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Quantification of soil organic carbon sequestration potential in cropland: A model approach

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Agroecosystems have a critical role in the terrestrial carbon cycling process. Soil organic carbon (SOC) in cropland is of great importance for mitigating atmospheric carbon dioxide increases and for global food security. With an understanding of soil carbon saturation, we analyzed the datasets from 95 global long-term agricultural experiments distributed across a vast area spanning wide ranges of temperate, subtropical and tropical climates. We then developed a statistical model for estimating SOC sequestration potential in cropland. The model is driven by air temperature, precipitation, soil clay content and pH, and explains 58% of the variation in the observed soil carbon saturation (n=76). Model validation using independent data observed in China yielded a correlation coefficient R^2 of 0.74 (n=19, P<0.001). Model sensitivity analysis suggested that soils with high clay content and low pH in the cold, humid regions possess a larger carbon sequestration potential than other soils. As a case study, we estimated the SOC sequestration potential by applying the model in Henan Province. Model estimations suggested that carbon (C) density at the saturation state would reach an average of 32 t C ha^{-1} in the top 0–20 cm soil depth. Using SOC density in the 1990s as a reference, cropland soils in Henan Province are expected to sequester an additional 100 Tg C in the future.

cropland, model, soil organic carbon, potential, saturation

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Soil organic carbon (SOC) is a large proportion of the carbon pool that is part of the global carbon cycle [1]. It has an important role worldwide in mitigating climate change and guaranteeing food security [2]. The SOC level is a dynamic balance between soil carbon (C) inputs and outputs. Soils gain C from photosynthetic carbon input while losing C via soil respiration, organic matter erosion and leaching [3]. Globally, agricultural soils hold a remarkable potential for sequestrating carbon and play an irreplaceable role in the process of global carbon cycling [2]. However, SOC in agroecosystems is fragile and highly sensitive to human activities. Under improper practices such as reduction of carbon input (e.g., residue removal, without input of organic manure) and tillage, cropland is likely to lose soil carbon, acting as a carbon source [4,5]. By contrast, practices that increase the photosynthetic input of carbon into the soil (e.g., application of organic manure) or slow the release of soil carbon (e.g., no-tillage) help to increase the amount of stored carbon, thereby sequestering C from the atmosphere [2,6,7]. Although it has been well recognized that agricultural soils have the potential for the expansion of carbon sequestration, quantifying this potential is far from robust due to the spatial heterogeneity of soils and region-specific climates.

SOC sequestration potential (SOC_P) refers to the soil's organic carbon holding capacity under local circumstances.

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Two main approaches have been widely adopted to estimate the regional or global potential. One is based on long-term field experiments, and the other is based on model simulation under various scenarios [8]. Improved agricultural management practices such as application of manure, reduction of tillage intensity, increased rotation complexity and the addition of nitrogen fertilizer together with crop residues are recognized to have the potential to increase SOC storage [9–11]. When the SOC sequestration rates were obtained from long-term field experiments where one or several improved practices were adopted, site-specific SOC_P could be estimated. By upscaling the rates of SOC_P into China's cropland, Lal [12] and Lu *et al.* [13] estimated SOC sequestration potential on a national scale. However, upscaling site-specific SOC sequestration rates to a larger area may introduce errors into the estimates of the total SOC_P because natural circumstances in some areas may not be suitable to put specific management options into practice. Moreover, climate and soil conditions regulate SOC turnover, and hence soil carbon sequestration potential. Ignoring the role of climate and soil conditions in determining SOC sequestration potential will inevitably result in uncertainties in the estimates when the site-specific rates of SOC_P are upscaled.

Several process-level models such as CEVSA [14–16], CENTURY [17], DNDC [18], Roth C [19] and EPIC [20] could be used to estimate cropland SOC_P for specific management practices. Although process-level models have a theoretical foundation, and thus the model estimates are reliable at least on a regional scale, they have several limitations. Some process-level models need site-specific parameters that are not available in practice, and some may accurately simulate the observed SOC change in a given area but not in others [14], which makes it hard to extrapolate these models to a wider area [21].

In this paper, we establish a new statistical model based on global datasets of long-term field experiments, aiming to estimate cropland SOC_P. And we estimate SOC_P in Henan Province, China using the model. Our objective is to develop a practical approach to quantifying cropland SOC sequestration potential.

1 Materials and methods

1.1 Rationale

We adopted the concept of SOC evolution with time and organic C input from Stewart *et al.* [22] and West *et al.* [23] as shown in Figure 1. Changes in SOC are time asymptotic for certain carbon input levels. Soils with low C concentrations accumulate significant amounts of C in the preliminary stage. Thereafter, the sequestration rate becomes lower and SOC tends to reach a steady state [24,25]. Increasing carbon input into a soil with relatively low C concentration continues to promote SOC accumulation until SOC achieves another steady state (Figure 1A). However, the gradual accumulation process is neither necessary nor unlimited for a given soil. Theoretically speaking, soils may not hold additional carbon even with increasing carbon input when a maximum equilibrium C level is reached. The maximum equilibrium C level is termed soil C saturation [23].

For the SOC evolution with input organic C, the C concentration at a steady state also increases in an asymptotical pattern (Figure 1B). Soils with low C concentration easily reach an equilibrium C level with increasing carbon input over a certain time. The equilibrium SOC increases with greater C input rates, but the rate of increase declines gradually. When SOC approaches the saturation level, increasing C input no longer results in additional soil carbon [22].

Previously, "saturation" patterns have been ignored or not well recognized [22]. Studies of soil carbon storage, or soil carbon sequestration potential, have been based on the

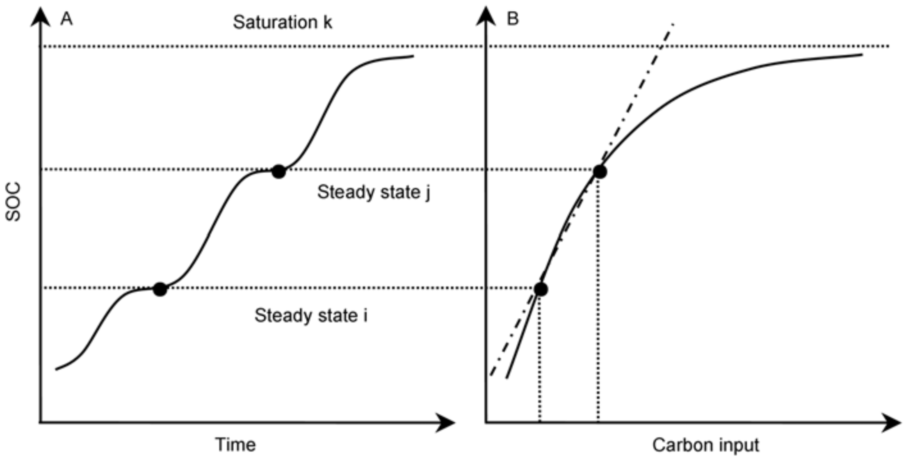

Figure 1 Dynamics of SOC following time and C input changes. (A) SOC content changes with time under different C input levels; (B) SOC content at steady state changes with C input levels. Redrawn from Stewart *et al*. [22] and West *et al*. [23].

assumption that SOC content changes linearly with the level of carbon input. In other words, SOC could increase without limit when carbon input increases (dash-dot line as shown in Figure 1B). Stewart *et al*. [22] explained that the linear relationship of SOC and carbon input was a result of using a narrow range of carbon input. Without a large enough carbon input, soil could not reach its saturation level, and thus a temporary change was mistaken as linearity. When C input is maximized, the soil C content approaches a saturation level.

With this understanding of SOC saturation, we hypothesize that the SOC level at saturation [22,23] is the C sequestration potential, and that the spatial variation of SOC_P is mainly determined by climate and soil conditions [2,8,14,26]. The site specific SOC_P may be determined from long-term field experiments with maximum carbon input.

1.2 Data sources

1.2.1 Long-term experiment data

We extracted datasets from the literature and compiled a database to develop a SOC_P model. The database includes information from 95 global long-term agricultural experiments (LTE) distributed across a vast cropland area spanning wide ranges of temperate, subtropical and tropical climates1) (Figure 2, Appendix A). The annual input rate of organic matter as manure, or crop straw, ranged from 10 to 40 t ha^{-1} in these experiments. Of the 95 experiments, 22 lasted 10–14 years and 73 lasted longer than 15 years (Appendix A). We presumed that the SOC measured at last several years had approached saturation, and thus regarded it as SOC_P.

The database consists of site-specific information including location (longitude, latitude), climate (temperature, precipitation), soil properties (clay fraction, pH, total nitrogen, bulk density), experimental detail and measurements (experiment duration, crop rotation and irrigation, amount of annual organic matter input, soil sampling depth), and SOC concentration.

Where the literature did not report some of this related data, we acquired data from other sources, including internet web sites (for site and climate information), World Soil Database from FAO [30] (for complementing and checking soil information), and an online soil database2) from the Institute of Soil Science, Chinese Academy of Sciences. We contacted several authors of these papers to obtain missing information and unpublished data. The SOMNET database3), a global network and database containing many long-term experiments concerning soil organic matter, was used to get necessary experimental information.

1.2.2 Spatial database of Henan Province

We developed a spatial database to quantify the SOC_P in Henan Province. Henan Province is located at latitudes between 31°23′–36°22′N and longitudes between 110°21′–116°39′E (Figure 3) with a total area of ~16.5 million ha, presenting a humid-semi humid monsoon climate, with a cold dry winter and warm wet summer. The mean annual temperature in Henan Province ranges from 12°C to 16 °C, (−3°C to 3°C in January and 24°C to 29°C in July). The mean annual precipitation is about 500–900 mm, of which 50% occurs in the summer season. The cropping system tends to be winter wheat followed by maize over the course of the year.

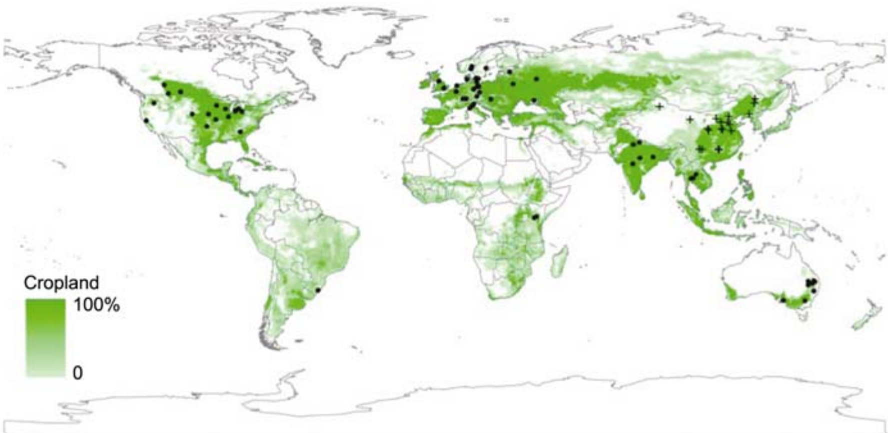

Figure 2 Distribution of global cropland long-term experiments. Shaded areas indicate the global cropland distribution (cropland fraction is the percentage of cropland area to whole grid area. Source: Ramankutty *et al*. [27]; Folley *et al*. [28]; Leff [29]); Solid dots(·) represent the sites for model establishment (*n*=76), cross points (+) represent sites in China (*n*=19), for model validation.

1) Global cropland distribution, see: http://www.sage.wisc.edu/iamdata/

2) Institute of Soil Science, Chinese Academy of Sciences. Chinese Soil Database. See: http://www.soil.csdb.cn/

3) SOMNET. A Global Network and Database of Soil Organic Matter Models and Long-Term Experimental Datasets. From: http://www.rothamsted.bbsrc.ac.uk/aen/somnet/intro.html

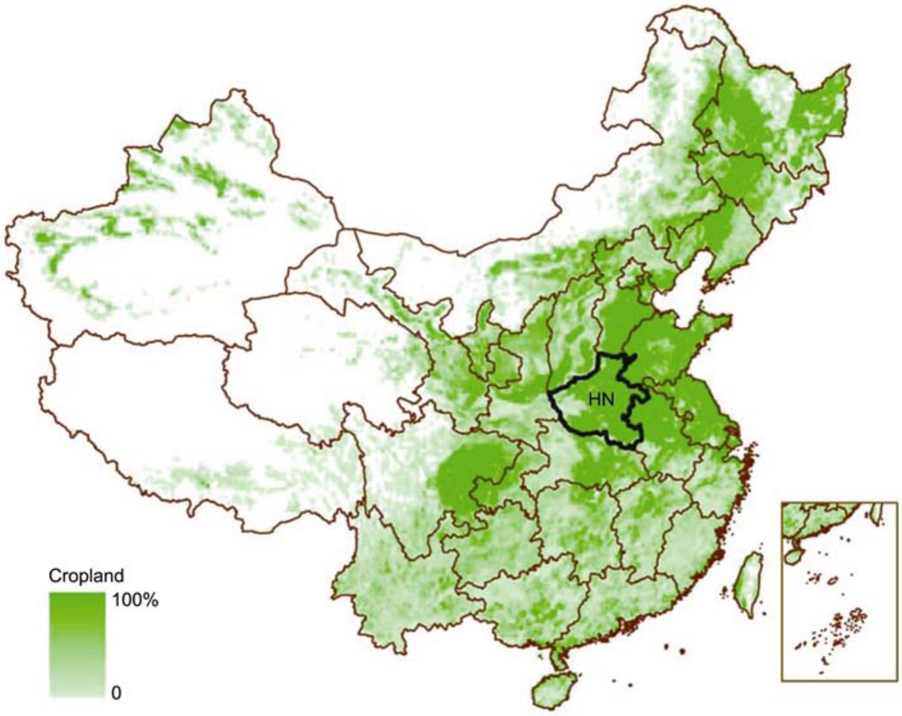

Figure 3 Cropland (shaded area) distribution in China (RESDC, see: http://www.resdc.cn/). Henan Province (HN) is located in the North China Plain.

The spatial database of Henan Province used to estimate regional SOC_P, included climate, soil and land use data. Climate data consist of mean annual temperatures and mean annual precipitation, which were calculated from temperature and precipitation data for years 1990 to 1999 from 751 nation-wide meteorological stations. Soil data (SOC, clay fraction and pH) were extracted from the 1:1000000 scale Soil Database of China, developed by the Institute of Soil Science, Chinese Academy of Sciences [31–33]. Both climate and soil data were converted to spatial raster data (10 km×10 km grid) through ArcGIS spatial analysis [34]. Land use data was used to classify the cropland areas. According to remote sensing land use data from RESDC and cropland area estimation of Liu *et al*. [35], we defined, in Henan, the grids with >42.8% upland area as cropland grids, and others lower than this value as non-cropland grids.

1.3 Determination of site specific SOC_P

Using datasets from the 95 LTEs, the site specific SOC_P was determined by [36]:

$$SOC_p = SOC \times H \times BD \times (1-F) \times 10^{-1}, \tag{1}$$

where SOC_P is SOC sequestration potential per unit area (t ha^{-1}). SOC is the corresponding SOC concentration (g kg^{-1}). H and F represent the soil depth (cm) and the fraction of >2 mm fragments (%) in soil, respectively. BD is the soil bulk density (g cm^{-3}). In the experiments where bulk density was not available, BD was estimated from soil organic matter content (SOM, %) by Eqn. 2: [26,37]:

$$BD = \frac{100}{\dfrac{SOM}{0.244} + \dfrac{100 - SOM}{1.64}} \tag{2}$$

SOC_P in the top soil layer (0–20 cm) was calculated from the SOC_P at different depths, according to SOC vertical distribution (cm) [38,39]:

$$SOC_{0\text{-}10} : SOC_{10\text{-}20} : SOC_{20\text{-}30} : SOC_{30\text{-}40} = 23:18:13:10.$$

1.4 Statistical method and model estimation

Bivariate correlation evaluates the degree of relationship between two quantitative variables without distinction between the independent and dependent variables. Partial correlation measures the degree of association between two variables, while taking away the effects of a set of controlling variables on this relationship. We used these two methods to investigate the impacts of climate and soil on SOC_P. Levenberg-Marquardt (LM) and Universal Global Optimization (UGO) algorithms (convergence at 1.00E-10) [40,41] were used to determine the SOC_P model. Of the 95 LTE datasets, 76 datasets from sites outside China were used to perform a correlation analysis and parameterize the model, and 19 LTEs from within China were used to validate the model. Model sensitivity analysis [42] was also conducted to clarify factor sensitivities to SOC_P. With spatial database of climate and soil in Henan Province, we estimated the provincial SOC_P using the model, and assessed the SOC_P spatial distribution through spatial analysis [34].

2 Results

2.1 Dependence of SOC_P on soil and climate parameters

The values of r_{MT}, r_{MP}, r_{CL} and r_{PH} in Table 1 represent the Pearson correlation coefficient (Bivariate correlation) and Partial correlation coefficient between SOC_P and the mean annual temperature (*MT*), annual total water input (*MP*), soil clay fraction (*CL*) and soil pH (*PH*). Results in Table 1 suggested that SOC_P is negatively correlated to MT and soil pH, regardless of whether the Pearson correlation or Partial correlation was applied. In contrast, the Pearson correlation shows no significant impact of *MP* and *CL* on SOC_P, while the Partial correlation, that controlled all potentially confounding variables, suggested a positive impact (Table 1), which agrees with previous findings that climate and soil conditions regulate *SOC* accumulation [3,43–46].

2.2 Model establishment and validation

Based on the correlation analysis (Table 1), we established a statistical model to estimate SOC_P. The model integrated linear and nonlinear responses of SOC_P to climate and soil parameters (Eqn. 3).

$$SOC_P = 140.5\times e^{-0.021\times MT} - 98.8\times e^{-0.42\times MP} - 39.6\times e^{-0.10\times CL} - 4.1\times PH - 27.7 \quad (R^2=0.58,\ n=76), \qquad (3).$$

where *MT* is the mean annual temperature (°C). *MP* refers to annual total water input that is a sum of mean annual precipitation and irrigation (100 mm). *CL* and *PH* represent the soil clay (<0.002 mm) fraction (%) and pH value, respectively. Datasets from the sites outside China were used to determine model coefficients.

The statistical model (Eqn. 3) was validated against independent data from 19 LTEs in China (Figure 1 and Appendix A). The root mean square error (RMSE) [47], the mean absolute error (MAE) [47], model efficiency (EF) [21], index of agreement (IA) [48] and linear regression analysis [49] were used to evaluate model performance.

Model validation indicated that site specific SOC_P could be quantified from local climate and soil parameters. The regression of modeled against observed SOC_P yields an R^2 of 0.74, with a slope of 0.82 and an intercept of 5.2 t ha^{-1} (Figure 4). Values of RMSE, MAE, EF and IA are 7.0 t ha^{-1}, 5.7 t ha^{-1}, 0.71 and 0.92, respectively, suggesting that the model performs well.

Table 1 Correlation coefficients between SOC_P and *MT*, *MP*, *CL* and *PH*

Correlation	r_{MT}	r_{MP}	r_{CL}	r_{PH}
Bivariate	-0.62^{***}	NS	NS	-0.22^{*}
Partial	-0.65^{***}	0.26^{**}	0.31^{***}	-0.20^{*}

*, **, *** Significant at $P<0.1$, $P<0.05$ and $P<0.01$, respectively. NS: Not statistically significant.

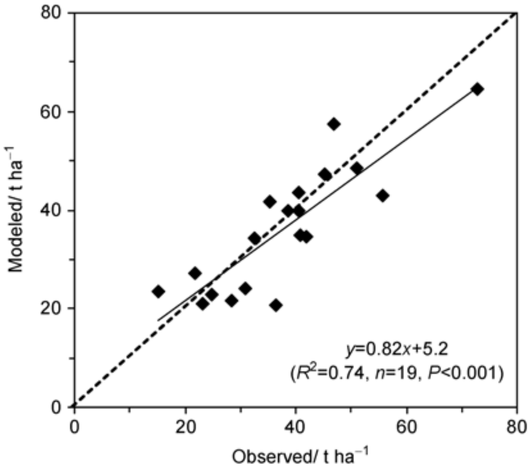

Figure 4 Modeled vs. observed SOC_P. Dashed line is 1∶1.

2.3 Model sensitivity analysis

Sensitivity analysis was conducted to better understand the response of the SOC_P model to the drivers. To perform model sensitivity analysis, we ran the SOC_P model (Eqn. 3) by changing the value of one driver while holding the remaining factors constant. For instance, the response of the SOC_P model to mean annual temperature was iteratively simulated within the MT range of 2.1°C–28.3°C while MP was set to be 7.5 (100 mm), CL to be 23.2 (%) and PH to be 6.6 (Figure 5A). These values of MT, MP, CL and PH are based on 76 LTEs from outside China (Table 2).

Model sensitivity analysis suggested that SOC_P decreases with increasing MT at a relatively constant rate (Figure 5A). By contrast, SOC_P ascends exponentially with increasing MP, but levels off when MP is higher than 1000 mm (Figure 5B). Figure 5A and 5B suggested that cropland in cold humid regions possess relatively higher SOC_P than warm dry regions, and that SOC_P in the areas of MP>1000 mm would not be affected by water supply. SOC_P increases exponentially with increasing CL, and levels off when CL is higher than 30% (Figure 5C). It appears that SOC_P decreases linearly with increasing soil pH (Figure 5D). Figure 5C and 5D suggest that soils with high clay content and/or low pH could potentially hold more carbon than those with low clay content and high pH. SOC_P in soils with >30% clay content may not be regulated by soil particles.

2.4 Estimated SOC_P in Henan Province

Based on the spatial database, we estimated SOC_P of the

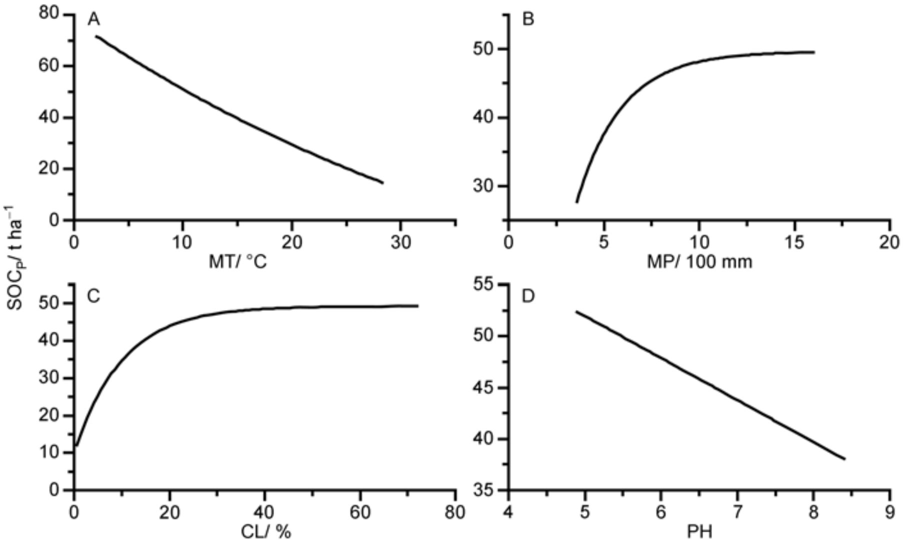

Figure 5 Model sensitivity to climate and soil parameters. A, B, C, D show the SOC_P sensitivity to temperature, precipitation, soil clay fraction and pH, respectively.

Table 2 Statistical character of climate and soil parameters

Statistics	MT /°C	MP /100mm	CL /%	PH
Minimum	2.1	3.6	0.6	4.9
Mean	12.4	7.5	23.2	6.6
Maximum	28.3	16.0	72.0	8.4

top soil (0–20 cm) in Henan Province using the SOC_P model (Eqn. 3), and SOC density in the 1990s (SOC_B) was computed in a similar manner to Eqn. (1). Figure 6A and 6B show the spatial distribution (10 km×10 km resolution) of SOC_B and SOC_P in Henan Province, respectively, suggesting that cropland in the southern region holds larger amounts of SOC than the northern region of this province. A considerable difference between SOC_P and SOC_B ($\Delta SOC = SOC_P - SOC_B$) exists in the eastern and central regions of the province (Figure 6C).

The SOC density in Henan Province averaged 20.0 t ha^{-1} in the 1990s, with a range between 4 and 28 t ha^{-1} in 90% of the grids (Figure 7A). When the SOC sequestration potential is achieved, the SOC_P density would reach 20–44 t ha^{-1} in 90% of the grids, with an average of 31.8 t ha^{-1} (Figure 7B), approximately 60% higher than the SOC level of the 1990s. The additional carbon sink was thus estimated to be 11.8 t C ha^{-1}. From the estimates in Figure 6C, the cropland in Henan Province could sequester an additional 103.4 Tg C in the top 0–20 cm soil depth when the SOC sequestration potential is achieved.

3 Discussion

3.1 Uncertainties and limitation

Uncertainties in modeling originate from three sources of error: model error, parameter error and input error [50]. Theoretically, SOC density at the carbon saturation level (as 'saturation k' shown in Figure 1A) should be the sequestration potential, which remains constant with time, carbon input level and management practices. However, carbon input in some of the LTEs might not have been maximized. Thus, the SOC levels in these LTEs had not achieved a saturation level but rather stable levels 'i' or 'j' (Figure 1A). As a result, the site specific SOC_P might be underestimated. In such a case, predicted SOC_P using the model (Eqn. 3) may represent the local maximum SOC sequestration level rather than SOC_P at carbon saturation.

The LTEs are distributed across a vast cropland area (Figure 2, Appendix A), which should be representative of global agroecosystems. However, data quality in the LTEs may not be in good agreement as a result of investigator bias, experimental conditions, or different methodologies, which would result in inconsistent data quality [51]. We employed several standards and criteria to make data suitable for model development, including the condition that only LTE sites with high C input and an experimental duration of longer than 10 years were selected. Soil data were cross checked using the FAO soil database and Chinese Soil Database, and SOC data were standardized to a 0–20 cm depth. These practices may have improved the data quality to some extent, and thus the model reliability.

Uncertainties in the estimated SOC_P in Henan Province may come from three aspects. First, the interpolation of site-specific climate and soil data within a region may not properly represent the spatial variations of complex environments [52,53], and therefore result in uncertainties of the estimated SOC_P. Second, due to a lack of available data, we did not include annual irrigation in the annual water input (MT in Eqn. 3) when SOC_P was estimated, which may have

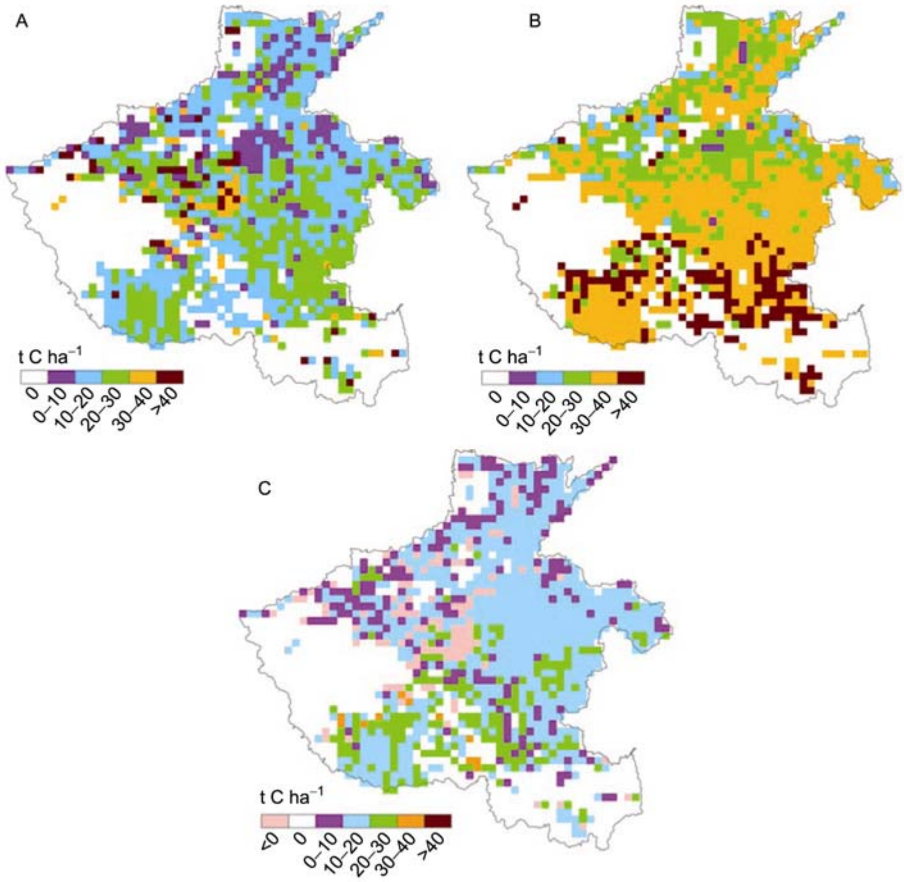

Figure 6 Spatial distribution of SOC density in Henan Province. (A) SOC_B; (B) SOC_P; (C) SOC_P-SOC_B.

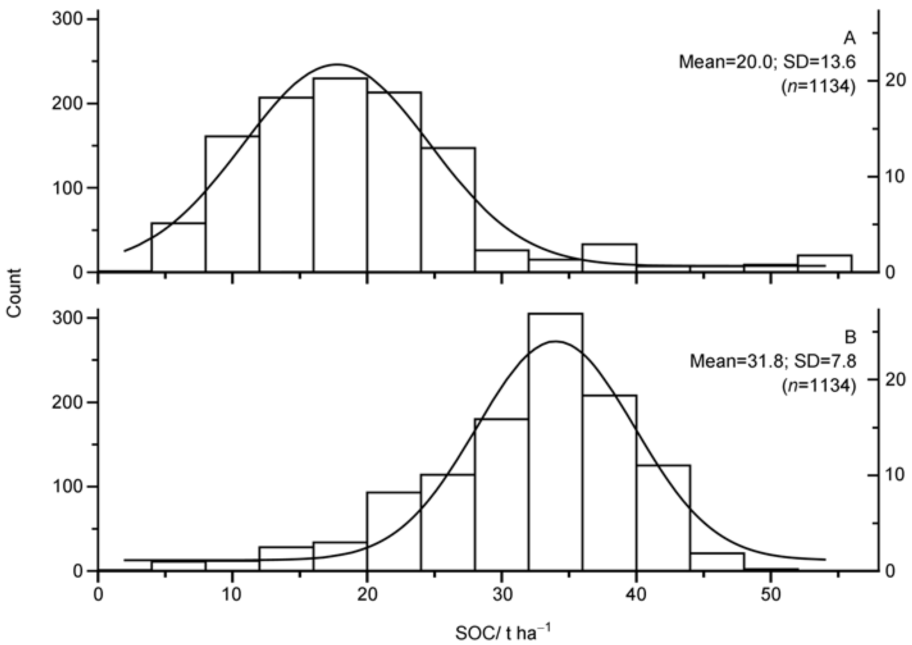

Figure 7 Frequency distribution of SOC_B and SOC_P in Henan Province. (A) SOC_B frequency; (B) SOC_P frequency. SD: Standard deviation. *n* is the number of grids.

Table 3 Time needed for achieving carbon sequestration potential in Henan Province*

Management practices	Methods of upscaling	Sequestration rate /kg C ha^{-1} yr^{-1}	Source	Predicted sequestration duration /yr.
Recommended management Practices	Upscaling filed observations to China	200–300	Lal [12]	59–39
Straw return	Upscaling filed observations to Henan Province	610	Lu *et al*. [13]	19
Nitrogen fertilizer		209		56
50% CR	Process-level model	130	Yan *et al*. [14]	91
100% CR		319		37
50% NT		120		98
100% NT		240		49
50% NT+50% CR		182		65
100% NT+100% CR		401		29

*100% NT: 100% croplands adopt no tillage; 100% CR: 100% straw return; sequestration duration was calculated.

resulted in an underestimation of SOC_P. For example, the estimated SOC_P in some grids was lower than SOC in the 1990s (Figure 6C), which appears contradictory to the SOC_P definition. As far as the model sensitivity to water input is concerned (Figure 5B), the estimates of SOC_P in these grids are expected to be higher than current estimates. Third, the low-resolution of land use images may lead to a misinterpretation of forest or grassland as cropland. Cropland area in the grids with negative values (Figure 6C) accounts for 66% of the grid area, which would inevitably introduce errors into the estimates.

Because very few LTEs with large amounts of carbon input could be found in rice paddies, the present SOC_P model (Eqn. 3) is dedicated to upland soils. Using this model to estimate SOC_P in rice paddies may result in bias. It is expected that the present SOC_P model will be modified when the data in rice paddies are available.

3.2 Duration of carbon sequestration

It is well recognized that improved management practices promote soil carbon sequestration, and thus increase soil carbon storage [2,7,12,13]. When the SOC_P is quantified, we may be in a position to predict the duration of carbon sequestration. Several investigations have suggested that the SOC sequestration rates could be 120–610 kg C ha^{-1} yr^{-1} under different management practices [12–14]. Based on these sequestration rates, the duration of carbon sequestration is predicted to be 19–98 years before the SOC_P (Figure 6B) is achieved in Henan Province (Table 3), which is in accordance with Yan *et al*. [14] and West *et al.* [23]. Actual sequestration duration may even be longer than the predicted value, because soil carbon sequestration rates could become smaller and smaller as SOC levels approach the saturation level [22].

4 Conclusions

With an understanding of soil carbon saturation, a statistical model using the data from global long-term experiments was developed to quantify SOC sequestration potential in upland soils. Model validation suggested that the SOC sequestration potential could be properly estimated from temperature, precipitation, irrigation, soil clay fraction and pH. Model estimates in Henan Province showed that carbon density at the saturation state would reach an average of 32 t C ha^{-1} in the top 0–20 cm soil depth. Using SOC density in the 1990s as a reference, cropland in this province could sequester an additional 100 Tg C, which could be achieved in 19–98 years when agricultural management is improved. Because carbon input in some of the global long-term experiments might not have been maximized over the length of the experiments, the carbon density may not have reached saturation. Consequently, the predicted carbon sequestration potential predicted by the model may be lower than that at carbon saturation state.

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Appendix A: Description of global long-term experiments

Location	Latitude	Longitude	MT/°C	MP/100 mm	CL/%	PH	Duration	Crops	C input type	References
Australia	31º06´S	150º56´E	17.5	6.76	50.0	8.4	29	cereal	residue	[1–3]
Australia	34º58´S	138º38´E	16.8	6.04	18.0	6.2	70	wheat, oats	organic C	[1–3]
Australia	27º07´S	148º40´E	20.3	5.60	18.0	6.5	20	sorghum, sunflower, wheat, barley, oats	stubble	[4–6]
Australia	28º38´S	148º40´E	20.5	4.77	59.0	7.2	23	sorghum, sunflower, wheat, barley, oats	stubble	[4–6]
Australia	28º24´S	150º17´E	19.9	5.80	34.0	7.4	25	sorghum, sunflower, wheat, barley, oats	stubble	[4–6]
Australia	27º15´S	151º24´E	18.5	5.97	40.0	7.4	35	sorghum, sunflower, wheat, barley, oats	stubble	[4–6]
Australia	26º52´S	150º55´E	19.4	6.15	49.0	7.4	45	sorghum, sunflower, wheat, barley, oats	stubble	[4–6]
Australia	27º12´S	151º12´E	19.0	6.12	72.0	8.1	70	sorghum, sunflower, wheat, barley, oats	stubble	[4–6]
Australia	35º05´S	147º20´E	16.0	5.50	29.0	4.9	21	wheat	residue (stubble)	[7,8]
Australia	31º06´S	150º56´E	17.5	6.76	44.3	6.9	34	wheat	residue	[9–13]
Belarus Re-public	53º31´N	28º07´E	5.5	6.96	5.0	5.4	14	potato, oats	FYM	[14,15]
Belgium	50º24´N	4º43´E	9.1	7.67	13.5	6.6	32	sugar Beet, cereals	FYM	[3,16,17]
Brazil	30º51´S	51º38´W	19.4	14.40	22.0	5.3	18	oat, maize, cowpea	residue	[18–20]
Canada	53º07´N	114º28´W	2.1	5.47	12.0	5.9	69	wheat, oat, barley	manure	[21,22]
Canada	50º17´N	107º48´W	3.5	3.58	42.0	7.0	12	wheat	residue	[23–25]
Canada	50º18´N	107º49´W	3.5	3.58	10.0	5.8	12	wheat	residue	[24]
Canada	49º42´N	112º47´W	5.0	4.02	30.0	7.0	37	wheat	FYM	[14,26,27]
Canada	42º13´N	82º44´W	8.9	8.76	37.0	5.7	45	corn, soybean	residue	[28,29]
China	40º13´N	116º14´E	11.0	6.00	20.0	8.8	13	wheat, maize	FYM	[30–34]
China	38º56´N	100º27´E	7.0	5.37	15.0	8.4	22	wheat, maize	FYM	[35–37]
China	37º46´N	115º44´E	12.6	5.18	10.0	8.1	24	wheat, maize	green manure	[38–41]
China	47º27´N	126º56´E	1.5	5.30	20.0	6.8	18	wheat, maize, soybean	FYM	[42,43]
China	45º40´N	126º35´E	3.5	5.33	9.3	7.2	22	wheat, maize, soybean	FYM	[44,45]
China	35º04´N	113º10´E	14.5	10.05	9.0	8.7	14	wheat, maize	organic compost	[46,47]
China	34º48´N	113º40´E	14.0	6.34	10.0	8.3	14	wheat, maize	FYM	[48,49]
China	26º31´N	112º22´E	18.0	13.37	20.5	5.7	13	wheat, maize	FYM	[50,51]
China	26º45´N	111º53´E	18.0	12.55	35.7	5.7	14	wheat, maize	FYM	[52–54]
China	34º16´N	117º11´E	14.0	12.67	6.0	8.3	20	wheat, maize	FYM	[55–57]
China	41º19´N	124º30´E	4.5	5.50	31.0	7.6	22	maize, soybean	FYM	[58–61]
China	35º12´N	107º40´E	9.2	5.86	24.0	8.4	18	crops unclear	FYM	[62]
China	34º18´N	108º01´E	13.0	9.98	16.8	8.6	12	wheat, maize	FYM	[63]
China	36º54´N	116º36´E	13.1	5.91	10.0	7.8	14	wheat, maize	FYM	[64]
China	37º54´N	113º06´E	7.3	5.20	10.0	7.9	12	maize	FYM, stover	[65,66]
China	44º17´N	87º56´E	6.6	3.60	10.0	8.5	13	wheat	residue	[67,68]
China	39º18´N	111º06´E	8.8	4.60	10.0	8.1	12	potato	FYM	[69]
China	26º42´N	105º18´E	13.6	12.67	25.0	7.6	11	wheat, maize	FYM	[70]
China	26º48´N	104º12´E	11.2	9.51	32.5	7.7	11	potato, maize	FYM	[70]
Czech Re-public	50º05´N	14º20´E	8.1	4.50	31.3	6.9	51	sugar beet, barley	FYM	[2,3,71–73]
Czech Re-public	50º05´N	14º20´E	8.8	5.49	22.3	6.6	46	crops unclear	FYM	[2,74,75]
Denmark	55º28´N	09º07´E	7.7	8.62	12.0	6.5	73	cereals	FYM	[76,77]
Denmark	55º28´N	09º07´E	7.7	8.69	4.0	6.5	102	cereals	FYM	[3,77]
Estonia	58º23´N	26º40´E	4.8	5.82	10.0	6.3	10	potato, wheat, barley	FYM	[78,79]
France	54º28´N	2º18´W	11.0	6.40	25.3	8.2	121	wheat, maize	FYM	[3,80–82]
Germany	51º24´N	11º53´E	8.7	4.84	21.0	6.6	93	Sugar beet, barley, pota-toes, wheat	FYM	[2,3,72,83,84]
Germany	51º31´N	12º00´E	9.2	4.94	12.0	6.0	12	potato, wheat, maize, barley, sugar beet	FYM	[85,86]
Germany	51º31´N	12º00´E	9.2	4.94	8.0	6.3	120	rye	FYM	[85–87]
Germany	48º22´N	13º12´E	8.7	8.86	16.4	6.9	41	wheat, maize	residue	[88]

(*To be continued on the next page*)

(*Continued*)

Location	Latitude	Longitude	MT/°C	MP/100 mm	CL/%	PH	Duration	Crops	C input type	References
Germany	52°28´N	13°18´E	8.7	4.96	2.7	5.0	62	wheat, potato	FYM	[3,89]
Germany	52°30´N	14°8´E	8.4	5.11	5.0	5.6	38	sugar beet, wheat, barley, rye	FYM	[90–95]
Hungary	47°19´N	19°00´E	10.3	9.31	31.0	5.8	44	crops unclear	FYM	[96,97]
India	20°42´N	77°02´E	25.5	9.75	52.4	8.1	14	sorghum, wheat	FYM	[98,99]
India	23°30´N	85°15´E	23.1	16.00	25.3	5.3	30	soybean, wheat	FYM	[98–100]
India	23°12´N	79°57´E	25.0	14.03	58.9	7.6	28	soybean, wheat, maize	FYM	[101,102]
India	29°36´N	79°40´E	16.0	10.19	5.8	6.2	33	soybean, wheat	FYM	[103–109]
India	28°38´N	77°09´E	25.5	10.10	14.0	8.3	34	cowpea, maize, wheat	FYM	[110–115]
Italy	45°21´N	11°58´E	12.8	8.50	52.0	7.9	37	maize, wheat, tomato, sugar beet	FYM	[116,117]
Italy	45°21´N	11°58´E	12.8	8.50	0.6	8.1	37	maize, wheat, tomato, sugar beet	FYM	[116,117]
Italy	45°21´N	11°58´E	12.8	8.50	15.0	7.8	39	maize, wheat	FYM	[116,117]
Italy	45°21´N	11°58´E	12.4	8.50	29.2	7.8	27	maize, sugar beet, soy-bean	residue	[116,118]
Italy	44°33´N	11°21´E	13.0	7.00	28.0	6.9	34	wheat, maize, sugar beet	FYM	[119]
Italy	43°40´N	10°19´E	20.0	9.07	13.9	7.7	26	sunflower, wheat, maize	residue	[120,121]
Kenya	01°15´S	36°46´E	19.5	9.81	40.0	5.9	25	maize	FYM, residue	[14,122,123]
Kenya	0°47´S	37°40´E	24.3	7.30	30.8	6.6	13	sorghum, cowpea, maize, pigeon pea	FYM	[122,124]
Netherlands	52°51´N	5°18´E	9.0	8.00	20.0	7.0	65	barley	FYM/municipal solid waste	[125–128]
Norway	59°40´N	10°46´E	5.3	9.40	25.0	5.5	48	cereals	FYM	[129,130]
Norway	60°47´N	11°11´E	4.5	6.00	14.0	6.1	74	oats, potatoes, wheat, barley	FYM	[37,131,132]
Russia	55°30´N	37°36´E	4.9	5.38	19.0	6.2	28	potatoes, wheat, barley	FYM	[15,133]
Sweden	55°42´N	13°43´E	7.3	7.64	13.5	5.6	18	barley, wheat, potatoes	FYM	[134,135]
Sweden	54°24´N	13°14´E	8.1	5.90	15.0	5.8	37	crops unclear	FYM	[14,136]
Sweden	60°´N	17°´E	6.7	5.55	37.0	6.6	37	cereals, fodder beet	FYM	[3,96,137]
Sweden	54°24´N	13°14´E	8.1	5.90	17.0	7.5	34	wheat, oat, sugar beet	FYM	[138,139]
Sweden	55°49´N	13°30´E	7.1	7.77	13.0	6.2	34	wheat, oat, sugar beet	FYM	[138]
Sweden	55°38´N	13°25´E	7.2	6.57	8.0	6.6	34	wheat, oat, sugar beet	FYM	[138]
Sweden	55°53´N	12°52´E	8.0	5.69	15.0	7.2	38	wheat, oat, sugar beet	FYM	[138,140]
Switzerland	47°30´N	7°33´E	9.5	7.85	20.0	6.4	21	potato, wheat, barley	FYM	[14,141]
Switzerland	47°29´N	8°54´E	8.4	11.83	16.0	6.0	19	wheat, maize	residue	[16,142,143]
Thailand	16°29´N	102°50´E	27.6	11.84	6.9	5.4	27	cassava	cassava stalk	[14,144]
Thailand	14°48´N	100°48´E	28.3	12.60	11.4	5.1	27	maize	rice straw	[14,144]
Thailand	14°52´N	101°39´E	27.0	10.80	11.4	7.0	28	cassava	cassava stalk	[14,144]
UK	51°49´N	0°21W´	9.2	7.04	23.0	8.0	141	barley	FYM, residue	[3,145]
UK	51°49´N	0°21W´	9.1	7.28	18.0	7.5	150	wheat	FYM, residue	[3,145–147]
Ukraine	46°49´N	36°40´E	6.7	3.89	39.0	7.6	33	corn, wheat, sugar beet, barley	FYM	[14 15]
USA	38°32´N	121°47´W	16.0	4.50	21.0	7.0	12	tomato, safflower, corn, oats, pea, bean	FYM, residue	[148]
USA	45°43´N	118°38´W	11.0	4.22	18.0	6.0	70	wheat	FYM	[149–152]
USA	40°06´N	88°12´W	11.1	9.39	27.0	5.8	122	corn, oats	FYM	[153,154]
USA	38°57´N	93°20´W	12.4	9.16	18.0	5.6	110	corn, oat	FYM	[153,155]
USA	36°07´N	97°04´W	15.6	8.65	20.0	6.2	110	wheat	FYM	[156–158] & 1)
USA	44°43´N	93°04´W	7.0	8.20	25.0	6.4	14	corn	residue	[159]
USA	33°56´N	83°22´W	16.3	12.45	22.0	7.0	16	sorghum, soybeans, corn	residue	[160,161]
USA	43°18´N	89°21´W	7.6	7.91	29.0	6.8	32	corn	residue	[162–166]
USA	43°20´N	84°07´W	8.7	7.88	26.5	6.8	20	corn, sugar beet	FYM, residue	[167,168]
USA	42°40´N	85°28´W	8.6	7.82	7.5	6.5	30	grain	FYM	[168,169]
USA	41°12´N	96°24´W	10.2	8.16	30.0	7.1	26	corn	FYM	[153,170]
USA	42°24´N	85°24´W	9.2	9.20	14.0	6.2	12	corn, soybean, wheat	FYM	[171–174] & 2)
USA	41°14´N	103°00´W	9.0	4.40	15.0	6.3	31	wheat	residue	[175–178]

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