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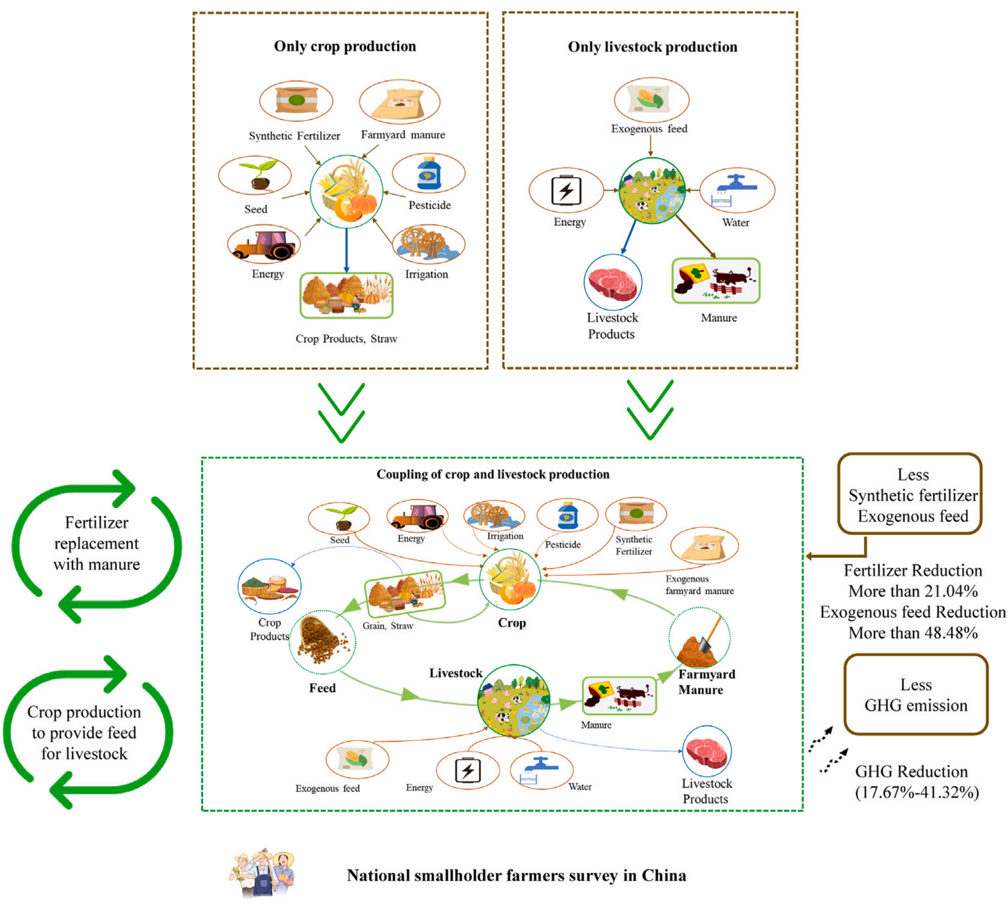

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Highlights

An Agri-LCA model based on a localized database of environmental impact parameters was developed to quantify GHG emissions

GHG emission reduction potentials by CCLP by national smallholder survey were assessed on a case-by-case basis

CCLP can reduce the GHG emission intensity by 17.67%, with its own feed and manure returning to the field as an essential path

The reduction in GHG emissions of 28.09%–41.32% will be achieved by restructuring the CCLP

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Coupling of crop and livestock production can reduce the agricultural GHG emission from smallholder farms

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SUMMARY

Ensuring global food security and environmental sustainability is dependent upon the contribution of the world's hundred million smallholder farms, but the contributions of smallholder farms to global agricultural greenhouse gas (GHG) emissions have been understudied. We developed a localized agricultural life cycle assessment (LCA) database to calculate GHG emissions and made the first extensive assessment of the smallholder farms' GHG emission reduction potentials by coupling crop and livestock production (CCLP), a redesign of current practices toward sustainable agriculture in China. CCLP can reduce the GHG emission intensity by 17.67%, with its own feed and manure returning to the field as an essential path. Scenario analysis verified that greater GHG emission reduction (28.09%–41.32%) will be achieved by restructuring CCLP. Therefore, this mixed farming is a mode with broader benefits to provide sustainable agricultural practices for reducing GHG emissions fairly.

INTRODUCTION

Hundreds of million smallholder farms have become the focus of global agendas in reducing greenhouse gas (GHG) emissions and also safeguarding the growing global food demand. Five-sixths of the farms in the world own less than two hectares (hereafter called smallholder farms) and produce about 35% of the world's food.[1] In China, 200 million farmers manage 70% of the arable land and provide most food for the 1.4 billion population with an average productive area of no more than 0.93 hm^2/per household.[2,3] China's food security needs to rely on the contribution of smallholder farmers. The practices of Chinese farmers directly determine their livelihoods, as well as the average agricultural development mode of all low- and middle-income countries and even the world.[4] Given the number and magnitude of these farms, their practices have far-reaching consequences for planetary health regionally and globally. Populous countries like China have promoted intensive agricultural production over the past few decades,[5] and the emissions of GHG, nitrogen, and phosphorus have increased substantially,[3] with food production contributing 30% of the global GHG emission.[6–8]

Traditional "self-sustaining" mixed crop and livestock production of smallholder farms offer inspiration for the future of food systems, as two-thirds of the world's population already lives on these systems.[6] The big-scale farming reveals its environmental shortcomings. The traditional coupling of crop-livestock systems (CCLP) must be revitalized.[2,9] This does not simply imply a reversal of old traditions, but a redesign of current practices toward sustainable agriculture. Improved planting and breeding practices, manure management, and replacement of synthetic fertilizers with manure have demonstrated positive economic and environmental benefits.[6,10,11] The promotion of localized feed to reduce nutrient excess at the district level can promote the achievement of GHG emission reduction in the agricultural system. However, the challenges are also huge.[12,13] Such practices are also becoming more economically feasible in light of the recent increase in natural gas prices, shortage of, and increased prices, of synthetic fertilizers as well an increasing shortage of phosphate supply.[14] Sustainable agriculture is essential to fulfilling the ambition of achieving high food production efficiency while reducing GHG emissions, land use, and loss of excess nutrients for a sustainable future[15–18] in pursuit of the UN Sustainable Development Goals.

The first step to realize this is to carry out an accurate assessment of the environmental effects of CCLP with recognition of positive and negative developmental trajectories. Life cycle assessment (LCA) is a widely

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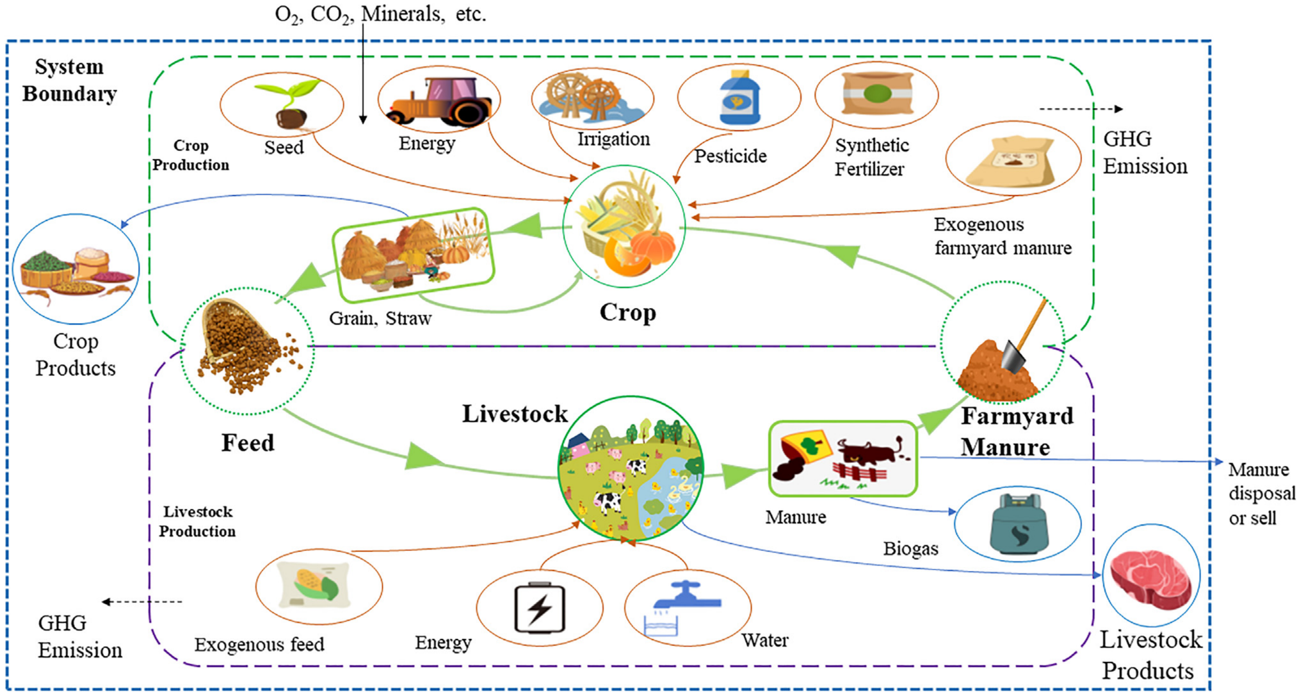

Figure 1. Farming system boundaries for crop and livestock enterprises

adopted approach for quantifying the environmental impacts of all life cycle of a product or activity, starting from the "cradle" (i.e., upstream agricultural production) and ending at the "farm gate" (i.e., the output of the agricultural process, including agricultural products and pollutant emissions). Several studies evaluated the GHG emissions from agricultural food systems, in livestock production[18,19] and crop production,[20,21] in global[22,23] and Chinese[15,22] settings. However, the lack of localized model parameters (e.g., environmental impact coefficients) and farmer-scale agricultural survey data (e.g., agricultural input-output data) is a major challenge, because such studies are often limited to a particular area or technology. There is a need for more precise evaluations of China's smallholder GHG emissions. In addition, the inequality in GHG emissions has been widely acknowledged,[24] but few studies have focused on this inequality.

This study comprehensively analyzed the GHG emission features of 1015 smallholder farms in major agricultural regions in China, using the agricultural LCA database (CALCD, Chinese Agriculture Life Cycle Database) based on SimaPro software. A cradle-to-farm-gate life cycle analysis of each household's agricultural activities was conducted to directly assess the GHG emissions and inequality in the coupling of crop and livestock production at the smallholder level. This study analyzed the effect of the CCLP and conducted a scenario analysis focused on optimizing agricultural practices which could provide a small farm's practice assessment scheme for the future development of sustainable food systems, with relevance not only in China but to agricultural practices worldwide.

RESULTS

The broader benefits of mixed farming

Over 82% of the surveyed smallholder farms were engaged in agricultural production activities in China. More than 55% of the farmers practiced CCLP (Figure 1, Method S2), i.e. both crop and livestock production, 5% only livestock production (OLP), and the rest were farmers who only produced crops (OCP) (Figure S1). It appears that the number of smallholder farms engaged in mixed farming is decreasing, relative to previous decades.[25] To complete coupling of crop and livestock production means that smallholder farmers grow crops to feed their livestock and livestock manure is returned to farmland for sustainable mixed farming. Among farmers who practiced CCLP, 42% were completed coupling (CCCLP) and 58% were incomplete coupling (ICCLP) (Method S3). Among the CCLP farms, the average GHG emission of CCCLP was 178.46 ± 137.66 $kgCO_2eq/100$ USD, which was 17.67% lower than that of ICCLP. For the OCP

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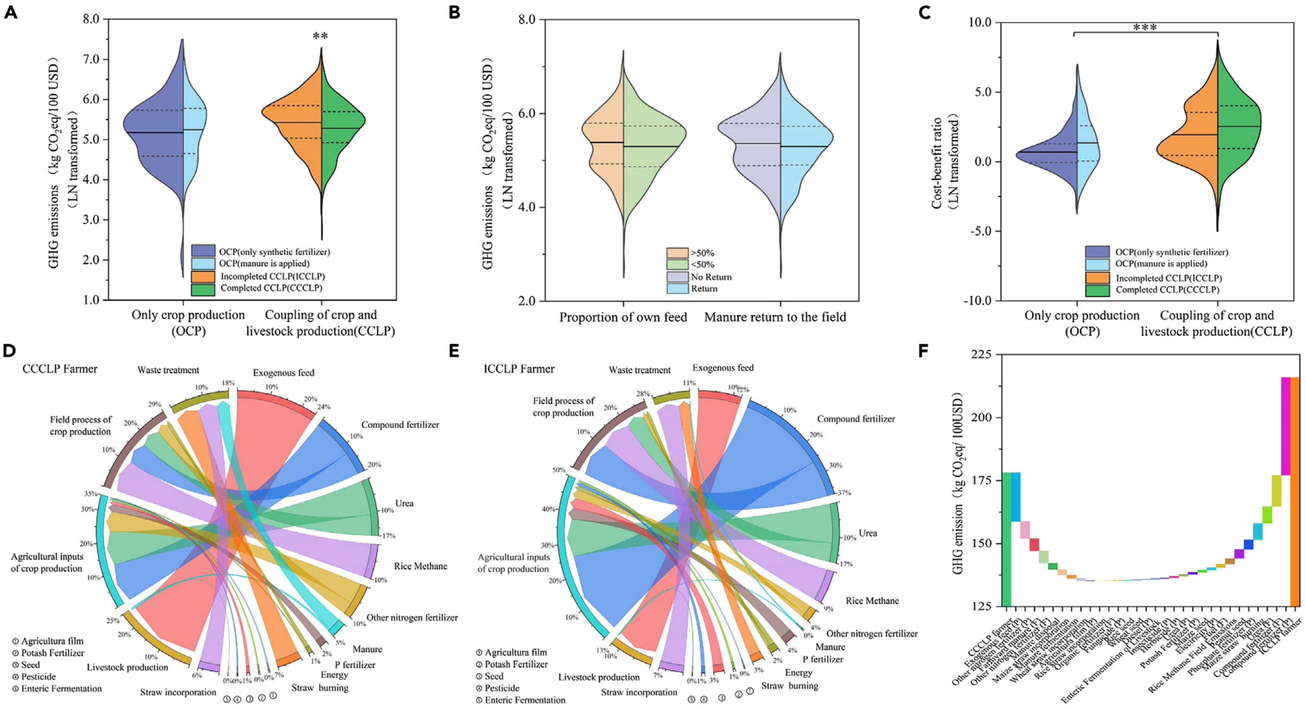

Figure 2. GHG emissions between different types of smallholders

(A) GHG emissions per unit output value of smallholder farms.

(B) Differences in GHG emissions in own feed and manure return.

(C) Cost-benefit ratios of smallholder farms.

(D) Composition of GHG emissions from CCCLP farms in agricultural production.

(E) Composition of GHG emissions from ICCLP farms in agricultural production.

(F) Cumulative differences in GHG emissions between CCCLP and ICCLP farms in the agricultural production chain. Note: Only Livestock Production (OLP), Only Crop Production (OCP), Coupling of Crop and Livestock Production (CCLP), Incomplete Coupling of Crop and Livestock Production (ICCLP), Completed Coupling of Crop and Livestock Production (CCCLP). Significance level *0.05, **0.01, ***0.001.

farms, the average GHG emission of farms that applied farmyard manure was 183.16 ± 165.24 kgCO$_2$eq/100 USD which was similar to the farms that only use synthetic fertilizers (Figure 2A). The cost-benefit ratio for CCLP farmers was as high as 58.60, which was 482.21% higher than that for OCP farmers (Figure 2C). The cost-benefit ratio for ICCLP farmers could grow by 41.76% once realizing complete coupling. Livestock production could significantly increase farmers' income, implying the rising economic benefits of mixed agriculture.

The key linkage in mixed farming is its own livestock feed production and the return of manure to the field. Increasing own feed to more than 50% will reduce farmers' GHG emissions (184.38 ± 204.69 kgCO$_2$eq/100 USD) by an average of 11.02%. After returning the manure to the field, instead of selling and discarding it, farmers' GHG emissions (183.66 ± 143.47 kgCO$_2$eq/100 USD) decreased by 8.10% on average. The closing of the cycle has a certain reduction effect on farmers' GHG emissions (Figure 2B). Whether they are CCCLP or ICCLP farmers, the GHG emission from crop production was always greater than that of livestock production. The field process emission (35.86% for CCCLP farmers) and the upstream production emission of agricultural materials (42.62% for ICCLP farmers) account for the largest proportion of household emissions. In addition, livestock production and straw management did not exceed 30% of household emissions. Livestock emissions accounted for less than 30% of all households, 26.68% of CCCLP households, and 12.75% of ICCLP households. Differences in the specific emission compositions could better explain the differences in emissions from the two types of households (Figures 2D–2F and S2). Fertilizer application, field management, seed input, and straw management all accounted for a large proportion of the GHG emissions increment of incomplete coupling farms. CCCLP farms had higher GHG emissions in exogenous feed, manure treatment, etc. This is because although they achieved mixed farming, but the proportion of their own feed was not increased, and more manure was produced, highlighting the importance of optimizing its utilization in future efforts.

GHG emission reduction of livestock production by mixed farming

Most livestock production at the household level was backyard breeding. The livestock production capacity of smallholder farms was limited because they do not have enough investment and land. The average livestock number of the OLP farms was the highest at 45.72 (pig equivalent), followed by complete CCLP farms and incomplete CCLP farms, less than 22.20.

The average GHG emission of OLP farms was 95.98 ± 77.91 $kgCO_2eq$/100 USD, and there was no significant difference between CCCLP farms and ICCLP farms (Figure 3A). From the perspective of GHG emission per unit of livestock (1 pig equivalent) (Supplementary Material), however, the CCCLP (195.90 ± 227.72 $kgCO_2eq$/pigeq) may reduce GHG emissions by 12.56% ($p < 0.05$) compared with OLP farms (Figure 3B). Feed input, manure management, and enteric fermentation were major sources of GHG emissions. Farm management and machinery were almost non-existent, and the labor force was only based on household rather than hired labor, resulting in lower total GHG emissions.[26] Assuming the slaughter weight of 100 kg for each pig, the average GHG emission from livestock production of smallholder farmers did not exceed 2.12 $kgCO_2eq$/kg carcass, which was far lower than the average level around China and the world.[27,28]

Mixed farming could effectively improve feed supply and manure recycling, thereby reducing additional GHG emissions. Farms producing more than 50% of their own feed reduced average GHG emissions by 44.79%. With the increase in the proportion of own feed, GHG emissions continued to decrease. Compared with farms whose manure could not be completely returned to the field, returning all the manures to the field (177.77 ± 207.88 kgCO2eq/pigeq) could reduce GHG emission by an average of 15.53% (Figure 3C). In terms of the livestock species, the average emission of multispecies livestock production was the highest (415.69 ± 379.74 $kgCO_2eq$/pigeq), followed by ruminants, pigs, and poultry (Figure S3A). Almost all kinds of livestock production reflected the benefits of the coupling of crop and livestock, which could effectively reduce GHG emissions by 26.21% on average. After completed coupling, GHG emissions could be reduced by 40.51% on average (Figure S3B).

GHG emission reduction of crop production by mixed farming

The area of cultivated land per household was 0.93 hm^2, and the average number of cultivated land parcels exceeded 5.41, which fully reflected the small scale of cultivated land at the level of smallholder farms in China. The average GHG emission of CCLP farmers was 239.71 ± 244.23 $kgCO_2eq$/100 USD, which was 26.13% higher than OCP farms; however, the internal differences within each of the two types of farms were not significant. (Figure 3D).

In terms of cultivated land, the average GHG emission of CCLP farms was 5305.97 ± 5050.39$kgCO_2eq/hm^2$, which was 45.10% higher than OCP farms. That of OCP (farmyard manure applied) was 2851.45 ± 3751.95 $kgCO_2eq/hm^2$, which was 28.35% lower than OCP (only synthetic fertilizer) farms (Figure 3E). The significant difference in the amount of synthetic fertilizers (especially nitrogen fertilizers) used by farms is the main reason for the difference in GHG emissions, which contributed more than 60%.[29] The average synthetic fertilizer usage of the farmers in the survey was 228.46 kgN/hm^2, similar to other related studies,[30] but higher than the recommended usage level (approximately 190 kg N/hm^2) defined by the Ministry of Agriculture, China. The OCP (farmyard manure applied) farms had the lowest fertilizer usage, 190.80 kgN/hm^2; it seemed that they realized the role of manure as a substitute for synthetic fertilizers. However, the usage of synthetic fertilizer used by CCLP farms seemed to be significantly higher, reaching 268.77 kgN/hm^2, even with the application of farmyard manure (Figure 3F). Interestingly, it seemed that as the use of farmyard manure increases, so does the use of synthetic fertilizers. Many farmers considered that more synthetic fertilizer input would result in yield,[31,32] but we did not observe such results, and this would not be achieved in the wider range,[33] since the N demand of crops was always nearly constant. Farmers did not use recommended amounts of manure as part of an integrated nutrient balance approach, rather they simply disposed of manures to land without considering the opportunity of replacing some of their synthetic fertilizers' addition.

For the production of staple grains and vegetables, rice had the highest GHG emissions (362.72 ± 185.84 $kgCO_2eq$/100 USD,1.40 ± 0.75 $kgCO_2eq$/kg, 10550.63 ± 3642.96 $kgCO_2eq/hm^2$), whether it was the unit output value, yield, or area, it reflects the same trend: rice > maize > wheat > vegetables (Figure S4). The GHG emissions of crop production in this study were almost in the low emission range in China and the world[20,34](Table S1). In particular, the GHG emission per unit area of rice was about 10% lower than the

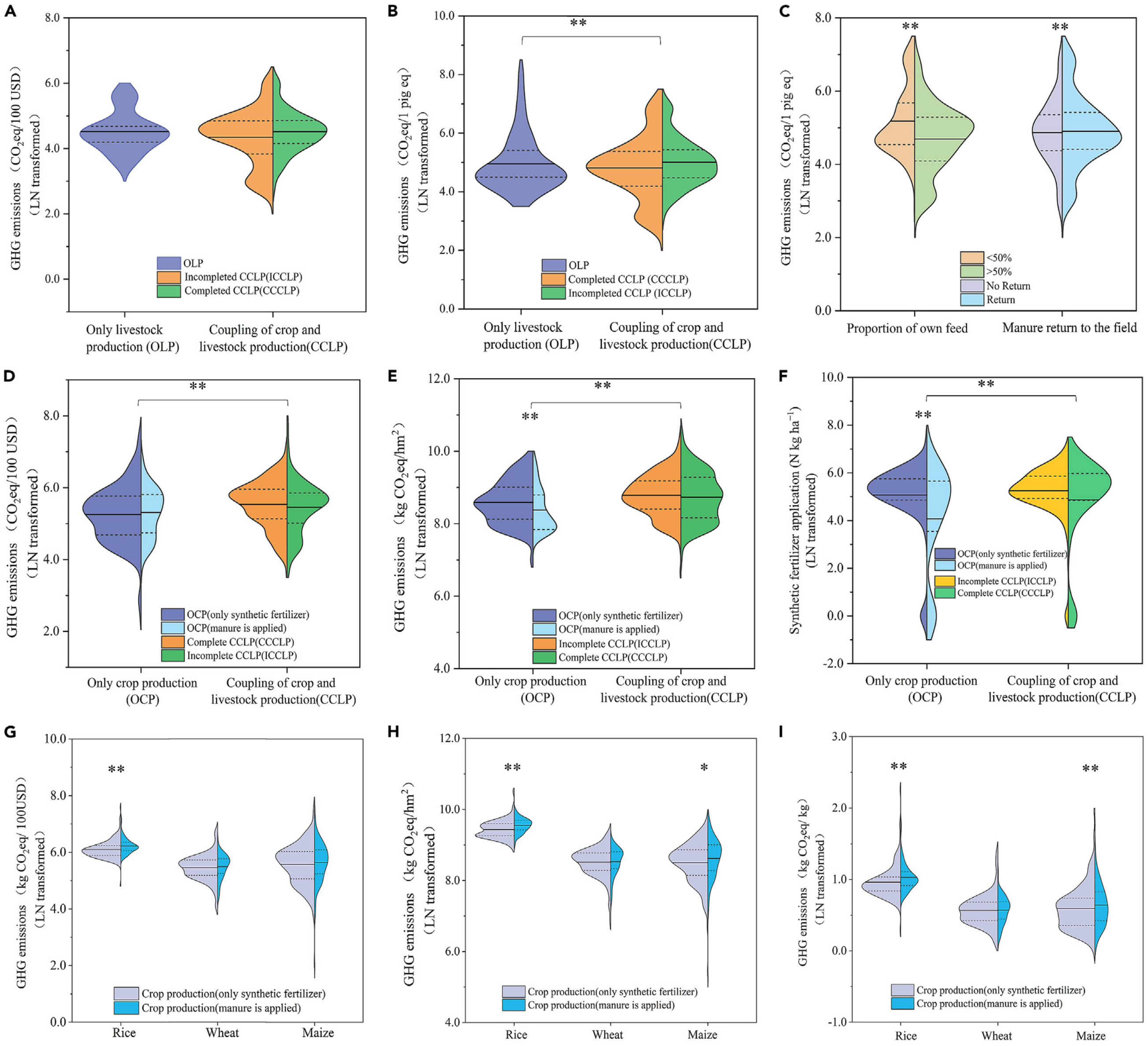

Figure 3. GHG emissions in livestock enterprises and crop enterprises

(A) GHG emissions per unit output value of OLP and CCLP farms in livestock production.

(B) GHG emissions per unit pig equivalent of OLP and CCLP farms in livestock production.

(C) Differences in GHG emissions in own feed and manure return in livestock production.

(D) GHG emissions per unit output value of OCP and CCLP farms in crop production.

(E) GHG emissions per unit area of OCP and CCLP farms in crop production.

(F) Synthetic fertilizer application of OCP and CCLP farms in crop production.

(G) GHG emissions per unit output value of OCP and CCLP farms in grain crop production.

(H) GHG emissions per unit area of OCP and CCLP farms in grain crop production.

(I) GHG emissions per unit yield of OCP and CCLP farms in grain crop production. Note: Only Livestock Production (OLP), Only Crop Production (OCP), Coupling of Crop and Livestock Production (CCLP), Incomplete Coupling of Crop and Livestock Production (ICCLP), Completed Coupling of Crop and Livestock Production (CCCLP). Significance level *0.05, **0.01, ***0.001.

national and global average (that of unit yield is lower than 19.05%), 19.34% lower than the national average for wheat (that of unit yield was lower than 17.54%) and close to the world average, 23.73% higher than the national and global average for maize (that of unit yield was higher than 56.04%), while 52.74% lower than the national average and 49.51% lower than the global average for vegetables (that of unit yield was higher

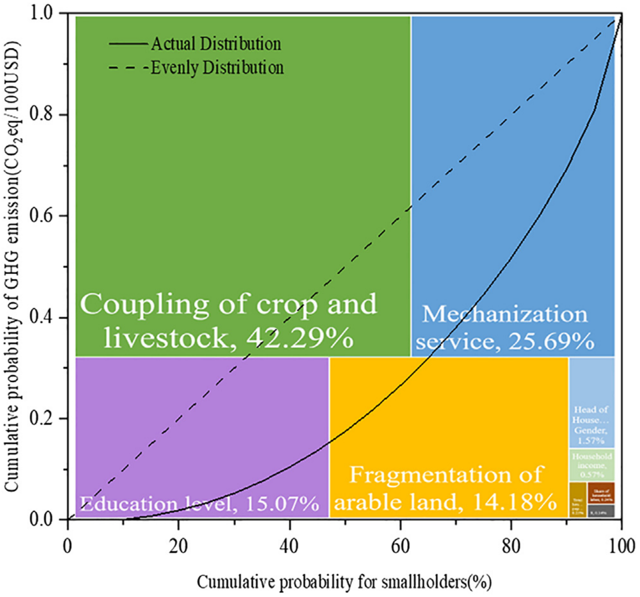

Figure 4. Inequality of GHG emissions among smallholder farms and its contributing factors

Note: Lorenz curve of GHG emissions. The diagonal is the line of perfect equality. The numbers presented in parentheses are the Gini coefficients and factors contributing to GHG emission inequality and their importance (decomposition of Gini coefficient).

than 106.45%) (Table S1 in Supplementary Data). Although the overall investment of small farms was always less than that of more specialized farms, there was still a great possibility of emission reduction. At present, most farms had a high proportion of straw returning to the field, which improved soil carbon sequestration, thereby gradually reducing the contribution of net GHG emissions, which was a good start.[28] The synthetic fertilizer usage of rice was the highest among the staple crops, with an average of 324.56 kgN/hm^2, followed by wheat and maize, which was also consistent with their GHG emission profiles (Figures S5 and S6). The average GHG emissions of CCLP farms that grow three staple crops were higher than those of OCP farms, given that application of synthetic fertilizers is mostly higher. There was another case where less synthetic fertilizer is used, and farmyard manure was not replaced proportionally, increasing total nitrogen, which also increased GHG emissions, without additional yield increase (Figures S7 and S8).

Crop production of synthetic fertilizer users and combined users (using both synthetic and manure fertilizers) was compared. We found that farmyard manure users tended to use more synthetic fertilizers, especially grain producers. The average synthetic fertilizer usage was higher than 19.97%, and GHG emissions also increased by an average of 8.73% (area), 9.90% (yield), and 14.55% (output value) under this condition, but with no observation of a significant increase in crop yield. This effect was most evident in maize farms, with an increase in GHG emissions of more than one-third (Figures S9 and S10). It was clear that farms should reduce the use of synthetic fertilizers while applying farmyard manure, which would reduce GHG emissions but maintain current production levels.

Inequality in GHG emissions among smallholder farms

At present, the essence of the issue of GHG emission fairness on the global scale is the right for development.[35] In the future, smallholder farms need to eliminate the inequality caused by low efficiency and high investment which means narrowing the development gap and achieving the same high productivity as specialized farms. The national GHG emissions inequality was 0.467 (Figure 4) when the Shapley decomposition method was used to quantify the relative contributions of the influence factors. The main contributor to the inequality of GHG emissions (kgCO_2eq/100 USD) was whether crops and livestock were coupled, with a relative contribution rate of 42.29% (Figure 4). Differences between monoculture and mixed farming resulted in increased inequality (GHG emissions (kgCO_2eq/100 USD)). Mechanization services (technology), educational attainment (farmer awareness), and arable land fragmentation (availability of contiguous cultivated land) determined more than 97% of GHG emission inequality.

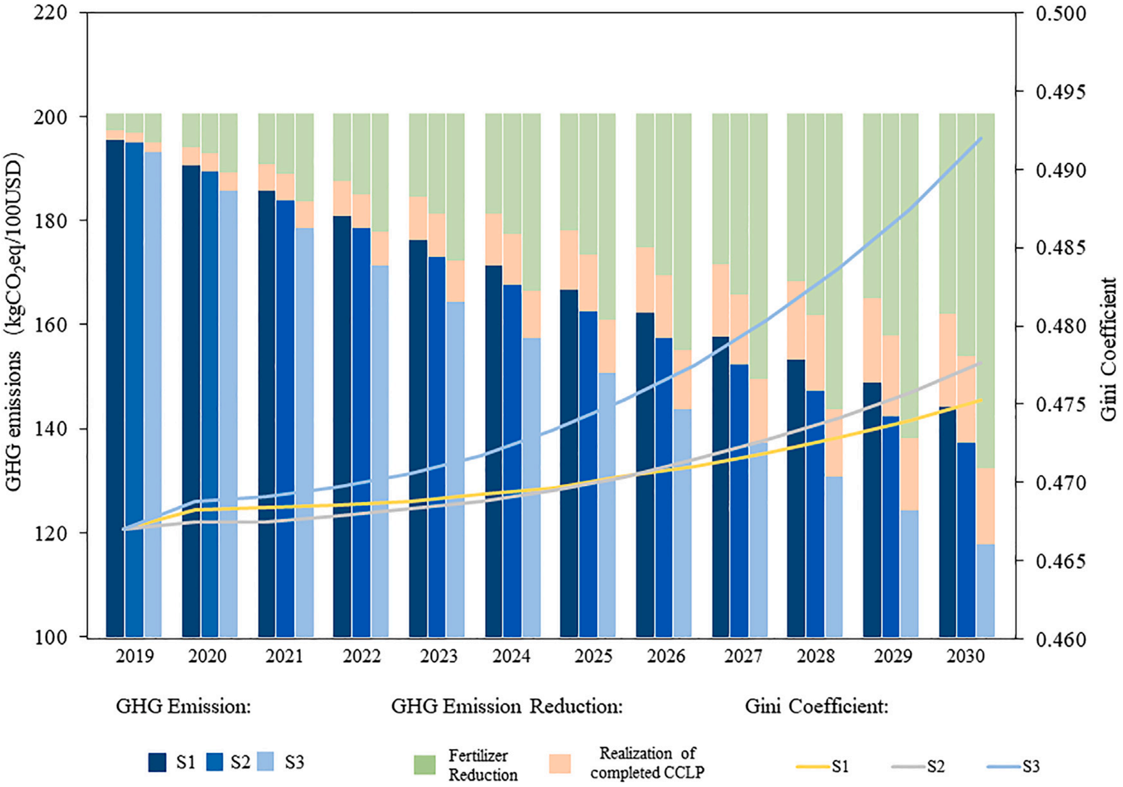

Figure 5. Changes in GHG emissions and inequality in future scenarios

Scenario simulations were carried out for the study results and possible future improvements. The simulations were for CCLP farms and were based on the production and production value in 2018. S1: Reduce the synthetic fertilizer application of CCLP farms to that of OCP farms that use farmyard manure, and promote the coupling of crop and livestock production. S2: Reduce the synthetic fertilizer application of CCLP farms to 70% of the CLP farms that use farmyard manure, and promote the coupling of crop and livestock production. S3: Reduce the synthetic fertilizer application of CCLP farms to 40% of the CLP farms that use farmyard manure, and promote the coupling of crop and livestock production. Note: Only Livestock Production (OLP), Only Crop Production (OCP), Coupling of Crop and Livestock Production (CCLP), Incomplete Coupling of Crop and Livestock Production (ICCLP), Completed Coupling of Crop and Livestock Production (CCCLP).

Scenarios for GHG emission reduction of CCLP

The reduction of synthetic fertilizers and the coupling of crop and livestock production had greatly reduced the GHG emissions of CCLP farms (Figure 5). In the S1 scenario, after finally achieving completed coupling in CCLP farms, their synthetic fertilizer levels were reduced to the level of OCP farms who replaced synthetic fertilizers with manure, their GHG emissions dropped by 28.09% and remained at 144.27 $kgCO_2eq$/100 USD. In the S2 scenario, the fertilizer continued to be reduced to 60% of the original, and the GHG emission after the completed CCLP was reduced by 31.60% and maintained at 137.24 $kgCO_2eq$/100 USD. In the S3 scenario, the fertilizer continued to be reduced to 30% of the original, and the GHG emission after the completed CCLP was reduced by 41.32% and maintained at 117.74 $kgCO_2eq$/100 USD. This proved that when all CCLP farms successfully practice complete coupling, replace synthetic fertilizers with manure, and realize the huge potential of rational use of nutrients to reduce GHG emissions, it could become a practical solution for farmers in developing countries to improve their livelihood and reduce environmental pressure. However, the GHG emission inequality of the whole farm increased slightly in all scenarios. The coupling of crop and livestock production was not limited to closing the cycle, regional-scale nutrient cycling was also worth consideration, but it must be developed based on maximizing localized nutrient cycling.[10,12]

DISCUSSION

Sustainable nutrient management for manure returning to facilitate fertilizer reduction

To improve the internal nutrient cycle of the farm, a linear plant-animal flow must be converted to a plant-animal-plant cycle. Providing endogenous feed and returning organic fertilizer to the field is the key to strengthening the coupling of crop and livestock production, and re-establishing the close spatial and temporal connection between livestock and farmland. Besides farm-related CO_2 emission reduction, this will also be beneficial to the economy and the environment by reducing nutrient losses, emissions of N_2O and NH_3, and pollution of soils, freshwaters, and marine ecosystems.[36–38] Moreover, in the context of already high, and increasing costs of synthetic fertilizers, limited and depleting resources of phosphate rocks would be another strong incentive for more use of manure and recycling both from an economic and environmental perspective. These aspects are relevant not only to small-scale farming in developed countries but also in low- and middle-income countries across the globe.[25] At present, 76% of the smallholder farms have an incompleted coupling of crop and livestock production in China and the potential for improvement is huge both here and worldwide. China's agricultural development has made remarkable achievements, but this has been accomplished mainly by the excessive application of agrosynthetics.[39] From the perspective of GHG emission of CCLP farms (8.85–498.95 $kgCO_2eq$/100 USD), GHG emission from synthetic fertilizers (mainly nitrogen fertilizers) is the largest source of total agricultural emissions in China, accounting for more than 57%.[29,40] The proportion of manure usage was quite low, 39.25% of farms used manure, among which 56.16% were vegetable producers, while the proportion of grain producers was only 27.17% (rice 31.20%, wheat 24.35%, and corn 25.97%). When crop demand for N is saturated, further use of fertilizers will lead to the runoff of excess N and increased emissions of NH_4 and N_2O exponentially with little or no additional yield gain.[29]

Manure replacement and reduction of synthetic fertilizers are important ways to reduce GHG emissions. The advantages of replacing synthetic nitrogen fertilizers with manure in terms of yield and environmental benefits have also been demonstrated. In addition, manure has advantages in improving nutrient conversion in crop-soil systems, effectively increasing soil biodiversity, especially in poor soils.[41,42] In recent years, various measures have been taken to improve nutrient management in China, such as promoting the CCLP, accurate fertilization with soil testing and formula, and reducing the use of synthetic fertilizers as much as possible, but the implementation is slow and challenging. To a large extent, this seems to be rooted in a lack of awareness of the benefits both for the economy and the environment. According to our findings, the anti-fertilizer substitution effect may occur in the process of promoting the CCLP; particularly, smallholder farms have little awareness that they may be driving greenhouse gas emissions, which needs special attention.

Improving feed self-sufficiency to promote healthy animal source food system

The products or crop residues generated on-farm are gathered and repurposed as a source of animal feed. This approach optimizes nutrient utilization by maximizing the use of available resources within the farm. We found that due to scale constraints, feed production dominated the entire GHG emissions of livestock production (78.18%, including 55.35% from purchased feed and 22.83% from own feed). Feeds are mainly composed of energy grains, such as corn, soybean meal, and wheat bran, and their production process contributes a large proportion of GHG emissions.[43] Unlike specialized single farms, smallholder farms can consider how crop and livestock production are coupled depending on their arable land, enabling subsistence farming systems to withstand the uncertainty of fluctuating input prices. The current source of feed for farms is mainly the in-province (42%–60%), followed by the domestic (26%–43%), and self-production only accounts for less than 10%.[13] Even with low dependence on international imported feed, it is still affected by the bulk market. Low prices in global markets and climate change-induced production losses are placing increasing pressure on the livelihoods of smallholder farms, and expanding the use of their own feed may offer a solution to lower economic inputs.[44]

The coupling of crop and livestock production was delivered in smallholder farms. In comparison with industrialized livestock production, it can not only reduce GHG emissions but also maintain agricultural biodiversity and cultural landscape, especially based on ruminant production.[45,46] Furthermore, it is a practice toward more sustainable production and consumption pattern that can provide a balanced and healthy diet for humans, with a rational layout of farmland, nutrient management, reduction of food waste, and dietary changes.[47] Mixed agriculture may thus provide an effective foundation for ecologically benign, socially fair, and economically viable food systems.[48,49]

Fairness-oriented policy optimization

Over the past few decades, China has made unprecedented progress in increasing income and reducing poverty. The inequality of GHG emissions has attracted more and more attention. The results suggested that the CCLP can make a major contribution to reducing the inequality of farms' agricultural production GHG emissions. However, with the continuous promotion of the CCLP, we should be on guard against the expansion of the inequity of agricultural GHG emissions. To make small farms benefit from technological progress and raise their awareness of environmental protection requires the "top-down" commitment and implementation of the government's publicity system, and extended services to smallholder farms to assist them in optimizing nutrient management. Favorable manure treatment technologies for the removal of antibiotics and heavy metals and appropriate techniques for facilitating fertilization should be applied to ensure the quality of organic fertilizers according to the local conditions.[50,51] The certification of green agricultural products could encourage farmers to increase the diversity of crop-livestock systems. Farmers' livelihoods could be enhanced with green tax rebates while GHG emissions would be reduced.[52] Only in this way can farmers transform from the traditional low-efficiency system "bottom-up" to a crop-livestock system with high productivity and high resource utilization efficiency, to reduce inequalities in yield, awareness, technology, and policy. CCLP is the best approach to reap the multiple benefits of improving production and increasing local income while meeting regional and national GHG reduction targets and more. This will not happen overnight and require continuous adjustment and advancement, but it is the only way to achieve fairness.[53–55]

Limitations of the study

The results of the sensitivity analysis were shown in Figure S11. For the 12 possible input parameters like methane in rice production, when it changed by ±10%, the result will change no more than 3%, implying that the robustness is very good. The influence of the coefficient changes of the input factors on the results was visualized in Table S2. Monte Carlo simulations are widely used to assess the uncertainty of LCA.[56,57] The sample size of the Monte Carlo simulation in this study is 5000. The mean of the simulated results was 179.10 kgCO2eq/100 USD with a 95% confidence interval (173.62 kgCO2eq/100 USD, 184.50 kgCO2eq/100 USD). The coefficient of variation (1.5%) was less than 10%, and the uncertainty of the calculation results is low.

Uncertainties exist due to random sampling error, measurement error, coverage of research objects, and the LCA model. Inevitably, there are random errors and measurement errors in the process of sampling and investigation. We adopted the principle of stratified random sampling to reduce sampling error and carry out training, on-site practice, face-to-face interviews, and four rounds of checking to reduce measurement error, as well as to ensure the accuracy of data. When determining the research scope for measuring the CCLP, we excluded aquaculture from our definition which may lead to a certain bias in the conclusion. As in previous studies, the LCA model has many uncertainties, such as model uncertainty and inventory uncertainty.[58] To reduce the model uncertainty caused by regional heterogeneity in China, we collected environmental fate coefficients according to paddy fields, dry fields, and different crop types. In addition, we conducted the GHG emissions accounting at the farm's crop scale to reduce the uncertainty of model inventory data.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2023.106798.

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AUTHOR CONTRIBUTIONS

X.X., Y.X.: Methodology, Writing - Original draft, Data curation. Y.L., J.L.: Conceptualization, Writing - Review & editing, Supervision. A.J., R.F., H.L., N.S., D.H., Z.O., E.M.: Review & editing, Supervision. L.Z., C.L., B.G., S.J., M.S.: Validation, Formal analysis.

DECLARATION OF INTERESTS

The authors declare no competing interests.

INCLUSION AND DIVERSITY

We support inclusive, diverse, and equitable conduct of research.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
The Agri-LCA models	This paper	Method S1
The localized database of parameters of environmental impacts	This paper	Tables S3–S13
The household-level data	This paper	Table S14
Software and algorithms		
SimaPro 9.0	PRé Sustainability B.V.	https://simapro.com/
STATA @15	STATA Version 15	https://www.stata.com/
Code	Authors	From the lead contact upon request

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Y. Lu (yllu@rcees.ac.cn).

Materials availability

This study did not generate new unique reagents.

Data and code availability

- Data: All the data used in this study can be obtained from the lead contact upon request.
- Code: This paper does not report any original code. However, the codes used for analysis are written in Stata, and are available from the lead contact upon request.
- Additional information: Any additional information required to reanalyse the data reported in this paper is available from the lead contact upon request.

METHOD DETAILS

Household-level data

A nationally representative survey, namely the China Rural Development Survey (CRDS) was used. Face-to-face interviews were conducted by a team of nearly 100 trained enumerators. Structured survey questionnaires were designed to elicit information by interviewing household heads or other able persons. Sample households were stratified and randomly screened and detailed information on agricultural production was collected in 2019. 10 households were randomly selected from each of the 100 sampled villages of 50 townships in 25 counties which yield a sample of 1015 households (Figure S12), representing five agricultural regions in China, including the northeast, eastern coast, southwest, northwest, and central areas.[59]

Agricultural input-output data collection process

Agricultural input-output data included the inputs of synthetic fertilizer, organic fertilizer, pesticide, irrigation water, mulching material, seeds, and utilization and treatment of straw at the crop level of each household and the inputs of animal feed and utilization and treatment of livestock and poultry manure in livestock/poultry-level of each household (Table S3). Totally, 1653 items of crop planting information including 127 crops were collected, and 787 pieces of livestock and poultry breeding information were collected, including 10 kinds of livestock and poultry. The most critical part was the collection of chemical fertilizer and pesticide ingredients. Due to space limitations, please refer to the attachment for the collection process (Method S1). Finally, 159 kinds of pesticides (Table S4) and 105 kinds of chemical fertilizers (Table S5) were collected.

Parameters of environmental impacts

We constructed a localized database of parameters of environmental impacts based on peer-reviewed Chinese studies. When collecting the parameters of environmental impacts, we take into account not only the differences caused by crop types but also the differences caused by climate and environment in the north and south of China (Tables S6–S13).

The Agri-LCA models

The Agri-LCA models were used to assess the GHG emissions of agricultural production by each sample household farm in rural China. Three types of farming systems were considered: crop farming, livestock farming, and mixed crop-livestock farming. The system boundary applied in the Agri-LCA model is from cradle to grave, i.e., the GHG emissions of the production of agricultural inputs, on-farm-based processes, and utilization and disposal of agricultural straw are included in the life cycle inventory.[60] The downstream activities including distribution, agricultural product processing, consumption, and disposal of product waste were not included. The Functional Unit (FU) was set as the production of 100 USD of agricultural products when evaluating mixed farming systems. In the evaluation of crop production, three FUs of unit value (100 USD), unit area (1 ha), and unit yield (1 kg) were used. In the evaluation of livestock production, two FUs of unit value (100 USD) and unit pig equivalent (1 pig) were applied. The life cycle inventory is a combination of inputs and emissions for all crop and livestock production (Table S14). Life cycle impact assessment results at the midpoint were conducted using the ReCiPe impact assessment method introduced by SimaPro 9.0 database manual. At the midpoint level, the climate change impact of 18 categories was focused on. Attributional LCA was employed to identify the GHG emission.

The cost-benefit ratio

The cost-benefit ratio of farms was based on the output value and actual input obtained in the survey. The calculation method (Equation 1) is as follows:

$$\text{Cost} - \text{benefit ratio} = \frac{\text{Product output value} - \text{Actual input}}{\text{Actual input}} \qquad \text{(Equation 1)}$$

Shapley decomposition for inequality of GHG emissions

The approach of Shapley Decomposition was deployed to reveal the contributions of influencing factors on the inequality of agricultural GHG emissions in rural China. The decomposition for inequality of agricultural GHG emissions was conducted by STATA @15.

Scenario simulation

The simulations were for CCLP farms based on production in 2018. As a sustainable agricultural production method, mixed agriculture provides endogenous feed for livestock through crop production, and returns livestock manure to the field to replace synthetic fertilizers to enhance nutrient cycling. It is expected that with technology advancement and policy support, the ICCLP farms will achieve completed coupling while increasing manure applications to replace synthetic fertilizer by 2030. Since synthetic fertilizer applied by the OCP (farmyard manure) farms was in line with the officially recommended amount, the nutrient management practices of OCP farms were used as a benchmark reference. The combination of the three scenarios was set so that all CCLP farms would take a complete coupling model, and farmyard manure would be applied as major fertilizer like OCP farms by 2030. Details: S1: Reduce the synthetic fertilizer application of CCLP farms to that of OCP farms that use farmyard manure, and promote the coupling of crop and livestock production. S2: Reduce the synthetic fertilizer application of CCLP farms to 70% of the CLP farms that use farmyard manure, and promote the coupling of crop and livestock production. S3: Reduce the synthetic fertilizer application of CCLP farms to 40% of the CLP farms that use farmyard manure, and promote the coupling of crop and livestock production. The calculation of the simulation was carried out by constructing the code in STATA @15. Firstly, based on the random principle and the Bootstrapping method, the target proportion of farms was selected from the ICCLP farms to achieve completed coupling, and then the target proportion of farms was selected from the CCLP farms to reduce the amount of synthetic fertilizer. The GHG emission reductions of the two were converted with reference to the reductions of the simulation targets. Each simulation was repeated in 500 iterations to obtain objectively credible values.