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Energy Use and Greenhouse Gas Emissions from Chemical Fertilizer Application in Crop Production in the Middle Reach of Yangtze River After Implementing Zero-Growth Actions

Lu Chen ^{1,2}, Fangbo Cao ^{1,2,3}, Jiana Chen ^{1,2,3,*} and Min Huang ^{1,2,3,*}

¹ Rice and Product Ecophysiology, Key Laboratory of Ministry of Education for Crop Physiology and Molecular Biology, Hunan Agricultural University, Changsha 410128, China; lchen_rpe@163.com (L.C.); fangbocao@hunau.edu.cn (F.C.)

² Yuelushan Laboratory, Changsha 410128, China

³ National Engineering Research Center of Rice, Changsha 410128, China

* Corresponding author. E-mail: jianachen@hunau.edu.cn (J.C.); mhuang@hunau.edu.cn (M.H.)

Received: 2 July 2026; Revised: 8 July 2026; Accepted: 30 September 2026; Available online: 16 October 2026

ABSTRACT: Minimizing energy inputs and greenhouse gas (GHG) emissions is essential for achieving sustainable crop production. This study analyzed changes in energy use and GHG emissions associated with chemical fertilizer application in crop production in the middle reach of the Yangtze River from 2014 (one year before the implementation of zero-growth actions) to 2022. Results revealed significant reductions in both total energy inputs and energy inputs per unit area from chemical fertilizers, with annual declines of 10.72 PJ and 0.48 GJ·ha⁻¹, respectively. The energy use efficiency of chemical fertilizer application increased significantly at an annual rate of 0.40. Concurrently, total GHG emissions, emissions per unit area, and emissions per unit of energy input associated with chemical fertilizer application decreased significantly, with respective annual reductions of 0.31×10^7 kg, 14.08 kg·ha⁻¹, and 0.26 kg·GJ⁻¹. These reductions were primarily due to decreases in inputs of straight nitrogen (N), phosphorus (P), and potassium (K) fertilizers, rather than changes in compound fertilizers, as the input of compound fertilizers saw a significant increase. This study suggests that zero-growth actions, with the substitution of compound fertilizers for straight N, P, and K fertilizers as a key approach, are associated with lower energy inputs and GHG emissions from chemical fertilizer application in the middle reach of the Yangtze River. However, given the descriptive nature of this analysis, these findings should be interpreted as correlational, and further quasi-experimental studies are warranted to confirm causality.

Keywords: Chemical fertilizers; Energy inputs; Greenhouse gas emissions; Sustainable crop production

1. Introduction

Energy is a fundamental component of crop production and plays a pivotal role in driving the economic development of societies and nations [1]. Energy inputs in crop production can be categorized into direct inputs, such as diesel fuel, electricity, and human labor, and indirect inputs, including the energy used in the manufacture of agricultural machinery and agrochemicals [2]. Since most of these inputs are derived from non-renewable energy sources, it is essential to use energy efficiently and reduce energy inputs in crop production to ensure sustainable development. Moreover, energy use in agriculture is one of the major contributors to greenhouse gas (GHG) emissions, including both CO₂ and non-CO₂ gases [3], which exacerbate global warming and pose severe risks to ecosystems, human health, and socio-economic progress [4]. These factors further emphasize the critical need to minimize energy inputs in crop production.

To address the rising food demand driven by population growth and economic development, intensive farming practices have become increasingly prevalent in global crop production [5]. However, these practices have substantially increased energy inputs, mainly due to the heightened use of machinery and agrochemicals, such as fertilizers and pesticides [6], resulting in significant environmental challenges, including GHG emissions [7]. Consequently, there is an urgent need to implement new policies and adopt innovative practices to reduce energy inputs and ensure the sustainability of intensive crop production systems [8].

China is home to 22% of the global population but accounts for only 9% of the world's arable land [9]. The development of intensive crop production systems has been crucial for maintaining food security in the country. However, these systems consume approximately 30% of the world's chemical fertilizers and pesticides, and this overuse—mainly due to a lack of knowledge-based management practices—has caused substantial environmental degradation and posed risks to human health [10]. In recent years, the Chinese government has placed greater emphasis on environmental protection and implemented several policies aimed at reducing the use of chemical fertilizers and pesticides in intensive crop production systems. Notably, in 2015, the Ministry of Agriculture and Rural Affairs of China launched the first nationwide zero-growth policy for chemical fertilizers, aiming to limit the annual growth rate of fertilizer use to less than 1% from 2015 to 2019 and achieve zero growth for major crops by 2020 [11].

Due to its favorable light and thermal conditions, the middle reach of the Yangtze River constitutes one of China's most intensive crop production areas. In 2012, the three provinces comprising this region—Hunan, Jiangxi, and Hubei—ranked first, second, and fourth, respectively, among China's 31 provinces in terms of the multiple cropping index [12]. Together, they account for nearly 12% of the country's total crop output and more than 30% of its rice production [13]. Against this backdrop, this study examines trends in energy inputs, energy use efficiency, and greenhouse gas (GHG) emissions from chemical fertilizer application in this region over the period 2014–2022. Although several years have elapsed since the policy's implementation, an assessment of its subsequent environmental and energy implications in this highly intensive agricultural zone remains lacking. This study aimed to assess changes in energy inputs and GHG emissions following the implementation of zero-growth actions for chemical fertilizers in 2015.

2. Materials and Methods

2.1. Site Description

The study region, *i.e.*, the middle reach of the Yangtze River, spans the provinces of Hubei, Hunan, and Jiangxi. It lies between latitudes 24°29' N and 33°20' N and longitudes 108°21' E and 118°29' E, covering a total area of 56.5×10^4 km². This region experiences a subtropical monsoon climate. A wide variety of crops are grown here, including cereals, beans, tubers, oil crops, cotton, ramie, sugarcane, tobacco, vegetables, fruits, and tea. The main chemical fertilizers used in crop production within this region are nitrogen (N), phosphorus (P), potassium (K), and compound fertilizers.

2.2. Data Collection and Calculation

This study covered a nine-year period from 2014 to 2022. The starting year was chosen as the year prior to the implementation of zero-growth actions, while the ending year was selected based on the availability of current data. Data on the sowing area for each crop type, the inputs of straight N, P, and K fertilizers as well as compound fertilizers, and the crop production for each crop type in Hubei, Hunan, and Jiangxi provinces in each year were sourced from the online database of the National Bureau of Statistics of China (<https://data.stats.gov.cn>, accessed on 15 February 2026). The energy output for each crop type was calculated by multiplying its annual production by a specific energy factor. The energy factors used were 14.7 MJ·eq·kg⁻¹ for cereals and beans, 3.6 MJ·eq·kg⁻¹ for tubers, 25 MJ·eq·kg⁻¹ for oil crops, 11.8 MJ·eq·kg⁻¹ for cotton, 18.5 MJ·eq·kg⁻¹ for ramie, 1.2 MJ·eq·kg⁻¹ for sugarcane, 0.8 MJ·eq·kg⁻¹ for tobacco, vegetables, and tea, and 1.9 MJ·eq·kg⁻¹ for fruits [2,14]. The total sowing area, total inputs of straight N, P, and K fertilizers as well as compound fertilizers, and total energy outputs for crop production in the middle reach of the Yangtze River in each year were obtained by summing the data from Hubei, Hunan, and Jiangxi provinces.

The energy input for each fertilizer type was calculated by multiplying its input by a specific energy factor. The energy factors used were 66.14 MJ·eq·kg⁻¹ for straight N fertilizers, 12.44 MJ·eq·kg⁻¹ for straight P fertilizers, 11.15 MJ·eq·kg⁻¹ for straight K fertilizers, and 12.83 MJ·eq·kg⁻¹ for compound fertilizers [2]. The total energy inputs for chemical fertilizer application in crop production in the middle reach of the Yangtze River each year were obtained by summing the energy inputs for each fertilizer type across Hubei, Hunan, and Jiangxi provinces. The energy input per unit area of chemical fertilizer application was calculated by dividing the total energy input by the total sowing area. The energy use efficiency of chemical fertilizer application was calculated by dividing the total energy output from crop production by the total energy input from chemical fertilizer application.

The GHG emissions from each fertilizer type were calculated by multiplying its input by a corresponding emission factor. The emission factors used were 1.526 kg CO₂ eq·kg⁻¹ for straight N fertilizers, 1.631 kg CO₂ eq·kg⁻¹ for straight P fertilizers, 0.6545 kg CO₂ eq·kg⁻¹ for straight K fertilizers, and 1.772 kg CO₂ eq·kg⁻¹ for compound fertilizers [7]. The total GHG emissions from chemical fertilizer application in crop production in the middle reach of the Yangtze River each year were calculated by summing the emissions from each fertilizer type across Hubei, Hunan, and Jiangxi provinces. The GHG emissions per unit area were calculated by dividing the total GHG emissions from fertilizer application by the total sowing area. The GHG emissions per unit energy input were calculated by dividing the total GHG emissions from chemical fertilizer application by the total energy input from chemical fertilizer application.

2.3. Statistical Analysis

Linear regression was used to analyze time trends in the changes of total sowing area, total inputs of straight N, P, and K fertilizers as well as compound fertilizers, and total energy outputs in crop production in the middle reach of the Yangtze River from 2014 to 2022 (Statistix 8.0, Analytical Software Co., Tallahassee, FL, USA). Additionally, it assessed total energy inputs, energy inputs per unit area, energy use efficiency, total GHG emissions, GHG emissions per unit area, and GHG emissions per unit energy output from chemical fertilizer application in crop production in the same region over the same period.

3. Results

No significant change was observed in the total sowing area from 2014 to 2022 (Figure 1A). However, the total inputs of straight N, P, and K fertilizers declined during this period, with annual reductions of 14.83×10^7 kg, 6.34×10^7 kg, and 3.73×10^7 kg, respectively (Figure 1B–D). In contrast, the total inputs of compound fertilizers showed a significant increase, rising by 2.51×10^7 kg per year from 2014 to 2022

(Figure 1E). Total energy outputs from crop production also significantly increased over this period, with an annual growth rate of 9.55 PJ (Figure 1F).

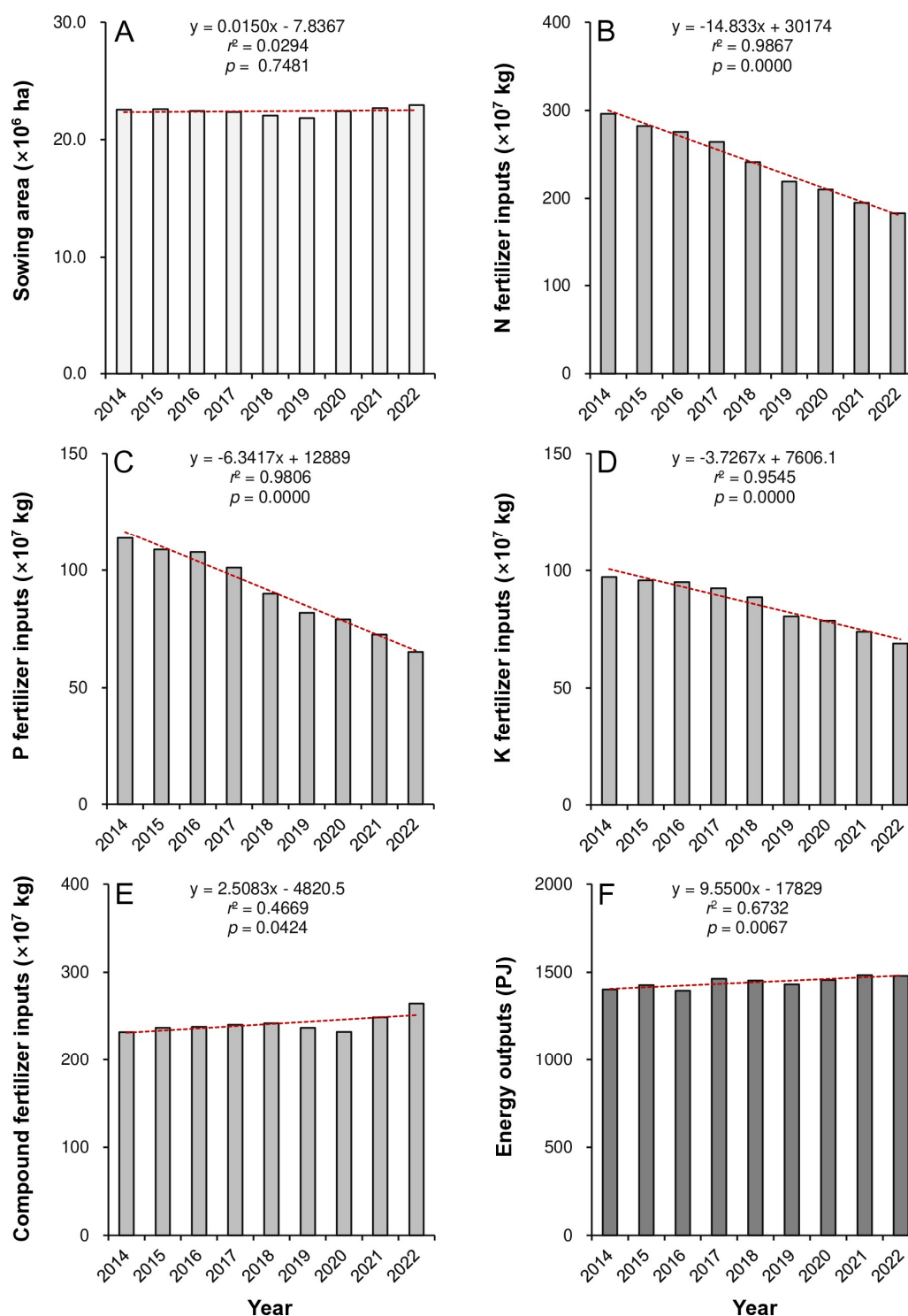


Figure 1. Total sowing area (A), total inputs of straight nitrogen (N), phosphorus (P), and potassium (K), as well as compound fertilizers (B–E), and total energy outputs (F) of crop production in the middle reach of the Yangtze River from 2014 to 2022.

Total energy inputs from chemical fertilizer application significantly decreased at a rate of 10.72 PJ per year from 2014 to 2022 (Figure 2A). Energy inputs per unit area of chemical fertilizer application also showed a significant decline during this period, with an annual decrease of $0.48 \text{ GJ} \cdot \text{ha}^{-1}$ (Figure 2B). There

was a significant improvement in the energy use efficiency of chemical fertilizer application, increasing by 0.40 per year from 2014 to 2022 (Figure 2C).

Total GHG emissions from chemical fertilizer application significantly decreased from 2014 to 2022, with an annual reduction of 0.31×10^7 kg (Figure 3A). GHG emissions per unit area also declined significantly during this period, with a yearly decrease of $14.08 \text{ kg} \cdot \text{ha}^{-1}$ (Figure 3B). GHG emissions per unit energy input from chemical fertilizer application decreased at a rate of $0.26 \text{ kg} \cdot \text{GJ}^{-1}$ per year from 2014 to 2022 (Figure 3C).

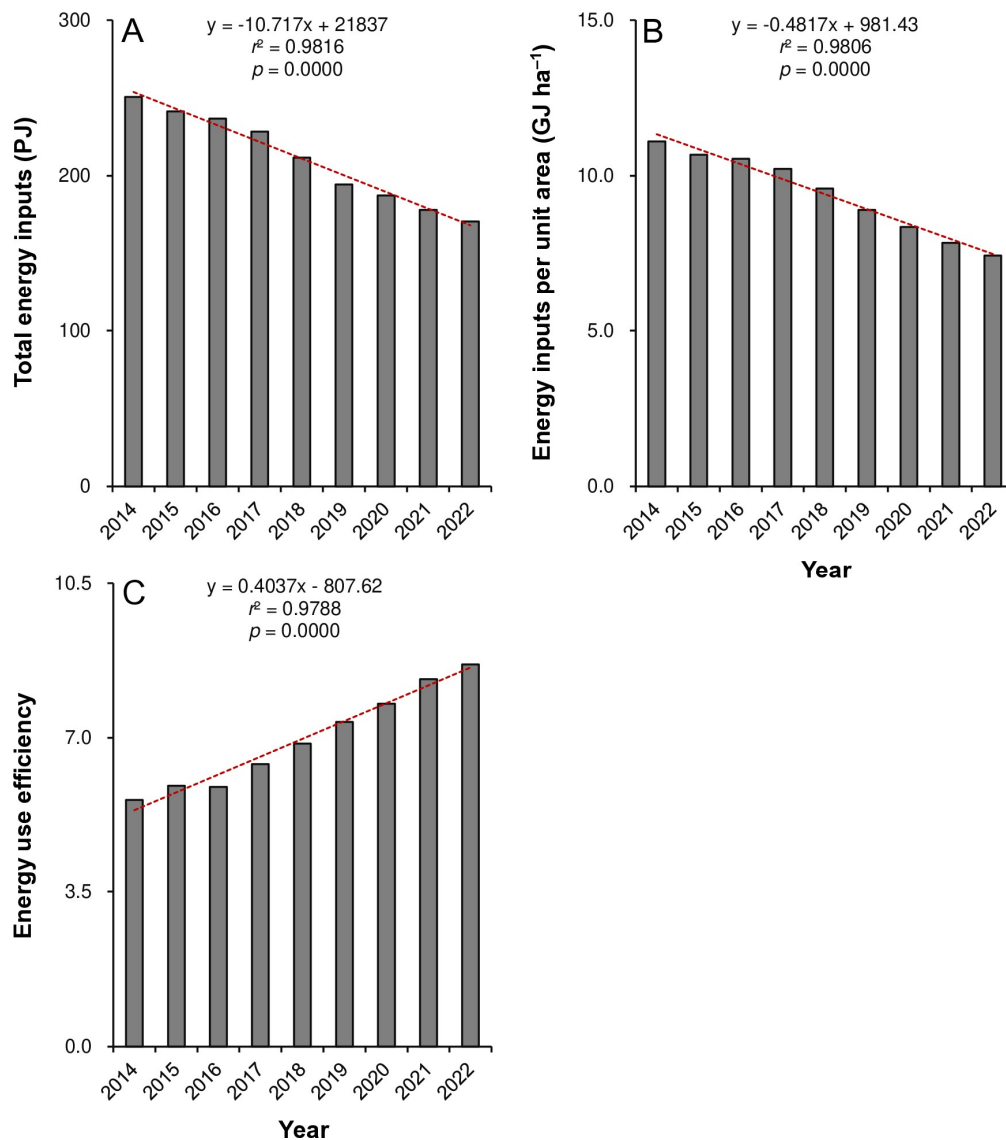


Figure 2. Total energy inputs (A), energy inputs per unit area (B), and energy use efficiency (C) of chemical fertilizer application in crop production in the middle reach of the Yangtze River from 2014 to 2022.

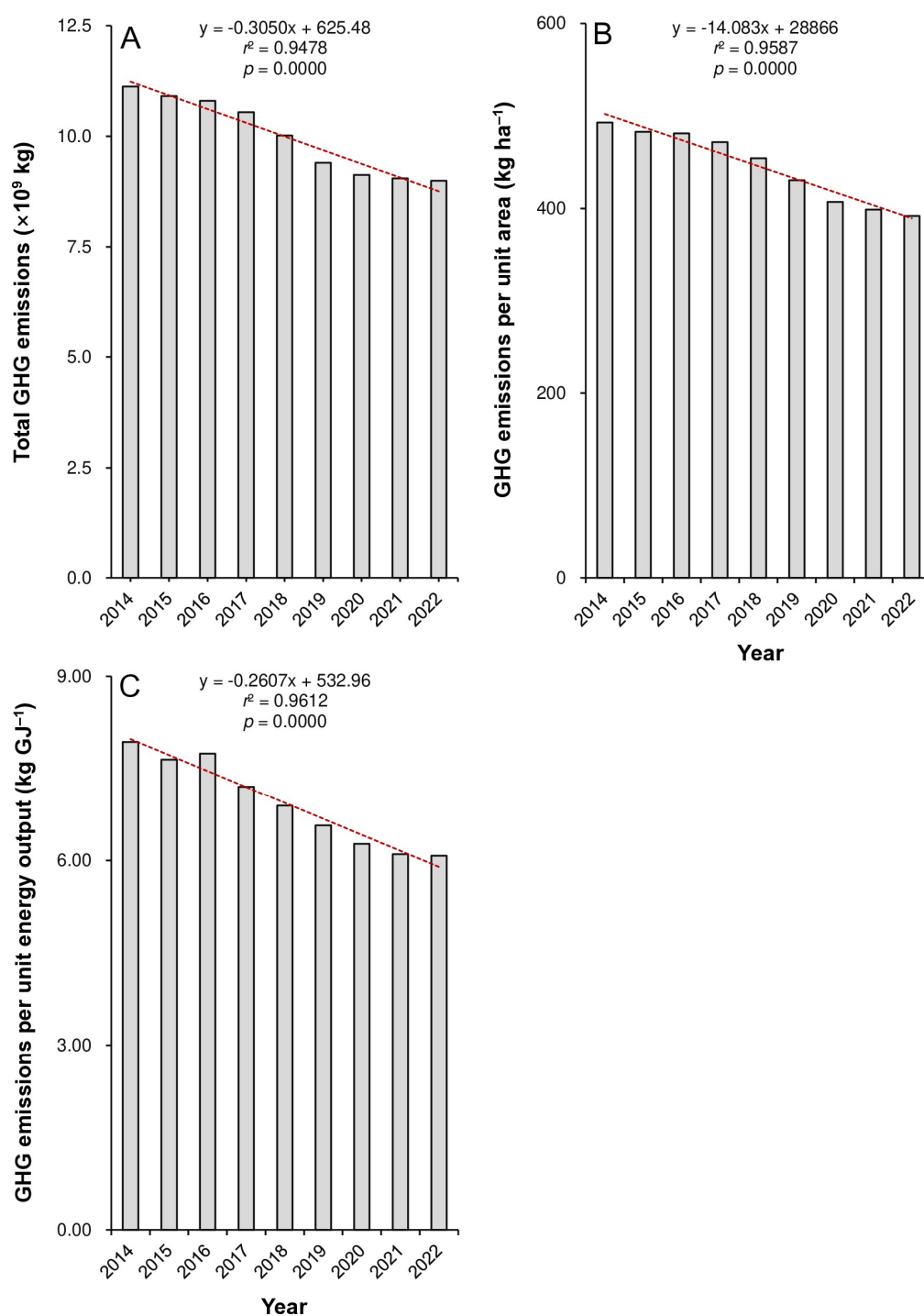


Figure 3. Total greenhouse gas (GHG) emissions (A), GHG emissions per unit area (B), and GHG emissions per unit energy output (C) from chemical fertilizer application in crop production in the middle reach of the Yangtze River from 2014 to 2022.

4. Discussion

This study shows an observed reduction in total energy inputs from chemical fertilizer application in the middle reach of the Yangtze River during the zero-growth action policy period (2015–2022). This decrease was primarily associated with a reduction in energy inputs per unit area of fertilizer application, rather than with changes in the total sowing area, which remained stable in the region during the policy period. These findings contrast with those reported by Yuan and Peng [2], who observed significant increases in both total energy inputs and energy inputs per unit area for chemical fertilizer application in China between 1991 and 2012.

The reduction in energy intensity may reflect a shift in the marginal productivity of fertilizers, which had arguably entered a phase of diminishing returns prior to 2015. The temporal coincidence of the policy with this phase of diminishing returns suggests that the mandatory cessation of excessive input increases may have reinforced, rather than initiated, an ongoing structural adjustment. Furthermore, the stable sowing area observed during the study period coincided with the reductions in energy inputs and GHG emissions. In the observed data, these changes were not accompanied by a contraction of agricultural scale. However, they occurred alongside intensive technological substitution—a pattern distinct from the expansive agricultural growth phase (1991–2012) studied by Yuan and Peng [2], which was characterized by area expansion and blanket nutrient application.

Additionally, this study reveals a substantial improvement in the energy use efficiency of chemical fertilizer application in crop production in the middle reach of the Yangtze River following the implementation of zero-growth actions. However, this result contradicts the findings of Liao et al. [15], who reported a significant decline in nutrient use efficiency in crop production in southwest China from 2009 to 2019. In this study, the increase in energy use efficiency was attributed to both higher energy outputs from crop production and reduced energy inputs for chemical fertilizer application. This implies that fertilizers were likely overused before the implementation of zero-growth actions. In this regard, Ren et al. [16] reported that the low ratio of fixed inputs, such as machinery and knowledge, to total inputs was a key factor contributing to the overuse of fertilizers on smallholder farms in China, where smallholder farming remains a prominent feature, with 200–300 million smallholders typically managing only a few areas of land [17].

In line with the reduction in energy use for chemical fertilizer application, total GHG emissions, GHG emissions per unit area, and GHG emissions per unit energy input from chemical fertilizer application have all significantly decreased in crop production in the middle reach of the Yangtze River since the implementation of zero-growth actions. This finding supports previous research indicating a close relationship between GHG emissions and energy inputs [18]. Furthermore, the observed decrease in GHG emissions from chemical fertilizer application contrasts with trends in crop production in China before the implementation of zero-growth actions [7]. These results underscore that the observed trends are consistent with the intended outcomes of the zero-growth actions in promoting ecological and environmental protection, thereby supporting the sustainable development of crop production. However, the present study did not disaggregate fertilizer application by individual nutrient type (N, P, K, and compound), preventing a formal decomposition of the emission reduction into scale and compositional effects. This limitation should be addressed in future research with more detailed fertilizer-category data.

Beyond immediate environmental benefits, the observed decoupling of GHG emissions from energy inputs in the Middle Reach occurred alongside a stable sown area, indicating no apparent trade-off with regional food security. These reductions are consistent with the implementation of the five key measures prioritized under the zero-growth actions—namely (1) promoting soil testing and formula-based fertilization, (2) improving fertilization methods, (3) encouraging the adoption of new fertilizers, (4) increasing the use of organic fertilizers, and (5) enhancing cropland quality [11]—although the present study does not have disaggregated implementation data to establish direct causal linkages between specific measures and the observed reductions. In particular, the promotion of organic fertilizers could have substituted for part of the chemical fertilizer inputs. Because organic fertilizer inputs were not tracked in this study, we cannot determine whether the observed reductions in chemical fertilizer inputs reflect a true reduction in total nutrient inputs or partial substitution with organic fertilizers. This limitation should be addressed in future research by quantifying both chemical and organic fertilizer inputs.

The significant increase in compound fertilizer adoption, alongside the decline in straight fertilizers, was observed together with a labor-scarcity context and is consistent with an adaptive strategy among smallholders. With the massive outmigration of rural labor to urban sectors [17], compound fertilizers offer a “time-saving”

and “labor-saving” solution, reducing the number of topdressing operations. In contrast to the decreases in straight N, P, and K fertilizer inputs, compound fertilizer inputs increased significantly during the zero-growth action policy period. This pattern indicates that a structural change in fertilizer use occurred under the zero-growth policy, characterized by the partial substitution of straight N, P, and K fertilizers with compound fertilizers. This substitution strategy has gained broad acceptance among farmers, largely because compound fertilizers provide a comprehensive nutrient supply [19], allowing multiple nutrients to be applied in a single pass and thereby offering a cost-effective means of mitigating labor shortages while improving farm production efficiency [20]. However, this finding contrasts with the conclusion of Wang et al. [7], who suggested that using straight N, P, and K fertilizers, rather than compound fertilizers, might be more effective at reducing greenhouse gas emissions and could be a viable practice for low-carbon agriculture in China. Additionally, a case study of a compound fertilizer enterprise in Jiangxi province found that nearly 98% of the energy input in the system was derived from non-renewable resources [21]. These findings underscore the need for further research to identify the optimal balance between straight N, P, and K fertilizers and compound fertilizers that maximizes agricultural output while minimizing energy inputs and GHG emissions in crop production in the middle reach of the Yangtze River.

5. Conclusions, Implications, and Limitations

5.1. Conclusions

Energy use and GHG emissions from chemical fertilizer application in crop production decreased significantly in the middle reach of the Yangtze River during the zero-growth action policy period (2015–2022). These reductions were mainly associated with decreased inputs of straight N, P, and K fertilizers. Importantly, these changes occurred alongside a stable regional sown area and a significant increase in energy use efficiency. In addition, the results indicate that a structural change in fertilizer use was observed during the policy period, characterized by the partial substitution of straight N, P, and K fertilizers with compound fertilizers.

5.2. Implications

This study observed significant reductions in energy inputs and GHG emissions from fertilizer application during the zero-growth policy period (2015–2022), accompanied by a structural shift from straight to compound fertilizers. During this period, nutrient reduction mandates and market-compatible fertilizer innovations co-occurred with measurable environmental improvements and no concurrent reduction in sown area. For policymakers, this pattern suggests that future agricultural sustainability strategies might consider not only setting reduction targets but also guiding the composition of fertilizer use toward labor-saving formulations, given the ongoing rural labor transition. For farmers, the observed adoption of compound fertilizers was consistent with a cost-effective response to labor scarcity, indicating that substitution measures aligned with on-farm economic incentives may be worth considering. However, the higher non-renewable energy embedded in compound fertilizer production [21] warrants a life-cycle perspective in future policy evaluation, rather than focusing solely on on-farm application rates.

5.3. Limitations

This study estimated energy use and GHG emissions using statistical data and emission factors reported in the literature, which may introduce estimation biases due to regional and temporal variations in actual production practices. The use of aggregated provincial-level data precluded analysis of crop-specific or farm-level heterogeneity. The short time series (2014–2022) also provided only a single pre-policy observation (2014), which may not adequately represent the counterfactual trend; extending the pre-policy baseline (e.g., 2010–2014) in future studies would help strengthen the analysis. Moreover, this short series

limited our ability to distinguish policy effects from multiple concurrent confounding factors—including fertilizer and crop market prices, weather and climate variability, technology diffusion (e.g., precision agriculture and soil testing), organic fertilizer substitution, changes in crop composition, land consolidation, and the COVID-19 pandemic—all of which may have influenced fertilizer use during the study period. Consequently, our findings are primarily descriptive and correlational, rather than causal. Further investigations employing quasi-experimental designs (e.g., difference-in-differences with control regions) and direct on-farm measurements are needed to validate these preliminary observations and to formally attribute the observed changes to the zero-growth policy.

Statement of the Use of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) solely to polish the language and improve the readability of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Author Contributions

Conceptualization, M.H.; formal analysis, L.C.; investigation, L.C. and F.C.; writing—original draft preparation, L.C. and M.H.; supervision, J.C. and M.H.; funding acquisition, M.H. All authors have read and agreed to the published version of the manuscript.

Ethics Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data are available upon reasonable request from the authors.

Funding

This research was funded by the Earmarked Fund for China Agriculture Research System (CARS-01).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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