Table 2).

Fig. 5 shows the spatial distribution of soil organic carbon (SOC) contents (0–20 cm depth) under different farm management scenarios. Under Scenarios 1, 2 and 3, the central and south of the county always had higher concentration of SOC. Here, the soil texture is heavy loam, rotationally planted with winter wheat and summer maize. The eastern area of the county where cotton was the dominant crop and the predominant soil texture was sandy loam had markedly lower SOC concentration. The model results suggest that particularly in this region, a higher proportion of residues incorporated into the soil may lead to enrichment of soils with SOC. A comparison the modelling results of Scenarios 4 (pure winter wheat/summer maize rotation) and 5 (pure cotton) with Scenario 3, indicates that SOC accumulation would be highly different according to the crops planted. Results indicate that a change from cotton to wheat/maize rotation leads to a great increase in SOC contents. On the other hand, when wheat/maize rotation fields are changed to monocultures of cotton, SOC contents decreased remarkably. These two scenarios show that even under optimized farming practices, the selection of crops is of great importance for C sequestration.

Table 2
Simulated carbon storage under different farm management scenarios at Quzhou County

Item		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Average SOC levels (0–20 cm, g/kg) in Quzhou County	Max. scenario	7.8	7.3	8.6	9.8	6.3
	Min. scenario	6.0	5.6	7.0	8.7	5.4
Total SOC content (0–20 cm, Mt C) in Quzhou County	Max. scenario	1.2	1.1	1.4	1.4	0.8
	Min. scenario	1.0	0.9	1.1	1.2	0.7

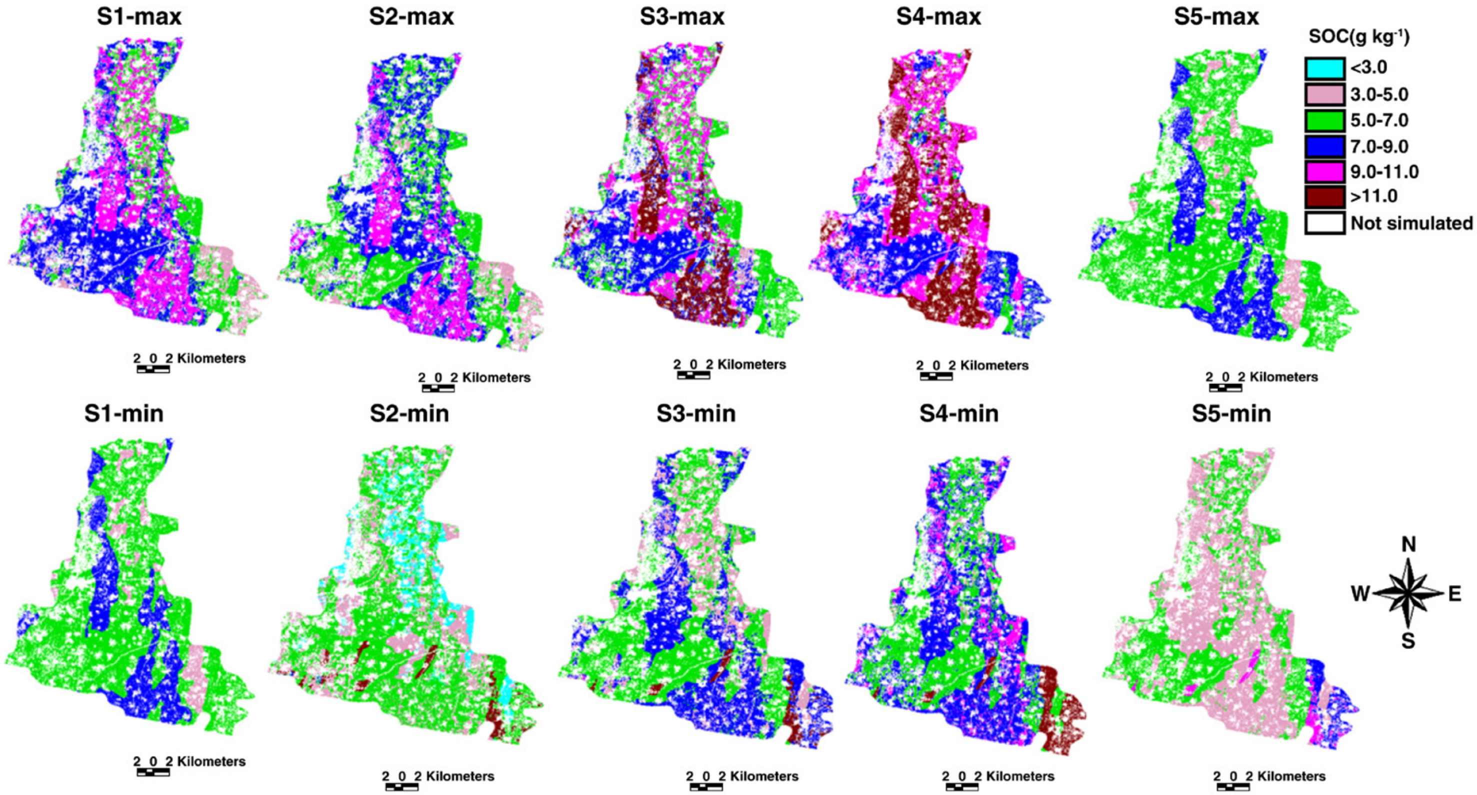

Fig. 5. Simulated distribution of soil organic carbon (SOC) contents (0–20 cm depth, unit: g kg^{-1}) under different farm management scenarios at Quzhou County, Hebei province. S1, S2, S3, S4 and S5 show modelling with Maximum (Max) and Minimum (Min) combinations of soil parameters under farm managing Scenarios 1, 2, 3, 4 and 5, respectively.

5. Discussions

Approximations of the spatial variability in SOC is critical for the understanding of large-scale carbon cycling and sequestration (Zou et al., 1995; Paustian et al., 1997), and to assess their response to changes in the anthropogenic management (Conant and Paustian, 2002). In an intensively used agricultural area like Quzhou, cropping pattern, soil characteristics and farm management practices are the main factors governing changes in the SOC pools. In order to simulate variations of SOC pools as a function of these parameters, models essentially need highly accurate spatial information at a high resolution. In our study area, cropping pattern and farm management may well be treated in equal units as farm surveys demonstrated that farm management mainly varied according to crop type. Therefore, information on the spatial distribution of different crops remained a crucial component, and high resolution remotely sensed images proved to be of great help in deriving such information. Unfortunately, financial and technical means proved insufficient to reliably identify all the crops in our research area. Crops with smaller sowing area hence had to be ignored. While this certainly affects modelling accuracy, we assumed that due to the overwhelming dominance of the winter wheat/summer maize and cotton sowing area, the model results still reflected the trend of SOC change at regional level in a realistic way, particularly as both maximum and minimum values of the key factors were considered separately.

By spatially explicit modelling, it was hence possible to identify areas and techniques that have a large potential to increase SOC sequestration and to understand future changes due to changing farm management practices.

In this respect, the modelling results for Quzhou County clearly identified the central and southern part of the county as an important SOC sink in the county. The model furthermore clearly suggests that a higher proportion of straw returned to the ground may provide a powerful measure for increasing SOC sequestration at Quzhou County. This information is helpful with regard to the design of a spatially explicit policy for soil fertility improvement. Nevertheless, it should be noted that particular changes in the cropping pattern can overwhelmingly affect the SOC pool (Scenario 4 and 5), as inputs and outputs of the two different cropping regimes to the soil are quite different.

Table 3
Dosage of N fertilizer at fields (unit: kg ha^{-1})

Crop	Level of fertility	N fertilizer (kg ha^{-1}) 1986–1988 [a]	N fertilizer (kg ha^{-1}) 1995 [b]	N fertilizer (kg ha^{-1}) 1999
Wheat	High	193	284	300
	Medium	191	336	308
	Low	180	267	312
Corn	High	116	183	129
	Medium	94	137	141
	Low	46	142	133

[a] Chen et al. (1991a, b).
[b] Wang (1997).

Past research at Quzhou indicated that an increased application of fertilizers, especially mineral fertilizers, contributed greatly to the increase of SOC contents in the last decades (Liu et al., 2005). However, an overuse of nitrogen has been recognized in this area, which is associated with numerous environmental problems. These have to be taken into account when regarding the benefits of increased C sequestration by a simple increase in fertilization. According to Chen et al. (2003), economic fertilizer dosages for winter wheat growing on soils with high, medium and low fertility levels in Quzhou were 129, 162, and 165 kg N ha^{-1}, while for summer maize, the economic dosages in soil with high, medium and low fertility levels were 89, 135 and 141 kg N ha^{-1}, respectively. As Table 3 shows, nitrogen applications were much higher than the proposed economic fertilizer dosages in Quzhou, which demonstrates the ongoing over-fertilization as a potential cause for the environmental problems observed in the county.

It needs to be mentioned that the currently recorded average SOC contents (6.9 g kg^{-1}) in 1999 were still at a deficient to medium level in the grading standard of the 2nd National Soil Survey (Jia and Zhao et al., 1996). The increment of SOC at fields where only chemical fertilizer were applied was significantly lower than at fields where additional organic manure was used, both as the only means of fertilization as well as in combination with chemical fertilizers (Paustian et al., 1992; Hao and Niu, 1996; Niu and Hao, 2001). At Quzhou, straw is commonly returned to the field, but only wheat and maize have a relatively high production of straw. In developed countries, up to about 90% of straw is returned to the field (Li, 2000), whereas levels are much lower in China. As chemical fertilizers are the dominant means of fertilization applied at Quzhou (Liu et al., 2005), there is still a great potential for an improvement in SOC levels simply by enhancing both the application of manure and the percentage of straw returned to the fields. This is strongly underlined by our DNDC model run simulating the development over 20 years under the Scenario 3 (Table 1). On one hand, modelling results indicated that a decrease of current levels of nitrogen fertilizer applications would lead to a slight decrease in carbon sequestration. However, as pollution problems are severe and greatly relate to the overuse of nitrogen fertilizer, current levels have to be considered as highly unsustainable. Hence, the indicated significant increase in carbon sequestration by the parallel promotion of greater amounts of crop residues returned to the field hint at a feasible possibility to combine enhanced C sequestration with a more sustainable fertilization regime.

Finally, our results point out a potential future problem for SOC contents in Quzhou County relating to changes in cropping patterns. These patterns are widely governed by market prices for cotton, wheat and maize, and while great fluctuations can be observed annually. There currently is a strong tendency towards a shift from wheat/maize rotation towards monocultures of cotton. According to our modelling results, these monocultures – even under an optimised management with residues being returned to the field – result in a strong decrease in SOC accumulation as compared to the wheat/maize rotation. As SOC levels in the county are still characterized as widely low to intermediate, this potential decrease in C sequestration by soils in Quzhou is seen as highly problematic.

6. Conclusions

As long-term monitoring of biogeochemical cycles is extremely cost- and labor-intensive and not suitable for urgently needed suggestions with regard to sustainable land-use practices, models provide a useful tool allowing an estimation of potential changes in a relatively restricted time frame. When modeled at regional levels, both spatial heterogeneity in environmental parameters and varying farm management practices can cause imprecise modelling results. Nevertheless, the case study of Quzhou County, an intensively cultivated agricultural county in the North China Plain, indicated that despite various existing uncertainties, if the most common planting systems in their temporal and spatial distribution are considered, the modelling results of the DNDC model reach an accuracy ($R^2=0.44$) which seemed acceptable to us. The creating of homogeneous modelling units with unique soil types, soil texture and crop type proved to be an effective method to perform the spatially explicit modelling. Based on this approach, simulations strongly suggested that the study area has a great potential for C sequestration particularly in the central, southern and eastern part of Quzhou County, with the spatial distribution of SOC values being governed mainly by soil texture and cropping patterns. Future changing farm practices will hence greatly affect the carbon sequestration in the county. In detail, spatially explicit modelling of a 20-year period indicated that a one-third decrease of nitrogen fertilizer application combined with an increase of straw returned to the field would increase the carbon sequestration in this intensively cultivated agricultural county, particularly when a rotation of winter wheat and summer maize is promoted in contrast to the currently expanding monocultures of cotton.

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