Economics- and policy-driven organic carbon input enhancement dominates soil organic carbon accumulation in Chinese croplands

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China's croplands have experienced drastic changes in management practices, such as fertilization, tillage, and residue treatments, since the 1980s. There is an ongoing debate about the impact of these changes on soil organic carbon (SOC) and its implications. Here we report results from an extensive study that provided direct evidence of cropland SOC sequestration in China. Based on the soil sampling locations recorded by the Second National Soil Survey of China in 1980, we collected 4,060 soil samples in 2011 from 58 counties that represent the typical cropping systems across China. Our results showed that across the country, the average SOC stock in the topsoil (0–20 cm) increased from 28.6 Mg C ha^{-1} in 1980 to 32.9 Mg C ha^{-1} in 2011, representing a net increase of 140 kg C ha^{-1} year^{-1}. However, the SOC change differed among the major agricultural regions: SOC increased in all major agronomic regions except in Northeast China. The SOC sequestration was largely attributed to increased organic inputs driven by economics and policy: while higher root biomass resulting from enhanced crop productivity by chemical fertilizers predominated before 2000, higher residue inputs following the large-scale implementation of crop straw/stover return policy took over thereafter. The SOC change was negatively related to N inputs in East China, suggesting that the excessive N inputs, plus the shallowness of plow layers, may constrain the future C sequestration in Chinese croplands. Our results indicate that cropland SOC sequestration can be achieved through effectively manipulating economic and policy incentives to farmers.

soil organic carbon | Chinese cropland | crop residue management | carbon sequestration

Soil organic carbon (SOC) in croplands is the core of soil fertility that ensures crop production and food security, while affecting climate conditions via mediating greenhouse gas emissions (1, 2). The net SOC stock depends on the balance between organic C inputs and C effluxes via microbial decomposition (3). Agricultural practices profoundly affect cropland SOC (particularly in the topsoil) by directly altering organic C inputs and indirectly modifying the environmental conditions for microbes (4).

Agricultural production in China supports nearly 20% of the world population with less than 10% of the world's arable land. From 1980 to 2010, China's agriculture has immensely intensified, with new crop cultivars and high inputs of chemical fertilizers and pesticides, leading to 65% increases in cereal grain yields (5). The impact of this intensification on SOC has recently drawn major attention from the scientific community and decision-makers because changes in SOC may not only affect future food production, but also water and soil quality, as well as greenhouse gas emissions. Consequently, many studies have examined SOC changes, but most estimates were local or regional (6, 7). Only a few studies estimated the SOC changes at the national scale, and their results were highly variable or even contrasting (8–11). Nationwide estimates using process models tended to show some SOC losses, and attributed these losses to low C inputs, in particular through crop straw/stover incorporation (8, 10). In contrast, long-term soil fertility monitoring and field investigations often found an opposite trend and attributed the observed gain to increased residue incorporation (9, 11). Therefore, the underlying mechanisms or processes that dominated the SOC dynamics at the national scale are still not fully understood. However, knowledge of these mechanisms or processes is critical for sustainable management of croplands to support an increasing population while maintaining their environmental functions.

Here we report results from a nationally coordinated effort that examined SOC and associated crop management data from 4,060 sites in 58 counties (Fig. S1) that represent a typical cropping system across China. The sampling sites were either identical or very adjacent to the soil sampling locations recorded by the Second National Soil Survey of China in 1980 (see *Materials and Methods* for details). We determined the changes in

Significance

Soil organic carbon (C) stock in Chinese croplands increased by about 140 kg C ha^{-1} year^{-1} from 1980 to 2011. This soil organic C sequestration was largely due to drastic changes in management practices, such as fertilization, tillage, and residue treatments, induced by economic and policy incentives. Our analysis also indicates that excessive N inputs and inability to incorporate residue C into deeper soils will likely constrain the future C sequestration in Chinese croplands. These findings provide new insights into the causes and limitations of economics- and policy-driven soil C sequestration in China and offer some guidance for soil C management in many developing countries that are going through the similar economic and social transformations.

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SOC over the three decades and identified the dominant agronomic, economic, and policy drivers and their implications for future C sequestration in Chinese croplands.

Results and Discussion

SOC Stocks and Crop Residue Return. The area-weighted mean SOC stock (0–20 cm) in 2011, as represented by 58 counties across China, was 32.90 Mg C ha^{-1}, with a 95% confidence interval of 32.34–33.47 Mg C ha^{-1} (Table 1). The SOC stock varied significantly among regions, ranging from about 21.0 Mg C ha^{-1} in Northwest and North China, to 42.2 Mg C ha^{-1} in Northeast China. SOC stocks in the southern parts of China (including Southwest, South Central, and East China) were intermediate, ranging from ~30.0–34.1 Mg C ha^{-1}. Area-weighted mean SOC stocks among the 58 counties investigated also exhibited substantial variations with the county level SOC stock, ranging from 13.2 to 69.6 Mg C ha^{-1} (Table S1). The average amount of residue return via crop straw/stover incorporation (that is, the plant residues were left in place and plowed into the soil rather than burned or removed) in 2011 was 0.89 Mg C ha^{-1} (Table 1). Crop straw/stover input was highest in North China, at an average of 1.38 Mg C ha^{-1}, and was lowest in Northeast China, with only 0.39 Mg C ha^{-1} in 2011 (Table 1).

SOC Stock Changes Between 1980 and 2011. The topsoil SOC stock (0–20 cm) in Chinese croplands increased from 28.56 Mg C ha^{-1} (27.91–29.23 Mg C ha^{-1}) in 1980 to 32.90 Mg C ha^{-1} (32.34–33.47 Mg C ha^{-1}) in 2011 (Fig. 1 and Table 1). Net increment of SOC stocks during that period was 4.34 Mg C ha^{-1} (3.44–5.22 Mg C ha^{-1}) (Fig. 1), representing an average increase of 140 kg C ha^{-1} y^{-1} (111–168 kg C ha^{-1} y^{-1}). Overall, cropland soils in China functioned as a significant carbon sink during this period. However, there was a significant difference in the SOC stock among the major agronomic regions: SOC stocks in croplands of East China, South Central China, Southwest China, North China, and Northwest China increased by 8.33, 6.67, 5.49, 5.14, and 2.84 Mg C ha^{-1}, respectively, while croplands in Northeast China lost 0.41 Mg C ha^{-1} (Fig. 1), equivalent to ~1% of the baseline SOC stock in 1980.

The SOC sequestration rate in China was significantly higher than in Europe and the United States. Across England and Wales, Bellamy et al. (12) reported a C loss of about 300 kg C ha^{-1} y^{-1} from the upper 15-cm soils over the period of 1978–2003. Similarly, repeated sampling of Belgian cropland soils indicated a mean annual soil C loss of 760 kg C ha^{-1} between 1989 and

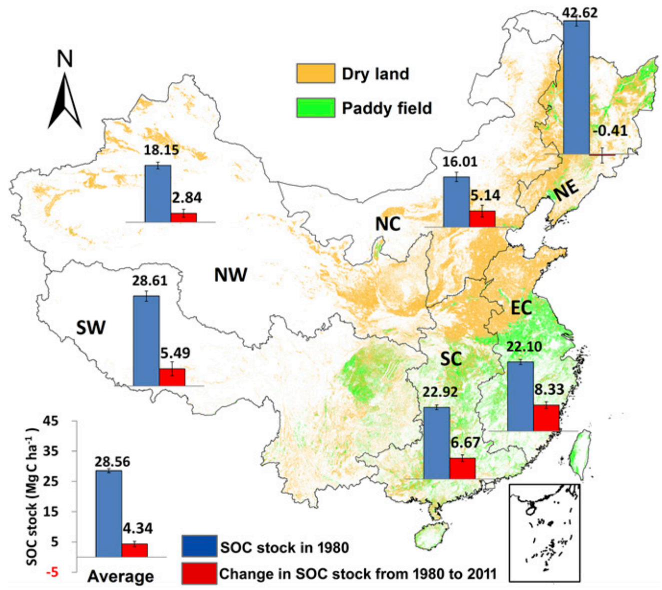

Fig. 1. Area-weighted mean SOC stocks (0–20 cm) in croplands of China's six agronomic regions (EC, East China; NC, North China; NE, Northeast China; NW, Northwest China; SC, South Central China; and SW, Southwest China). Bars represent 95% confidence intervals of the bootstrap estimates.

1999 (13, 14). The estimates across Europe were more variable. Based on the compiled SOC inventory data, Ciais et al. (15) inferred a mean C loss of 170 kg C ha^{-1} y^{-1} for croplands of EU-25 over the past several decades. Results from three process-based models disagreed on the direction and magnitude of change, from a loss of 76 kg C ha^{-1} y^{-1} to a gain of 150 kg C ha^{-1} y^{-1} (15). Still, these numbers were significantly lower than what were estimated by Janssens et al. (13), who reported a loss of 900 (±500) kg C ha^{-1} y^{-1}. In the United States, estimates using the inventory method developed by the Intergovernmental Panel on Climate Change indicated a moderate amount of SOC accumulation in United States cropland soils (upper 30 cm) at 28–35 kg C ha^{-1} y^{-1} from 1982 to 1997 (16). The Century model estimated that SOC stocks in United States croplands increased by 38 and 45 kg C ha^{-1} y^{-1} from 1990 to 1995 and from 1995 to 2000, respectively (17).

The total SOC stock in topsoils of Chinese croplands increased by 0.56 Pg C (cropland area: 130 M ha) over the last three decades, with a rate of change at 18.1 Tg C y^{-1}. Using the average soil C:N of 10.5 derived from 4,060 soil samples in 2011, we estimated that about 53 Mt N was simultaneously stored in the soils. The sequestrated N in the increased soil organic matter (SOM) is approximately equivalent to 2.2 times China's N fertilizer consumption in 2014 (23.93 Mt, National Bureau of Statistics of China, data.stats.gov.cn), indicating that cropland C sequestration also has significant benefits to soil nutrient supplies.

Driving Factors for SOC Changes. Correlation analysis using county-level rates of SOC stock change, climate, initial soil property, and management practice data (Table 2) showed that SOC stock changes in Chinese croplands were positively correlated with mean annual temperature, N fertilizer input, and crop residue C input, but negatively correlated with the initial SOC stock. The partial correlation and stepwise regression analyses further revealed that clay content was another important factor affecting SOC stock changes, while excluding the effect of all other factors (Table 2). While temperature influenced SOC turnover through affecting microbial activities (18), clay content influences SOC concentrations through its control on accumulation and mineralization.

Table 1. Area-weighted mean SOC stocks (0–20 cm) and amounts of returned crop straw/stover in 2011 (N refers to the number of counties investigated; the lower and upper limits of SOC stock refer to the 95% confidence intervals of the bootstrap estimates)

Region	*n*	SOC stock (Mg C ha^{-1}) Mean	Lower limits	Upper limits	Straw/stover residue input (Mg C ha^{-1})
Northeast China	8	42.20	40.68	43.76	0.39
North China	6	21.15	20.04	22.33	1.38
East China	16	30.42	29.79	31.03	0.82
Southwest China	8	34.07	32.66	35.56	0.72
South Central China	13	29.59	28.83	30.34	1.16
Northwest China	7	20.98	20.31	21.73	0.84
Whole China	58	32.90	32.34	33.47	0.89

Table 2. Correlation coefficients and stepwise regression model between county-level rate of SOC change (SOC_{rate}) and climate (mean annual temperature, MAT; and mean annual precipitation, MAP), initial soil properties (sand, silt, and clay content; soil pH in 1980, pH_{1980}; and SOC stock in 1980, SOC_{1980}), and management practices (cumulative N fertilizer input, Nf_{Ninput}; and average crop residue carbon input, $Residue_{Cinput}$) (n = 58)

	Climate		Initial soil properties					Management practices	
Factors	MAT	MAP	Sand	Silt	Clay	SOC_{1980}	pH_{1980}	Nf_{Ninput}	$Residue_{Cinput}$
Pearson R	0.32*	0.08	0.03	0.03	−0.11	−0.58***	0.01	0.28*	0.45***
Partial R	−0.1	−0.05	−0.07	0.07	0.29*	−0.57***	−0.2	−0.06	0.39***

Stepwise regression model. SOC_{rate}(Mg C ha^{-1} y^{-1}) = 0.13 − 0.009 × SOC_{1980} (Mg C ha^{-1}) + 0.005 × Clay(%) + 0.16 × $Residue_{Cinput}$(Mg C ha^{-1} y^{-1}). Adjusted R = 0.49, P < 0.001. *P < 0.05; ***P < 0.001.

Therefore, soils with high clay content may provide physical and chemical protection of organic matter from decomposition (19).

Initial SOC levels accounted for more than 30% of the variation in observed changes in SOC stocks (Fig. S2*A*). The inversely proportional effect of the initial SOC on the SOC change (negative baseline effect) (Fig. S2*A*) indicated that cropland SOC in China was not at steady state in 1980. The initial SOC stocks in most Chinese croplands in 1980 were very low (except for the black soil region in Northeast China) due to 1,000 y of cultivation and continual agricultural use (20). Furthermore, in the vast North China Plain, most croplands were recently reclaimed from saline and alkaline lands with extremely low productivity and organic C (7). In the Loess Plateau of Northwest China, soil erosion is a major cause of initial low soil C stock (21). Chinese croplands had an initial SOC stock (upper 20 cm) of about 26.63–28.56 Mg C ha^{-1} in 1980, based on different estimates using the Second National Soil Survey data (Table S2). In contrast, Europe and the United States had much higher initial SOC stocks, being about 40.2 and 43.67 Mg C ha^{-1}, respectively (Table S2). For example, cropland soils in Belgium had a SOC stock of 38 and 39 Mg C ha^{-1} in 1960 and 1990, respectively and have lost C since (Table S2). In addition, application of N fertilizer is often recommended to increase SOC on cropping lands that have low SOC due to long-term cultivation (2), because N fertilizer affects crop dry matter production and therefore C inputs to soils. Crop straw/stover incorporation influences the direct C inputs to soils. High crop residue C and N fertilizer inputs were often associated with high rates of SOC changes (Figs. S2*B* and S3*A*). Together, these results imply that the low initial SOC stocks in 1980 provided prerequisites for the SOC sequestration that was primarily due to enhancement of crop residue inputs.

Causes of Soil C Sequestration. Our results, together with the SOC inventory estimates by Yan et al. (11) and data from a meta-analysis of cropland soil monitoring literatures by Pan et al. (9), confirmed that cropland soils in China functioned as a significant carbon sink over the last three decades. The net increase in SOC indicates that organic C inputs were quantitatively higher than organic C losses (mainly through decomposition). Because soil C losses were likely associated with organic C inputs, we examined the C inputs during this period of rapid transformation of agriculture in China.

Organic material inputs to Chinese croplands went through three distinct stages that were closely related to the social and economic changes over the past decades. The first stage was characterized by low organic material inputs in the late 1970s (Fig. 2*A*). Labor-intensive manuring and plowing was a common practice then, whereas chemical fertilization was very limited, resulting in low crop productivity. Crop straw/stover in this stage was mainly used as a fuel/fodder; even crop roots (i.e., corn root) were dug out for fuel (22). Consequently, limited farmyard manure production, low root biomass input to soil, and crop residue removal limited the potential for soil C accumulation. The second stage (1980–1999) was dictated by steadily increasing inputs of root biomass resulting from chemical fertilization (Fig. 2*B*). Crop biomass and grain yield increased dramatically with the increasing chemical fertilizer inputs (23); only a small fraction of straw/stover was used for composting or as animal bedding and then returned to the field. Labor-intensive manuring and plowing practices decreased due to the decline in economic gains and the rising labor cost, compared with chemical fertilization (24). Labor shortage due to massive migration of farmers to cities and availability of alternative energy sources, such as coal and electricity, made dispersal of large amounts of residues a costly task. Straw burning began to appear in the 1990s. Although root inputs to soil increased significantly with increasing chemical fertilizer inputs, straw/stover return during this stage was still limited, constraining the soil C accumulation. The third stage started around 2000 when straw burning became the most common practice (25) to further reduce labor requirements. More importantly, intensive field burning activities caused severe air pollution, even closures of airports and highways. This prompted the government to enhance the monitoring of fire spots and ban straw burning through both administrative and economic penalties. In 1999, the crop residue return policy was strengthened, and implementation was required. To promote the implementation of crop residue return, the Chinese government introduced various economic incentives to the farmers and demonstration program (26), which led to more and more crop residues being returned to the soil.

The first two stages were mainly economically driven. In the first stage, limited farmyard manure production and fuel/fodder utilization of crop straw/stover were the main causes. The second stage was driven by enhanced plant productivity and root biomass production resulting from increasing fertilizer inputs. The third stage was predominantly policy-driven. Policy-enforced aboveground residue return led to more organic C inputs. The rapid increase in C input of straw/stover since 2000 provided the largest benefits to SOC sequestration (27).

The primary drivers that dominated SOC dynamics in Chinese croplands in the last several decades were clearly different from those in other developed countries. Insufficient organic C inputs were the primary cause leading to SOC decreases in European countries (15): for example, reduced use of farmyard manure in Belgium (14, 28). In the United States, increases in SOC mainly stemmed from farmland conversion into grasslands encouraged by the United States federally funded Conservation Reserve Program (16, 17), and reducing tillage intensity in the mid-Continental United States (29). Since 1980, China has vigorously promoted conservation of lands, particular grasslands, and marginal croplands on hilly or mountainous regions, which has significantly enhanced the C intensity (30, 31). However, an increasing population and limited arable land leave little room for conservation practices, such as cropland set-aside and long-term no-till, which may reduce crop yields (32). China's experience may be useful for many developing countries in Southeast and Southwest Asia. Carbon sequestration will mainly rely on

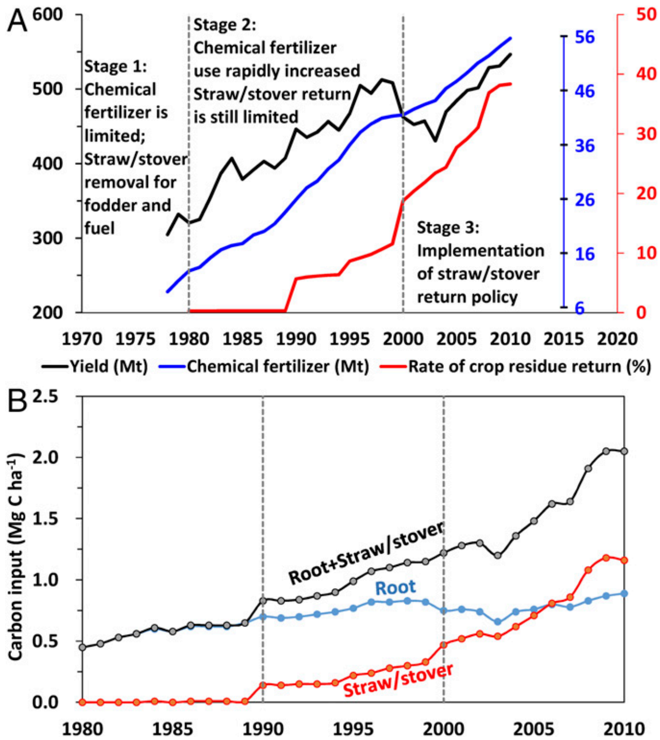

Fig. 2. Changes in agricultural managements and crop residue C inputs since 1980. (*A*) Changes in grain yield, chemical fertilizer consumption, and the rate of straw/stover return to soils in China since 1978. Grain production and chemical fertilizer data were sourced from National Bureau of Statistics of China (data.stats.gov.cn), and rates of crop straw/stover return were based on 4,060 sites in the 58 counties sampled in this study. (*B*) Changes in average C inputs across the 4,060 sites in the 58 counties investigated. C inputs through straw/stover incorporation were estimated using crop yield data recorded by county-level agricultural census, straw/stover return rate derived from 4,060 sites in the 58 counties, and the grain:straw ratios of 333 sampled plots across the 58 counties. C inputs by roots were estimated using the crop yield data reordered by county-level agricultural census and the root:grain ratios of 333 sampled plots across the 58 counties.

increases in organic C inputs and the return of crop residues is of paramount importance.

Contributions of Crop Residue Inputs to SOC Sequestration. Generally, increasing C input through return of crop residues can increase SOC concentration before the soil C is saturated. Across the 4,060 field sites in the 58 counties investigated, average straw/stover C inputs were minimal at first in 1980 and then increased since the early 1990s, whereas root C inputs increased continuously but at a slower rate (Fig. 2*B*). On average, the net increments of cumulative C inputs by crop roots and straw/stover were 7.96 and 10.67 Mg C ha^{-1}, respectively, during the periods of 1980 and 2010.

Changes in average crop residue C inputs during 1980–1989 were characterized by small net C input (Fig. 2*B*). Straw/stover C inputs in this period were minimal, stabilized at a low level (mean C input was only 0.005 Mg C ha^{-1} y^{-1}, whereas root C inputs were 0.57 Mg C ha^{-1} y^{-1}). From 1990 to 1999, both straw/stover and root C inputs increased steadily, with a rate of 0.023 and 0.018 Mg C ha^{-1} y^{-1}, respectively. After 2000, straw/stover C inputs increased rapidly, with a rate of 0.077 Mg C ha^{-1} y^{-1}, while the rate of root C inputs stabilized at 0.016 Mg C ha^{-1} y^{-1} during this period. To quantify the apparent conversion rate of crop residue (root plus straw/stover) C inputs to SOC, a linear regression analysis of SOC change rates by crop residue C inputs at the county level was conducted (Fig. S2*B*). A slope of 0.163 for the fitted regression model revealed that, on average, 16.3% of the crop residue C inputs were retained in the topsoil of Chinese croplands over the last three decades. Incorporation of crop roots and straw/stover has resulted in a SOC increment of roughly 1.30 and 1.74 Mg C ha^{-1}, respectively. Because the net increment of SOC over the last three decades was 4.34 Mg C ha^{-1} (Fig. 1), the contribution of other C inputs (i.e., manure) to SOC increment can be indirectly estimated at 1.30 Mg C ha^{-1}. Consequently, the root, straw/stover, and other C inputs contributed to about 30%, 40%, and 30% of total SOC stock increment, respectively.

Effects of Chemical N Fertilizers on SOC Sequestration. Enhanced crop biomass production resulting from increasing fertilizer inputs, in particular low-cost N fertilizers, has made a significant contribution to the SOC sequestration over the past three decades (7, 27). However, negative effects of chemical N fertilizer inputs on SOC accumulation began to appear. The rate of SOC sequestration in Chinese croplands continuously increased with cumulative chemical N fertilizer inputs at below approximately 290 kg N ha^{-1} y^{-1} but decreased thereafter (Fig. S3*A*). The cumulative N fertilizer inputs were positively correlated with the rate of SOC sequestration in the Northwest, North, and Southwest China (Fig. S3 *B–D*). In contrast, N inputs were negatively related to rate of SOC change in the East China (Fig. S3*E*), raising questions about the sustainability of C sequestration depending on nutrient-enhanced productivity. Chemical N inputs in China are abnormally high (33). Excessive chemical N inputs may constrain SOC sequestration in soils through stimulating decomposition of cellulose-dominant crop residues (34), reducing C retention efficiency by favoring bacteria over fungi (35), and even limiting root growth by stimulating soil acidification (36). They also lead to environmental problems, such as greenhouse gas (N_2O in particular) emissions and serious water pollution (33, 36). Chemical fertilizers have been key to the agricultural intensification in China. The pursuit of high yield and fertilizer-dependent grain yields led Chinese farmers to believe that "the more the chemical fertilizer, the higher the crop yield." Thus, nutrient excesses are widespread and an optimal balance between cost and benefit is missed (23). Although N fertilizer will continue to be indispensable for China's quest to produce sufficient food to meet its growing demands, grain yield per unit of fertilizer added in China has declined (37). Consequently, as an important component of agricultural intensification and increasing C sequestration, new strategies for rational use of N fertilizer in croplands of China need to be developed.

Implications and Perspectives. We present an extensive examination of changes in SOC in China's croplands from 1980 to 2011 and find that a significant SOC sequestration occurred during this period. Multiple factors contributed to this C sequestration, including the extremely low initial SOC content and increased residue inputs first due to enhancement of productivity by fertilizers and then policy-required straw return. Our results demonstrate that it is possible to promote economic benefits for farmers and environmental protection by enhancing SOC sequestration in croplands. However, this needs to incorporate economic and policy incentives. Although SOC is the core of soil fertility, it is a long-term process for the SOC build-up before farmers can harness significant economic benefits. Economic incentives should be established to compensate for the potential short-term losses experienced by farmers who adopt SOC-promoting practices.

Our analyses also identified challenges for future C sequestration in China's croplands. One major factor for the residue-dependent C sequestration is that the plow layer of most crop fields is too shallow to allow SOC accumulation at depth. Tillage is still indispensable to most Chinese cropping systems because China's priority is to maintain or increase yields but long-term no-tillage management may reduce yields. Additionally, many Chinese farmers do not have access to specialized planting equipment and chemical herbicides that are suitable for no-till systems. Tillage with animal-drawn implements was widespread in the early 1980s, and then the animal power was gradually replaced by low-power shallow tillage machineries, in particular rotovator with tilled depth usually less than 15 cm. Tillage practices facilitate crop residue incorporation and mixing of soil layers, leading to a more homogeneous C distribution across the entire tilled soil profile than the no-till systems (38). However, the long-term continuous shallow tillage and tractor wheel traffic in the field has made the plow layer shallower, and the plow pan thicker, harder, and closer to the surface, which critically limits the capacity of C preservation and crop productivity. Incorporating residues into the soil by tillage or leaving residues on the soil surface constitutes a dilemma for promoting C sequestration, as the former increases soil disturbance and decomposition of SOM, while the latter potentially limits soil C sequestration because most surface-placed residues decompose before reaching the mineral soil layer (39, 40). The intensity of Chinese cropping systems is very high and the time interval (window) between subsequent crops is very short. In the North China Plain, for example, the maize must be sown immediately once wheat is harvested. A large amount of straw/stover, if left on the soil surface, negatively affects germination of the subsequent crop plants and often induces diseases, prompting the farmers to burn the straw. Protection of organic C by the soil matrix is a primary mechanism for SOC stability (41). Conversion to deep tillage (a depth of 30 cm) after long-term shallow tillage (upper 10–12 cm; i.e., rotary tillage or harrow tillage) has been reported to improve soil carbon sequestration and crop yield in North China (42). While in the warm and humid South China, decomposition is fast and the shallow plow pan inhibits root penetration. Although residue incorporation by tillage may cause disturbance, soils in these regions contain high contents of iron and aluminum oxides and mineral clays, particularly in Oxisols, that can protect organic C from decomposition (43–45). Therefore, rational tillage rotation with deep tillage after long-term shallow tillage (i.e., tilling to a depth of 30 cm once every 2–3 y) has been shown to be an effective practice to facilitate C sequestration across China (42, 46, 47). However, the extremely low amount of arable land (only about 0.1 ha per capita) and the small size of farms in China generate very limited net profits for each farm. Consequently, most farmers are unable to acquire high-cost and deep-till machineries needed for deep tilling. Therefore, one priority should be to enable farmers to have access to powerful deep-tillage machinery that can incorporate residues into deep soils. The recently proposed Rural Land Circulation policy in China is promising for further aggregation of small cropland patches for large-scale grain production so that integrated crop residue return policy and suitable tillage rotation can be applied at a reasonable cost.

The second challenge is that high N inputs may constrain future soil C accumulation, as shown by the negative relationship between N inputs and soil organic C in croplands of East China. Small farm sizes and high chemical inputs have reenforced a positive feedback loop in which requests for high yields requires high N inputs. High N inputs not only reduce root production but also reduce farmers' enthusiasm for organic inputs. High chemical N inputs lead to soil acidity and even heavy metal toxicity, constituting the primary factor that leads to soil degradation in China (36). The exact mechanisms and their relative contributions to limiting soil C accumulation are not fully understood. The new research initiative of fertilizer reduction and pesticide reduction may help to understand these mechanisms and related processes.

For fostering both food production and potential C sequestration, the Chinese government also needs to modify policies to educate and award good management practices. The current incentives for residue return are most often "direct" subsidies, such as cash rewards for farmers (approximately \$25–75 ha^{-1}) and discount for straw-returning machine acquisition (20–30% purchase cost), depending on the economic levels of different regions. Such subsidy policy is largely supported by the quick development of China's industrial economy. However, farmers' enthusiasm may fade once such "direct" subsidy decreases or is ceased. One major challenge facing China's agriculture is a severe labor shortage, with old people and women with low education levels being the primary rural labor force. Thus, long-term sustainable residue return practices that rely less on manual work would be essential. Consequently, the development of farmer-friendly (simple, effective, and time-saving) residue incorporation techniques and specialized tillage machineries with relatively low soil disturbance is also important. Moreover, livestock and poultry manure utilization, a key task in China's "Fertilizer Use Zero-Growth Action Plan by 2020," may benefit the potential C sequestration in Chinese croplands, but policies and supporting technologies for eliminating the potential risks of heavy metal pollutants due to manure applications also need to be developed.

Finally, our findings may provide some guidance for residue management for cropland C sequestration in many developing countries. Because of low productivity and residue removal for fuel or feeds, low organic C inputs are the primary factor limiting SOC accumulation in many developing countries (1, 3, 23). The substantial contributions of Chinese crop residue return policy to SOC sequestration also indicates that the solutions for China may potentially be applicable in other developing countries where similar experiences and challenges exist, particularly in Southeast Asia and South Asia. Lessons from the excessive N fertilizer uses in China can be learned (36). However, crop residue return may not be equally effective in sequestering C in different countries due to regional differences in biogeochemical, climatic, and socioeconomic conditions. Therefore, scientific knowledge and technologies, economic and policy incentives, and stakeholder's active participation are inseparable components to realize the potential of global cropland C sequestration and agricultural sustainability.

Materials and Methods

Soil Data and Estimates of SOC Changes. China conducted its second national soil survey across the country in 1980 and all of the major croplands that covered typical soil types and cropping systems were sampled. This nationwide effort generated the most comprehensive and detailed legacy data that are available so far for extracting historical information on soil properties of China (11). In 2011, we collected 4,060 topsoil (0–20 cm) samples in 58 counties across China (Fig. S1). These sample sites were chosen to: (*i*) match the 1980s sample sites as closely as possible, (*ii*) be on identical soil types (soil series) and topographic characteristics, and (*iii*) have the most typical cropping system around the sites. The soil samples were collected by using a process of composite sampling (*SI Materials and Methods*). The topsoil was sampled to a depth of 20 cm, because the thickness of topsoil in China is generally less than 30 cm and the upper 20 cm was consistently sampled in the second national soil survey in 1980 (6).

Data on SOM, bulk density, and rock fragment contents were obtained from the reports of the second national soil survey of China in 1980 and the resampling campaign in 2011, respectively. Identical methods were used for measuring SOM contents and total SOC stock for both sampling dates. Briefly, SOM contents (the SOM here means SOC × 1.724) were measured using the potassium dichromate oxidation with external heating method, and bulk densities were measured using the cutting ring method (48).

For each of the sampling sites, the SOC content is calculated by multiplying SOM by 0.58, and the SOC by volume (Mg C ha^{-1}) was calculated by: $C_{fs} \times BD_{fs} \times Depth \times (1 - RF)/10$, where C_{fs} is the organic C content (fine soil, the part of the soil that passes through a 2-mm sieve, g kg^{-1}), BD_{fs} is the fine soil bulk density (g cm^{-3}), *Depth* represents topsoil thickness in centimeters (20 cm in this study), and *RF* represents the volume fraction of rock fragments (>2 mm). The site-level SOC stocks were further aggregated to county and then to region scales using the area-weighted mean method. For each county, the mean SOC stock per soil type in the county was first calculated, and then the areas of each soil type recorded in the soil survey report of the county were used as weights to calculate the area-weighted mean of SOC stock for the county. For each region, the mean SOC stock per investigated county in the region and the soil areas of the investigated counties were used to derive the area-weighted mean SOC stock for the region.

The locations of the 1980s sample sites were mainly recorded by text descriptions in soil survey reports of each county because GPS was not available then. Thus, some errors in relocating the 2011 sample locations may have occurred. To obtain a robust estimate of SOC stock and its change, during the area-weighted mean calculation of SOC stocks, bootstraps with 10,000 times of repeat sampling were applied to derive the 95% confidence interval of the estimates (*SI Materials and Methods*), and the median of the estimates was used to represent the area-weighted mean SOC stock. It should be noted that the estimates of SOC change made in this paper did not consider effects of lateral C transport on soil C stocks.

C Input from Crop Resides (Root Plus Straw/Stover). The C input into the soil was calculated based on the county-level major crop yields. For each county, the annual crop residue C input (Mg C ha^{-1}) during 1980–2010 was estimated based on the sum of root and straw/stover C inputs of individual crops divided by the total cropland area at the corresponding year (*SI Materials and Methods* and Tables S3 and S4). Only staple grain crops (wheat, corn, paddy rice), oil plants (soybean, rapeseeds), and cotton for each of the 58 counties were considered as sources of crop residue C inputs, as yield data for these crops during the last 30 y were readily available from the agricultural census yearbook of each county.

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