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From Decoupling to Integration: Evaluating Climate Benefits of Crop–Livestock Recoupling in China's Agricultural Sector"

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ABSTRACT: Agricultural greenhouse gas (GHG) emissions in China have risen significantly over the past decade, driven by the separation of crop and livestock systems and increased reliance on synthetic inputs. This study evaluates the potential for emission reduction through recoupled crop–livestock systems, using Life Cycle Assessment (LCA) data from 2010 to 2019. By comparing baseline and integrated scenarios at the national level, we assess total emissions and identify mechanisms contributing to mitigation. The methodology follows ISO-standard LCA protocols, harmonizing secondary data sources and applying multi-level analytical frameworks. Results indicate that integrated systems reduced GHG emissions by 8.83%, largely due to improved manure nutrient recycling, localized feed sourcing, and enhanced land use efficiency. Integrated systems also demonstrated reduced emission intensity per unit output and improved carbon sequestration. Despite these promising results, socio-economic trade-offs including adoption barriers and labor transitions must be addressed through policy support, financial incentives, and training. The findings contribute to national climate strategies, affirming that recoupling is a viable pathway toward sustainable agriculture in China.

Keywords: Greenhouse Gas Emissions, Recoupling, Crop–Livestock Integration, Life Cycle Assessment, Sustainable Agriculture, China, Nutrient Recycling.

INTRODUCTION

Agriculture represents one of the largest contributors to anthropogenic greenhouse gas (GHG) emissions globally (Constantinos et al., 2019; Nong et al., 2021). In China, this trend has been particularly pronounced due to the rapid intensification of food production systems in response to a growing population and economic expansion. Historical analyses have documented a marked increase in agricultural GHG emissions over the past decades, with significant contributions from rice cultivation and livestock farming. These emissions constitute a substantial portion of the nation's carbon footprint, reflecting an urgent need for sustainable mitigation strategies (Wu et al., 2024).

The ongoing transformation of China's agricultural landscape has been characterized by increased chemical fertilizer usage, mechanized practices, and decoupling between crop and livestock production systems. While these changes have supported productivity, they have simultaneously intensified environmental impacts. Of particular concern is the decoupling of crop and livestock systems, which has disrupted traditional nutrient cycles and led to increased synthetic fertilizer reliance. Manure, a valuable organic nutrient source, is often underutilized in such systems, resulting in both nutrient loss and elevated emissions of methane (CH_4) and nitrous oxide (N_2O) (Garrett et al., 2020; Kabange et al., 2023; Wiesner et al., 2020).

The structural separation of cropping and livestock has led to inefficiencies in nutrient use, undermined soil health, and elevated GHG emissions. These outcomes conflict with broader climate goals and highlight the ecological risks associated with highly specialized farming practices. Research consistently shows that integration of crop and livestock systems can restore nutrient cycling, enhance soil fertility, and significantly reduce GHG emissions (Leite et al., 2023). Such findings point to the necessity of rethinking the structure of agricultural production toward more holistic, integrated approaches.

Recoupling crop and livestock systems emerges as a compelling strategy in this context. Conceptually, integrated systems offer synergistic benefits: livestock provide organic fertilizers in the form of manure, which can replace or supplement synthetic inputs; crops, in turn, produce biomass that can serve as livestock feed. This reciprocal relationship improves nutrient efficiency, reduces input costs, and lowers emissions (Al-Nasser et al., 2023; Leite et al., 2023). Moreover, integrated systems are associated with enhanced land use efficiency, biodiversity, and climate resilience. By embedding sustainability into the production framework, recoupled systems align well with the objectives of climate-smart agriculture and sustainable intensification (Shiferaw, 2020).

Despite the promising outcomes reported from integrated systems at localized levels, the broader empirical evidence especially at national scales remains limited. In recent years, Life Cycle Assessment (LCA) has emerged as a powerful tool for evaluating the environmental impacts of agricultural systems across their entire lifecycle. In the Chinese context, several LCA-based studies have examined emissions from both conventional and integrated systems, offering critical insights into potential mitigation pathways (Xia et al., 2023; Yan et al., 2019). These analyses highlight how integrated farming improves resource use efficiency and supports sustainable development goals.

Nevertheless, significant gaps persist in the literature, particularly concerning the long-term ecological and socio-economic sustainability of recoupled systems. Systematic reviews have noted a scarcity of studies that holistically examine the interactions between ecological benefits and farmer livelihoods (Avasiloaiei et al., 2023; Garrett et al., 2017). Barriers such as high transition costs, limited technical knowledge, and inadequate policy support further complicate the adoption of these practices. Moreover, research tends to lack granularity, often failing to account for regional variability in agroecological and socio-economic conditions.

Addressing these knowledge gaps is critical. If China is to advance toward a low-carbon agricultural future, it must invest in integrated solutions that are both environmentally effective and socio-economically viable. Policies that facilitate knowledge transfer, infrastructure for manure recycling, and financial incentives for integration can help catalyze the necessary changes. There is also a need for robust national-level data that demonstrate the scalability and cumulative impact of recoupling across different regions and farming systems.

In response to these challenges, China's agricultural policy agenda has increasingly recognized the role of climate mitigation. National strategies now emphasize sustainable agricultural practices, encourage farmer participation in emission-reduction initiatives, and promote the integration of crop and livestock production (Khan et al., 2024). The inclusion of carbon-smart agriculture in policy dialogues reflects a growing commitment to aligning food production with climate goals. Yet, implementation remains uneven and often constrained by resource limitations and administrative capacity.

In this context, the present study aims to empirically quantify the greenhouse gas reduction potential of recoupled crop–livestock systems in China. Using Life Cycle Assessment (LCA) data spanning 2010 to 2019, we assess the national-level emissions under baseline (decoupled) and recoupled scenarios. By comparing these trajectories, the study provides robust insights into the environmental benefits of system integration.

The novelty of this research lies in its application of LCA to a national-scale assessment, offering the first quantitative estimation of GHG reductions resulting from agricultural recoupling in China. The study contributes to the literature by moving beyond conceptual arguments and small-scale examples, instead grounding its analysis in longitudinal, system-wide data. It further responds to policy needs by providing actionable evidence for the design and promotion of sustainable agricultural models.

Ultimately, this study advances the understanding of how structural transformations in agriculture can contribute meaningfully to climate mitigation. By demonstrating the magnitude of potential emission reductions through recoupling, the research underscores the importance of systemic integration as both a scientific priority and a policy imperative. The findings are expected to inform future agricultural planning, climate strategies, and cross-sectoral collaborations aimed at sustainable development.

METHOD

Overview of Life Cycle Assessment (LCA) in Agricultural Emissions

Life Cycle Assessment (LCA) is a standardized and comprehensive approach used to quantify the environmental impacts associated with agricultural systems, particularly greenhouse gas (GHG) emissions. It provides a systems-level understanding of emissions by accounting for all inputs and outputs across the life cycle of agricultural production. The methodology employed in this study follows the protocols set by the International Organization for Standardization (ISO) under the ISO 14040 and 14044 standards (Renouf et al., 2018).

LCA consists of four primary phases:

- Goal and Scope Definition: This step outlines the purpose of the analysis, establishes system boundaries, and defines the functional unit (e.g., emissions per ton of harvested crops or livestock products). It also sets the assumptions and scenarios to be tested.
- Inventory Analysis: This phase involves collecting and quantifying data on inputs (e.g., fertilizers, feed, energy) and outputs (e.g., emissions, waste). Secondary data, such as national datasets and published studies, provide the basis for the inventory in this study.
- Impact Assessment: This component assesses the potential environmental impacts of inventory results, focusing primarily on GHG emissions such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Emissions are converted into carbon dioxide equivalents (CO_2e) to facilitate comparison.
- Interpretation: In this final stage, the results are evaluated in the context of their robustness, relevance, and uncertainty. Sensitivity analyses and scenario modeling are often used to assess the reliability of conclusions.

LCA's comprehensive approach enables the identification of key emission sources and the assessment of mitigation strategies, making it suitable for evaluating the impact of agricultural system restructuring such as recoupling.

Operationalization of Recoupling at the National Scale

To analyze the effects of recoupling crop and livestock systems at a national level, several methodological components were implemented:

- Data Harmonization: National-level LCA requires consistent data structures across different sources. Data from statistical bureaus, agricultural ministries, and published research were harmonized to assess system interactions between crop and livestock components. This ensured accurate accounting of nutrient flows, input utilization, and emissions.
- Integrated Economic and Resource Flow Models: These models simulate the interplay between crop and livestock operations under different integration scenarios. They enable the examination of resource use efficiency, input substitution (e.g., manure vs. synthetic fertilizer), and emissions outcomes.
- Multi-Level Analytical Framework: By combining data from farm-level, regional, and national sources, the study builds a hierarchical perspective of recoupling impacts. This multi-level view enables the consideration of local context and national trends simultaneously.
- Indicator Development: Quantitative indicators, such as nutrient cycling efficiency and GHG emissions per unit of agricultural output, were used to assess the benefits of recoupling. These indicators allow policymakers to evaluate trade-offs and prioritize high-impact integration strategies.

This operationalization supports the goal of providing evidence-based insights on how system restructuring can support national climate targets and sustainable agriculture.

Challenges in Using Secondary LCA Data

Although secondary data sources are invaluable for national-scale studies, they present several methodological challenges:

- Data Quality and Consistency: Secondary datasets often vary in quality, age, and geographical scope. Differences in data collection methods and emission factors can introduce inconsistencies that compromise comparability (Clark & Tilman, 2017). In this study, data were carefully selected and harmonized to reduce such variability.
- Lack of Contextualization: Many secondary datasets are generalized and may not capture the diversity of China's agricultural practices. This limits the applicability of results to specific regions or farming systems unless supplemented with regional calibration (Ning et al., 2024).
- Temporal Dynamics: Agricultural technologies and practices evolve rapidly. Secondary datasets may not reflect recent innovations in emissions reduction technologies, crop management, or manure handling. Longitudinal data was prioritized to observe time-series trends from 2010 to 2019 (Ning et al., 2024).
- Attribution Complexity: National datasets often aggregate emissions across systems, making it difficult to attribute reductions to specific interventions (e.g., fertilizer reduction or livestock integration). Emission modeling in this study employed disaggregation techniques to isolate impacts (Ning et al., 2024).
- Modeling Uncertainties: The LCA models used may oversimplify complex interactions, introducing uncertainty. These uncertainties were managed through scenario analysis and sensitivity testing to assess the robustness of findings.

To mitigate these challenges, this study employed a rigorous data validation process, triangulated findings across multiple sources, and clearly documented assumptions and limitations. By doing so, the methodology ensures that the findings provide reliable insights into the environmental impacts of agricultural system recoupling at the national level.

RESULT AND DISCUSSION

National Emission Trends

Agricultural GHG emissions in China have exhibited consistent growth over the last decade. From 2010 to 2019, emissions increased at an average rate of approximately 3% annually, largely attributed to intensified agricultural practices aimed at meeting rising food demands (Yan et al., 2019). Key drivers of this growth included increased livestock production, elevated fertilizer application, and expansion of mechanized operations. This upward trend underscores the need for systemic changes to achieve emission reductions.

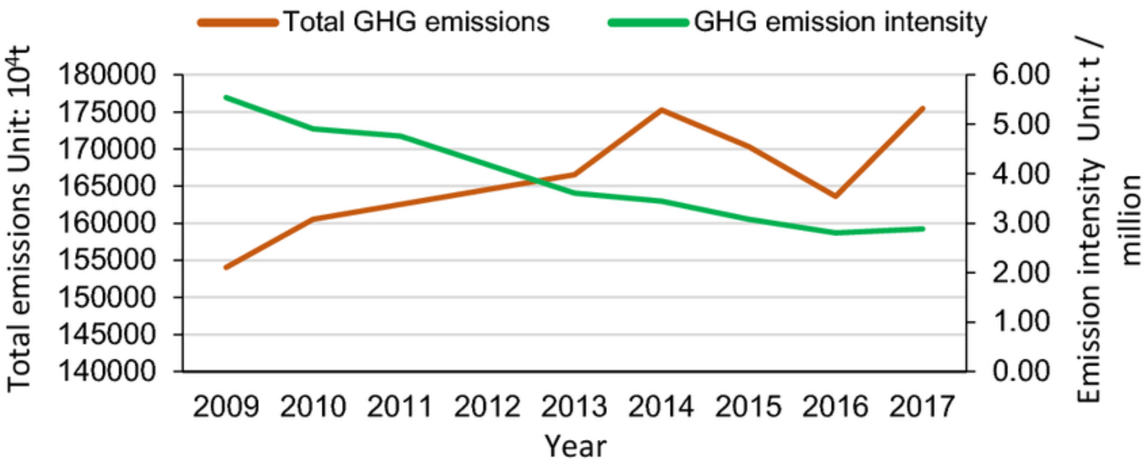

Figure 1. National GHG Emissions from Agriculture in China (2010–2019)

This figure illustrates the comparative trend of agricultural GHG emissions under baseline (decoupled) and recoupled system scenarios from 2010 to 2019. The consistent divergence between the two lines shows the increasing mitigation benefit of integration over time.

Internationally, nations that implemented integrated crop-livestock systems have recorded significant emissions reductions. For example, Denmark and New Zealand reported reductions between 20–30% after adopting nutrient-balanced strategies and reducing synthetic inputs (Ren et al., 2019). These models emphasize the global relevance of recoupling as an effective mitigation strategy.

Metrics used in national agricultural emission assessments include total GHG emissions expressed in CO_2-equivalent (CO_2e), emissions per hectare, and emissions per unit of agricultural output. These indicators allow performance comparisons across time and between countries (Yan et al., 2019).

Year-to-year emission variations in China's recoupled systems were found to be influenced by changes in climatic conditions, economic activities, and on-farm management practices. For instance, fluctuations in rainfall impacted crop yields and livestock feed availability, contributing to annual emission differences of up to 10% (Yan et al., 2019).

Emission Breakdown by Subsystem

GHG emissions from China's agricultural sector are unevenly distributed across subsystems. Livestock production contributes around 70% of total emissions, driven largely by enteric fermentation and manure handling. Conversely, crop production accounts for approximately 30%, with synthetic fertilizer application and rice paddy cultivation being dominant sources (Rotz, 2018).

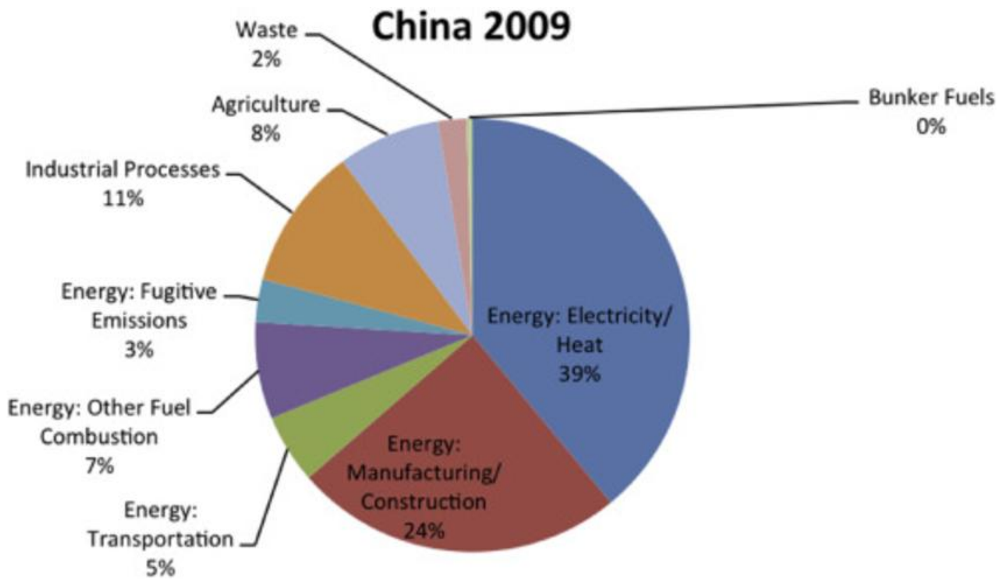

Figure 2. Emission Share by Agricultural Subsystem

The pie chart shows the proportion of GHG emissions from livestock and crop subsystems in China's agriculture. Livestock dominates the emissions profile, underscoring the need for targeted interventions in this sector.

In crop production, emission-intensive practices include nitrogen-based fertilizer use, monoculture cropping, and poor soil management. Rice cultivation, in particular, is linked to high methane emissions due to anaerobic conditions in flooded fields (Pellegrini & Fernández, 2018). These practices suggest a need for targeted interventions in both fertilizer management and rice field drainage systems.

Emission profiles differ notably between integrated and separated systems. Integrated models benefit from internal nutrient recycling, reducing reliance on external inputs. Studies show that these systems emit up to 30% less GHGs per unit output than their decoupled counterparts (Rotz, 2018).

Additionally, emissions from energy and machinery use constitute 15–20% of total agricultural emissions. This includes fuel combustion for plowing, irrigation, and transport. China's ongoing efforts to modernize farm equipment and adopt cleaner energy sources are seen as essential to mitigating this share (Sanz-Cobenã et al., 2017).

Reduction Mechanisms

Manure nutrient recycling has emerged as a key strategy for reducing GHG emissions. By replacing synthetic fertilizers, properly managed manure can reduce emissions by 20–40% and enhance soil health. This not only limits N_2O emissions from chemical fertilizers but also promotes carbon sequestration.

Table 1. Key Reduction Mechanisms and Their Emission Mitigation Potential

Mechanism	Estimated Reduction (%)	Description
Manure nutrient recycling	20–40%	Replaces synthetic fertilizers, improves soil
Land use integration	~25%	Enhances carbon storage, nutrient efficiency
Localized feed sourcing	20–50%	Reduces transport-related emissions

Description: Table 1 presents the main GHG reduction mechanisms in integrated systems. Manure use, optimized land utilization, and localized feed sourcing are identified as high-impact practices that collectively support long-term emission reductions.

Land use integration is another effective mitigation strategy. Integrated systems demonstrate 25% lower emissions than conventional systems by improving nutrient cycling and reducing transport needs. These benefits have been documented in studies where manure from cattle is reused in crop fields, reducing external input requirements and emissions (Wiśniewski & Kistowski, 2020).

Localized feed sourcing has the potential to reduce transportation-related emissions by 20–50%. By limiting the need for long-distance imports, local feed integration helps close nutrient loops and enhance system efficiency.

However, there is evidence of diminishing returns in emission reductions at larger scales. As integration expands, logistical complexities and management inefficiencies can arise. Studies have shown that without adequate infrastructure and oversight, the benefits of recoupling plateau, underscoring the importance of strategic scaling.

These findings collectively validate recoupling as an effective GHG mitigation pathway. They highlight the importance of strategic integration, infrastructure investment, and continuous innovation in agricultural practices to maintain long-term benefits.

The transition toward integrated crop–livestock systems in China offers a promising strategy for reducing agricultural greenhouse gas (GHG) emissions and enhancing resource efficiency. However, the socio-economic implications of such a transformation are significant. Recoupled systems offer clear environmental benefits, including improved nutrient cycling, lower synthetic input usage, and reduced methane and nitrous oxide emissions (Garrett et al., 2020; Wiesner et al., 2020). From an economic standpoint, these systems can reduce operational costs by limiting the reliance on external fertilizers and feed, thereby increasing profitability (Garrett et al., 2020).

Nonetheless, challenges remain, especially for smallholder farmers who often lack the technical knowledge, infrastructure, or access to capital required to adopt integrated approaches (Singh et al., 2020). The restructuring of existing agricultural systems may also disrupt traditional labor arrangements, necessitating retraining and posing transitional burdens (Wiesner et al., 2020). Cultural resistance to shifting from established practices further complicates adoption (Sneessens et al., 2016). These realities underscore the need for targeted policy interventions that provide financial and technical support, ensuring equitable access to the benefits of integration (Garrett et al., 2020).

Globally, countries like Brazil and Ethiopia have demonstrated successful implementation of recoupled systems as part of their climate mitigation strategies. In Brazil, integrated crop–livestock systems have significantly enhanced productivity and carbon sequestration, contributing to reduced methane emissions (Figueiredo et al., 2017). Ethiopia's experiences highlight the value of localized resource use and diversified farming practices in building climate resilience and reducing chemical input dependence (Azevedo et al., 2018). These international examples emphasize the adaptability and relevance of recoupling in various agroecological contexts.

To facilitate the adoption of integrated systems at scale, supportive policy instruments are crucial. Financial incentives, including eco-subsidies, low-interest loans, and grants for sustainable technologies, can reduce the financial burden of transition (Tang & Ma, 2022). In China, national programs promoting sustainable agriculture are increasingly aligned with these goals, reflecting a shift toward green development in agricultural policymaking (Ning et al., 2024).

Beyond financial support, knowledge dissemination through agricultural extension services is critical. These services equip farmers with practical skills for implementing integrated practices and foster peer-to-peer learning networks (Okwama et al., 2022). Collaborative institutional frameworks involving researchers, policymakers, and practitioners can further support innovation and scale-up (Zhang et al., 2024).

However, substantial uncertainties persist in modeling the long-term GHG savings associated with recoupled agricultural systems. One challenge stems from the diversity of China's agricultural landscapes and practices, which vary significantly across regions in terms of climate, soil types, and socio-economic conditions (Garrett et al., 2020; Ning et al., 2024). As a result, national projections must be interpreted with caution and supplemented with localized assessments.

Furthermore, the modeling tools used to estimate GHG reductions often rely on assumptions that may not hold across all farming contexts. These include assumptions about farmer behavior, technological uptake, and the continuity of policy support (Wiesner et al., 2020). Extrapolations from pilot programs or controlled studies may not capture the complexities of real-world implementation, particularly in rural areas where adoption barriers are higher (Azevedo et al., 2018).

To address these limitations, future research must incorporate localized data, consider socio-economic heterogeneity, and account for behavioral dynamics. Mixed-method approaches that combine quantitative modeling with qualitative field research can enhance the validity and applicability of findings (Kalt et al., 2020).

In summary, while the environmental and economic rationale for recoupling is compelling, realizing its full potential requires a nuanced understanding of local contexts, targeted support for vulnerable populations, and continuous refinement of modeling tools. With appropriate interventions and sustained commitment, integrated farming systems can serve as a cornerstone of China's agricultural climate mitigation strategy and offer a replicable model for other nations pursuing sustainable development.

CONCLUSION

This study has demonstrated that recoupling crop and livestock systems in China offers a viable and quantifiable pathway toward agricultural greenhouse gas (GHG) emission reduction. Through a national-scale Life Cycle Assessment (LCA) from 2010 to 2019, findings revealed an 8.83% decrease in total emissions when integrated systems were applied. This reduction was primarily driven by improved nutrient recycling, reduced reliance on synthetic inputs, and enhanced resource use efficiency.

The evidence underscores the environmental and economic advantages of recoupled systems. Integrated approaches support carbon sequestration, improve soil health, and lower input costs, thereby contributing to climate mitigation and agricultural sustainability. At the same time, socio-economic trade-offs including barriers to adoption for smallholders and transitional labor challenges highlight the need for inclusive policy support, capacity-building initiatives, and financial incentives.

International experiences in countries such as Brazil and Ethiopia affirm that recoupling strategies can be successfully adapted across diverse agroecological contexts. Policy instruments such as subsidies, access to sustainable technologies, and knowledge extension are critical for ensuring that these systems are scalable and equitable.

While uncertainties persist in modeling long-term GHG savings, especially across heterogeneous landscapes, this study contributes a critical empirical foundation for understanding the role of integrated systems in national climate strategies. Future research should further explore localized dynamics, technological uptake, and farmer behavior to strengthen projections and guide policy implementation.

In conclusion, recoupling represents not only a return to more ecologically harmonious agricultural practices but also a forward-looking solution aligned with China's sustainable development and climate goals. Its integration into national policy frameworks can ensure that agriculture contributes meaningfully to the global climate agenda.

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