Towards sustainable chemical fertilizer management in China：from theory to farm household

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List of Abbreviations

AKIS	Agricultural Knowledge and Innovation System
ARDL	Autoregressive distributed lag
Cd	Cadmium
CFPS	China Family Panel Studies
CNY	China Yuan
CPR	Cointegrating polynomial regression
EKC	Environmental Kuznets curve
FAO	Food and Agriculture Organization
FM-OLS	Fully modified ordinary least squares
GDP	Gross domestic product
GDR	Gross dependency ratio
GRP	Gross regional product
GVA	Gross output value of agriculture
GVC	Gross output value of crop production
K	Potash
MMT	Million metric tons
MoA	Ministry of Agriculture and Rural Affairs of China
MoE	Ministry of Education of China
N	Nitrogen
NBS	National Bureau of Statistics of China
NCP	North China Plain
NDRC	National Development and Reform Commission of China
NECP	Northeast China Plain
NSFS	National Scientific Fertilization Survey
NUE	Nitrogen use efficiency
P	Phosphorus *or* phosphate
PUE	Phosphorus use efficiency
SOC	Soil organic carbon
SSR	Self-sufficiency ratio
STA	State Taxation Administration of China
STB	Science and Technology Backyard
TFP	Total factor productivity
VAT	Value added tax
VECM	Vector error correction model

Chapter 1 General Introduction

The work presented in this dissertation was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation), as part of the Sino-German International Research Training Group "Adaptation of maize-based food-feed-energy systems to limited phosphate resources" (AMAIZE-P) - DFG 328017493/GRK 2366. The overall goal of the project is to adapt phosphate cycling and availability to the multipurpose phosphate demands in maize based food-feed-energy systems, thereby achieving high productivity, sufficient economic performance and high phosphate use efficiency under phosphate limited conditions.

The AMAIZE-P project consists of 12 joint Research Subjects (RS) at the University of Hohenheim and the China Agricultural University, each focusing on a different aspect of the phosphate cycle. The research in this dissertation was conducted within the framework of RS 4.1 “Economic analyses at plot, farm enterprise, regional and sectoral levels”, which aims to analyse and evaluate current and innovative agricultural production systems at various levels, with a special focus on phosphate-cycles in maize-based production systems. The AMAIZE-P project is planned for a duration of nine years and consists of three cohorts of doctoral research. The present study was conducted in the first cohort of the AMAIZE-P project.

In this context, this study analyses fertilizer use and management in China from an socioeconomic perspective at the national, regional, farm and household levels. Particular attention is paid to nitrogen and phosphorus fertilizer application and fertilizer nutrient surpluses, as well as fertilizer use in maize cultivation.

1.1 Chemical fertilizers in Chinese agriculture

1.1.1 Chemical fertilizers and food production

Chemical fertilizers, also known as mineral fertilizers or synthetic fertilizers, are industrially synthesized, chemical-based substances containing one or more plant nutrients, such as nitrogen (N), phosphate (P) and potassium (K) (Singh et al., 2021). The application of chemical fertilizers plays a major role in maintaining soil fertility and achieving high productivity in conventional agricultural production (Ali et al., 2021; Tilman et al., 2002). Since the 1960s, the use of chemical fertilizers has grown tremendously worldwide as a direct response to the need for increased food production (Carvalho, 2006). It was estimated that the average percentage of crop yield attributable to chemical fertilizer inputs generally ranges from 40-60% in temperate climates, and can be even higher in the tropics (Stewart and Roberts, 2012).

In China, the agricultural use of chemical fertilizers has grown drastically over the past few decades (**Figure 1**). From the 1960s to the 2010s, chemical fertilizer input per hectare of cropland – measured as the effective components of N, P_2O_5 and K_2O – increased 18-fold from 22 to 389 kg ha^{-1}, which was more than three times of the world's average (FAO, 2022). At the same time, domestic fertilizer production expanded rapidly, especially in the two decades since the mid-1980s, where China's fertilizer industry steadily entered the market-based system and received substantial subsidies (Li, 2014; Li et al., 2013). During this period, fertilizer production grew at an annual rate of 5%, with an average increase of 1.28 million tons per year. In 2015, China's fertilizer use and production peaked at 55 million tons and 65 million tons, respectively (FAO, 2022). Since then, both consumption and production have declined due to a series of fertilizer control measures. Today, China is still the world's major consumer, producer and exporter of chemical fertilizers. In 2020, China consumed a quarter of the world's total chemical fertilizers and produced 26% and 30% of the world's N and P fertilizers, respectively (FAO, 2022).

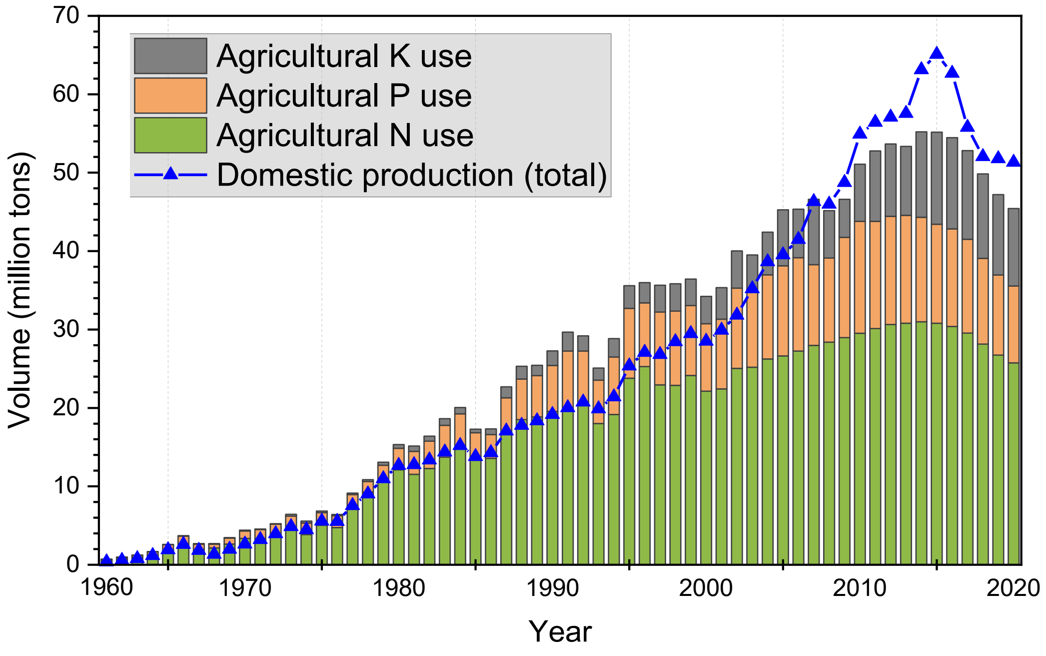

Figure 1 *Agricultural use of the nitrogen, phosphate and potash fertilizers in China - measured as the effective components of N, P_2O_5 and K_2O - and their total domestic production from 1960 to 2020. Source: (FAO, 2022).*

Along with the rapid increase in fertilizer use, China's food productivity has also experienced rapid expansion, as evidenced by the yields of major grain crops (**Figure 2**). In 2020, the average yields of rice, wheat and maize reached 7043, 5742 and 6318 kg ha^{-1}, 1.5, 1.7 and 1.1 times the world's average, respectively (FAO, 2022). Several studies have investigated the role of chemical fertilizers in increasing agricultural productivity in China. In addition to genetic improvement, the use of chemical fertilizers has generally been considered as the main factor to promote crop yield improvements in the past decades. For example, Zhang et al. (2013) concluded that increases in soil fertility and chemical fertilizer inputs accounted for 7.4% of the increase in wheat yield between the 1980s and 1990s, following only cultivar improvement (24.7%). Yu et al. (2012) suggested that crop management, i.e. nitrogen fertilization, contributed to 9.3% of rice yield growth over the last thirty years.

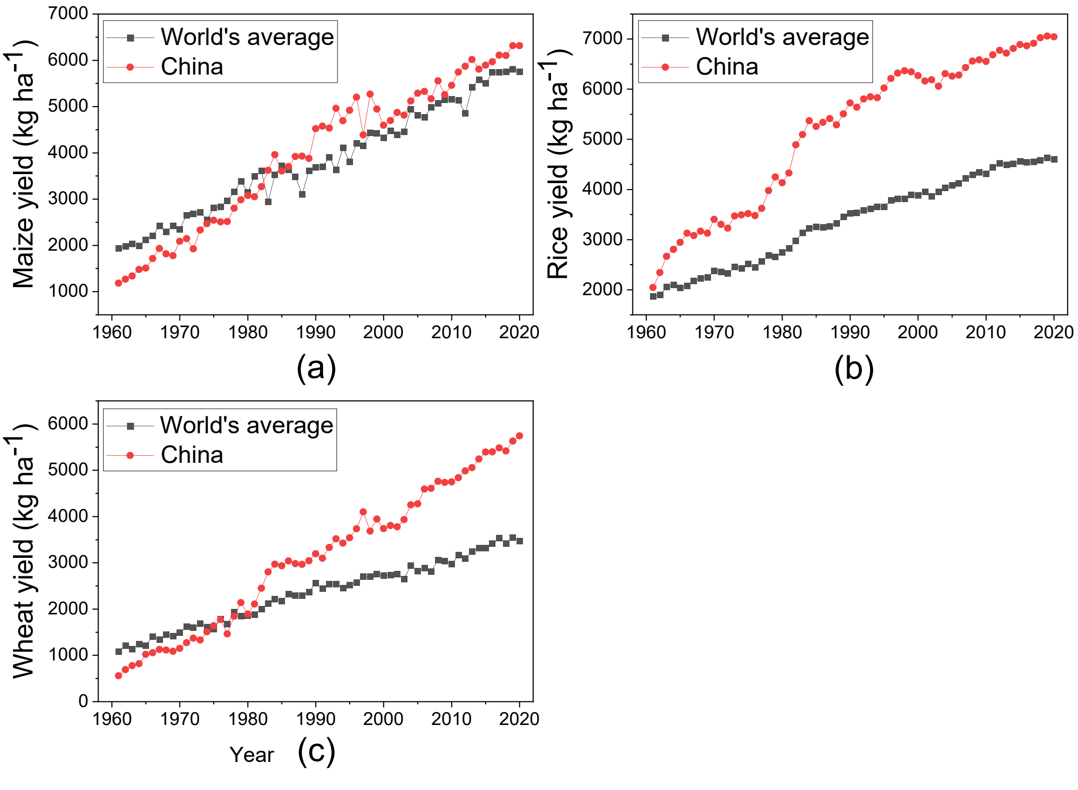

***Figure 2** Comparison of yields of the major grain crops maize (a), rice (b) and wheat (c) between China and the world's average.*

Over the past fifty years, China's total production of maize, rice and wheat of increased 3.4 folds to 622.3 million tons in 2021, accounting for about one-fifth of the world's total production (FAO, 2022; NBS, 2022a). The growth in China's agricultural productivity has not only fed its own huge population, but has also made the country a leading producer of various agricultural products in the world (Huang et al., 2010). Over the decades, the cumulative annual value of China's agricultural exports has continued to increase. In 2021, its value reached 84.4 billion USD, following the United States, the Netherlands and Brazil (Statistia, 2022).

1.1.2 China’s economic development, farm size and chemical fertilizer use

In addition to feeding a growing population, the growth of China’s agricultural productivity is also considered to be the main driver of China’s reallocation of resources from the agricultural to the non-agricultural sector during the 1970s and 1990s (Dekle and Vandenbroucke, 2012). This period is often referred to as China's *structural transformation*, with large numbers of rural laborers moving to urban areas, leading to rapid and massive urbanization (Deininger et al., 2014). During this period, China’s economy and labor productivity experienced rapid expansion, with an annual total GDP growth rate of 9.6% (Dekle and Vandenbroucke, 2012). The rapid modernization and urbanization has led to an increase in arable land over time, which provided opportunities for rural land redistribution (Tamauchi et al., 2021).

Historically, the distribution of agricultural land in rural China has been characterized by small scale and fragmentation, similar to that of many other developing Asian countries. (Nguyen et al., 1996; Wang et al., 2015). During the structural transformation, the Chinese government promoted rural land consolidation and farm size expansion through the land rental market (Deininger et al., 2014; Deininger and Jin, 2005). Since then, there has been a small increase in the overall size of farms (Dawe, 2015). However, smallholder farmers with an average of 0.6 ha of scattered cropland still constitute the bulk of Chinese farms today (Tan et al., 2013; Wu et al., 2018).

Over the past few years, several studies have investigated the development of Chinese agriculture in the context of the structural transformation, and many have argued that Chayanov's original concept of "small is beautiful" is no longer relevant in China (Jin and Deininger, 2009; Wang et al., 2015; Zhang and Diao, 2020). On the one hand, recent studies have found that in China, small farms are generally less productive than large farms, as evidenced by farm outputs or crop yields (Otsuka et al., 2016; Sheng et al., 2019). On the other hand, agricultural production on small farms is often considered less environmentally sustainable because of their higher use of agrochemicals and carbon emissions (Xie et al., 2020; Yan et al., 2015). In particular, strong inverse correlations have been found between farm size and chemical fertilizer use, i.e., small farms tended to overuse fertilizers without further yield gains. For example, Ju et al. (2016) found that in China, an increase in farm size led to a decrease in fertilizer use intensity and an increase in crop yield. Wu et al. (2018) concluded that farm size was negatively correlated with the application rates of agrochemicals. Zhang et al. (2021) investigated maize production in northern China and suggested that increasing farm size would lead to reduced agrochemical use without lowering the yield. Ren et al. (2019) also argued that expanding large-scale agriculture was the key pathway to achieve more sustainable food production, as increasing farm size had a positive impact on farmers' net profitability and reduced use of agrochemicals.

1.2 Nutrient surpluses from the excessive use of chemical fertilizers

1.2.1 Excessive use and misuse of chemical fertilizers and related consequences

The use of chemical fertilizers is widely recognised as a major cause of environmental pollution in agriculture (Norse, 2005; Paudel and Crago, 2021). In China, agricultural production has become the largest source of non-point source water pollution, surpassing industrial sources (Chen et al., 2017). And poor practices in chemical fertilizer use, often including excessive use and misuse of fertilizers, have become a major threat to sustainable agricultural production (Calabi-Floody et al., 2018; Chadwick et al., 2015).

Excessive use of chemical fertilizers, especially N and P fertilizers, has long been a phenomenon in conventional agriculture (Yadav et al., 1997; Yu et al., 2021). Studies have shown that the overall world nitrogen use efficiency (NUE) is about 42% (Zhang et al., 2015), while the overall phosphorus use efficiency (PUE) of grains is only 9.1% (Yu et al., 2021), meaning that the rest of the percentage is lost to the environment. Excessive use of N and P fertilizers have been proven to cause various environmental consequences, such as soil acidification (Miao et al., 2011), surface and groundwater contamination (Norse, 2005), eutrophication, and tropospheric pollution related to emissions of nitrogen oxides and ammonia gas (Zhang et al., 2015). In addition, long-term over-fertilization can also lead to reduced crop yield and quality (Albornoz, 2016), lower grain protein content and mineral bioavailability (Zhang et al., 2017), and increased chances of heavy metal contamination in crops, such as cadmium (Cd) (Cheraghi et al., 2012). All these factors pose a serious threat to sustainable food production and food security.

Chemical fertilizer misuse usually refers to unbalanced nutrient application, especially overuse of single nutrient N (Ladha et al., 2005). Since nitrogen plays a dominant role in determining crop yields and has a relatively low cost compared to the value of the crop product, the financial risk of overuse of N fertilizers is much less than the risk of underuse (Mosier et al., 2013; Omara et al., 2019). This has led farmers to misuse and over-apply N fertilizer without realizing that the omission of other plant nutrients can lead to undesirable consequences (Ladha et al., 2005). For example, a lack of P supply in maize cultivation can lead to substantial yield losses (Aliyu et al., 2021), while K deficiency can inhibit maize growth and development by causing leaf chlorosis (Du et al., 2019). Imbalanced N/P ratios in the soil due to unbalanced fertilization can also affect the chemical composition of crops, which may have a negative impact on human health (Peñuelas and Sardans, 2022). In addition to directly affecting crop performance, researchers also found that long-term unbalanced fertilization affects soil microorganisms and the chemical composition of soil organic carbon (SOC), which affects soil properties and fertility in the long run (Li et al., 2015; Ma et al., 2019; Zhang and Wang, 2005).

1.2.2 Fertilizer nutrient surpluses and the economic development

In China, the predominant application of N has been improved following the widespread use of compound fertilizers, which provide specific ratios of N, P, and K needed for plant growth (Sun et al., 2019). From 1978 to 2020, the proportion of single-N fertilizers applied in China declined from 76% to 35%, while the proportion of compound fertilizers applied increased almost 80-fold, from less than 1% to 42% (NBS, 2022a). At the same time, the applied P and K nutrients increased sharply from 13.6 and 2.4 kg ha^{-1} to 72.7 and 73.3 kg ha^{-1}, respectively (FAO, 2022). However, due to the generally low NUE and PUE in China (Zhang et al., 2019, 2015), there are high fertilizer nutrient surpluses, resulting in a large loss of N and P to the environment.

Fertilizer nutrient surpluses, which generally refer to N and P surpluses, are defined as a positive difference between fertilizer nutrient inputs and outputs in crop production (Bouwman et al., 2013; Liu et al., 2010). Similar to greenhouse gas emissions and the amount of agrochemicals applied, fertilizer nutrient surpluses are often used as an indicator of agriculture-induced pollutions in the framework of the Environmental Kuznets curve (EKC) hypothesis (Sarkodie, 2018; Sarkodie and Strezov, 2019; Zhang et al., 2015). The EKC hypothesis, developed from the pioneering work of Grossman and Krueger (1995, 1991) and Panayotou (1995), suggests that after an economy reaches a sufficient level of economic growth, further economic growth can improve environmental degradation. Therefore, the EKC exhibits an inverted U-shaped curve, which is similar to the original curve proposed by Simon Kuznets in 1955 on the relationship between income inequality and economic growth (Kaika and Zervas, 2013; Kuznets, 1984).

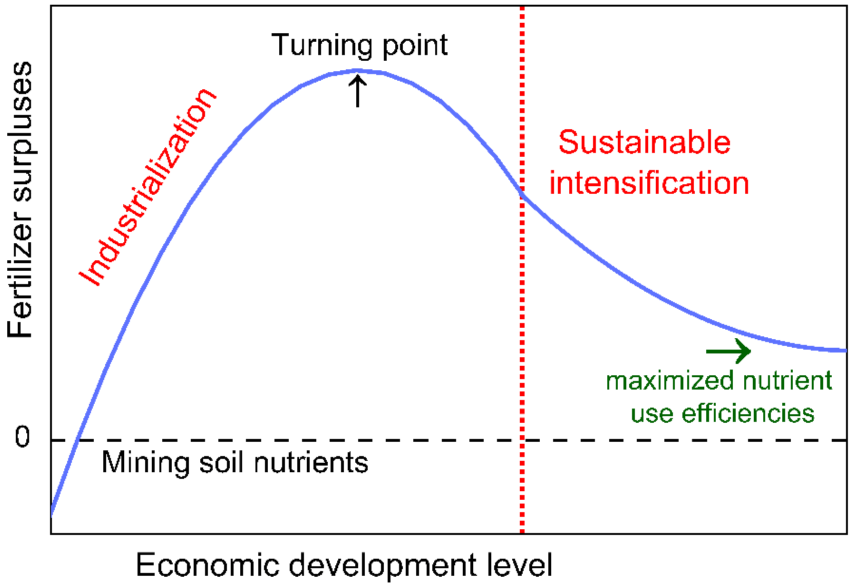

Figure 3 *An idealized fertilizer surpluses-induced EKC. Source: Yu et al. (2022)*

In terms of agricultural pollution caused by excessive chemical fertilizer use, the EKC hypothesis can be drawn as indicated in **Figure 3** above. In the pre-industrial economy, fertilizer surpluses increase rapidly with economic growth due to the expansion of the primary sector of the economy[1], i.e., agriculture (Kaika and Zervas, 2013). In China, this process may be accelerated by increased demand for food, expansion of cash crop production, supportive policies for agricultural production, highly subsidized chemical fertilizer and so on. Then, as the economy enters an industrial phase dominated by the secondary sector, the fertilizer surpluses will slowly reach the turning point. This may be due to, *inter alia*, the pursuit of improved environmental quality and cleaner production, the need for more efficient use of plant nutrients due to scarce resources, and technological improvements. With further economic growth, fertilizer surpluses are expected to decrease and nutrient use efficiency will be maximized due to sustainable agricultural intensification in the post-industrial economy.

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[1] According to NBS (2022b), the primary sector economy includes agriculture, forestry, animal husbandry and fishery (excluding agriculture, forestry, animal husbandry and fishery services). The secondary sector economy includes mining (excluding mining auxiliary activities), manufacturing (excluding metal products, machinery and equipment repair industry), electricity, heat, gas and water production and supply industry, construction. The third sector economy refers to industries other than the primary and secondary industry, i.e. service.

1.3 The development of China’s fertilizer management strategies

1.3.1 Historical development of China’s fertilizer policies (1949 – late 2000s)

The dynamics of fertilizer production, consumption and international trades in China have been largely influenced by relevant national policies. Based on the progress of fertilizer-related policies, Li et al. (2013) divided the historical development of China's fertilizer industry into four temporal phases (see **Table 1**). **Phase I (1949 - 1984)** is featured by the strict central planning and price control system. During this period, fertilizer manufacturing was dominated by state-owned enterprises with very limited access to international markets. Then, from **1985 to 1997 (Phase II)**, market adjustments were incorporated into the central planning system and a double-track price system for fertilizers was implemented. The double-track price system means that the price of the planned fertilizer supply (production quota) is determined by the government, while the price of surplus fertilizer is determined by the market (Ju et al., 2016). During this period, the demand for fertilizer increased rapidly, resulting in surplus fertilizer prices well above quota prices (Li et al., 2013). On the one hand, this stimulated domestic production and the government started to provide subsidies to fertilizer manufacturers. On the other hand, due to the gap between supply and demand, imported fertilizers – especially P and K - played an important role in meeting domestic fertilizer demand, accounting for 27% of total consumption during this period (Yu et al., 2020). In 1998, the State Council issued “Notice on deepening the reform of the fertilizer distribution system”, enabling private capital to enter the fertilizer industry. At the same time, fertilizer producers and retailers were allowed to set the price of fertilizers within the price range recommended by the government (price cap). During this period **(Phase III, 1998-2009)**, large-scale subsidy programs were also provided to the fertilizer industry and farmers. The former mainly included subsidies on rail transportation, electricity and gas, off-season commercial reserves and exemptions from value added tax (VAT); and the latter referred to the general subsidies for agricultural supplies, which was designed to help farmers purchase agricultural inputs such as agrochemicals, diesel fuel, seeds and machinery (Ju et al., 2016; Li, 2014; Li et al., 2013). In 2009, the State Council removed the price cap for fertilizers, indicating that China's fertilizer industry had entered a fully market-driven system (**Phase IV**) (Li et al., 2013). Nevertheless, the massive subsidy programs remained mostly in effect until the mid-2010s.

Table 1 summarizes the historical development of fertilizer-related policies in China, as well as changes in fertilizer production, consumption and international trade volumes.

***Table 1** The historical development of fertilizer-related policies in China. Source: modified based on Ju et al. (2016) and Li (2014), data from FAO (2022).*

Major characteristics and policies	Production	Use	Export	Import
	unit: million tons			
Phase I (1949-1984): Central planning (state monopoly)				
• Centrally planned purchase and supply; state ownership; strict price control system	15.21	20.06	0.14	5.01
Phase II (1985-1997): Central planning with market adjustment				
• Double-track price system for fertilizers; • Electricity subsidies for small and medium-sized fertilizer producers (since 1993)[a]; compound fertilizers exempted from VAT (since 1994)[b]	26.82	35.65	2.32	9.63
Phase III (1998-2009): Market-oriented with governmental interferences				
• Fertilizer prices determined by the market within the government-suggested price range (the price cap); • Massive production subsidies: Subsidies for rail transportation of fertilizers (1998 to 2005); urea VAT refund after collection (2001 to 2004); subsidies for off-season commercial fertilizer reserves (since 2004); fertilizers completely exempted from VAT (since 2005)[c]; gas subsidies for fertilizer producers (since 2005)[d]; • General subsidies for agricultural supplies for farmers (since 2004)	48.75	46.61	3.42	2.19
Phase IV (2009-2014): Fully market-oriented				
• Price cap eliminated, subsidy programs intact	63.13	55.21	13.47	5.55
Phase V (2015 -): Fully market-oriented with sustainable intensification				
• Eliminated preferential prices for electricity (2015) and gas (2016); regional adjustments on subsidies for rail transportation of fertilizers (2016); discontinuation of VAT incentives for chemical fertilizers (2015);	-	-	-	-

- “Zero growth plan for fertilizers by 2020” (2015); the “Environmental Protection Tax Law of the People's Republic of China” (2018)[e]

Note: The volume of fertilizer production, consumption, export and import refer to the value at the end of each phase.

[a] The preferential price of electricity for fertilizer production has been phased out since April 2015 and was completely eliminated by April 2016.

[b and c] Effective September 1, 2015, the implementation of the preferential VAT policy for chemical fertilizers was discontinued.

[d] Since November 2016, the price of fertilizer gas has been completely liberalized and determined by market transactions.

[e] A detailed list of recent fertilizer-related policies is available in **Table A1** in the Appendixes.

1.3.2 Current fertilizer management strategies in China

Supportive policies for fertilizer production and use have greatly increased the accessibility and availability of chemical fertilizer to farmers. However, these policies have also to a large extent contributed to the fertilizer overuse (van Wesenbeeck et al., 2021; Wang et al., 2022). Starting from 2015, a series of measures and policies to reduce fertilizer production subsidies and control fertilizer use have been introduced. Meanwhile, policies to promote the adoption of scientific fertilization techniques and subsidies for the production of scientific fertilizers (such as slow- or control- released fertilizers) were launched. This indicates that China’s fertilizer industry has entered **Phase V (2015-)**, fully market-oriented and moving towards sustainable intensification. A summary of recent fertilizer-related policies is presented in **Table A1** in the Appendixes.

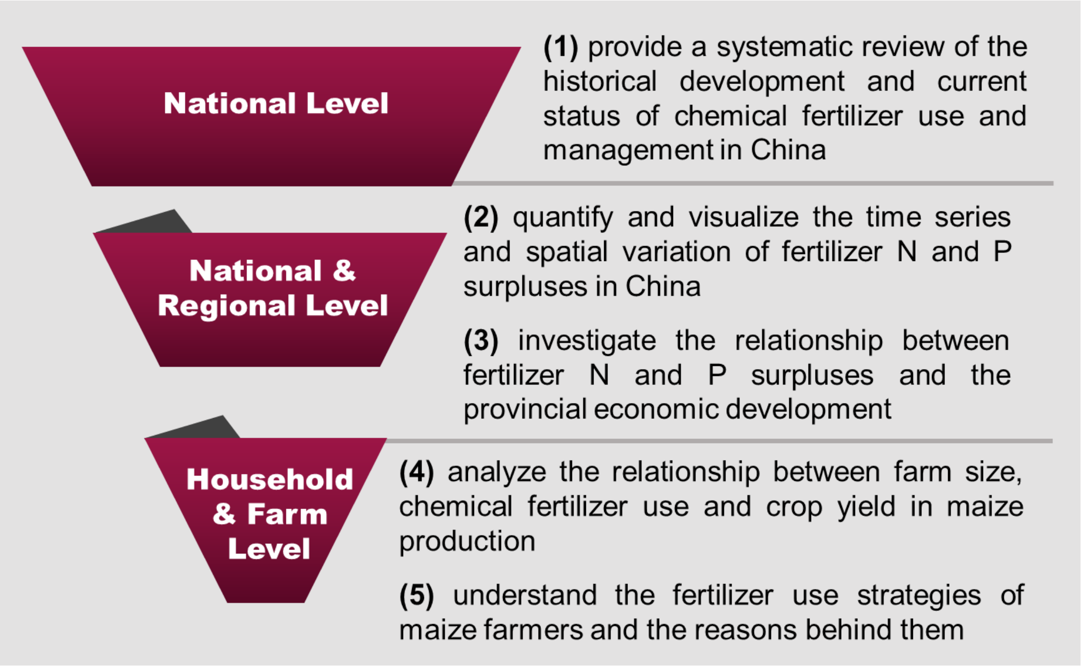
In 2015, the National Development and Reform Commission of China (NDRC) issued the “Notice on the reduction of coal-fired power generation feed-in tariffs and commercial and industrial electricity prices”, requiring the gradual elimination of preferential price of electricity for fertilizer production (NDRC, 2015). In 2016, several regional Railway Bureau reduced or discontinued the subsides on rail transportation of conventional chemical fertilizers. At the same time, NDRC began to promote the market-oriented reform of gas prices for fertilizers in order to achieve open and transparent gas prices for fertilizer production (NDRC, 2016). Moreover, the State Taxation Administration of China (STA) announced the discontinuation of VAT exemptions for chemical fertilizers as of September 2015 (STA, 2015).

In addition to policies to reduce or eliminate subsidies for fertilizer production and transportation, several government regulations aimed at reducing fertilizer application have been issued and implemented. For example, in 2015, the Ministry of Agriculture (MoA) released the “Zero growth plan for fertilizers by 2020”, as well as a series of implementation plans on fertilizer use control (MoA, 2015). In 2018, China's environmental protection tax law was officially launched (STA, 2018). This is the first single tax law in China that embodies a "green tax system" and provides for taxation of enterprises, institutions and other production operators that emit taxable pollutants directly into the environment (XinhuaNet, 2016).

Last but not least, scientific fertilization techniques began to be widely promoted by governments and research institutions. For example, to conserve water and improve the efficiency of fertilizer use, the MoA has issued an implementation plan to promote integrated irrigation and fertilization systems (MoA, 2016). Replacing conventional chemical fertilizers with organic, slow-/ or control-released and formulated fertilizers has also received considerable attention at the government and research levels (Chen et al., 2018; Li et al., 2020; Liu et al., 2019; Wang et al., 2018). Moreover, initialized in 2009, a group of agricultural scientists developed the concept of the Science and Technology Backyard (STB). The STB enables agricultural scientists and students to live and work among farmers, to transfer scientific agricultural knowledge, and improve agricultural productivity and sustainability (Jiao et al., 2019). Over the years, the STB model has been proven to contribute to sustainable agricultural development in several locations in China (Ding, 2022; Yang, 2016). In 2021 and 2022, three government circulars from the Ministry of Education (MoE), the MoA and the Chinese Association for Science and Technology were introduced to further promote the development of the STB (Ding, 2022).

1.4 Objectives and hypothesis of the study

The overall goal of this work is to contribute to the sustainable nutrient management in China from a socio-economic perspective. A comprehensive, systematic and in-depth understanding of chemical fertilizer use and management at different levels in China is to be established. More specifically, the objectives can be illustrated in **Figure 4** below.



(1) provide a systematic review of the historical development and current status of chemical fertilizer use and management in China

(2) quantify and visualize the time series and spatial variation of fertilizer N and P surpluses in China

(3) investigate the relationship between fertilizer N and P surpluses and the provincial economic development

(4) analyze the relationship between farm size, chemical fertilizer use and crop yield in maize production

(5) understand the fertilizer use strategies of maize farmers and the reasons behind them

Figure 4 *Specific objectives of the study.*

Correspondingly, the following general hypothesis tested in the study include:

(1) Despite recent declines in the application rate of chemical fertilizers, high nutrient surpluses persist in China with regional variations;
(2) The relationship between fertilizer N and P surpluses and regional economic development follows a typical EKC trajectory – an inverted U-shaped curve;
(3) Small farms tend to overuse fertilizers in maize production in China compared to large farms without further improving yields;
(4) The lack of knowledge and awareness among small farmers is the main reason for their excessive use of chemical fertilizers.

1.5 Analytical framework of the study

To achieve the research objectives and test the hypotheses, this study adopted an interdisciplinary approach with a combination of review, theory, and empirical analysis methods. As the detailed data sources and methods for each research article are presented in the corresponding chapters, at this point, **Chapter 1.5** outlines the overall analytical framework and indicates how each research section is interrelated and coherently serves a common overall goal.

Figure 5 shows the analytical framework of the study. In the review and theoretical analysis section, the study focuses on chemical fertilizer use at the national level. This section mainly answers the research questions *"What is the historical and current status of fertilizer use in China?"* and "*What are the spatial and temporal variations of fertilizer nutrient surplus in China?*". Illustrated in **Chapter 2**, this part of the study contributes to the theoretical and data base of the research. It provides a comprehensive quantitative review of fertilizer production, consumption, and international trade in China over the past six decades, and includes estimates and spatial visualization of fertilizer N and P surpluses by province.

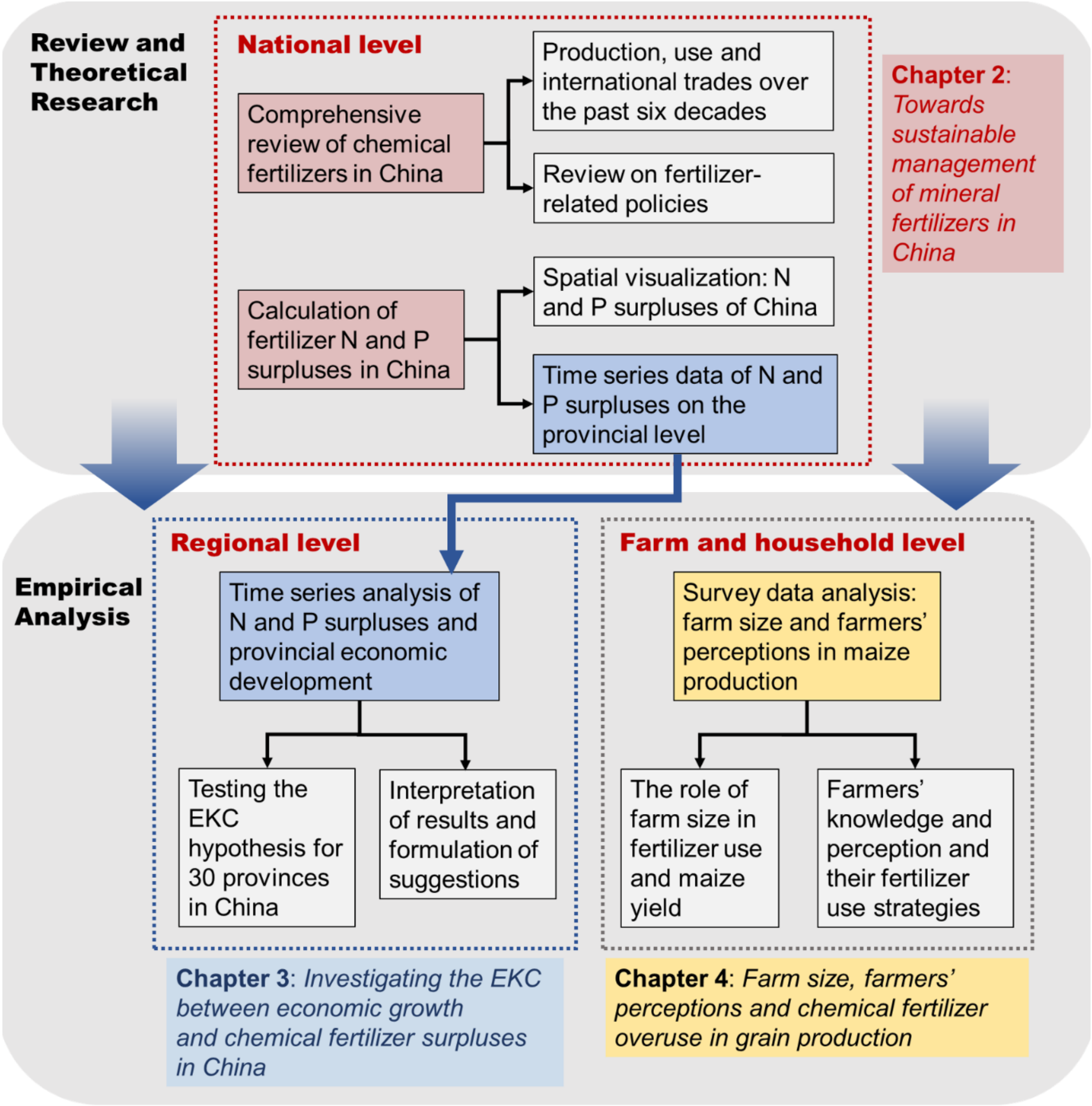


Figure 5 *Analytical framework of the study.*

The empirical analysis section of the study consists of two parts. At the regional level, a time series analysis of the relationship between fertilizer nutrient surpluses and provincial economic development is conducted. The research question, *"Is there a* *correlation between fertilizer nutrient surpluses and regional economic development?"* is answered in the illustration of **Chapter 3**. Chapter 3 employs some quantitative results from Chapter 2 (fertilizer N and P surpluses) and analyses them within the framework of the EKC hypothesis. Following Chapter 2, Chapter 3 provides a more in-depth assessment of China's recent performance in reducing fertilizer use. It also demonstrates the trade-offs between regional economic development and environmental pollution.

At the farm and household level, the focus of the study is further narrowed to answer the research question, "*Do small farmers use more chemical fertilizers? If so, why?*". Illustrated in **Chapter 4**, the analysis uses cross-sectional survey data from 774 maize producing farms in northern China in 2019 to examine the role of farm size and farmers' perceptions and knowledge in maize production and how they relate to farmers' fertilizer application strategies. This chapter provides insights into farm and household resolutions, which helps identify gaps in actual farm production and generate policy recommendations at the implementation level.

1.6 Structure of the dissertation

This cumulative dissertation consists of three journal articles and a general introduction and discussion. Chapters 2 to 4 include original research manuscripts that have been published in peer-reviewed international journals.

Chapter 2 is reprinted from *Sustainability* 12, 7028, Xiaomin Yu, Haigang Li, Reiner Doluschitz (2020): Towards sustainable management of mineral fertilizers in China: an integrative analysis and review. Doi: https://doi.org/10.3390/su12177028

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Chapter 2 - Publication

Towards sustainable management of mineral fertilizers in China: an integrative analysis and review[a]

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Review

Towards Sustainable Management of Mineral Fertilizers in China: An Integrative Analysis and Review

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Abstract: China has not only successfully fed 20% of the world's population using only 9% of the world's arable land; it has also become the world's largest producer of various agricultural products. The widespread application of mineral fertilizers played a critical role in accomplishing this achievement. In this study, we conducted an integrative analysis of China's mineral fertilizers over the last six decades from multiple perspectives—domestic production, consumption and international trade at national and international levels, and the agricultural use of fertilizers at a regional level. In addition, we quantitatively estimated fertilizer nutrient surpluses for 30 provinces in mainland China for the time period spanning from 1987 to 2018 and integrated the results as a reference to the evaluation of the implementation of the Zero Growth Action Plan regulating fertilizer use by 2020. We concluded that by 2019, 83% and 93% of the provinces had already achieved zero growth in fertilizer use and fertilizer nutrient surpluses, respectively. This shows promising potential for China in finalising the Zero Growth Action Plan of Fertilizers nationwide by 2020.

Keywords: mineral fertilizer; China; sustainability; quantitative review; Zero Growth Action Plan of fertilizers

1. Introduction

China has successfully fed 20% of the world's population with less than ten percent of the world's arable land [1]. Compared with 1965, the total production volume of major cereal crops in China (rice, maize and wheat) quadrupled with only 30% growth in their cropping surface area [1]. In fact, China is the world's largest producer of multiple important agricultural products. In 2018, China produced 20% of the world's cereal grains, 25% of the world's meat, 38% of the world's eggs and 50% of the world's vegetables [1]. Its value added in agriculture, forestry and fishing reached a total of USD 92 billion in 2017. This figure is five and four times that of the United States and the European Union, respectively [2]. This makes China the world's largest agricultural economy [3].

A significant reason contributing to China's boost in agricultural production is the dramatically intensified application of chemical fertilizers. In comparison with the mid-1960s, China's average fertilizer input per hectare on cropland in 2017—measured as the effective components nitrogen (N), phosphate (P_2O_5) and potash (K_2O)—increased from 25 kg to 390 kg ha^{-1}, which was more than three times the world's average [1]. Apart from being a strong consumer that utilizes one-quarter of the world's mineral fertilizers each year, China is also a major producer and exporter of nitrogenous and phosphate fertilizers, accounting for 30% of the world's annual production. However, the drastic increase in agricultural productivity due to the application of agrochemicals comes with an additional cost. A result of the better accessibility and availability of mineral fertilizers was the massive overuse and mismanagement of those chemicals, neglecting the actual crop demand. This has led to multiple environmental consequences. From 1980 to 2005, China's mean nitrogen use efficiency (NUE) and phosphorus use efficiency (PUE) in crop production dropped from 32% to 26%, and the mean NUE and PUE at the food chain level were even lower [4]. In 2009, 57% of the nitrogen and 69% of the phosphorus entering waterbodies in China were from agriculture, and the agricultural nutrient losses have been a major constituent of diffuse water pollution [5–7]. The excessive use of mineral fertilizers may also contribute to accumulating salt and nitrate concentrations in agricultural soils, deteriorating the soil quality, which may cause nitrate contamination of vegetables [8,9].

In 2015, the Ministry of Agriculture of China developed the Zero Growth Action Plans for fertilizer and pesticide use by 2020, seeking to achieve zero growth in the use of chemical fertilizers and pesticides by 2020 [10,11]. Multiple region-specific actions were proposed to reduce mineral fertilizer use specifying four technical elements: promoting precision fertilization; optimizing the structure of mineral fertilizers; improving fertilization practices; and substituting chemical fertilizers with organic fertilizers. At the same time, the sustainable management of mineral fertilizers in China is receiving increasing attention in scientific fields [12,13], with research particularly focusing on improving the nutrient use efficiency. Studies have been conducted at various levels in this aspect, from breeding to farming practices, and the whole food production chain [4,14–17].

Records from the National Bureau of Statistics of China (NBS) showed that the overall mineral fertilizer use per capita on arable land in China has been decreasing since 2016 [18]. However, regional and temporal variations in magnitudes of the recent fertilizer use reduction are still unclear. Therefore, a quantitative and comprehensive analysis of the historical trend and current status of China's mineral fertilizer use would be necessary to provide an overview and an initial evaluation of regional performances regarding the recent fertilizer use reduction.

Against this background, the main objectives of this paper are: (1) to obtain a comprehensive review of China's agricultural inputs and food production over the last six decades, with special focuses on the historical trend of the use, production and trade of mineral fertilizers; (2) to provide an overview of the regional and temporal variations of fertilizer use in China; and (3) to roughly quantify mineral fertilizer surpluses—indicated by fertilizer N and P surpluses—in agricultural soils of 30 provinces in mainland China from 1987 to 2018. The quantitative results from the study will be helpful in assessing the performance of different provinces in China regarding the Zero Growth Action Plan of fertilizer use, and will provide insights into the sustainable management of mineral fertilizers in China on a regional level.

2. An Overview of China's Agricultural Inputs and Food Production

China has enjoyed rapid economic growth since the market-oriented reforms in the late 1970s, accompanied by profound changes in the structure of resource application levels, allocation and outputs between agricultural and nonagricultural sectors [19]. One of the drawbacks following the continuous processes of urbanization and industrialization is the increasing pressure on the available agricultural land. During the last 20 years, the area of arable land in China has declined by 0.3 million hectares annually. Compared with 1961, China's arable land area per capita in 2017 shrank by nearly 50%; whereas other agricultural inputs such as fertilizer, agricultural machinery use and irrigation drastically increased [1]. Despite the reduced area of arable land, this greatly intensified agricultural input certainly plays an important role in meeting China's growing demand for food.

Table 1 presents a comparison of agricultural inputs and food production in China and the world's average based on the FAOSTAT: the Statistical Database of the Food and Agricultural Organization of the United Nations. Arithmetic means of the selected indicators over the four time periods between 1961 and 2018 are illustrated. While the average arable land per capita keeps decreasing worldwide, China's relative share of that remained fairly constant over recent decades, namely 35–40% of the world's average. Considering China's limited surface area of arable land per capita, its per capita food production is high. For example, the major cereal production tripled from 128.5 kg per capita in 1961 to 424.5 kg in 2018, while the yield increased nearly fivefold from 1282 to 6220 kg ha^{-1}, an amount considerably higher than the world's average of 4631 kg ha^{-1} [1]. Significant growth in food production also appears in animal products such as meat and eggs.

Table 1. Comparison of agricultural inputs and food production in China and the world average. Arithmetic means of the selected indicators of each 15 years between 1961 and 2018 are illustrated. Data source: FAOSTAT.

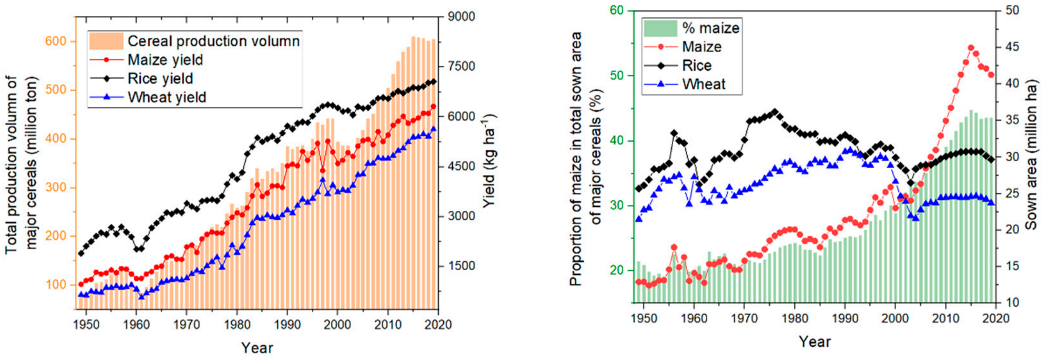
	1961–1975		**1976–1990**		**1991–2005**		**2006–2018** [f]	
	China	**World**	**China**	**World**	**China**	**World**	**China**	**World**
Agricultural Inputs								
Arable land per capita (ha/capita)	0.13	0.37	0.10	0.29	0.09	0.23	0.08	0.19
Mineral fertilizer consumption [a] (kg/ha)	35	44	150	85	275	92	407	115
Mineral fertilizer consumption per capita (kg/capita)	4	17	16	26	28	23	37	25
Energy consumed in agriculture [b] (kWh/ha)	/	/	1152.4	729.5	1689.6	1035.1	2153.8	1182.6
Energy consumed in agriculture per capita [c] (kWh/capita)	/	/	130.8	210.5	171.2	257.6	193.7	259.4
Share of the land area equipped for irrigation over cropland [d]	0.45	0.13	0.43	0.16	0.42	0.19	0.54	0.21
Food production								
Cereal yield [e] (kg/ha)	2101	1865	3650	2679	4946	3437	5860	4232
Cereal production per capita (kg/person)	194	239	284	284	317	292	380	331
Meat production per capita (kg/capita)	8.3	26.3	16.1	31.2	41.5	37.0	58.3	42.9
Egg production per capita (kg/capita)	2.3	5.3	4.0	6.4	14.7	8.5	21.4	10.4

[a] Mineral fertilizer consumption (kg ha^{-1}) was calculated as the sum of effective components of mineral fertilizers (N, P_2O_5 and K_2O) divided by the total cropland area; [b] and [c] energy consumption in agriculture here includes energy generated from gas—diesel oil, motor gasoline and electricity. Natural gas consumed in agriculture was excluded due to the lack of data. Energy consumed in fisheries (incl. fuel oil and gas—diesel oils used in fisheries) was not included. Data period of energy use on FAOSTAT is from 1986 to 2012 for mainland China, and from 1970 to 2012 for the world. The mean agricultural energy consumption values for 1976–1990 were, therefore, calculated for the period 1986–1990, and values for 2006–2018 were calculated for the period 2006–2012. [d] Ratio of land area equipped for irrigation over cropland was selected as an indicator of agricultural inputs, because data regarding actual irrigated land area were incomplete on FAOSTAT. [e] Cereal here refers to the major cereals—maize, wheat and rice. [f] Time period 2006–2018: until the paper was submitted, data regarding land use and fertilizer use in 2018 were still missing. As 2018 data were missing, the mean values of 2006–2017 were adopted.

Among China's agricultural inputs, the mineral fertilizer consumption per hectare of cropland shows the most radical change, with an average annual increasing rate of 20% over the period of 1961 to 1975, and 8% over the period from 1976 to 1990. Meanwhile, China's agricultural machinery use—indicated by energy consumed per hectare of cropland—also doubled over the last 30 years, from around 1200 kWh ha^{-1} in the 1980s–1990s to more than 2000 kWh ha^{-1} after the new millennium.

Apart from intensified infrastructural inputs in agriculture, technology inputs, e.g., national and international investments in agricultural research and extension services, also largely accounted for the productivity boost in China. Jin et al. investigated the impacts of crop-specific investment in national research programs on the productivity improvements, and concluded that the total factor productivity (TFP) of major cereals in China grew rapidly during the 1980s and 1990s owing mostly to new technologies [20]. For example, new cultivars of winter wheat accounted for 25% and 52% of yield improvements in the 1990s and 2000s; whereas the contribution of chemical fertilizer inputs was only about 7% during both periods [21]. In terms of rice and maize, crop genetic gains contributed to 74% and 53% of the yield improvements, respectively, over the last three to four decades [22,23].

Production records of China's major cereal crops since 1949 can be obtained from the National Bureau of Statistics of China). From 1949 to 2019, yields of maize, rice and wheat increased dramatically from 960 to 6320 kg ha^{-1}, 1890 to 7060 kg ha^{-1} and 640 to 5630 kg ha^{-1}, respectively. The total production volume of the crops increased eightfold (Figure 1a) [18]. Fluctuations in land use for rice, wheat and maize production have been closely related to government legislation and policies, cereal prices and economic development [24]. Until the late 1980s, sown areas of maize, rice and wheat in China steadily increased with temporal fluctuations (Figure 1b). Since the early 1990s, production areas for wheat and rice started to decrease before stabilizing; whereas the maize production area quickly expanded and its proportion over the total cereal sown area jumped from 25% in 1991 to 45% in 2015 [18]. The recent growth in maize production was mainly driven by the rapid development of the animal husbandry and agricultural deep processing industry in China, caused by the increasing domestic demand for animal feed and highly processed maize products, e.g., starch and alcohol [25]. In 2012, the production volume of maize exceeded that of rice for the first time, becoming the most produced cereal crop in China [26]. Since 2015, the Ministry of Agriculture of China has promoted the "Grain to Feed" transformation to support animal husbandry, which has led to a reduction in the sown areas of the major cereal grain crops, especially maize. During the period from 2015 to 2019, the total sown areas of maize, wheat and rice decreased by 5.6 million ha, with 65% of the reduction attributable to maize [18].



(**a**) (**b**)

Figure 1. Production overview of major cereal crops in China from 1949 to 2019, including (**a**) production volumes and yields of maize, rice and wheat in China and (**b**) sown areas of the major cereal crops and the proportion of maize. Source of data: National Bureau of Statistics of China (NBS).

3. Mineral Fertilizers in China

3.1. The Historical Trend of China's Mineral Fertilizer and Its Driving Forces

A database on the production, consumption and international trade of mineral fertilizers in China from 1961 to 2017 was obtained from the FAOSTAT [1]. Chemical and mineral fertilizers are quantified by the three major plant nutrients nitrogen (N), phosphate (P) and potash (K). Over the last six decades, both China's domestic production and agricultural use of mineral fertilizers showed significant increases, with overall annual increasing rates of 11% and 9%, respectively. In 2008, the volume of domestically produced mineral fertilizers exceeded that of the agricultural use for the first time, reaching 46 million metric tons (MMT). This gap continued to grow in the following consecutive years [1].

Li et al. [27] categorized the development of China's mineral fertilizer industry into four chronological phases based on the progressing policies (Figure 2). Phase 1 (1949–1984) featured centrally controlled production with state ownership, where production and agricultural use of fertilizers steadily increased from 0.4 and 0.7 MMT in 1961 to 15 and 20 MMT at the end of the phase, respectively [1]. Access to international markets during this phase was very limited. Beginning in the mid-1980s, China started the transition from a central-planning economy to a market economy. Multiple factors such as the increasing food demand due to population growth and gradually liberalized rural markets for agricultural products led to a rapidly growing demand for mineral fertilizers. During phase 2 (1985 to 1997), although both fertilizer production and consumption doubled in volume, the demand was not in balance with domestic production. Imported fertilizers played an important role during this period and accounted for 27% of the total consumption, the highest among all four phases. Since the late 1990s, the fertilizer industry slowly moved into a market-oriented system where massive and rather specific governmental subsidies began to be granted and private capital started to enter the market. From 1998 to 2008 (Phase 3), a governmental price-cap policy was in effect that mandated the maximum profit in the fertilizer industry. This price-cap policy was abolished in 2009. Nonetheless, domestic fertilizer production during this period experienced a swift expansion with an average increment of 1.7 MMT per year, and imports kept shrinking. At the end of phase 3, imported fertilizers only occupied 17% of China's total agricultural consumption. In 2009, China's fertilizer industry implemented a completely market-driven system with all domestic price control and restrictions removed. Since then, the overall production volume has always been higher than consumption, and in the meantime, China's fertilizer exports have become increasingly active.

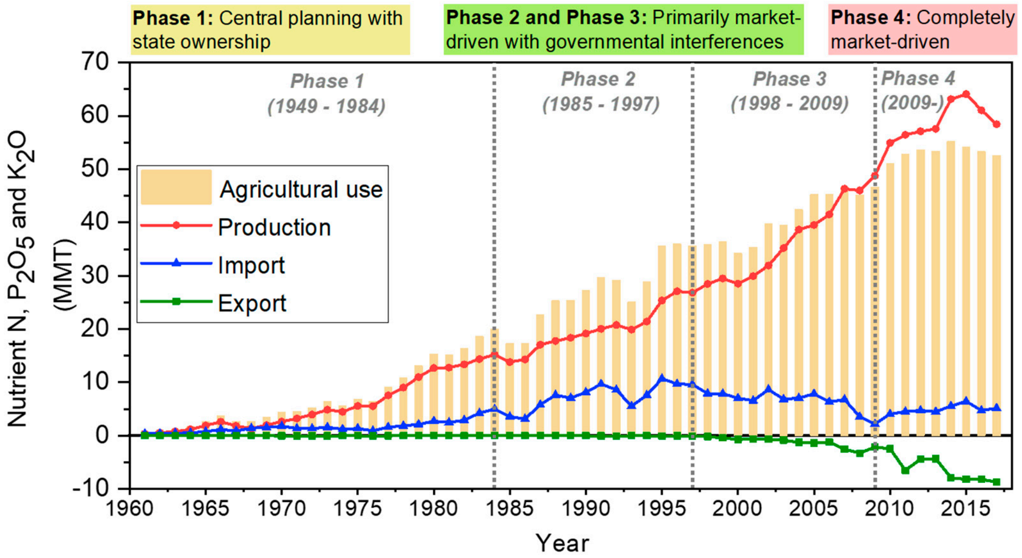


Figure 2. Production, consumption and international traded fertilizers in China (1961–2017) and the four development phases categorized by Li et al. [27]. Source of data: FAOSTAT.

Despite the progressive policies, other potential reasons behind China's fertilizer escalation have also been actively discussed over recent years. Some argued that the transformation of planting structure from cereal-based crops to nutrient-demanding cash crops has led to the substantial increase in mineral fertilizers [28,29]. Some proposed that the increasing opportunity costs of land and labor due to China's rapid urbanization, i.e., shrinking agricultural land area and increasing urban wages (urban–rural gap) contributed to the high amount of fertilizer use, as farmers substituted those inputs with mineral fertilizers [30,31]. Zhang et al. [32] as well as Huang et al. [33] emphasized the importance of agricultural extension systems, the lack of which has led to farmers' unwitting overuse of chemical fertilizers. Wu et al. demonstrated that the average small farm size in China is strongly related to the overuse of agrochemicals, which likely stems from the ineffective implementation of technological innovations and modern practices due to high fixed costs of adoption [34].

3.2. Production, Consumption and International Trade of Nitrogen, Phosphate and Potash Fertilizers in China

Although China's overall mineral fertilizer production has exceed that of domestic use since 2008, it does not necessarily indicate that China has achieved self-sufficiency in fertilizer supplies. Figure 3 illustrates a detailed picture of the production, agricultural use and internationally traded nitrogen, phosphate and potash fertilizers in China from 1961 to 2017. While agricultural use of all nutrients has drastically increased over recent decades, nitrogen and phosphate fertilizers share similar dynamics in terms of domestic production, imports and exports. Agricultural use of nitrogen and phosphate fertilizers were both restricted by their domestic production until the mid-1980s (Figure 3a,b), as their production growth could barely catch up with the prompt demand increase. The fertilizer demand grew especially quickly after the introduction of the "household responsibility system" in the early 1980s, when Chinese farmers were allowed to retain the profits from any additional harvest once their mandated quotas were fulfilled [24,35]. From then until the mid-2000s, imports started to play a role in compensating the need before China reached self-sufficiency. From 1985 to 2005, imported nitrogen and phosphate accounted for 16% of their total agricultural use, and the imported volume reached its peak in 1995 (783 MMT) [1]. Since the early 2000s, the growth rate in agricultural N and P use has started to decelerate, and their domestic production has expanded rapidly, shifting China's position from an importer to a major exporter of N and P. In 2017, China produced 29% and 31% of the world's nitrogen and phosphate fertilizers, constituting 13% and 26% of the export market share, respectively [1].

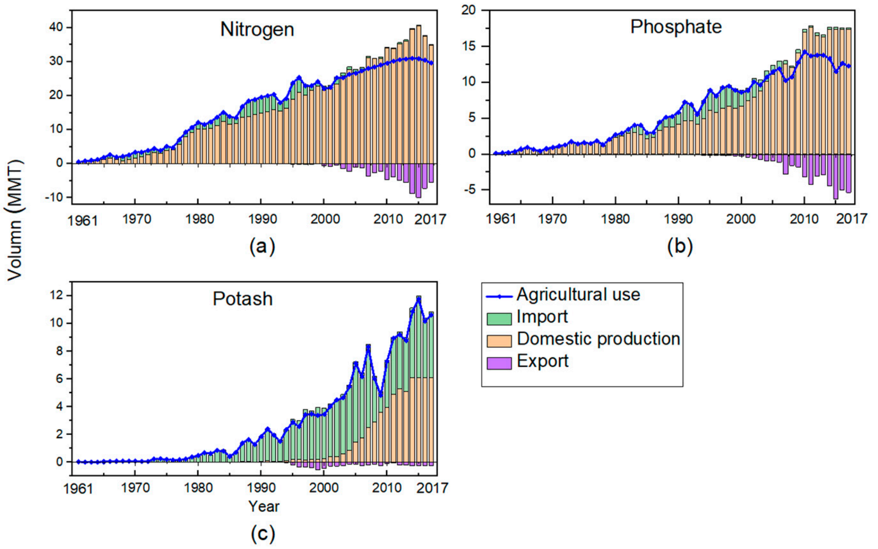


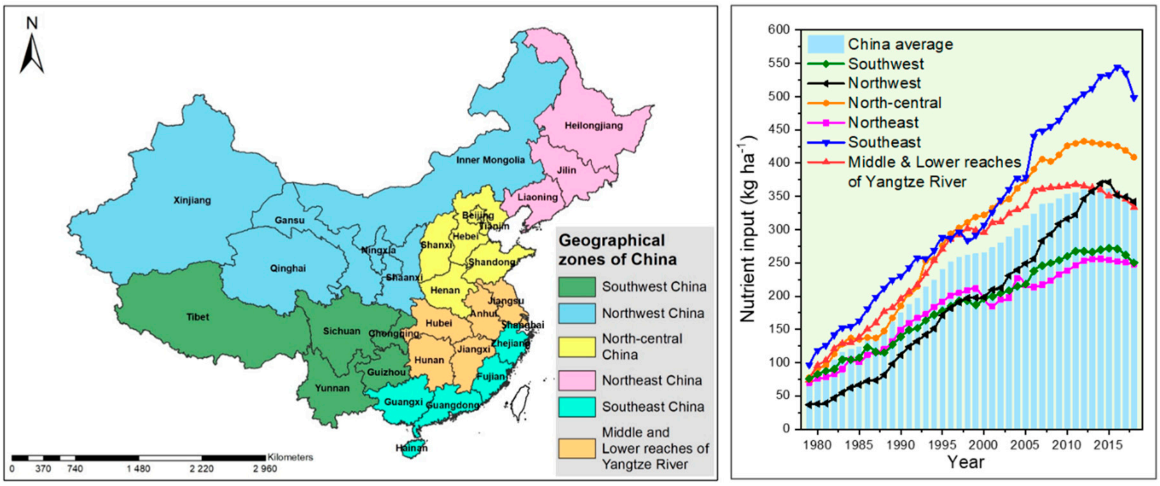
Figure 3. Production, consumption and internationally traded (**a**) nitrogen, (**b**) phosphate and (**c**) potash fertilizers in China (1961–2017). Source of data: FAOSTAT.

In contrast to the self-sufficiency in nitrogen and phosphate fertilizers, China's potash fertilizers have been heavily dependent on imports due to the low proved potash reserves and limited mining capacity [36]. Since the early 1990s, domestic potash fertilizer production slowly started and began to grow in the 2000s, with an annual growth rate of 30% between 1990 and 2000. However, it could barely meet the potash fertilizer demand, and consumption is still profoundly restricted by its imported volume (Figure 3c). In 2017, 57% of the potash fertilizer used in China was domestically produced, showing a significant increase compared with its 5.4% annual average throughout the 1990s [1]. Production data show that the expansion of China's potash production has stagnated over the last few years, while the future demand for potash might still increase due to insufficient input or low potash use efficiency [36,37]. This indicates that China's dependency on imported potash may still remain, adding the vulnerability of China's agricultural sector to the international market and energy price fluctuations.

4. Regional Use and Surpluses of Mineral Fertilizers in China

4.1. Mineral Fertilizer Use in China on Regional Level

Data regarding the agricultural use of mineral fertilizers in 30 provinces of China from 1979 to 2018 were obtained from NBS. Mineral fertilizer use in China showed an obvious spatial distribution over the last four decades (Figure 4). Eastern coastal and central regions of China have generally higher rates of fertilizer use compared with western and northern regions. The agricultural nutrient input of the former (incl. southeast, north-central and middle and lower reaches of the Yangtze River zones) is mostly above the national average, while that of the latter (incl. northwest, southwest and northeast zones) is the opposite.



(**a**) (**b**)

Figure 4. (**a**) Six geographic zones of China and (**b**) their historical fertilizer use (1979–2018). Nutrient input refers to the effective components of mineral fertilizers—nitrogen, phosphate and potash. Nutrient input per hectare was estimated as total nutrient input of the year divided by total sowing area of the year. Source of data: NBS.

As the major grain crop producers of China with intensive agriculture systems, the north-central as well as the middle and lower reaches of the Yangtze River regions contribute to more than 50% of the total cereal grain production volume each year. Fertilizer use in these regions enjoyed rapid growth in the 1980s and 1990s with a mean annual growth rate of 7.5% [18]. In the mid-2000s, the increase in fertilizer inputs in those areas slowed and has started to decrease since the 2010s.

In comparison with the cereal producing regions, regions with high cash–crop ratios (i.e., ratio of the cropping area of cash crops to the total cropping area) showed rather constant and rapid growth of fertilizer use, such as the northwest and southeast regions. Cash crops such as fruit, vegetables, as well as oil and fiber crops are generally nutrient-demanding, and farmers tend to apply more fertilizers to achieve higher profits [38]. Chen et al. [39] concluded that major cereal crops used nearly 90% of fertilizers in China up until the 1980s. After that, cash crops including vegetables and fruit together with maize became the major drivers of fertilizer consumption.

During 1979 to 2014, fertilizer use in northwest and southeast China increased by a factor of 10 and 6, respectively, from 36.7 and 96.8 to 396.3 and 530.4 kg ha^{-1} [18]. Although the mean fertilizer use in northwest China has been below China's average over the decades under consideration, it has the highest overall annual increasing rate (6.0%). The fertilizer expansions are especially significant in Xinjiang and Shaanxi provinces in northwest China, as well as Hainan, Guangdong and Fujian provinces in southeast China. Reasons behind this regional variation may include various cash-crop and grain-crop distribution, and multiple cropping indexes (i.e., ratio of sown area to cropping area). The Xinjiang and Hainan provinces have the highest cash–crop ratios in China (both 0.69 in comparison with the national average of 0.36 in 2018). The former is the largest cotton producer in China, and the latter has a substantial share of vegetables and tropical fruit production over its total agricultural land [18]. Guangdong and Fujian provinces not only have high cash–crop ratios (both 0.60 in 2018) but also high multiple cropping indexes due to their high temperatures and abundant water supply [40,41].

Shaanxi province has both intensive staple food production (incl. cereals, tubers and pulses) and orchard production, accounting for 56% and 21% of its agricultural land, respectively [18].

4.2. Mineral Fertilizer Surpluses in China on Regional Level

The drastic increase in fertilizer application over China has not only contributed to the growth in food production but has also caused environmental problems. To address the environmental consequences which may be associated with the overuse of mineral fertilizers, we quantified the regional nutrient surpluses in agricultural soils that originated from the applied mineral fertilizers. We used N and P surpluses as an indicator of the potential losses of applied mineral fertilizers to the environment, and conducted the estimation for 30 provinces in mainland China for the period from 1987 to 2018. A surplus of K was not included in the quantification, considering that potash in agricultural soils has been deficient in most of the regions in China [37].

N and P surpluses (kg ha^{-1} yr^{-1}) are defined as a positive difference between the sum of N and P inputs (e.g., fertilizers, manures, etc.) and its outputs (e.g., harvested crops) [42,43]. To estimate regional N and P surpluses due to the application of mineral fertilizers, we assumed that differences among NUEs and PUEs of various sources of N and P are negligible. This assumption has to be made, otherwise the approximation of nutrient surpluses out of mineral fertilizers on a regional level would be impossible. We derived NUEs of 30 provinces of mainland China based on published data of Zhang et al. [44] and Li et al. [45], and PUEs of the 30 provinces based on survey data of Zhang et al. [46] (Figure S1 and Table S1 in the Supplementary Materials). We then multiplied the NUEs and PUEs by the respective regional N and P fertilizer input data. Details regarding the calculation of regional NUE and PUE, and further N and P surpluses are available in the Supplementary Materials.

It is worth mentioning that nutrient surpluses from the application of organic fertilizers i.e., manure, human excreta, compost and crop residuals, were not included in the estimation for three reasons. Firstly, the present study focuses specifically on mineral instead of organic fertilizers in China. Secondly, the application of organic fertilizer in China is generally insufficient, especially in the recent two to three decades when farmers have had improved access to more effective chemical fertilizers [9,47]. Thirdly, environmental concerns regarding the application of organic fertilizers have been raised predominantly in the context of contamination by heavy metals or metalloids, microplastic, etc., as well as nitrate leaching and P accumulation, rather than nutrient surpluses due to their overuse [13,48–50].

Figure 5 illustrates regional and temporal variations of estimated fertilizer N and P surpluses over China from 1988 to 2018. Large differences in fertilizer N and P surpluses were observed among different provinces in China, and the gaps have continued to grow over recent decades. In 1988, N and P surpluses of the 30 provinces ranged from 26.6 to 170.4 kg ha^{-1}, whereby the top five provinces with the highest nutrient surpluses are all located in the south and southeast coastal areas (Shanghai, Fujian, Guangdong, Jiangsu and Zhejiang). Those are not only economically developed areas with dense populations but are also areas with high cropping indexes (triple cropping) [40]. Until 2008, regions with comparatively high nutrient surpluses have expanded to also include north-central and northwest China, and N and P surpluses of nearly half of the provinces exceeded 200 kg ha^{-1}. In 2015, the national mean nutrient surplus reached the peak (206.3 kg ha^{-1}), with Fujian being the highest (404.7 kg ha^{-1}) and Heilongjiang being the lowest (60.1 kg ha^{-1}). Since 2015, the nutrient surpluses of most provinces have started to decrease, apart from Beijing in the north-central region; Shanghai in the Yangtze River Delta, Fujian, Guangdong, Guangxi, Hainan in the southeast region; Yunnan in the southwest region; and Inner Mongolia in the northwest region (Table 2).

Table 2. Fertilizer N and P surpluses (kg ha^{-1}) of 30 provinces of mainland China from 1987 to 2018; average values of each of the four years are presented. The calculation method of N and P surpluses is available in the Supplementary Materials.

	Year	**1987–1990**	**1991–1994**	**1995–1998**	**1999–2002**	**2003–2006**	**2007–2010**	**2011–2014**	**2015–2018**
Northeast	Liaoning	98.8	125.5	149.5	145.5	154.5	166.1	169.0	159.9
	Jilin	67.1	85.3	101.5	95.7	104.7	106.1	113.9	106.2
	Heilongjiang	29.8	45.9	54.6	52.2	54.4	56.0	60.8	58.5
Northcentral	Beijing	121.4	173.1	222.7	248.8	287.5	269.3	310.3	389.8
	Tianjin	61.1	86.8	151.0	191.6	280.2	351.8	320.7	257.8
	Hebei	88.2	125.6	166.7	175.8	192.4	211.7	215.0	205.7
	Shanxi	70.9	99.3	124.3	130.6	147.0	165.5	175.5	167.7
	Shandong	118.3	165.6	199.0	214.7	236.7	241.0	230.3	210.0
	Henan	86.0	133.0	167.7	190.7	206.8	239.3	261.0	257.1
Middle and lower reaches of Yangtze River	Shanghai	194.9	220.5	215.1	246.6	229.0	195.1	159.8	167.8
	Jiangsu	148.7	191.4	239.2	255.2	261.3	317.2	246.7	222.9
	Zhejiang	130.9	139.9	153.6	164.6	203.9	245.9	252.1	236.2
	Anhui	97.8	120.5	160.8	165.5	167.1	174.7	180.9	178.1
	Jiangxi	74.5	91.7	105.1	105.3	124.0	124.3	124.6	116.2
	Hubei	111.7	150.2	203.9	203.5	239.3	267.3	261.6	219.6
	Hunan	87.8	103.3	117.0	122.5	138.2	149.9	146.7	140.4
Southeast	Fujian	160.3	189.9	219.4	242.9	272.1	309.9	366.7	396.4
	Guangdong	160.4	186.8	197.7	201.5	236.8	287.5	306.3	311.0
	Guangxi	85.9	106.1	123.9	133.7	160.6	193.7	208.2	211.0
	Hainan	93.9	107.5	133.0	168.6	272.4	311.6	323.5	358.7
Southwest	Sichuan (incl. Chongqing)	88.4	109.2	122.3	136.7	145.1	164.4	163.8	153.1
	Guizhou	63.9	83.0	86.7	91.4	97.8	103.0	103.5	94.6
	Yunnan	72.7	97.0	116.7	118.3	143.9	161.6	180.7	184.9
	Tibet	41.4	57.1	85.8	81.4	112.7	142.5	146.8	140.5
Northwest	Inner Mongolia	37.2	53.5	72.3	80.6	105.4	132.7	141.9	143.6
	Shaanxi	69.6	112.7	155.2	176.4	209.4	229.1	306.0	303.1
	Gansu	51.9	75.8	100.4	114.0	125.2	140.9	145.5	137.7
	Qinghai	51.7	72.3	78.8	89.8	96.2	104.9	109.7	104.9
	Ningxia	74.0	98.4	130.0	146.1	140.5	153.2	167.5	163.4
	Xinjiang	59.1	89.3	125.5	129.2	149.1	190.8	206.3	203.8

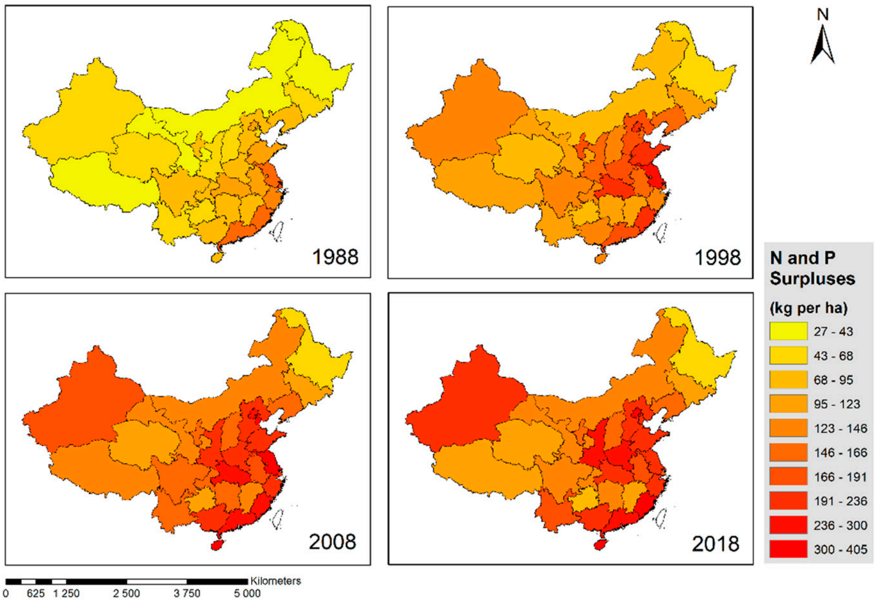


Figure 5. Temporal and regional variations of N and P surpluses in China in 1988, 1998, 2008 and 2018.

4.3. The Zero Growth Action Plan for Fertilizer Use by 2020: Provincial Performances in Fertilizer Use Reduction

Multiple policies have been issued in recent years to control the agricultural nonpoint source pollution in China, with aspects ranging from national environmental legislation to the specific sectoral regulations and action plans [11]. China's Zero Growth Action Plan of Fertilizer Use by 2020 specifies the goal of gradually controlling the annual growth rate of chemical fertilizer use to within 1% from 2015 to 2019, and achieving zero-growth by 2020 [10]. To gain an initial assessment of different provinces' performances in response to the Zero Growth Action Plan so far, and to determine whether China was able to achieve zero growth in fertilizer use in 2020, we quantified the average annual growth rates of fertilizer use as well as N and P surpluses for 30 provinces in mainland China. We categorized the provinces into three clusters in terms of per hectare fertilizer input and per hectare N and P surpluses, based on whether the average annual growth rate is above 1%, positive but below 1% or negative, during 2013–2015 and 2016–2018 (Table 3).

During 2013 to 2015, more than half of the provinces still had an increasing annual fertilizer input rate, with Beijing being the highest (7.6%) followed by Tibet (5.4%), Hainan (5.3%) and Xinjiang (5.2%). Eleven provinces showed negative annual growth rates, averaging −1.12% per year. Between 2016 and 2018, there were only five provinces that continued to have increasing rates of fertilizer use, and three of those had their annual growth rate controlled within 1% (Hunan 0.5%, Anhui and Hainan 0.3%). During 2013–2015, the national average growth rate of fertilizer use was still positive (1.1%), as opposed to the negative 2.3% growth rate between 2016 and 2018. This indicates the temporally realization of the Zero Growth Action Plan on a national level.

In comparison with the reduction in fertilizer use, that of fertilizer N and P surpluses was more promising. Between 2013 and 2015, the national average annual growth rate of N and P surpluses was only 0.48%, which further decreased to −3.1% for the period from 2016 to 2018. In 2018, all provinces showed negative annual growth rates in N and P surpluses, averaging −5.0%.

Following the Zero Growth Action Plan of Fertilizer Use by 2020, a detailed Implementation Plan was formulated in May 2015 [51]. Detailed targets of fertilizer use reductions were given, specifying an annual growth rate of fertilizer use less than 1%, 0.8%, 0.6% and 0.4% for 2015, 2016, 2017 and 2018. An overview of the performance of each province responding to the annual reduction targets is available in Table S2 in the Supplementary Materials.

Table 3. Average annual growth rates of fertilizer use and N and P surpluses of 30 provinces in China, for 2013 to 2015 and 2016 to 2018.

		Avg. Annual Growth Rate > 1%	**0 < Avg. Annual Growth Rate < 1%**	**Negative Avg. Annual Growth Rate**
2013–2015	Fertilizer input (kg ha^{-1})	(13): Beijing, Tibet, Hainan, Xinjiang, Fujian, Inner Mongolia, Qinghai, Yunnan, Gansu, Guangdong, Ningxia, Guangxi, Shanghai	(6): Shanxi, Jilin, Henan, Hebei, Zhejiang, Jiangxi	(11): Shaanxi, Heilongjiang, Guizhou, Anhui, Sichuan (incl. Chongqing), Hunan, Liaoning, Jiangsu, Shandong, Tianjin, Hubei
	Fertilizer N and P surpluses (kg ha^{-1})	(11): Beijing, Tibet, Hainan, Fujian, Qinghai, Xinjiang, Inner Mongolia, Yunnan, Guangdong, Gansu, Ningxia	(2) Shanghai, Guangxi	(17): Henan, Shanxi, Hebei, Jiangxi, Zhejiang, Shaanxi, Heilongjiang, Sichuan (incl. Chongqing), Guizhou, Anhui, Liaoning, Jilin, Hunan, Jiangsu, Shandong, Tianjin, Hubei
2016–2018	Fertilizer input (kg ha^{-1})	(2): Beijing, Shanghai	(3): Hunan, Anhui, Hainan	(25): Guangxi, Liaoning, Shaanxi, Henan, Jilin, Heilongjiang, Hebei, Shanxi, Jiangsu, Ningxia, Shandong, Sichuan (incl. Chongqing), Yunnan, Inner Mongolia, Fujian, Hubei, Guangdong, Zhejiang, Xinjiang, Jiangxi, Guizhou, Gansu, Qinghai, Tianjin, Tibet
	Fertilizer N and P surpluses (kg ha^{-1})	(1): Beijing	(1): Shanghai	(28) the rest

5. Conclusions, Recommendations and Perspectives

In the present study, we conducted a comprehensive review of mineral fertilizers in China over the last six decades, from the domestic production, consumption and international trade on national and international levels, to the agricultural use of fertilizer at a regional level. In addition, we quantitatively analyzed fertilizer N and P surpluses for 30 provinces in China from 1978 to 2018, integrating those results as a reference for evaluating the implementation of the Zero Growth Action Plan of fertilizers. Some researchers have already conducted initial or midterm evaluations of the implementation of the Zero Growth Action Plan of fertilizers [52,53]; however, our study is the first integrated assessment which also takes regional fertilizer N and P surpluses into consideration.

Chemical fertilizers have played a significant role in boosting China's food production. From 1961 to 2017, China's grain yield and mineral fertilizer use per hectare increased by a factor of 5 and 56, respectively. In 2014, China's mineral fertilizer use per hectare reached a peak (453.6 kg ha^{-1}) of 3.7 times of the world's average. Since 2015, the average fertilizer use volume in China has started to decrease as a response to multiple government policies and regulations seeking the reduction in mineral fertilizer use. By 2019, 83% of the provinces had reached a negative three-year average annual growth of fertilizer use, showing the potential of successfully completing the Zero Growth Action Plan nationwide by 2020. Some local government also issued crop-specific fertilization standards to regulate the regional application rate of chemical fertilizers [54,55]. Nevertheless, reducing annual growth rates of mineral fertilizer use is just one aspect of the Zero Growth Action Plan. Further specific objectives need to be reached, including optimizing the structure of fertilization, improving fertilization methods and enhancing the utilization rate of fertilizers. Therefore, a comprehensive analysis covering all those aspects will be necessary in order to have an overall evaluation of the implementation of the Zero Growth Action Plan of mineral fertilizers.

Fertilizer N and P surpluses in China have shown stronger reductions in comparison with the fertilizer use reduction. By 2019, only Beijing and Shanghai still had a three-year average positive growth rate of fertilizer nutrient surpluses. This indicates an overall improvement in nutrient use efficiency in recent years. However, large variations of N and P surpluses per hectare were observed among provinces in China. The southeast coastal region (Fujian, Guangdong, Guangxi and Hainan) has the highest fertilizer nutrient surpluses, whereas that of the northeast region (Liaoning, Jilin and Heilongjiang) is the lowest. This regional variation pattern is in line with the pattern of fertilizer input volume. Nutrient surpluses or potential environmental damages which could originate from organic fertilizers were not considered in the current study. However, it could be an interesting perspective for future research, especially after the implementation of the Zero Growth Action Plan of mineral fertilizers when the application rate of organic fertilizers is expected to increase profoundly.

China's agricultural sector still has a long way to go in facing the challenges of further enhancing agricultural productivity while minimizing the negative environmental impacts. Continuous efforts should be made to improve nutrient use efficiency—enhancing nitrogen and phosphorus efficiency with zero increment in chemical fertilizer use, and improving potash use efficiency to reduce the dependency on the imported K fertilizers. From one perspective, it can be seen that the future focus of China's fertilizer use will lie on continuously improving the use efficiency of mineral fertilizers, while enhancing the utilization of organic fertilizer resources for a more sustainable nutrient management scheme.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/12/17/7028/s1, Figure S1: (a) estimated NUE of China from 1961 to 2011 and (b) the estimation of regional-corrected NUEs of six zones in China; Table S1: estimated PUEs of 30 provinces in mainland China; Table S2: growth rate of fertilizer use of 30 provinces in China from 2015 to 2018.

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Supplementary Materials

1. Estimating Regional Nutrient Surpluses

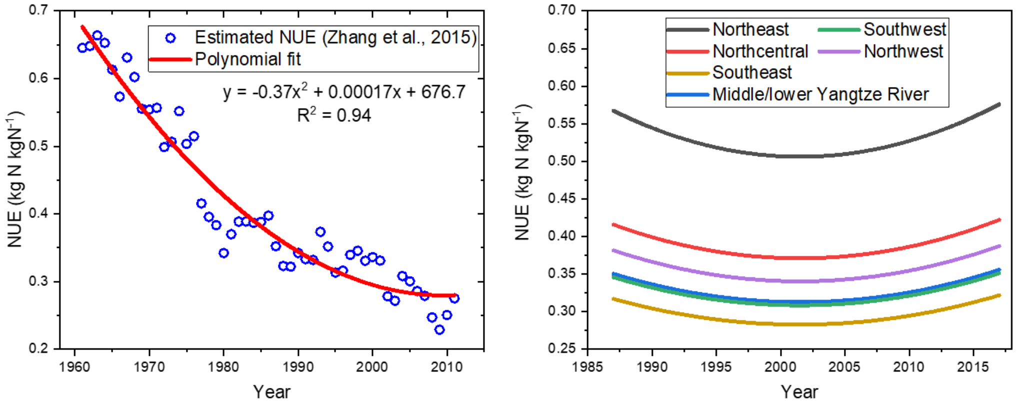
In agricultural soils, the total N inputs generally include N from fertilisers (mineral and organic), biologically fixed N and N deposition [1], whereas the total P inputs mainly refer to P from fertilisers. To derive regional N and P surpluses due to the application of mineral fertilisers, an estimation can be established as presented in equation (1), assuming the differences among NUEs and PUEs of various sources of N and P are negligible.

$$NP_{sur(ij)} = N_{fert(ij)}\left(1 - NUE_{ij}\right) + P_{fert(ij)}\left(1 - PUE_{ij}\right) \tag{1}$$

where $NP_{sur(ij)}$ is the sum of N and P surpluses from mineral fertiliser of *j-province* on *i-th* year, N_{fert} and P_{fert} refer to N and P inputs from mineral fertilisers (measured as the effective components), and NUE_{ij} and PUE_{ij} are the regional N and P use efficiency of year *i*. According to fertilisation data from National Bureau of Statistics of China, N_{fert} and P_{fert} have two further sources, respectively N or P from nitrogenous or phosphate fertilisers, and N or P from compound fertilisers. N and P from compound fertilisers were estimated based on the N: P_2O_5: K_2O ratio in different regions of China: 1:2.0:0.2 in the northeast region, 1:1.5:0.4 in the northcentral and northwest regions and 1:1:0.8 in the middle and lower reaches of Yangtze River, southwest and southeast regions [2].

1.1 The estimation of regional NUEs

We estimated regional NUEs of China based on published data of Zhang et al. [1] and Li et al. [2]. We firstly obtained a polynomial fit of the time-series NUE of China based on published data of Zhang et al. **(Figure S1a)**. Then, to reflect regional variations of NUEs over different regions, we derived a variation factor based on Li et al.'s published data regarding regional NUEs of China in 2008. We assumed that the regional variation of NUEs over China in 2008 can represent that of the time period 1993 to 2018, and the variation factor is therefore attained as the ratio of the regional NUE and China's average NUE of the year 2008. Estimated NUEs of different regions in China for the time period needed are presented in **Figure S1b.**



(a) (b)

Figure S1. (a). Estimated NUE of China from 1961 to 2011 based on Zhang et al. [1], and (b) the estimation of regional-corrected NUEs of six zones in China. The regional variation factors were derived by dividing the regional NUE by the mean NUE of China in the year 2008, based on published data of Li et al. [2].

1.2 The Estimation of Regional PUEs

Regional PUEs used in the study were estimated from a 10-year panel dataset generated by field surveys of Zhang et al. [3]. Zhang et al. measured total field P inputs (mineral fertiliser input, manure and human excreta) and total harvested P within crops and straw fields of 30 provinces in mainland China, with 186 collected samples during 2004 to 2009 and 155 collected samples during 2010 to 2014. As the calculated PUEs of most of the provinces in China have rather small variations, the arithmetic mean of the 10-year PUEs of each province was adopted in the study **(Table S1)**.

Table S1. Estimated PUEs of 30 provinces in mainland China. Source of data: Zhang et al. [3].

Northeast	Liaoning	0.35	**Southeast**	Fujian	0.18
	Jilin	0.57		Guangdong	0.16
	Heilongjiang	0.61		Zhejiang	0.28
Northcentral	Beijing	0.19		Guangxi	0.20
	Tianjin	0.22		Hainan	0.12
	Hebei	0.34	**Southwest**	Sichuan (incl. Chongqing)	0.27
	Shanxi	0.32		Guizhou	0.33
	Shandong	0.31		Yunnan	0.27
	Henan	0.31		Tibet	0.05
Yangtze River	Shanghai	0.27	**Northwest**	Inner Mongolia	0.35
	Jiangsu	0.35		Shaanxi	0.32
	Anhui	0.36		Gansu	0.26
	Jiangxi	0.33		Qinghai	0.16
	Hubei	0.27		Ningxia	0.32
	Hunan	0.36		Xinjiang	0.41

2. Performances of Each Province in Responding to the Annual Target

In the Implementation Plan following the Zero Growth Action Plan of fertiliser use by 2020, detailed annual targets in fertiliser use reduction were given, specifying the aim of having an annual growth rate of fertiliser use less than 1%, 0.8%, 0.6% and 0.4% for 2015, 2016, 2017 and 2018 [4]. **Table S2** illustrates the growth rates of fertiliser use per hectare of 30 provinces in China from 2015 to 2018. Provinces with a growth rate exceeding the annual targets are marked with *.

Table S2. Growth rate of per hector fertilizer use of 30 provinces in China from 2015 to 2018. Provinces with the growth rate exceeding the annual targets are marked with *.

		2015	**2016**	**2017**	**2018**
Northeast	Liaoning	−2.32%	−0.52%	−0.09%	−1.13%
	Jilin	0.19%	−0.06%	−1.48%	−1.09%
	Heilongjiang	−0.81%	−1.12%	−0.20%	−1.59%
Northcentral	Beijing	2.29% *	8.38% *	6.63% *	-0.65%
	Tianjin	−4.30%	−2.34%	−16.53%	−3.64%
	Hebei	−0.07%	−1.22%	−1.96%	−0.80%
	Shanxi	0.54%	−0.67%	−3.96%	−1.52%
	Shandong	−1.54%	−0.62%	−2.13%	−4.19%
	Henan	0.45%	−0.30%	−0.02%	−2.31%
Middle & Lower reaches of Yangtze River	Shanghai	3.11% *	6.23% *	3.92% *	−5.06%
	Jiangsu	−2.12%	−1.65%	−1.70%	−3.29%
	Anhui	−1.80%	5.43% *	−1.83%	−2.67%
	Jiangxi	0.12%	−0.78%	−4.42%	−7.36%
	Hubei	−6.44%	−0.84%	−3.64%	−6.92%
	Hunan	0.01%	0.12%	−0.25%	1.49% *
Southeast	Fujian	4.28% *	4.45% *	−6.11%	−6.49%

	Guangdong	3.51%	2.09%	−2.12%	−11.53%
	Zhejiang	−1.90%	−1.92%	−3.90%	−5.78%
	Guangxi	−3.24%	2.77% *	0.59%	−3.37%
	Hainan	6.39% *	2.45% *	4.67%	−6.28%
Southwest	Sichuan (incl. Chongqing)	−0.72%	−1.20%	−2.90%	−3.05%
	Guizhou	1.95% *	−1.30%	−8.63%	−3.34%
	Yunnan	2.57% *	2.08% *	−1.61%	−7.64%
	Tibet	11.65% *	−14.45%	−3.08%	−11.82%
Northwest	Inner Mongolia	−1.21%	−3.79%	−0.46%	−3.22%
	Shaanxi	0.86%	−2.19%	1.97% *	−1.74%
	Gansu	0.53%	−4.11%	−9.63%	−2.12%
	Qinghai	3.13%	−13.42%	−0.59%	−4.37%
	Ningxia	0.55%	2.80% *	−1.02%	−8.54%
	Xinjiang	2.64% *	−11.86%	0.80% *	−1.35%

* Provinces with a growth rate exceeding the annual targets.

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Chapter 3 - Publication

Investigating the environmental Kuznets curve between economic growth and chemical fertilizer surpluses in China: a provincial panel cointegration approach[a]

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RESEARCH ARTICLE

Investigating the environmental Kuznets curve between economic growth and chemical fertilizer surpluses in China: a provincial panel cointegration approach

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Abstract

This study investigated the relationship between fertilizer nitrogen (N) and phosphate (P) surpluses and economic development on the regional level in China. With a balanced panel dataset covering 30 provinces of mainland China from 1988 to 2019, we employed panel cointegrating polynomial regression (CPR) analysis using fully modified OLS (FM-OLS) estimators. Our results suggested that all provinces exhibit a long-run cointegrated relationship between fertilizer surpluses and real per capita gross regional product (GRP). A total of 22 provinces out of 30 showed a significant inverted U-shaped environmental Kuznets curve (EKC). Among those, 14 provinces are considered to have reached the peak and 8 provinces are considered to be before the peak. The group-mean turning points on the EKC are CNY 7022, CNY 9726, CNY 4697, CNY 3749, and CNY 5588 per capita GRP (1978 = 100) for the Northeast, Northcentral, Middle, and lower reaches of the Yangtze River, Southwest and Northwest China, respectively. The overall turning point of China is CNY 6705 per capita real gross domestic product (GDP), which was reached in circa 2012. This shows a general improvement of chemical fertilizer management in China. However, six provinces still exhibit linear growth in fertilizer surpluses when the economy grows. These regions are characterized by high cash-crop ratios and are mostly located along the southeast coast. Therefore, more effort and attention should be given to these regions to promote further fertilizer reduction. At the same time, nutrient use efficiencies should be improved, especially for cash crops such as fruit and vegetables.

Keywords Chemical fertilizer surplus · China · EKC · Cointegrating panel regression · Regional

Introduction

Chemical fertilizer use has been an essential component in modern agricultural production, comprising the majority of plant nutrients to sustain the current crop yields and soil fertility (Tilman et al. 2002; Stewart et al. 2005). An evaluation of long-term studies showed that fertilizer inputs accounted for 40 to 60% of crop yields in temperate climates, and for even higher proportions in the tropics (Stewart and Roberts 2012). On the one hand, this has substantially contributed to hunger reduction worldwide and the sustainment of food security (Bruinsma 2003; Bindraban et al. 2020). On the other hand, the excessive use of fertilizers in recent decades has not only led to its diminishing returns in yield improvement, but also caused numerous environmental problems, such as water impairment, soil acidification, and air pollution (Tilman et al. 2002; Gruber and Galloway 2008; Parris 2011; Savci 2012).

The fertilizer dilemma — food or the environment — is especially pronounced in the case of China. In recent decades, China has experienced a significant expansion in agricultural productivity. While per capita arable land kept decreasing, the average major grain yields (wheat, rice, and maize) more than doubled from 2952 kg ha^{-1} in 1978 to 6378 kg ha^{-1} in 2019 (NBS 2020). At the same time, China's value added in agriculture, forestry, and fishery increased 25-fold and reached USD 1.02 trillion in 2019

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(The World Bank 2021). Significant factors contributing to the agricultural productivity boost are the drastically intensified agricultural inputs (Fig. 1). Over the last four decades, China's per hector inputs of chemical fertilizer and agricultural machinery increased 5.5-fold and eightfold, respectively. The ratio of sown area under irrigation also grew from 0.30 in 1978 to 0.41 in 2019 (NBS 2020). In 2014, China's chemical fertilizer use per sown area reached its peak (363 kg ha^{-1}), which is three times the world's average (121 kg ha^{-1}) and more than twofold that of the US and the European Union (FAOSTAT 2020; NBS 2020).

Coupled with China's excessive use of chemical fertilizers, in recent years, there have been reports of massive agricultural non-point source pollution (Ongley et al. 2010; Zhao et al. 2011; Sun et al. 2012; Smith and Siciliano 2015). To cope with this, in 2015, the Chinese Ministry of Agriculture developed the Zero Growth Action Plans for fertilizer and pesticide use by 2020 (MoA 2015; Jin and Zhou 2018). Since then, an overall reduction of fertilizer consumption in China has been observed, although regional variations still persist (Jin et al. 2018, 2019; Yu et al. 2020).

Introduced by the pioneering work of Grossman and Krueger (1991, 1995) and Panayotou (1995), the environmental Kuznets curve (EKC) theory has been widely discussed in recent decades in studies investigating the relationship between environmental pollution and economic growth. The EKC theory implies that, as the economy develops, the environmental degradation first increases and, when a certain income level is reached, decreases again. Therefore, the relationship between the environmental and economic indicator appears as an inverted U-shaped curve. Our objective is to analyze the relationship between chemical fertilizer surpluses and economic growth on the regional level in China as well as to test the existence of an inverted U-shaped EKC between the two indicators. The chemical fertilizer surpluses here are defined as the positive difference between fertilizer nitrogen (N) and phosphate (P) inputs and their outputs (Liu et al. 2010; Bouwman et al. 2013). We collected a balanced panel dataset covering 30 provinces of mainland China with a sampling period from 1988 to 2019. Panel cointegrating polynomial regressions (CPR) (Wagner and Hong 2016; Wagner and Reichold 2018) were estimated using fully modified OLS (FM-OLS) to study the EKC relationship.

Our study contributes to the existing literature in multiple ways. Firstly, we explicitly analyzed time-series fertilizer N and P surpluses for each province of China and used them as the environmental indicators instead of using the fertilizer application rates. This helped to exclude confounding factors related to the inhomogeneity of nutrient use efficiencies and soil conditions of different regions. Secondly, in contrast to existing studies, we applied state-of-the-art methods to model our nonstationary variables, namely estimating CPRs with appropriate FM-OLS estimators (Wagner 2015; Wagner and Hong 2016), to provide valid inferential results. Finally, our analysis integrated the empirical results with, inter alia, regional socio-economic backgrounds and policy implications in China, providing a comprehensive analysis and overview of China's chemical fertilizer use.

The present paper proceeds as follows. The "Literature review" section provides a literature review concerning agrochemical consumption in the context of the EKC hypothesis. The "Methodology" section introduces the theoretical framework, data, and methodology employed in the study while the "Results" section presents the results of the empirical analysis. The "Discussion" section discusses the results in the context of socio-economic development, policy interventions, and cropping structures in China. The "Conclusion" section draws conclusions, puts forward policy implications, and addresses limitations and further research directions of the study.

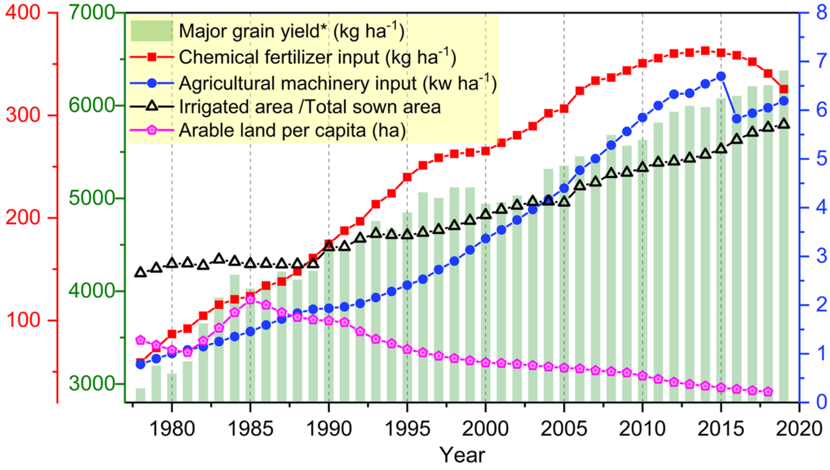


Fig. 1 This figure displays average yields of major grains and major agricultural inputs in China from 1978 to 2019. *Major grains here include rice, wheat, and maize. Source of data: NBS and FAOSTAT

Literature review

Although various pollution indicators have been applied in the EKC context, overwhelmingly, it has been greenhouse gas emissions that have been selected and investigated (e.g., Yang et al. 2017; Ali et al. 2017; Olale et al. 2018; Hanif et al. 2019; Murshed et al. 2020; Anwar et al. 2021; Alharthi et al. 2021). Sarkodie and Strezov (2019) categorized the indicators used in the majority of EKC-related studies into four categories, namely atmospheric indicators; land indicators; oceans, seas, coasts, and biodiversity indicators; and freshwater indicators. Their findings revealed that the current EKC-related studies were predominately based on atmospheric indicators, whereas studies concerned with other aspects were still limited.

Previous studies concerning agrochemical use in the EKC context

Over the last decade, research investigating the relationship between economic development and agriculture-induced pollution has gained considerable attention (Liang 2016; Ali et al. 2017; Ridzuan et al. 2020; Selcuk et al. 2021). Among those, a few studies discussed agrochemical consumption (e.g., chemical fertilizers, pesticides, and agricultural plastic films) as a land indicator in the framework of the EKC hypothesis, recognizing them as a source of agricultural non-point pollution (see Tables 1 and 2 for an overview of the literature). Longo and York (2008) are some of the pioneers mentioning fertilizer and pesticide consumption in the EKC context. They employed cross-national data from the year 2000 to empirically investigate the relationship among structural factors, e.g., economic development, export intensity, and agrochemical consumption among nations using OLS regression models. Their results showed that, within the range of the observed GDP per capita, there was some indication of an EKC in terms of pesticide use but not fertilizer use.

Since 2009, multiple studies included agrochemical consumption in the EKC context using time-series data. While some of those were conducted at a world scale covering various nations (see Table 1), many were specifically focused on China, either nationwide or region specific (see Table 2). For instance, Liu et al. (2009) investigated the relationship between chemical fertilizer consumption and per capita real gross output value of agriculture (GVA) of 31 provinces of China from 1949 to 2007, and concluded that 7 provinces had significant inverted U-shaped EKCs while 10 had N-shaped and linearly increasing curves. Li and Zhang (2009) tested the relationship between per capita GDP and chemical fertilizer use, pesticide use, and the density of livestock and poultry excrement, respectively. They found empirical support for the hypothesized inverted U-shaped EKC between China's agricultural non-point source pollution and economic growth.

While the majority of the above-mentioned studies used the absolute application rates of fertilizers or pesticides as the environmental indicator, only a few adopted fertilizer pollution emission as an alternative (Zhang et al. 2015; Li et al. 2016; Celikkol Erbas and Guven Solakoglu 2017; Yao 2019). Zhang et al. (2015) established an N-budget database for 113 countries for the period 1961 to 2011, and used N surplus, i.e., the sum of N inputs minus N outputs (biologically fixed N and N deposition were also considered), as an environmental indicator in the EKC hypothesis. They investigated the EKC for each individual country using autoregressive distributed lag (ARDL) models and revealed a significant quadratic relationship between GDP per capita and N surplus. Similar to Zhang et al. (2015), Li et al. (2016) and Yao (2019) also adopted fertilizer surpluses instead of the application rates in their analysis. Both of the studies investigated the relationship between agricultural-related pollution and economic growth in China. In addition to fertilizer N surplus, they further included fertilizer P surplus and pesticide. Li et al. (2016) applied panel cointegration and panel-based dynamic OLS analysis, and Yao (2019) used fixed effects regression analysis. Both of their empirical findings revealed a long-run inverted U-shaped EKC in China between the environmental index and economic growth. Other than using fertilizer surpluses, Celikkol Erbas and Guven Solakoglu (2017) suggested an alternative path of quantifying the agricultural emissions. They estimated N_2O emission from N fertilizers, and they investigated its relationship with economic development for 145 countries from 2002 to 2010. They revealed a short-run EKC relationship between agricultural emissions and income using vector error correction models (VECM).

Research gaps

In the literature, we identified the following shortcomings or research gaps in the context of agrochemical consumption and the EKC hypothesis.

Firstly, the majority of studies used fertilizer application rates as the indicator of agricultural non-point source pollution. However, considering the inhomogeneity of nutrient use efficiencies among regions and over time, fertilizer nutrient surpluses are a better alternative. In addition, among the limited number of studies in which fertilizer surpluses were used as an indicator, only a few (e.g., Zhang et al. 2015) clearly stated how and from where the fertilizer surpluses data were derived. Secondly, in comparison to other EKC-related studies (e.g., EKC for greenhouse gas emissions), the majority of agrochemical-related EKC studies have rather

Table 1 A collection of *cross-national* EKC-related studies using agrochemical use as the environmental indicator

Reference	Case study	Data period	Key variables	Methodology	Major results
(Celikkol Erbas and Guven Solakoglu 2017)	145 countries	2002–2010	N_2O emission from N fertilizers, per capita GDP and the share of agricultural sector in GDP	Vector Error Correction Model (VECM)	A long-run causality between agricultural emissions and income, agriculture share, and land temperature anomalies was confirmed. A short-run EKC relationship was found between agricultural emissions and incomes of various countries
(Hedlund et al. 2020)	106 nations	1990–2014	Total pesticide consumption (incl. insecticide, herbicide, and fungicide), value added in agriculture, agricultural employment, arable land, food exports, GDP per capita, population	Fixed effects panel regression models	A positive relationship between economic growth and pesticide consumption over time was revealed. At higher levels of economic development, there would be no decline in pesticide use
(Longo and York 2008)	Cross-national	2000	Chemical fertilizer and pesticide use, agricultural exports, GDP per capita, irrigated land as a proportion of arable land, population	Ordinary least squares (OLS) regression models	While there is some indication of an EKC in terms of pesticide use, there is no indication of an EKC in relation to fertilizer use. The increases in exports of agricultural products contribute to increases in fertilizer and pesticide consumption within nations
(Pincheira et al. 2021)	177 countries	1973–2013	Planetary boundaries (incl. global chemical fertilizer consumption), and real GDP	OLS and fixed effect model, and the system generalized method of moment (GMM)	The existence of the classic EKC is supported for climate change and ocean acidification panels. However, biochemical cycles, ozone depletion and freshwater use, land change, and biodiversity loss boundaries do not support the EKC hypothesis using the same methodology
(Zhang et al. 2015)	113 countries	1961–2011	N surplus[a] and GDP per capita	ADF unit root test and Autoregressive Distributed Lag (ARDL) (fixed effects model)	A significant quadratic relationship between GDP per capita and N surplus was revealed ($p < 0.001$). Regressions between GDP per capita and N surplus for each individual country fall into five response types: Bell shape, U-shape, linearly increase, not significant, and negative N surplus

Table 2 A collection of *China-specific* EKC-related studies using agrochemical use as the environmental indicator

Reference	Case study	Data period	Key variables	Methodology	Major results
(Chai et al. 2020)	Heilongjiang province, China	2005–2017	Application rates of chemical fertilizers, pesticides and agricultural films, and *farmers' income*	Regression analysis	N-shaped relationships were found between both the application rate of chemical fertilizers and pesticide, and farmers' income. The relationship between the consumption of agricultural films and farmers' income followed an inverted U-shaped curve
(Gong and Tian 2010)[b]	China (average)	1978–2008	Application rate of chemical fertilizers, and per capita real *gross output value of crop production (GVC)*[c]	ADF unit root test and OLS regression	A significant inverted U-shaped EKC was observed between chemical fertilizer use and rural economic development in China. The per capita real GVC at the turning point was 547.67 CNY (1978 = 100), which has occurred in 2008
(Guo and Sun 2012)[b]	Jiangsu province, China	2001–2010	Application rates of chemical fertilizers and pesticides, density of livestock and poultry excrement, and real per capita GDP *of rural population*	ADF unit root test and non-linear regression analysis	Inverted U-shaped EKC were observed between agricultural pollution and rural economic development for the study area. GDP per capita at the turning points were 2130, 1970, and 3440 CNY for chemical fertilizers, pesticides, and livestock and poultry excrement, respectively
(Hong 2013)[b]	Chongqing municipality, China	1996–2010	Application rate of chemical fertilizers and *per capita real GVC*	OLS regression	There was a significant inverted U-shaped EKC between agriculture economic development and fertilizer input intensity. Turning point of the EKC occurred in 2009
(Li 2019)	Various provinces in China	1989–2017	N and P fertilizer use per capita (rural population), per capita real *gross output value of agriculture (GVA)*[c], and per capita real GDP	Panel unit root test and panel cointegration	A significantly inverted U-shaped relationship was confirmed between economic growth variables and agricultural environmental pollution variables
(Li et al. 2016)	31 provinces in China	1989–2009	Fertilizer N and P surplus[a], pesticide use intensity, and GDP per capita	Panel unit root, panel cointegration and panel-based dynamic OLS	A long-run cointegrated inverted U-shaped EKC was revealed between the environmental index and real GDP per capita. The value of the turning point is approximately 10,000–13,000, 85,000–89,000, and over 160,000 CNY, for synthetic fertilizer N indicator, fertilizer P indicator, and pesticide indicator, respectively

Table 2 (continued)

Reference	Case study	Data period	Key variables	Methodology	Major results
(Li and Zhang 2009)[b]	31 provinces in China	1998–2006	Application rates of chemical fertilizer and pesticide, density of livestock and poultry excrement, and per capita GDP	Random and fixed effects models	The inverted U-shaped EKC was confirmed between China's agricultural non-point sources pollution and economic growth. Curves of all the three pollution sources are before the turning point
(Liu et al. 2009)[b]	31 provinces in China	1949–2007	Chemical fertilizer use and real *per capita GVA*	Non-linear regression analysis	27 provinces out of 31 had a significant relationship between fertilizer use and per capita GVA. 7 provinces had inverted U-shaped curves, while 10 had N-shaped and linear increase curves, respectively
(Liu et al. 2021a)	Three Gorges Reservoir region, China	2002–2017	Consumption of agrochemicals (chemical fertilizers, pesticides, and agricultural films), and per capita GDP	Spatial panel regression analysis	Inverted U-shaped EKCs were confirmed between economic development and chemical fertilizers and pesticides, respectively. Around half of the counties/districts have not met the corresponding inflection points of the EKCs
(Liu et al. 2021b)	Hubei province, China	2000–2017	Application rates of chemical fertilizers and the annual index of gross farming output	Unit root tests and panel regression analysis	An N-shaped EKC was confirmed between the annual county-specific fertilizer-impact indexes and the rural household income in Hubei, China
(Peng 2014)	Chengdu (a city in China)	1995–2012	Application rates of chemical fertilizers, pesticides and agricultural plastic films, density of slaughtered fattened hogs, and *per capita real GVA*	Non-linear regression analysis	The relationship between per capita real GVA and fertilizer input density reveals an N-shaped pattern. Inverted U-shaped curves were found between per capita real GVA and pesticide use intensity, agricultural film density, and density of slaughtered fattened hogs, respectively
(Shang et al. 2017)[b]	Heilongjiang province, China	1992–2014	Application rates of chemical fertilizers, pesticides and agricultural plastic film, density of livestock and poultry excrement, and *real per capita GVA*	ADF unit root test and regression analysis	Inverted U-shaped EKC was found between pesticide use and agricultural development. N-shaped EKCs were found between chemical fertilizer use, livestock and poultry excrement, and agricultural development, respectively

Table 2 (continued)

Reference	Case study	Data period	Key variables	Methodology	Major results
(Wang 2011)[b]	10 cities from Zhejiang province, China	2000–2008	Application rates of chemical fertilizers and pesticides, density of pigs and poultry, *real per capita GVA*, and rural population	Fixed effect model	The inverted U-shaped EKC was confirmed between agricultural pollution and agricultural growth for the study area. The per capita GVA at turning point was 6418.7 CNY. EKCs of all cities were before the turning point
(Xu et al. 2021)	30 Provinces in China	2006–2015	Nitrogen oxides emissions per capita from energy and nitrogen fertilizers, and GDP per capita	Panel unit root tests, panel cointegration test, and Dumitrescu–Hurlin causality tests	The inverted U-shaped EKC exists between economic growth and nitrogen oxides emissions in China. During the survey period, all provinces have reached their turning points
(Yao 2019)	31 provinces in China	2007–2016	N and P fertilizer pollution emission[a], crop production value, and the proportion of crop production value in total agricultural output value	Fixed effects regression analysis	An inverted U-shaped EKC was confirmed between economic scale and non-point source pollution of chemical fertilizers
(Zhang and Hu 2020)	25 provinces in China	1995–2017	Fertilizer use intensity, per capita rural income, and urban–rural income gap	Dynamic panel-data model	An inverted U-shaped relationship exists between fertilizer use intensity and per capita rural income. However, the peak turning point is much higher than the actual per capita rural income of all provinces in China

[a] Fertilizer N and P surpluses were calculated differently in various studies. F. Li et al. (2016) estimated China's N and P surpluses from synthetic fertilizers based on regional fertilizer input, nutrient uptake from crop products, and soil basic fertility. X. Zhang et al. (2015) established an N budget database for 113 countries. They quantified the N use efficiencies (NUE) for each country, taking into consideration the application rate of chemical and organic fertilizers, N fixation, atmospheric N deposition, and harvested N in yield Yao (2019) estimated the pollution emission of N and P fertilizers in China, by multiplying fertilizer application rates by fertilizer loss rates in the literature

[b] Original language in Chinese

[c] In this paper, the *gross output value of agriculture (GVA)* refers to the sum-up of the *gross output values of crop production (GVC)*, forestry, animal husbandry, and fishery

short sampling periods ($T < 25$). This may reduce the robustness of their results considering that it is difficult to model nonstationarity in short time series. Nonetheless, this weakness might be unavoidable due to the lack of agrochemical data at a higher sampling frequency, and the fact that agrochemical overuse has only gained attention in recent decades (Yadav et al. 1997; Wu et al. 2018). Thirdly, various economic variables were used to indicate economic growth in the EKC context, especially in studies focused on China (see Table 2). The existing differences were mainly among real/nominal, GDP/GVA/GVC/farmers' income, and per capita population/rural population. Therefore, the results should always be interpreted with caution and a comparison of EKC turning points across studies is difficult. Last but not least, while many EKC studies listed in Tables 1 and 2 account for the nonstationarity of the variables in the EKC regression (Gong and Tian 2010; Guo and Sun 2012; Shang et al. 2017), they still apply unit root and cointegration techniques that are not suitable for such cointegrated polynomial regressions (Wagner 2015). Particularly, they do not account for the fact that powers of an integrated process are in a deterministic relationship with the underlying integrated process which requires specific estimators (Wagner and Hong 2016).

Methodology

Theoretical framework and data

We hypothesize that the chemical fertilizer surpluses in China follow a similar pattern to the idealized EKC projection (Fig. 2). In the early stages of the industrialization, fertilizer surpluses increase rapidly with economic growth. This could be due to the increasing demand for food as the population grows, the expansion of nutrient-intensive cash crop production, and/or highly subsidized fertilizer prices. Then, as the economy further develops, the quest for, inter alia, environmental sustainability, and resource efficiency would emerge. This will slow down the increasing rate of fertilizer surpluses and eventually lead to the reduction. Later on, the fertilizer surpluses are expected to keep decreasing as a result of the sustainable intensification of agriculture throughout the post-industrialization period (Zhang et al. 2015; Murshed et al. 2021). It is important to understand the dynamic between economic development and fertilizer surpluses in the EKC context. This knowledge could help to evaluate the current fertilizer management and the resulting policy implications for China. Furthermore, understanding this relationship can provide a guideline towards a more sustainable agricultural production in the future.

The empirical analysis of the study employs balanced panel data covering 30 provinces of mainland China from 1988 to 2019 (Table 3). We selected real gross regional product (GRP) per capita as the indicator of economic development since it is a general indicator for economic progress at the regional level. The per capita GRP data were gathered from two sources: data from 1993 to 2019 were obtained directly from the National Statistical Bureau of China (NBS), and data from 1988 to 1992 were derived based on each year's China Statistical Yearbook. All per capita GRPs were calculated at a constant price (1978 = 100).

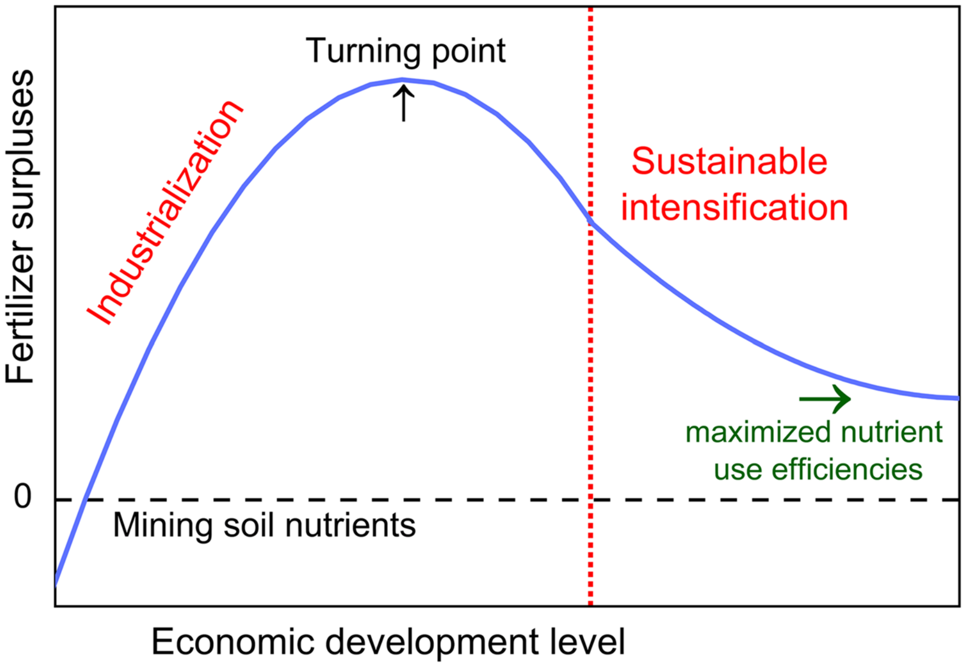


Fig. 2 An idealized fertilizer surpluses-induced EKC. Modified from Zhang et al. (2015) and Murshed et al. (2021)

Table 3 Description of the variables and data sources

Variable	Description	Data needed	Data source
Real GRP per capita (1000 CNY year^{-1})	Gross regional product per capita at a constant price (1978 = 100)	GDP of China[a]	NBS
		Indices of GDP (1978 = 100)	NBS
		GRP per capita	NBS (1993–2019), China statistic yearbooks (1988–1992)[b]
Fertilizer N and P surpluses (kg ha^{-1} year^{-1})	The difference between the sum of N and P inputs from chemical fertilizers, and the output from harvested crops	N and P from single-nutrient fertilizers	NBS
		N and P from compound fertilizers	NBS, China Agriculture Yearbook[c]
		Regional total sown area and regional orchard area[d]	NBS
		Regional NUE	Li et al. (2013a); Zhang et al. (2015)
		Regional PUE	Zhang et al. (2019)

[a] The GDP data of China were used to derived annual GDP deflators for further real GRP calculation, i.e., the GDP deflator of *t*-year is $\text{GDP deflator}_t = \frac{\text{Nominal GDP}_t}{\text{GDP}_{1978} \times \text{GDP Index}_t} \times 100$;

[b] Since GRP per capita data from 1988 to 1992 were not directly available, they were calculated by dividing the year's GRP by the average value of the year's year-end population and that of the previous year;

[c] N and P from compound fertilizers were estimated based on the $N:P_2O_5:K_2O$ ratio in different regions of China: 1:2.0:0.2 in the northeast region, 1:1.5:0.4 in the northcentral and northwest regions, and 1:1:0.8 in the middle and lower reaches of Yangtze River as well as the southwest and southeast regions (MOA 2010);

[d] According to NBS, the "total sown areas of farm crops" cover 10 categories of crops: grain, oil-bearing crops, cotton, hemp, sugar crops, tobacco, medicinal materials, vegetables, melons, and other farm crops (NBS 2020). The cultivation area of orchard fruits, e.g., apples, pears, and tropical fruits are not included. Therefore, we used the sum-up of total sown area and orchard area as the total cultivated land area. Note that tea plantations were not included in the calculation, considering their small fraction and lack of data in many regions

To address the environmental impacts due to the overuse of chemical fertilizers, we estimated the potential nutrient losses to the environment — N and P surpluses — from the applied chemical fertilizers. N and P surpluses (kg ha^{-1} year^{-1}) are defined as a positive difference between N and P inputs and their outputs in crop production on an annual basis (Liu et al. 2010; Bouwman et al. 2013). By assuming that the differences among plant N and P use efficiencies (NUEs and PUEs) of various sources of N and P (e.g., chemical fertilizers, manures, etc.) are negligible, we quantified annual fertilizer N and P surpluses in agricultural soils of 30 provinces in China:

$$\text{NP}_{\text{sur(tj)}} = N_{\text{fert(tj)}} \bullet \left(1 - \text{NUE}_{\text{tj}}\right) + P_{\text{fert(tj)}} \bullet \left(1 - \text{PUE}_{\text{tj}}\right), \tag{1}$$

where $\text{NP}_{\text{sur(tj)}}$ (kg ha^{-1}) is the sum of N and P surpluses from chemical fertilizers of province j in year *t*. N_{fert} and P_{fert} (kg ha^{-1}) refer to the effective components of fertilizer N and P from single-nutrient and compound fertilizers. NUE_{tj} and PUE_{tj} are the regional N and P use efficiency in year t. The regional NUEs of China used in this study were derived from Zhang et al. (2015) and S. Li et al. (2013a), and the regional PUEs were estimated by Zhang et al. (2019). Fertilizer input data as well as regional land use data were attained from NBS. Note that a surplus of potash fertilizer was not considered in the study, given that potash in agricultural soils in China has been deficient in most of the regions (He et al. 2015). For simplicity, the Chongqing region was included in Sichuan province.

For a more detailed description concerning the calculation of the regional N and P surpluses in China, see Yu et al. (2020).

All variables were transformed into their natural logarithm for further analysis.

Unit root tests, cointegrating polynomial regressions, and panel analysis

Considering the criticism regarding the use of nonstationary data in some classic EKC-related studies (Müller-Fürstenberger and Wagner 2007; Wagner 2008, 2015), we performed unit root tests for our data to test the variables for their order of integration. We applied three types of unit root tests: the Phillips–Perron (PP) and augmented Dickey-Fuller (ADF) tests, testing the null hypothesis of a unit root; and the Kwiatkowski–Phillips–Schmidt–Shin (KPSS) test, testing the null hypothesis of mean (trend) stationarity. All tests were conducted with a constant and trend specification.

After determining the order of integration, we specified the EKC regression for each province. Following Wagner (2015), the classical EKC regression is a cointegrating polynomial regression, and its coefficients and standard errors need to be estimated with a specific methodology. For this purpose, we implemented the FM-OLS approach proposed by Wagner and Hong (2016) based on the following equation:

$$\mathrm{NPsur}_{\mathrm{it}} = \beta_0 + \beta_1 \mathrm{GRP}_{\mathrm{it}} + \beta_2 \mathrm{GRP}_{\mathrm{it}}^2 + e_{\mathrm{it}}, \tag{2}$$

where $\mathrm{GRP}_{\mathrm{it}}$ is assumed to be integrated of order one and e_{it} is a stationary error term. The variables were log-transformed before they entered the regression. We then tested for cointegration using either the P_{u} statistic (null hypothesis of no polynomial cointegration) or the KPSS-type statistic (null hypothesis of polynomial cointegration) suggested by Wagner (2015) and Wagner and Hong (2016). Should the null hypothesis of the P_{u} test be rejected, or the null hypothesis of the KPSS-type test not be rejected (ideally both test decisions should align), we conclude that GRP and *NPsur* hold a stable non-linear long-run relationship over the sampling period. Otherwise, the error terms would be deemed nonstationary and Eq. 2 would represent a spurious regression purely driven by the variables trending in the same direction. After cointegration testing, we need to further classify the estimated EKCs according to their shape. For this purpose, we need to conduct valid inference on the coefficients of the EKC regression which is guaranteed (at least asymptotically) by using the FM-OLS estimator. Conceptually, the FM-OLS estimator uses a two-part transformation to dynamically orthogonalize the variables and removes an additive bias term to allow for standard asymptotic inference. For these non-parametric corrections, long-run variances need to be estimated. Following Grabarczyk et al. (2018), we estimate all long-run variances based on the Bartlett kernel and the data-dependent bandwidth rule of Newey and West (1994). Specifically, we tested whether the coefficient β_2 is significantly different from zero to distinguish linear from quadratic curves. Only if the null hypothesis $\beta_2 = 0$ is rejected, the conditions $\beta_1 > 0$ and $\beta_2 < 0$ hold, we can classify the estimated curve as being consistent with the inverted U-shape suggested by the EKC hypothesis. We can then use our coefficient estimates to calculate the turning points,$\exp(\frac{-\beta_1}{2\beta_2})$ for each EKC relationship.

Since we are limited to a short sampling period but have a panel structure with 30 provinces, we also estimated several panel cointegration models according to Wagner and Reichold (2018) to benefit from the available cross-sectional dimension. To do so, we computed the cross-sectional average over the FM-OLS coefficients obtained from the individual EKC regressions. Moreover, they provide the necessary tools to conduct inference. These results can then be compared to EKC regressions for yearly country-level data employed in the literature (Gong and Tian 2010; Guo and Sun 2012; Li et al. 2016). In addition, we also computed the group-mean estimates over the six regions in China, i.e., Northeast, Northcentral, Middle and lower reaches of Yangtze River, Southeast, Northwest, and Southwest zones. This helped to gain more insights into the regional dispersion of the results and to investigate the spatial pattern.

For the robustness check of the GRP−NPsur nexus from Eq. 2, we further introduced a control variable into the model. Similar to Celikkol Erbas and Guven Solakoglu (2017), we included the share of crop production sector to GRP (CropGRP) to incorporate the level of agricultural activities in regional economies. The modified model can be specified as:

$$\mathrm{NPsur}_{\mathrm{it}} = \beta_0 + \beta_1 \mathrm{GRP}_{\mathrm{it}} + \beta_2 \mathrm{GRP}_{\mathrm{it}}^2 + \gamma \mathrm{CropGRP}_{\mathrm{it}} + e_{\mathrm{it}}, \tag{3}$$

We derived CropGRP for 30 provinces of China from 1988 to 2019. After determining the order of integration for CropGRP, we performed the earlier described FM-OLS approach for the coefficient estimations. Signs of the coefficients and their significant levels from Eq. 3 will be later compared with the main results from Eq. 2 for a robustness check.

Results

Unit root tests

We conducted three types of unit root tests for each regional variable. The test specification either included a constant or a constant with linear trend term. The results are presented in Table 7 in the Appendix. The PP tests showed that the NPsur variables of 14 provinces, and the GRP variables of 29 provinces were determined to have a unit root, but both variables turned stationary after first differencing for the large majority of the provinces. The ADF test results are similar to those of the PP test for the variables in levels. However, only less than half of the provinces' NPsur and GRP are determined to be integrated of order one, according to the ADF results. In contrast to the ADF and PP test, the KPSS test has the null hypothesis that the stochastic process generating the respective time series is mean-stationary or trend-stationary depending on the exact specification of the test regression. Our results showed that the null hypothesis cannot be rejected for both variables in their level form if we include only a constant term. However, the results were more ambiguous when we included an additional linear trend term. Here, the results agreed with the PP test results for NPsur, but we only determined a minority of provincial GRP variables to be nonstationary. Moreover, only a couple of GRP variables were found to be stationary after first differencing. Although some provinces had variables that were stationary according to the ADF, PP, and KPSS test, we argue that the variables were integrated of order one, which is the conservative choice considering that the polynomial EKC regression can be estimated straightforwardly for stationary variables as well. The main reason for our argument is that, due to the data availability, our sample size was limited to $T = 30$, which is very small in the context of unit root testing. Unit root tests are known to suffer from size distortions and low power when the sample size is too small. Particularly, the KPSS test has unfavorable small sample properties (Caner and Kilian 2001). Secondly, there was no overlap of nonstationarity results among the three tests; in other words, both variables of all the provinces tested nonstationary in at least one test.

Estimating the relationship between chemical fertilizer surpluses and economic growth in China

Table 4 presents the results of both polynomial cointegration tests and parameter estimates for each province using Eq. 2. The KPSS-type cointegration tests for each province showed that the residuals of the EKC regressions follow a stationary trajectory. This means that a significant cointegrated relationship between fertilizer surpluses and per capita GRP was maintained for all provinces. The corresponding test with the opposing null hypothesis of no cointegration (P_u statistic) again suffers from low power in small samples. In this case, we can only reject the null hypothesis for two provinces at

Table 4 Results of cointegration tests and CPR coefficient estimates

	Cointegration tests		FM-OLS estimates		
Province	P_u statistic	KPSS statistic	β_0	β_1	β_2
Liaoning	10.731	0.065**	4.46***	0.52***	−0.12***
Jilin	16.169	0.058**	4.40***	0.25***	−0.05
Heilongjiang	9.391	0.073**	3.63***	0.49***	−0.14**
Beijing	9.507	0.07**	4.41***	0.64**	−0.09
Tianjin	10.158	0.102**	3.10***	1.84***	−0.34***
Hebei	13.579	0.061**	4.71***	0.58***	−0.16***
Shanxi	9.063	0.053**	4.60***	0.49***	−0.14***
Shandong	10.869	0.088**	4.89***	0.6***	−0.18***
Henan	7.844	0.037**	5.00***	0.51***	−0.13***
Shanghai[a]	17.939	0.087**	4.86***	0.65	−0.2**
Jiangsu	4.215	0.063**	5.02***	0.63***	−0.18***
Zhejiang	15.322	0.104**	4.79***	0.23**	−0.01
Anhui	13.45	0.082**	4.96***	0.38 ***	−0.15***
Jiangxi	16.716	0.065**	4.58***	0.32***	−0.15***
Hubei	9.406	0.058**	5.02***	0.72***	−0.26***
Hunan	13.944	0.069**	4.67***	0.34***	−0.12***
Fujian	21.169*	0.089**	5.04***	0.22***	0.03
Guangdong[b]	18.605	0.083**	4.99***	0.1	0.05
Guangxi	16.175	0.096**	4.71***	0.34***	−0.04*
Hainan	9.183	0.141**	4.63***	0.79***	−0.12
Sichuan	20.72*	0.061**	4.78***	0.34***	−0.12***
Guizhou	15.254	0.059**	4.56***	0.2***	−0.16***
Yunnan	17.778	0.097**	4.68***	0.48***	−0.13***
Tibet	28.43**	0.059**	4.36***	0.77***	−0.26***
Inner Mongolia	9.873	0.053**	4.04***	0.62***	−0.1***
Shaanxi	10.485	0.063**	4.80***	0.6***	−0.14***
Gansu	18.748	0.044**	4.56***	0.55***	−0.25***
Qinghai	23.509**	0.064**	4.29***	0.5***	−0.18***
Ningxia	17.522	0.062**	4.68***	0.51***	−0.18***
Xinjiang	12.092	0.057**	4.33***	0.85***	−0.21***

Triple, double, and single denote statistical significance at 1%, 5%, and 10%, respectively

[a,b]Since the linear terms of Shanghai and Guangdong were insignificant in the quadratic model specification, we conducted F-tests of the joint hypothesis that both coefficients are zero for the two provinces. The null hypothesis was rejected for both provinces ($p < 0.001$), so we re-estimated the linear model specification. The t-statistics showed that the linear term was significant for both provinces and the parameter estimates were Guangdong: NPsur = 4.921 + 0.236GRP, and Shanghai: NPsur = 5.687–0.200GRP

the 5% level. However, we closely studied the residuals for those provinces where the results of the two cointegration tests disagreed and found that their trajectory much more resembled that of a typical stationary process. Therefore, we assume that the variables are cointegrated and that the opposing test results were driven by the small sample size which makes it difficult to distinguish between stationary and nonstationary processes. Moreover, these ambiguous results are not surprising if we take into account that the results for the preceding unit root tests were ambiguous as well.

The FM-OLS estimates in Table 4 indicate that 22 provinces out of 30 exhibit an inverted U-shaped EKC between GRP and NPsur ($p < 0.05$), 7 provinces showed positive linear relationship whereas 1 province exhibit a negative linear relationship between GRP and NPsur. These results are largely in line with those from the robustness check using Eq. 3 (see Tables 8 and 9 in the Appendix), where 23 provinces (the same 22 provinces plus Beijing) showed a significant inversed U-shaped EKC. Results of the linear specification of Eq. 3 also showed similarities to those using Eq. 2, despite that some linear coefficients of Eq. 3 are insignificant. This results further established the robustness of our results using Eq. 2.

Table 5 reports the group-mean panel FM-OLS results for China and the six regions. The panel results for five out of six regions imply an inverted U-shaped EKC.

Providing the existence of a significant cointegration between fertilizer surpluses and the economic growth of all the provinces, we categorized the provinces into four groups. Similar to the approach of Zhang et al. (2015), we grouped the provinces based on the significance and the sign of the coefficients of the linear and quadratic terms. Provinces with a significant inverse U-shaped EKC ($p < 0.05$) were defined as Group 1 — *inverted U-shaped curves*. Provinces that exhibit significant linear relationships between GRP and NPsur were categorized as *Group 2 — linearly increase* or *Group 3 — linearly decrease,* depending on the sign of the linear coefficient. If none of the quadratic or linear terms were significant, we conducted an F-test of the joint hypothesis that both terms are insignificant. If this null hypothesis was not rejected, that province was relegated to *Group 4 — insignificant.*

To indicate whether the fertilizer surpluses of a province had passed the peak and started to decline as the economy grew, we further characterized Group 1 — inverted U-shaped curves into three subgroups. We compared those provinces' recent 3-year (2017–2019) and 5-year (2015–2019) averages of fertilizer surpluses and per capita GRP with their corresponding estimated EKC peak positions. A province was considered to *have passed the peak (Group 1a)* if the following two conditions were met: (1) both of its 3-year and 5-year averages of fertilizer surpluses were lower than the lower bound of the 95% confidence interval for the estimated fertilizer surpluses peak, and (2) both of its 3-year and 5-year per capita GRP averages were higher than the per capita GRP at the peak ($\frac{-\beta_1}{2\beta_2}$). Similarly, a province was considered to be *at the peak (Group 1b)*, if *only* its 3-year averages of fertilizer surpluses and per capita GRP fulfilled the previously described criteria. Lastly, a province was considered to be *before the peak (Group 1c)*, if it did not fall into the former two subgroups.

Figure 3 illustrates the distribution of various response types of EKCs over China. Among the 22 provinces with significant inverted U-shaped EKCs, 8 provinces were considered to have passed the peak (Group 1a: Shandong, Jiangsu, Jiangxi, Hubei, Hunan, Qinghai, Sichuan, and Guizhou), indicating fertilizer surpluses of these regions had been decreasing as the economy developed. Six provinces were considered to be at the peak with the tendency of levelling off (Group 1b: Liaoning, Shanxi, Anhui, Gansu, Ningxia, and Tibet). Examples of provinces in Groups 1a and 1b are shown in Fig. 4 a. The provinces belonging to Groups 1a and 1b have around half of the cultivated land in China, covering the region of the middle and lower reaches of Yangtze River, a large fraction of southwest China, and some parts of the northcentral, northeast, and northwest

Table 5 Panel results based on the group-mean FM-OLS

	Provinces included	β_0	β_1	β_2	Turning point (in CYN per capita, 1978 = 100)
Northeast	Jilin, Liaoning, Heilongjiang	4.16***	0.42***	−0.11***	7022
Northcentral	Beijing, Tianjin, Hebei, Shanxi, Shandong, Henan	4.45***	0.78***	−0.17***	9726
Northwest	Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang, Inner Mongolia	4.45***	0.61***	−0.18***	5588
Middle and lower reaches of Yangtze River	Shanghai, Jiangsu, Anhui, Jiangxi, Hubei, Hunan	4.84***	0.47***	−0.15***	4697
Southeast	Zhejiang, Fujian, Guangdong, Guangxi, Hainan	4.84***	0.36***	−0.02	–
Southwest	Sichuan, Guizhou, Yunnan, Tibet	4.60***	0.45***	−0.17***	3749
China		4.59***	0.54***	−0.14***	6705

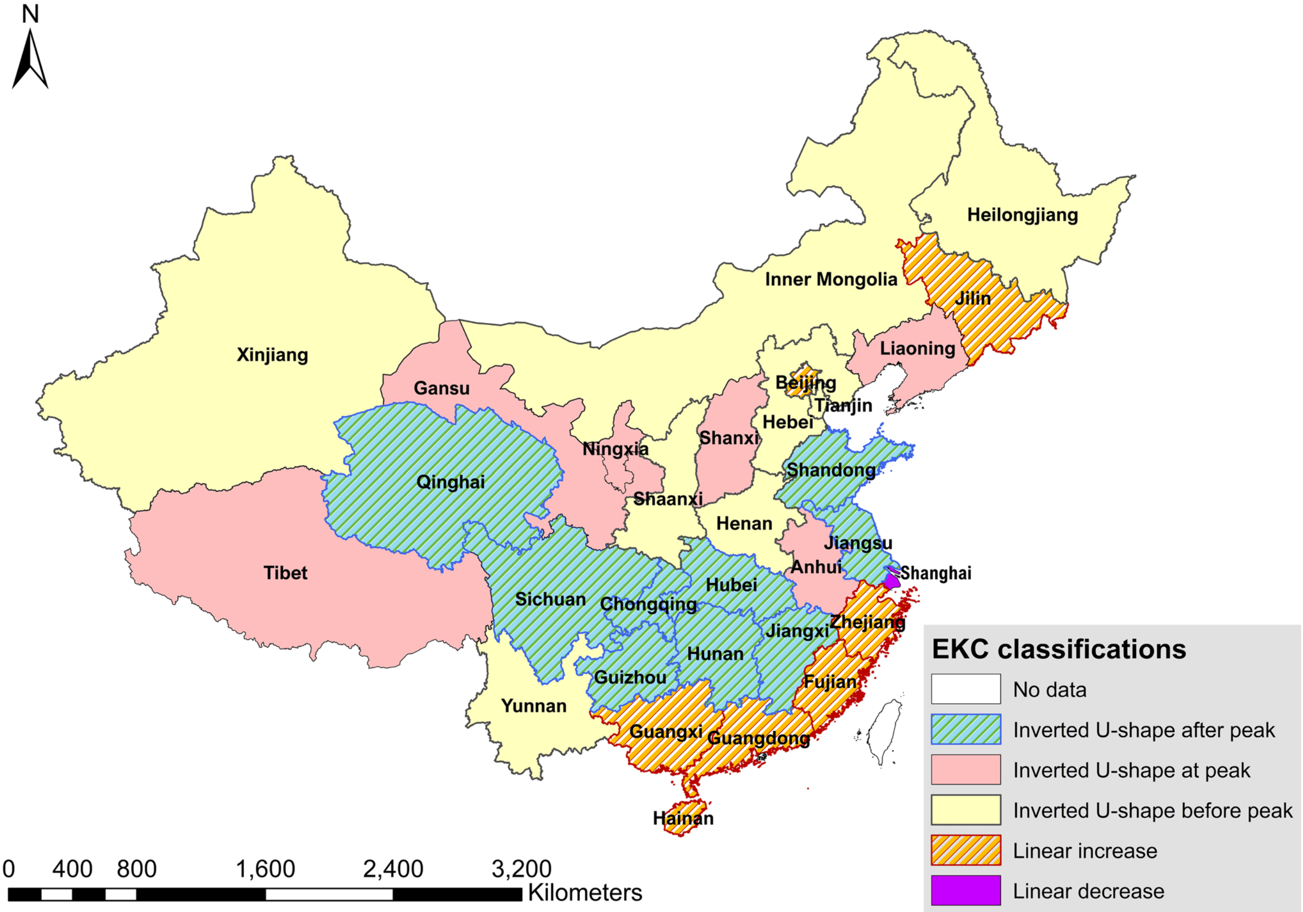


Fig. 3 The distribution of different shapes of EKCs in China. Source of data: own calculation

China. Besides Groups 1a and 1b, eight provinces fell into Group 1c — inverted U-shape before peak, suggesting that the fertilizer surpluses of those provinces will still increase as the economy grows but with diminishing increasing rates. With the exception of Yunnan province, the majority of the Group 1c provinces are located in northern China, including Heilongjiang, Henan, Tianjin, Hebei, Inner Mongolia, Shaanxi, and Xinjiang. In 2019, those 22 provinces with inverted U-shaped EKCs covered 86.3% of the cultivated land in China and were responsible for 82.5% of the total chemical fertilizer consumption. Their total GVC accounted for 82% of the domestic GVC (NBS 2020). These data provide support for a classic EKC relationship between agricultural pollution and economic development. Considering that most of the regions in China have already achieved negative annual growth rates of fertilizer consumption as a response to the "Zero growth plan for fertilizers by 2020" (Jin et al. 2019; Yu et al. 2020), those results further support the hypothesis that chemical fertilizer management has improved in China since 2015. In contrast to those findings, one province — Shanghai — exhibited a decreasing linear relationship between per capita GRP and fertilizer surpluses (see Fig. 4c).

Nevertheless, in addition to the inverted U-shaped and linear decreasing curves, seven provinces still showed a positive linear relationship between fertilizer surpluses and economic development (Group 2). These provinces include Guangdong, Zhejiang, Fujian, Guangxi, and Hainan in Southeast China as well as Jilin and Beijing in the north. In contrast to the provinces in Group 1c, those in Group 2 tended to have constant increases in fertilizer surpluses as the per capita GRP grew (see Fig. 4b). The current observations suggest that an occurrence of EKC turning points for these seven provinces is unlikely in the near future.

Discussion

Although the existence of an inverted U-shaped relationship between economic and environmental indicators has been empirically supported in various studies, the potential factors influencing the shapes and turning points of EKCs are controversially discussed in the literature. Many have

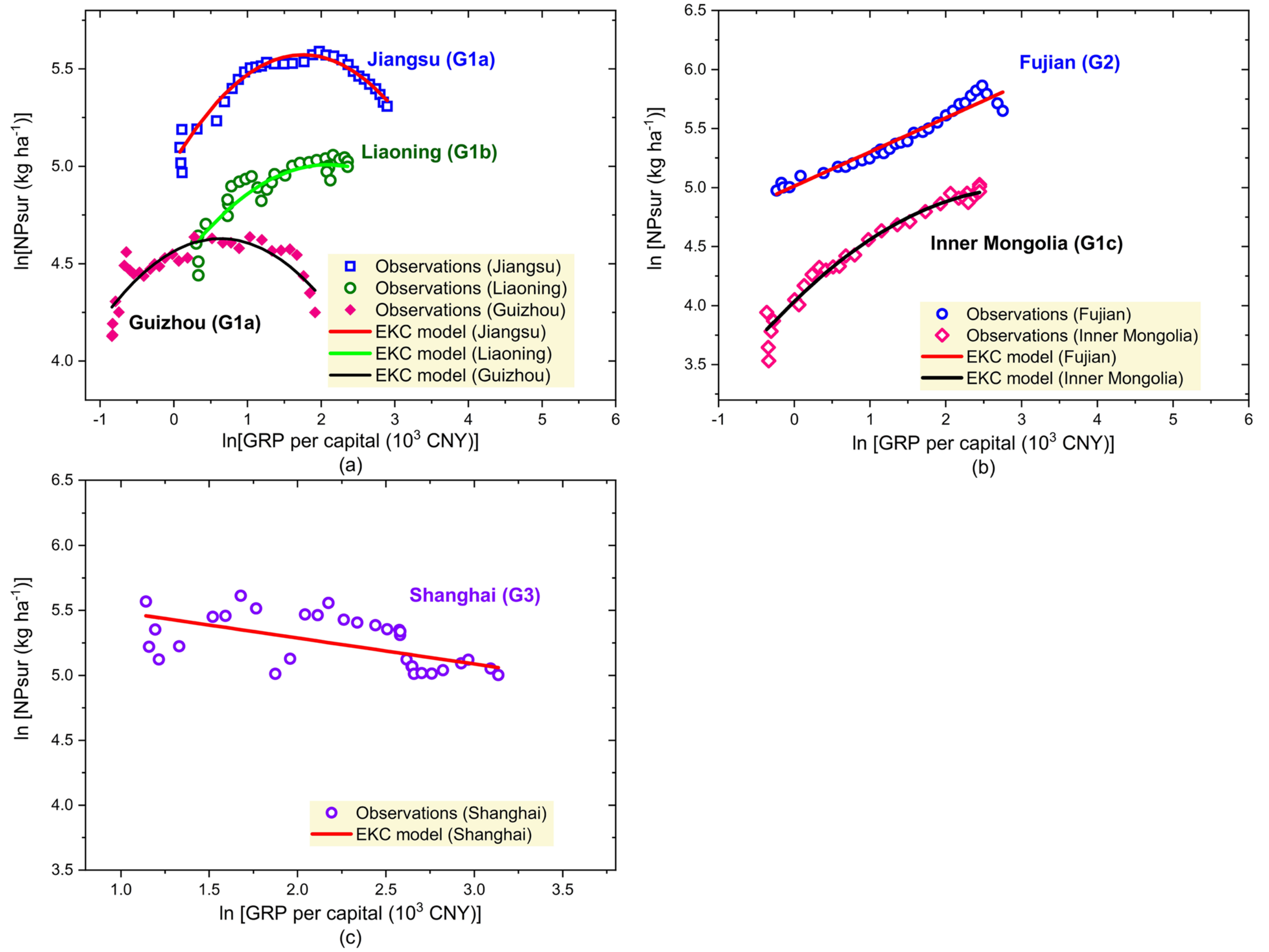


Fig. 4 Examples of the relationships between economic growth and fertilizer surpluses. **a** Comparison between Jiangsu and Guizhou in *Group 1a — inverted U-shaped curves after peak*, and Liaoning in *Group 1b — inverted U-shaped curve at peak*. **b** Comparison between Inner Mongolia in *Group 1c — inverted U-shaped curve before peak*, and Fujian in *Group 2 — linear increase*. **c** Shanghai in *Group 3 — linear decrease*

suggested that the potential causes are complex and may be affected conjointly by, inter alia, environmental and socio-economic conditions, cultures, technologies, international trades, and policies (Dinda 2004; Kaika and Zervas 2013; Sarkodie 2018). This makes it difficult to evaluate horizontal comparisons of EKC results among different nations or regions.

Over the last two decades, there has also been a sizeable amount of literature criticizing the EKC hypothesis. One common criticism was that the shapes and turning points of the EKCs vary notably depending on the chosen indicators and the scale of the studies, making it difficult to find a specific value as a good predictor of the EKC turning points among nations (Dinda 2004; Zhang et al. 2015). Another criticism concerned the incomparability of EKCs between developed and developing countries. For instance, Stern (2004) argued that the EKCs estimated for developing countries are more likely to show an inverted U-shape than those for developed countries because the former could adopt the latter's technological innovations to reduce pollution with a short time lag. Furthermore, Nahman and Antrobus (2005) suggested that the EKC hypothesis is a "historical artifact" resulting from the relocation of pollution-intensive industries from developed to developing countries.

Nevertheless, the objective of the present study was not to investigate the validity of the EKC theory. Our intention was to visualize and discuss the interconnections among chemical fertilizer consumption, socio-economic development, cropping structures, and policy implications using the existing EKC framework. In addition, our focus was specifically on regional China, which narrowed down the potential factors that may confound our empirical results.

Socio-economic development, policy interventions, and the turning points on the EKC

Our results suggest that a total of 22 provinces in China out of 30 had a significant inverted U-shaped relationship between fertilizer surpluses and economic development. Yet, the modeled peak positions, i.e., turning points on the EKCs, appeared to have large variances among and within the groups (see Fig. 5). Generally, provinces belonging to Group 1a reached the turning point at lower levels of per capita GRP (1978 = 100) in comparison to the provinces belonging to Groups 1b and 1c. In addition, the provinces in Group 1c have the highest average turning point both in terms of per capita GRP and fertilizer surpluses. On average, the fertilizer surpluses of provinces in Group 1a started to decrease when the real GRP reached CNY 4044 per capita, and the corresponding value was CNY 9820 for provinces in Group 1c. Considering that large areas in provinces of Group 1c are regarded as socio-economically less-developed regions of China — especially in Heilongjiang, Henan, Shaanxi, Xinjiang, and Yunnan (Gu et al. 2011; Tian et al. 2020), the high per capita GRP at the turning point added uncertainties in their future EKC projections.

The variations in turning points also appeared on the regional level (see Table 5). For example, since the large majority of provinces in the region of Lower and middle reaches of Yangtze River have reached their turning points, this region has a rather low level of group-mean GRP at the turning point (CNY 4697 per capita). On the contrary, the estimated turning point of the Northcentral region is CNY 9726 per capita, as three out of five provinces there have not reached their respective turning points yet. Our group-mean panel results showed that the overall turning point for China is CNY 6705 per capita real GDP, which was reached in circa 2012. This result is basically in line with the reported turning points for agrochemicals in China from other studies (Gong and Tian 2010; Wang 2011; Hong 2013; Li et al. 2016). Although it appears difficult to compare the exact peak values due to various indicators selected, the estimated time points of the peak position are similar. For example, Li et al. (2016) concluded that China had reached its turning point of nitrogen indicator in 2009 whereas the turning point of phosphate indicator was still far ahead. Gong and Tian (2010) argued that China's turning point of fertilizer consumption had been reached in 2008, whereas Li and Zhang (2009) noted that in 2005 the fertilizer-induced EKC was still in the increasing phase. Some regional studies indicated that Chongqing had reached its turning point of fertilizer input in 2009 (Hong 2013), and Jiangsu was approaching the turning point in 2010 (Guo and Sun 2012).

In addition, we also found that provinces that still exhibit positive relationships between fertilizer surpluses and economic growth, i.e., the provinces in G1c and G2, have generally large proportions of gross output value of crop production over the total gross regional product. For example, the three provinces with the highest ratio of GVC to GRP in 2019 were Heilongjiang (0.28) and Xinjiang (0.19) from Group 1c, and Hainan (0.15) from Group 2, in comparison to the national average 0.07 (NBS 2020). The reliance of those

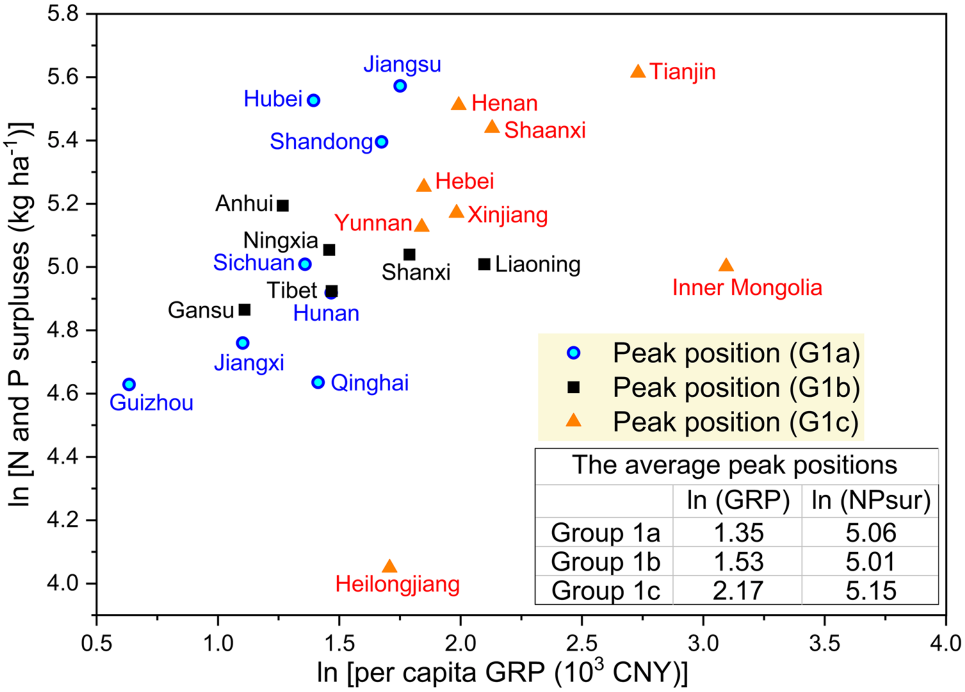


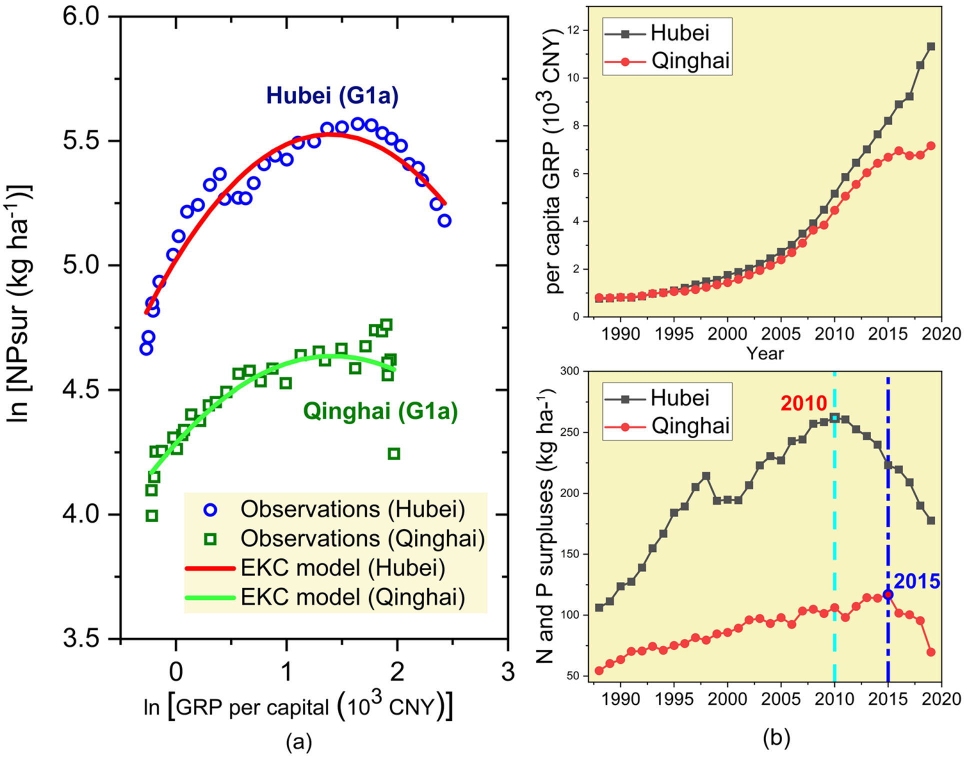
Fig. 5 The estimated peak positions (turning points) of the provinces with inverted U-shaped EKCs between fertilizer surpluses and economic growth

regions on crop production also makes it more challenging to reduce fertilizer consumption.

Besides the differences of turning points among the subgroups, there are also large variations within each group. For example, both Hubei (G1a) and Qinghai (G1a) reached the turning point when the real GRP was approx. CNY 4000 per capita, but the peak fertilizer surpluses of Hubei was 251 kg ha^{-1}, 2.4 times of that of Qinghai (103 kg ha^{-1}). Figure 6 illustrates the EKCs of Hubei and Qinghai as well as their corresponding records of per capita real GRP and fertilizer surpluses from 1988 to 2019. While both provinces' per capita real GRP increased steadily at different paces, their fertilizer surpluses started to decline at different time points. The fertilizer surpluses of Hubei reached their peak in 2010. During 2011 to 2014, the average annual growth rate of fertilizer surpluses was – 2%, which increased to – 5% during 2015 to 2019. On the contrary, the fertilizer surpluses of Qinghai only started to decrease in 2016 — 1 year after the implementation of the "Zero growth plan for fertilizers by 2020." During 2016 to 2019, Qinghai enjoyed a sharp decline in fertilizer surpluses with a mean annual reduction rate of 12%. It can be argued that, without policy interventions, the fertilizer surpluses of Qinghai might have still increased, or reduced at a lower speed, which would have possibly shifted its EKC turning point to a higher level of GRP. On the other hand, the policies may have only accelerated the fertilizer use reduction of Hubei, without making any great impact on its turning point.

Sharp drops in fertilizer surpluses after 2015 were also found in Jiangxi and Guizhou of Group 1a, all provinces of Group 1b, and most of the provinces in Group 1c. The gradual implementation of the "Zero growth plan for fertilizers by 2020" since 2015 seemed to have played a role in shifting the potential EKC turning points to lower positions nationwide. Yet, its influences may vary depending on the regional governmental executive abilities and cropping structures. These results emphasize that such policies can have positive effects on fertilizer reduction in China and on the EKC shapes. However, more research needs to be conducted to estimate the causal effects of this policy.

One special case in our results is the case of Shanghai, where a negative linear relationship between per capita GRP and fertilizer surpluses was found. To the best of the authors' knowledge, such a relationship was not indicated in other EKC-related studies. One possible explanation would be that Shanghai, as one of the most economically developed regions in China, had its potential turning point far before our sampling period. Therefore, only the "tail" of the inverted U-shaped curve was captured. Nevertheless, due to data restrictions we could not further investigate this issue.



(a)

(b)

Fig. 6 **a** EKCs of Hubei and Qinghai and **b** their corresponding records of per capita real GRP and fertilizer surpluses. Source of data: NBS and own calculation

The EKCs and crop mix

Another factor that may be closely associated with the response types of the EKC is the crop mix (Zhang et al. 2015; Sarkodie 2018). Since the 1990s, the monoculture of cash crops in China quickly expanded due to its profitability and the improved agricultural infrastructures such as drip irrigation (Wang et al. 2004; Su et al. 2016). The expansion was especially notable in tropical and subtropical China as well as in northwest China. The former had massive tracts of arable land transformed to plantations for commercial fruits, palm oil, and rubber (Su et al. 2011; Yang et al. 2016), and the latter is the most dominate cotton-growing region in China (Feng et al. 2017). During the time span from 2017 to 2019, the southeast and southwest regions had the highest cash-crop ratio in China (0.60 and 0.44), followed by the northwest region 0.42 (see Table 6).

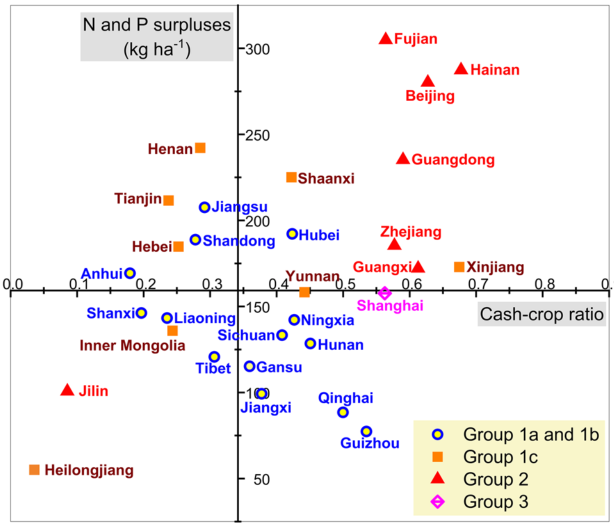


Fig. 7 Scatter plot of all provinces' cash-crop ratios (*x*-axis) versus fertilizer N and P surpluses (*y*-axis). The origin is located at the average values of the cash-crop ratio and fertilizer N and P surpluses of China, where $x = 0.34$ and $y = 159.28$. All of the data points were calculated based on a three-year average between 2017 and 2019. Source of data: NBS and own calculation

Figure 7 shows the scatter plot of all the provinces' cash-crop ratios (*x*-axis) versus fertilizer surpluses (*y*-axis) in China over a 3-year average from 2017 to 2019. Our results showed that the provinces with above-average fertilizer surpluses can be roughly divided into two clusters: the traditional grain cereal producers with intensive farming on the North China Plain (NCP), i.e., Shandong, Henan, Hebei, Anhui, Jiangsu, and Tianjin as well as those provinces with high cash-crop ratios in southeast and northwest China. While provinces on the NCP have either reached (G1a and 1b) or are approaching (G1c) the turning point, provinces with high cash-crop ratios still mostly show a linear growth of fertilizer surpluses when per capita GRP increases. Driven by the high returns and subsidized fertilizer prices, farmers producing cash crops normally tend to overuse fertilizers (Zhen et al. 2006; Li et al. 2013b). Nowadays, cash crops such as fruit and vegetables account for 30% of China's total consumption of N and P fertilizers, leading to low nutrient use efficiencies and high fertilizer surpluses (Heffer 2013; Zhang et al. 2015). Although commercialized cash crop farming has brought wealth to numerous farmers, the dilemma between profitability and environmental sustainability remains.

Contrary to the majority of the provinces that exhibit a positive relationship between fertilizer surpluses and economic growth, Heilongjiang (G1c) and Jilin (G2) in northeast China have both low cash-crop ratios and low

Table 6 Average cash-crop ratios and fertilizer surpluses of the six zones of China. According to NBS, farm crops can be divided into grain crops and cash crops. Grain crops include cereal grains, pulses, and tubers while cash crops include oil crops, fruits and vegetables, cotton and hemp, sugar crops, tabaco, and medicinal herbs. The cash-crop ratio here is calculated as $1-[sownareaofgraincrops/(totalsownareasoffarmcrops+orchardarea)]$ of the corresponding regional scale. Calculations were based on a 3-year average between 2017 and 2019. Source of data: NBS and own calculation

Zone	Provinces included	Cash-crop ratio	Fertilizer N and P surpluses (kg ha^{-1})
Northeast	Jilin, Liaoning, Heilongjiang	0.08	81.85
Northcentral	Beijing, Tianjin, Hebei, Shanxi, Shandong, Henan	0.27	204.58
Northwest	Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang, Inner Mongolia	0.42	158.73
Middle and lower reaches of Yangtze River	Shanghai, Jiangsu, Anhui, Jiangxi, Hubei, Hunan	0.34	161.96
Southwest	Sichuan, Guizhou, Yunnan, Tibet	0.44	127.67
Southeast	Zhejiang, Fujian, Guangdong, Guangxi, Hainan	0.60	212.85
China average		**0.34**	**159.28**

fertilizer surpluses. The EKC trajectories of the two provinces were probably influenced by the northeast region's socio-economic conditions, in which economic recessions, population declines, and urban shrinkage have been observed in recent decades (Li 1996; Tan et al. 2017; Yang 2019).

Conclusion

This study investigated the relationship between chemical fertilizer surpluses and economic development on the regional level in China. We employed a balanced panel dataset covering 30 provinces of mainland China from 1988 to 2019. Unit root tests, such as the ADF, PP, and KPSS tests, were conducted to determine the variables' order of integration, EKC regressions were estimated using FM-OLS for cointegrating polynomial regressions, and group-mean coefficients were computed for each zone. Our results suggested that all of the provinces exhibit a long-run cointegrated relationship between fertilizer surpluses and per capita real GRP. A total of 22 out of 30 provinces showed a significant inverted U-shaped EKC between fertilizer surpluses and economic growth. Among the 22 provinces, 8 provinces are considered to have passed the peak, indicating that the fertilizer surpluses have been decreasing as per capita GRP grows. These provinces include Shandong, Jiangsu, Jiangxi, Hubei, Hunan, Qinghai, Sichuan, and Guizhou, and the average per capita real GRP at the peak is CNY 4044. Six provinces are considered to be at the peak, transitioning to a phase of declining environmental degradation when the economy grows. Those provinces are Liaoning, Shanxi, Anhui, Gansu, Ningxia, and Tibet, with an average per capita GRP at the peak CNY 4890. A total of 8 provinces are considered to be before the peak, meaning their fertilizer surpluses are still increasing while the economy grows, with diminishing increasing rates. These provinces include Yunnan, Heilongjiang, Henan, Tianjin, Hebei, Inner Mongolia, Shaanxi, and Xinjiang, with the average peak GRP of CNY 9820 per capita. The group-mean panel results showed that the regional mean turning points are CNY 7022, CNY 9726, CNY 4697, CNY 3749, and CNY 5588 per capita real GRP for Northeast, Northcentral, Middle, and lower reaches of the Yangtze River, and Southwest and Northwest China, respectively. The overall turning point for China is CNY 6705 per capita real GDP. This was reached in circa 2012.

Our results provide more empirical evidence that the gradual implementation of the "Zero growth plan for fertilizers by 2020" since 2015 has improved the overall fertilizer management in China. While several studies have evaluated the execution of the Zero growth plan in terms of absolute reduction of the fertilizer consumption (e.g., Jin et al. 2019), we are the first to have considered the impact of the policy in the framework of the EKC. Our findings show that multiple provinces' turning points on the EKC were likely pulled to lower positions due to the recent decline in fertilizer consumption. This revealed the positive impacts of effective policies on the environmental performance of agricultural production. If appropriate policies are in place and effectively executed, then economic growth and environmental sustainability could be compatible.

On the basis of our empirical results, we propose the following policy recommendations. (1) Despite the existing agrochemical related policies, continuous efforts are needed to further reduce chemical fertilizer consumption in China. Supervision and agricultural extension services should be enhanced in order to promote scientific fertilization concepts to the farmers. (2) Incentives and guidelines for the proper use of organic fertilizers should be provided to farmers in order to increase the share of organic fertilization and to close the nutrient cycle. (3) Special attention on fertilizer use reduction should be paid to regions with high cash-crop ratios. This especially refers to the provinces in Southeast China, where Guangdong, Fujian, Hainan, Guangxi, and Zhejiang still exhibited linear growth in fertilizer surpluses when the economy grows. At the same time, nutrient use efficiencies should be improved, especially for cash crops such as vegetables and tropical fruit.

Small sample size and data unavailability were the major limiting factors in this study. The former increased the uncertainty in our statistical analysis, since both the unit root tests and cointegration tests are known to suffer from size distortions and a lack of power in small samples. And the latter made it difficult to include other potentially intervenient variables that would satisfy all panels. As part of the future scope of the study, country-specific causal relationship between fertilizer-related policies and the shapes and turning points of the EKC can be investigated. Moreover, structural equation models can be built and applied in the context of fertilizer surpluses-economic growth nexus. This would help to keep up with the increasing complexity of this research topic.

Appendix

Table 7 A summary of the stationarity tests of the variables at level and after the first differencing. The numbers in the column refer to provinces for which the respective null hypothesis was rejected at the 5% significance level ($T=30$). More detailed results of the unit root tests can be obtained from the authors upon request

	ADF test[a]		PP test		KPSS test	
	Constant	Trend	Constant	Trend	Constant	Trend
NPsur	12	6	16	1	28	26
GRP	3	4	1	1	30	12
Δ NPsur	12	–	27	–	25	–
Δ GRP	13	–	25	–	17	–

[a] A maximum number of one lag was used in the ADF test, and the optimal lag length was chosen based on the AIC

Table 8 Coefficient estimations from the robustness check with a control variable

	FM-OLS estimates			
Province	β_0	β_1	β_2	γ
Liaoning	5.03***	0.7***	−0.15***	0.32***
Jilin	4.77***	0.36***	−0.04	0.29**
Heilongjiang	3.93***	0.74***	−0.27***	0.24***
Beijing	3.62***	0.55***	−0.17***	−0.34***
Tianjin	4.1***	2.32***	−0.32***	0.6**
Hebei	5.05***	0.67***	−0.14***	0.24**
Shanxi	4.83***	0.59***	−0.15***	0.13
Shandong	5.07***	0.66***	−0.18***	0.13
Henan	5.02***	0.52***	−0.13***	0.02
Shanghai[a]	7.92***	−0.18	0.21	0.79**
Jiangsu	5.1***	0.68***	−0.18***	0.07
Zhejiang[a]	4.51***	0.04	−0.001*	−0.21
Anhui	5.24***	0.54***	−0.16***	0.21
Jiangxi	4.68***	0.38***	−0.15***	0.07
Hubei	5.66***	1***	−0.27***	0.47***
Hunan	4.65***	0.34***	−0.12***	−0.01
Fujian[a]	4.79***	0.11	0.03	−0.17
Guangdong[a]	4.77***	−0.26	0.1	−0.23
Guangxi	4.84***	0.39***	−0.05*	0.09
Hainan	4.37***	0.72***	−0.11	−0.2
Sichuan	4.88***	0.36***	−0.12***	0.06
Guizhou	4.83***	0.31***	−0.21***	0.16
Yunnan	4.25***	0.31***	−0.1***	−0.29*
Tibet	4.1***	0.64***	−0.27***	−0.17
Inner Mongolia	4.29***	0.71***	−0.11***	0.18*
Shaanxi	5.85***	1.14***	−0.27***	0.7**
Gansu	5.11***	0.73***	−0.27***	0.4
Qinghai	4.83***	0.77***	−0.27***	0.28**
Ningxia	5.72***	0.99***	−0.28***	0.69**
Xinjiang	4.79***	1.16***	−0.29***	0.5***

[a] Since the linear terms of Shanghai, Zhejiang, Fujian, and Guangdong were insignificant in the quadratic model specification, we re-estimated the linear model specification for those four provinces. The *t*-statistics showed that the linear terms were still insignificant in the linear model specification

Table 9 A comparison of results from the reduced model (**Eq. 2**) and the model with control variable (**Eq. 3**)

	Reduced model (Eq. 2)	Model with control variable (Eq. 3)
Inverted U-shaped curve ($p\_\beta_2 < 0.05$ and $\beta_2 < 0$)	**(22)** Liaoning, Heilongjiang, Tianjin, Hebei, Shanxi, Shandong, Henan, Jiangsu, Anhui, Jiangxi, Hubei, Hunan, Sichuan, Guizhou, Yunnan Tibet, Inner Mongolia, Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang	**(23)** Liaoning, Heilongjiang, Beijing, Tianjin, Hebei, Shanxi, Shandong, Henan, Jiangsu, Anhui, Jiangxi, Hubei, Hunan, Sichuan, Guizhou, Yunnan, Tibet, Inner Mongolia, Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang
Linear increase ($p\_\beta_2 > 0.05$, $p\_\beta_1 < 0.05$, and $\beta_1 > 0$)	**(7)** Beijing, Jilin, Guangxi, Hainan, Guangdong, Zhejiang, Fujian	**(3)** Jilin, Guangxi, Hainan; *(2^a) Zhejiang (insignificant), Fujian (insignificant)*
Linear decrease ($p\_\beta_2 > 0.05$, $p\_\beta_1 < 0.05$, and $\beta_1 < 0$)	**(1)** Shanghai	*(2^a)Shanghai (insignificant), Guangdong (insignificant)*

[a] Signs of the coefficient match with the criteria, but not the significance level

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Data availability The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

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Chapter 4 - Publication

Farm size, farmers' perceptions and chemical fertilizer overuse in grain production: evidence from maize farmers in northern China[a]

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Research article

Farm size, farmers' perceptions and chemical fertilizer overuse in grain production: Evidence from maize farmers in northern China

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ABSTRACT

China's agriculture is characterized by small-scale farms whose overuse of chemical fertilizers is widespread. This makes it a key challenge for China to sustainably feed its growing population. In this study, we investigate the role of farm size in maize production and how it relates to farmers' fertilizer application strategies. We use cross-sectional survey data of 774 maize-producing farms in northern China, and develop a conceptual framework that links farm production, on-farm resources, the socio-economic characteristics of the households and farmers' knowledge and perceptions as a whole. We use linear and logistic regression models to show that despite the recent declines in fertilizer application rates, excessive fertilizer use persists in maize cultivation in northern China. Farm size has a negative effect on chemical fertilizer use and a positive effect on maize yield. In addition, farmers on large farms achieve significantly higher knowledge scores in terms of fertilizer use and maize cultivation. They are also more likely to attend agricultural training and adopt scientific fertilizer use techniques. Increased farm size, participation in training, better farming knowledge, and having a family member as a village cadre are associated with farmers' decisions to reduce the use of conventional fertilizers. The key to achieving more sustainable grain production in China is to increase farm size, while enhancing the effectiveness of agricultural extension and promoting scientific fertilization techniques. Social networks within and between villages should also be utilized for knowledge transfer. In addition, cooperation between research institutions and fertilizer companies should be further emphasized to improve the accessibility of regionally adjusted formulated fertilizers.

1. Introduction

The relationship between farm size and productivity is a long debated topic in agricultural economics, as it can be region-specific and varies with the stage of economic development (Rada and Fuglie, 2019; Sheng et al., 2019). In the past few years, there has been a growing body of research around the world that provides new perspectives on the role of farm size, not only in terms of farm productivity, but also in terms of farm sustainability. Where productivity is usually expressed by farm performance indicators such as crop yield, production volume and farmers' net profit, farm sustainability is often indicated by the use of agrochemicals or the adoption of environmentally conscious production practices (Chen et al., 2011; Dong et al., 2015; Ren et al., 2019).

In high-income countries where agricultural production is dominated by large-scale operations, such as the United States and Australia, the relationship between farm size and farm productivity/sustainability is often considered to be positive (see Key, 2019; Ren et al., 2019; Robertson et al., 2012; Sheng and Chancellor, 2019). However, in many low-income and developing countries, small farmers, often with less than 2 ha of land, still persist (Rigg et al., 2016). Empirical results on the relationship between farm size, productivity and sustainability in these countries are often inconsistent and contradictory. On the one hand, some argue that certain small farms may have productivity advantages in Africa and South Asia (Eastwood et al., 2010; Rada and Fuglie, 2019). On the other hand, several studies suggest that small-scale farms tend to be associated with higher energy inputs and agrochemical use and are

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less likely to adopt new technologies (Akudugu et al., 2012; Pishgar-Komleh et al., 2012).

China is a typical developing country dominated by small-scale family farms (Wang et al., 2015). In China, 183 million farmers are considered smallholders, representing 43% of the world total (Rigg et al., 2016). A typical Chinese family farm operates less than 0.6 ha of fragmented farmland, with about 0.1 ha per plot (Tan et al., 2013; Wu et al., 2018). Although the small farm size usually limits mechanization and requires more intensive labor inputs in comparison to large-scale farms (Chen et al., 2011), China's agricultural productivity has experienced swift expansion over the last decades. Compared to the 1960s, the average yield for the major grain crops (maize, rice and wheat) tripled and reached 6295 kg ha^{-1} per harvest in 2020 (NBS, 2022), which was 1.3 times of the world's average (FAO, 2022). Besides technical advances such as improved crop varieties, this boost was largely due to the highly intensified agricultural inputs, especially the use of chemical fertilizers (Yu et al., 2020, 2022).

Several recent studies have investigated the role of farm size in grain production in China. However, the results are often contradictory. For example, Sheng et al. (2019) made the first attempt to analyze the relationship between farm size and maize yield after China's rural land reform. They surveyed 574 maize farms in Northern China and found a mild U-shaped curve between the farm size and productivity in maize production. Zhang et al. (2021) studied 120 maize farms in Northeast China. They argued that maize yield did not vary with farm size, yet increasing farm size would reduce the intensity of agrochemical use and thus contribute to sustainable maize production. In contrast to Zhang et al. (2021), Hu et al. (2019) focused on rice farms in Jiangsu province of China, and concluded that small farms achieved higher fertilizer use efficiency scores than larger farms.

In this article, our main objective is to analyze the role of farm size in maize production with a special focus on chemical fertilizer use and maize yield. Here, farm size refers to the land area sown to maize. We use maize farms as a case study for grain production in China, because as a major cereal crop for human consumption and animal feed, maize has surpassed rice and wheat as the largest grain crop in China (NBS, 2022). It was predicted that maize production in China will continue to expand due to the constantly increasing demand for meat (X. Chen et al., 2014; Ying et al., 2020). Hence, results from this study provide important insights into China's sustainable food supply. To better understand the mechanism behind potential fertilizer overuse in maize production, we also analyze the relationship between farm size and farmers' farming knowledge while controlling for the socioeconomic context of the household. In addition, we apply a logistic regression model to investigate factors that determined farmers' decisions to reduce conventional fertilizer use in maize production. We also analyze farmers' strategies regarding scientific fertilizer application and perceived barriers to reducing conventional fertilizer use.

Our study contributes to the literature in the following ways. First, in our study, we develop a conceptual framework that links farm production, on-farm resources, the socioeconomic characteristics of the households and farmers' knowledge and perceptions as a whole. Unlike other studies that focus on one aspect of production, we organically combine the correlation analysis with the analysis for farmers' decision-making behavior and the descriptive statistics. This helps us to better understand the mechanisms of farm size influence in maize production and thus to provide realistic and accurate policy recommendations. Second, as noted earlier, the recent literature on the role of farm size in China's agriculture is limited and contradictory. Our regional analysis of northern China, using household-level data collected in 2019 provides an updated and more focused perspective in this regard. Thus, our results add necessary empirical evidence to this strand of literature.

The present paper proceeds as follows. Section 2 and Section 3 provide the conceptual framework, data sources and model specifications of the study. Section 4 presents the results and a discussion of the main findings, and puts forward policy implications. Section 5 draws conclusions and addresses limitations of the study.

2. The conceptual framework

The study develops a conceptual framework to analyze the role of farm size (maize sown area) in maize production, with particular attention to maize yield as farm output and chemical fertilizer application rates as agrochemical input (see Fig. 1). We identify three main aspects that appear to influence maize production of a household farm, namely on-farm resources, socioeconomic characteristics of the household (incl. background of the household head and household economic status), as well as external factors such as trainings, governmental regulations, subsidies, etc. Among these, farmland resources represent the physical, geologic, and chemical attributes of the farm, as well as its crop management. It has a direct impact on maize production as it governs crop performances and farmers' choices on technology application (Burnham and Ma, 2016; Qi et al., 2021). Socioeconomic and external factors, on the other hand, indirectly influence the production process by affecting farmers' perceptions, attitudes and intentions, thus shaping their production behaviors (Wang et al., 2019; Zhang et al., 2018, 2020).

Based on this framework, our empirical analysis was performed in three steps. We first investigated the relationship between chemical fertilizer use, maize yield and farm size. Similar to Duan et al. (2021), Ren et al. (2021) and Wu et al. (2018), in this step, we controlled for confounding factors related to on-farm resources that would influence the two dependent variables. We then examined whether farm size also played a role in influencing farmers' knowledge about fertilizer use and maize farming, while controlling for the socio-economic factors. In this study, farmers' knowledge scores were quantified by a total of ten questions (see Table S1 in the Supplementary materials). In a final step, we conducted logistic regression analyses to investigate the specific factors that determine farmers' decision to reduce conventional fertilizer use.

3. Materials and method

3.1. Model specification

We analyze the relationship between chemical fertilizer use and maize yield with farm size using **Eq. (1)** below:

$$Y_i = \alpha + \beta \bullet farm\ size_i + \sum_j \gamma_j X_{ji} + \varepsilon_i, \tag{1}$$

where i denotes households, Y is either the logarithm of the application rate of chemical fertilizers (kg ha^{-1}) or maize yield (kg ha^{-1}), or the ratio of phosphate and potassium to the total fertilizer inputs for the household; *farm size* is the logarithm of maize sown area (ha) of the household. X_j are various control variables that may influence the application rate of chemical fertilizers and/or maize yield, including crop type, cropping structure, land fragmentation, soil fertility, soil texture, and the dummy variable for the province. β and γ_j are estimated coefficients and ε is the error term.

To examine the relationship between farmers' overall knowledge with *farm size*, we again employ **Eq. (1)**, with Y as the *total knowledge score*. During the survey, farmers were asked a total of 10 questions concerning their maize cultivation skills and fertilizer application knowledge. Each area accounted for 5 questions, so scores ranged from 0 to 5. The total knowledge score is the sum of these two scores. A list of the 10 questions and the corresponding answers and points can be found in Table S1 of the Supplementary materials. In this step, we control for the socio-economic characteristics of the household head, including age, education level, whether she or he is a village cadre and main occupational activities.

After determining the relationships between maize fertilizer input, maize yield and farmers' knowledge score with farm size, we employ a

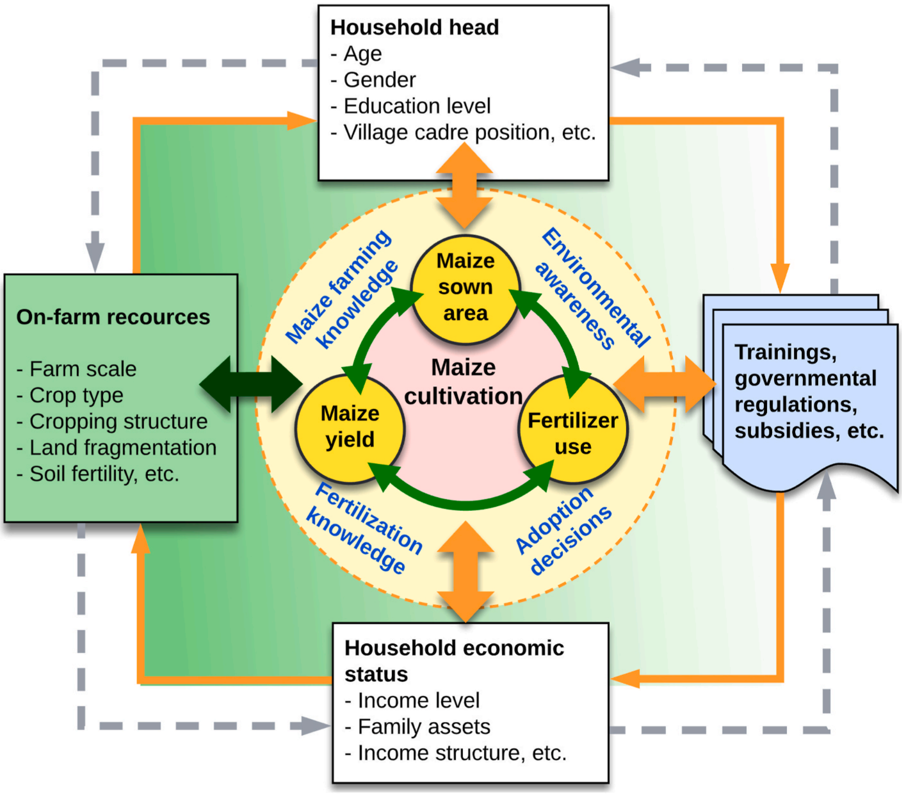

Fig. 1. The conceptual framework of how maize production is influenced by on-farm resources, socio-economic background of the household and external factors.

logistic model to analyze the factors that influence farmers' decisions to reduce conventional fertilizer application. In our study, farmers were asked whether they had reduced the use of conventional fertilizer in maize production in the past calendar year. Therefore, their answer is a binary variable defined as Y = 1, if "the household reduced conventional fertilizer use in maize production" and Y = 0 otherwise. The binary logistic model can be written in Eq. (2) as:

$$P\ (Y=1)=\frac{e^{(\delta_0+\delta_1 Z_1+\delta_2 Z_2+\ldots+\delta_i Z_i+\varepsilon)}}{1+e^{(\delta_0+\delta_1 Z_1+\delta_2 Z_2+\ldots+\delta_i Z_i+\varepsilon)}}, \tag{2}$$

where $P\ (Y=1)$ is the probability of reducing conventional fertilizer use intensity, Z_1, Z_2, …, Z_i are the independent variables indicating the various factors that influence farmers' decisions on reduced conventional fertilizer use, δ_0, δ_1, …, δ_i are the estimated coefficients and ε is the error term. In the logistic model, we again control for potential region-specific effects by including the dummy variable for the province. A household's decision to reduce conventional fertilizer use in maize production is driven by a variety of factors in the decision-making process (Wang et al., 2019). Similar to Qi et al. (2021) and Uhunamure et al. (2019), we consider three major dimensions of a rural household in our logistic regression analysis, namely the socio-economic background of the household, maize farming condition, and training and knowledge. The **socioeconomic background** of the household includes basic information of the household head (incl. gender, age, education, whether the respondent is a village cadre and main occupational activities) and the household's economic situation (incl. income level, the share of income from grain production to total income, and whether the household owns a private car). These factors can limit a household's access to resources and agricultural inputs, thereby affecting farmers' livelihood strategies (Chen et al., 2011; Xie and Jin, 2019). **Maize farming conditions** include farm size, land fragmentation, and perceived soil productivity. Here we use *perceived soil productivity* rather than *soil fertility* as a soil indicator because we believe that fluctuations in soil productivity levels have a more timely effect on farmers' fertilizer use decision processes. As stated by Karltun et al. (2013) and Dawoe et al. (2012), crop performance is one of the most common and primary indicators used by farmers to determine soil fertility. Therefore, it can influence farmers' fertilization decisions in the short term. The aspect of **training and knowledge** plays an important role in transforming conventional agriculture, reflecting the influence of agricultural extension services and farmers' knowledge on their decision-making process (Liu et al., 2019). It includes whether the farmer had received trainings on fertilizer use reduction, and their knowledge score on maize cultivation. Here, we use the *maize cultivation knowledge* score rather than the total knowledge score to avoid the potential confounding effect of high fertilization knowledge score due to the fertilizer-related trainings.

An overview of the variables used in the study and their definitions is presented in Table 1.

3.2. Data sources

The study uses data from the 2019 National Scientific Fertilization Survey (NSFS). The NSFS was commissioned by the Department of Crop Production (Department of Agrochemical Management), Ministry of Agriculture and Rural Affairs of China, and was undertaken and implemented by the National Academy of Agriculture Green Development, China Agricultural University (https://naagd.cau.edu.cn/).

The survey covers 2080 households from 11 provinces of China, including Heilongjiang, Jilin, Hebei, Henan, Shandong, Shaanxi, Gansu, Anhui, Jiangsu, Hunan and Guangxi. The survey uses a multi-stage stratified random sampling approach. Specifically, from each sampling province, three or four counties are randomly selected based on the ordering of their cultivated areas. Within each of the counties selected, five or six villages from three townships representing different levels of average per capita income are randomly selected. The NSFS was conducted from March to June 2019 and collected information on e.g., land use, crop production, scientific fertilization in grain production and household characteristics of the year 2018.

Table 1
Variables used in the study and their definitions.

Variables	Definition
Dependent variables	
Fertilizer input (y_1 in Eq. (1))	Total fertilizer input, measured as the effective components of N, P_2O_5 and K_2O (kg ha^{-1})
PK ratio (y_2 in Eq. (1))	Proportion of P_2O_5 and K_2O to the total effective components of fertilizer input
Maize yield [a] **(y_3 in Eq. (1))**	Maize yield (kg ha^{-1})
Total knowledge score [b] **(y_4 in Eq. (1))**	Total knowledge score = Maize cultivation knowledge score + Basic fertilization knowledge score. Ratio variable, score ranging from 0 to 10.
Reduce decision (y in Eq. (2))	The household reduced conventional fertilizer use in maize production in the last year = 1, Otherwise = 0
Independent variables	
Information of the household head	
Gender	Male = 1; Female = 0
Age	The actual age of the household head
Education level	No formal education received (0 years of education) = Edu0; Primary school (1–6 years of education) = Edu1; Junior high school (7–9 years of education) = Edu2; High school or secondary school (10–12 years of education) = Edu3; Above high school (≥13 years of education) = Edu4
Village cadre	Yes = 1; No = 0
Main occupational activity	Farming only/Off-farm employment only/Farming and off-farm employment/No job/Others
Household economic status	
Income level	Superior/Upper middle/Medium/Lower middle/ Inferior
Grain income ratio	The ratio of incomes from grain production (maize, rice and wheat) over the total household income
Private car	The household owns a private car for non-commercial use = 1; Otherwise = 0
Farm characteristics	
Farm size	Total sown area of maize (ha)
Crop type	Grain and cash crops = 1, Grain crops only = 0
Crop structure [c]	Monocropping/Intercropping/Crop rotation
Land fragmentation	Multiple land parcels = 1; Only one parcel of land = 0
Soil fertility	Good/Moderate/Bad
Soil texture	Sandy/Loam/Clay
Perceived soil productivity [d]	High/Medium/Low
Training, knowledge and decision	
Training	A member of the household has received trainings on fertilizer use reduction = 1, No training received = 0
Maize cultivation knowledge score	Ratio variable, score ranging from 0 to 5.

[a] During the survey, information concerning the fresh yield of harvested maize and the water content were collected. Thus, the final maize yield was calculated as: $\text{Maize yield} = \text{Fresh weight at harvest} \times (1 - \text{measured water content}) \times (1 - \text{Inpurity rate})/(1 - 14\%)$. 14% here is the national standard water content for maize, and by default, the impurity rate equals to 1%.

[b] Details concerning the calculation of *Total knowledge score* can be found in Table S1 in the Supplementary materials. The variable *Total knowledge score also serves as an independent variable in Eq. (2)*.

[c] Since a typical farm in the study areas cultivates more than one maize plot, collected data on cropping structure, soil and land properties, etc. refer to the largest plot of the household cultivated with maize.

[d] To define soil productivity, farmers were asked how productive their land was compared to other farms in the village.

In this study, we focus on maize farmers in China's major maize-producing regions. We use data of maize farms from Shandong, Henan, Hebei in the North China Plain (NCP) as well as Jilin and Heilongjiang in the Northeast (Fig. 2). In 2018, nearly 40% of the total sown area in these five provinces was sown to maize. They are also among the six strongest maize producers of China, occupying 53% of the year's total maize production volume (NBS, 2022). Therefore, we believe that they are a good representation of maize producers in northern China. After eliminating invalid data and outliers*, we used data from a total of 774 households from 105 administrative villages of 18 counties.

* Invalid data and outliers here mainly refer to survey documentation errors, e.g. missing values recorded as "0" or "999", total percentage of N, P_2O_5 and K_2O in fertilizer input data higher than 100%, duplicate data for the same household, etc.

4. Results and discussion

4.1. *The role of farm size in maize production*

4.1.1. *Major farm characteristics of the sampled households*

Table 2 summarizes the descriptive statistics of the major farm characteristics. Our results show that the majority of the total sampled farms are small-scale farms (67.7%) with an average of 0.44 ha maize-cropped land. The overall maize yield in 2018 ranges from 2358 kg ha^{-1} to 11,938 kg ha^{-1}, with an average of 8054.8 kg ha^{-1}. This is higher than the national average of 6104.3 kg ha^{-1} in 2018 (NBS, 2022), indicating generally better soil and crop management in the study region. However, the average maize yield is still lower than that of developed countries such as the USA (11,075 kg ha^{-1}), France (8821 kg ha^{-1}) and Germany (8139 kg ha^{-1}) in the same year (FAO, 2022). It is also well below the theoretical maize yield potential of 15.9 Mg ha^{-1} and 17.6 Mg ha^{-1} for Northeast China and the NCP, respectively (Meng et al., 2013).

Our results show that the average fertilizer use in maize production – measured as the effective components of N, P_2O_5 and K_2O – amounts to 379.6 kg ha^{-1} in our study area. It is slightly lower than the value of 439 kg ha^{-1} reported by Zhang et al. (2021) for maize production in north-eastern China. However, it is much higher than the recommended fertilizer use of about 277 kg ha^{-1} at the corresponding yield level (MoA, 2018). It is also higher than the theoretical fertilizer requirements of maize in our study area, which range from 250 to 340 kg ha^{-1} in the north-central region and 290–360 kg ha^{-1} in the northern Northeast (Xu et al., 2017). These results indicates the general fertilizer overuse problem in maize production in northern China, although overall fertilizer use has been declining in recent years. The average PK ratio over total applied fertilizer nutrients is 0.31, and the average expenditure on fertilizers was 1074 CNY ha^{-1} (ca. 170 USD). Medium-scale farms have the lowest fertilizer expenditures compared to small- and large-scale farms.

The vast majority of the maize farmers have fragmented farmlands and grow only grain crops (maize, wheat and/or rice). Crop diversity is generally higher on larger farms, with almost half of the respondents growing cash crops in addition to maize. Concerning cropping structure, crop rotation is the most common form of cropping (68.9%), followed by monoculture (26.9%). The most common crop rotation is maize and wheat, accounting for 87.1% of the total sample. The vast majority of farmers consider their soil fertility levels to be medium or high, with the majority of farms having loamy soils.

One-third of the respondents report that they have tried to reduce the use of conventional fertilizers in maize cultivation. Detailed information on decisions and strategies to reduce conventional fertilizer use is discussed in **section 4.2.2**. The decision to reduce conventional fertilizer use is most common among large farms (50%) and least common among small farms (28.2%). Similarly, knowledge scores for basic fertilization and maize cultivation also seem to increase with farm size. Respondents on larger farms on average receive higher scores on both topics compared to respondents on smaller farms.

4.1.2. *Fertilizer use, maize yield and farmers' knowledge in relation to farm size*

As presented in Table 3, our results show that farm size is negatively associated with chemical fertilizer use in maize production ($p < 0.05$). This result is consistent with recent literature on this topic in China, such

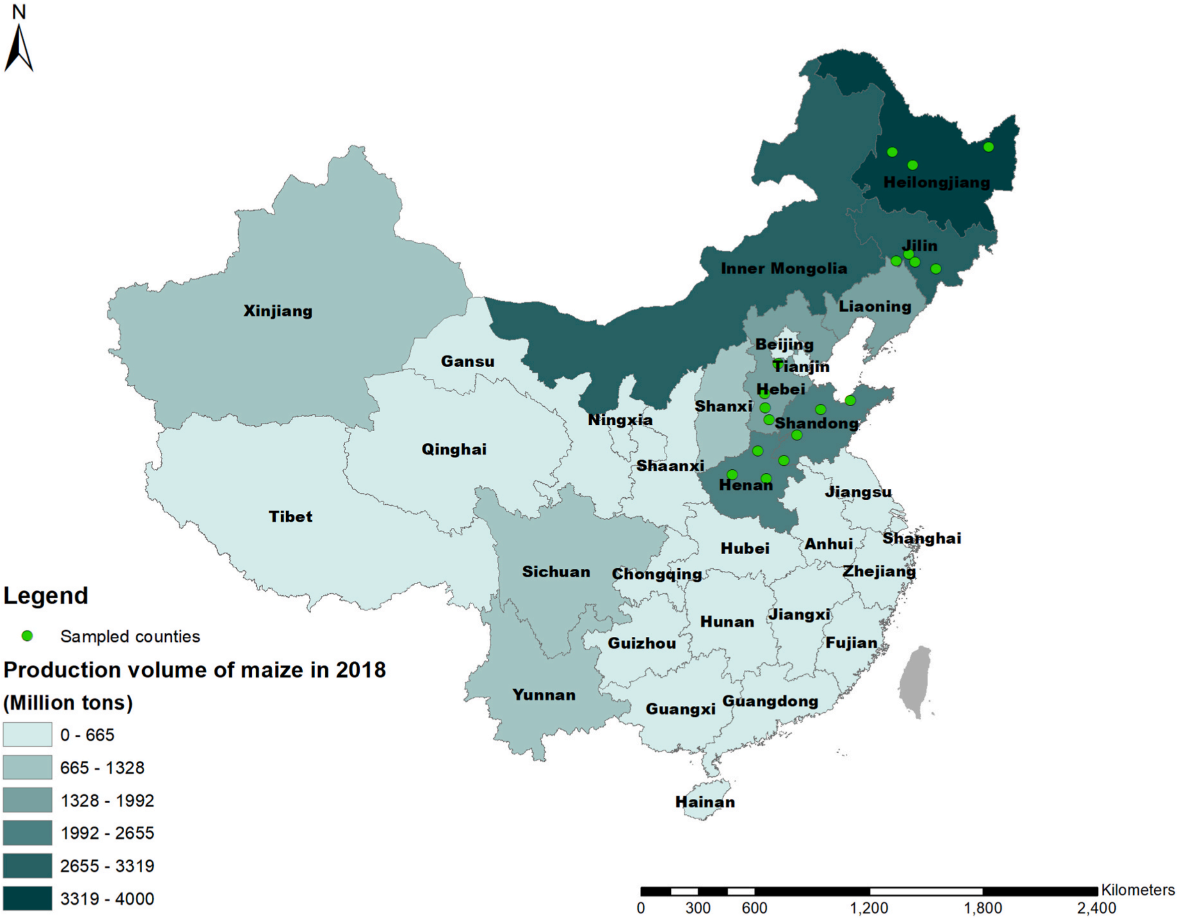

Fig. 2. Data used in the study.

as Ju et al. (2016), Wu et al. (2018) and Zhang et al. (2021). More specifically, a 1% increment in farm size is associated with a 0.03% decrease in chemical fertilizer input. This number is lower than the results of Wu et al. (2018), who concluded that a 1% increase in farm size contributed to a 0.3% decrease in fertilizer use. However, Wu et al.'s study included all major cereal crops. The fertilizer use in rice and wheat cultivation has been shown to be much higher than in maize production, and thus may have more potential for reduction (Tong et al., 2003). Besides, Wu et al.'s study used data from 2015, when the overall fertilizer use had not yet begun to decline due to the recent fertilizer reduction policies (Yu et al., 2022). Considering these aspects, we believe that our result is reasonable and comparable to the existing literature.

In addition, we find no significant effect of farm size on the proportion of N, P and K applied by farmers in maize cultivation. However, farmers who grow cash crops in addition to maize consume a higher proportion of P and K ($p < 0.01$) as a percentage of total nutrients.

Despite the negative association between farm size and fertilizer use, we find a significant positive association between farm size and maize yield ($p < 0.05$). Specifically, for every 1% increase in farm size, maize yield increases by 0.02%. These results suggest that larger farms typically use fertilizer more efficiently and with less nutrient loss to the environment than smaller farms. Ju et al. (2016) argued that this trend could be found in post-1990 China, where structural transformation was accompanied by larger farms beginning to be operated by more knowledgeable farmers. The technological advances and more scientific crop management on large farms have led to improved nutrient cycling, resulting in higher crop yields (X. Chen et al., 2014; Ju et al., 2009). Ren et al. (2019) also suggested that the relatively low availability of fixed inputs such as machinery and knowledge had led to over-fertilization by smallholders without leading to higher yields.

To add to the empirical evidence in this regard, we investigate the association between farmers' knowledge and farm size while controlling for the socioeconomic background of the household head. As shown in Table 3, we find a significant positive effect of farm size on farmers' overall knowledge scores ($p < 0.01$), with a 1% increment in farm size contributing to a 0.34% increase in the total knowledge score. Not surprisingly, farmers' education level also appears to be an important factor, with more educated farmers obtaining higher knowledge scores. However, for the most educated category of farmers (above high school), this difference is no longer significant. This may be due to the fact that well-educated farmers are generally less involved in agricultural production (Huang et al., 2009), and therefore may possess limited farming skills. Related to this argument, we also find that respondents with only non-farm employment have significantly lower agricultural knowledge scores compared to full-time farmers ($p < 0.05$). In addition, being a village cadre is associated with a higher knowledge score. This may be explained by the notion that a household with a member holding a village cadre position can have better access to agricultural inputs and information (Chen et al., 2011; Walder and Zhao, 2006), and are more inclined to attend trainings (Chen, 2015). Similar trends in terms of education and village cadre position are also found in the logistic regression analysis, which is discussed in detail in section 4.2.3.

4.2. Farmers' decisions, fertilization strategies and barriers to reducing conventional fertilizer use

4.2.1. Sociodemographic and farm characteristics

A total of 701 valid samples completed the questionnaire section on fertilizer reduction behavior. Of the total sample, 36.8% report that they

Table 2
Major farm characteristics of the sampled households.

Variables	Small-scale[a] farms	Medium-scale farms	Large-scale farms	Total sample
Number of households (2018)	524 (67.7%)	149 (19.3%)	101 (13.0%)	774
Maize sown area (ha)	0.44 (0.32)	1.55 (1.22)	16.63 (30.75)	2.77 (12.34)
Maize yield (kg ha^{-1})	7939.9 (1850.6)	8206.8 (1972.4)	8522.5 (1644.2)	8054.8 (1858.7)
Fertilizer input (kg ha^{-1})	388.6 (118.9)	371.4 (98.8)	338.9 (109.8)	379.6 (115.5)
PK ratio	0.30 (0.26)	0.32 (0.26)	0.33 (0.26)	0.31 (0.26)
Expenditure on fertilizers (CNY ha^{-1})	1087.6 (391.4)	1035.8 (297.4)	1064.4 (501.1)	1073.8 (392.0)
Crop type (%of respondents)				
Grain and cash crops = 1	16.6%	28.2%	49.5%	23.1%
Grain crops only = 0	83.4%	71.8%	50.5%	76.9%
Cropping structure (% of respondents)				
Monocropping	22.7%	34.9%	36.6%	26.9%
Intercropping	3.2%	1.3%	3.0%	2.8%
Crop rotation	72.5%	61.7%	60.4%	68.9%
Land fragmentation (%of respondents)				
Multiple parcels = 1	72.7%	91.9%	95.0%	79.3%
One parcel = 0	27.3%	8.1%	5.0%	20.7%
Soil fertility (%of respondents)				
Good	43.3%	45.0%	40.6%	43.3%
Medium	50.0%	46.3%	49.5%	50.0%
Bad	5.1%	7.4%	9.9%	5.1%
Soil texture (%of respondents)				
Sandy	18.5%	16.1%	6.9%	16.5%
Loam	52.1%	59.1%	75.2%	56.5%
Clay	28.2%	23.5%	14.9%	25.6%
Decision to reduce conventional fertilizer use (% of respondents)				
Yes = 1	28.2%	40.3%	50.0%	33.3%
No = 0	63.7%	47.7%	37.6%	57.2%
Total knowledge score	5.4 (1.9)	5.9 (2.0)	7.0 (1.7)	5.7 (1.9)
Basic fertilization score	2.9 (1.4)	3.2 (1.5)	3.8 (1.2)	3.0 (1.4)
Maize cultivation score	2.6 (1.0)	2.7 (1.1)	3.2 (1.0)	2.7 (1.1)

Note: When the total percentage of a binary or categorical variable is less than 100%, it means that there is missing data for that variable.

[a] Farm scale is classified according to the total sown area of the farm. Since the average farm scale in Northeast China is much larger than that in the NCP, we use different cut points to split among different scales of the farms. Similar to Sheng et al. (2019), for provinces in the Northeast, we use 30 mu (1.99 ha) and 100 mu (6.66 ha) as the cut point for small, medium and large farms. For provinces in the NCP, the cut points are 20 mu (1.33 ha) and 50 mu (3.33 ha), respectively.

reduced conventional fertilizer use in maize production. Those households typically have larger farm sizes and higher levels of soil productivity than those that did not reduce conventional fertilizer use. The levels of land fragmentation between the two groups are similar. Interestingly, although the difference of fertilizer use between the non-reduced and reduced groups is minor (380.0 and 375.4 kg ha^{-1}, respectively), the latter have a much higher average maize yield of 8408 kg ha^{-1} compared to 7836 kg ha^{-1}.

The vast majority of all sampled households are headed by men (90.0%), with an average age of 60 years and an average of 8 years of formal education. One-fifth of the household heads work as a village cadre in addition to their main occupation. It is worth mentioning that the proportion of village cadres among households with reduced fertilizer use decision (28.2%) is much higher than that of the opposite group (15.8%). The main occupational activity of the household heads is farming (about 70%), followed by a combination of farming and off-farm employment. Most households consider their income levels to be medium or lower middle, and the average share of income from grain production to total household income is 0.31. About one-third of the households own a private car for non-commercial use. Table S2 in the **Supplementary Materials** summarizes the main sociodemographic and farm characteristics of households with reduced/non-reduced use of conventional fertilizers and of the full sample.

4.2.2. Trainings, knowledge and farmers' perception on scientific fertilization

The positive relationship between technical trainings and the adoption of more environmentally-conscious techniques in agricultural production have been well documented in many studies (Huang et al., 2008, 2012; Liu et al., 2019). In our survey, 229 households report that they reduced conventional fertilizers by replacing them with scientific fertilization techniques including formulated fertilizers, slow-/-control-released fertilizers (SRFs or CRFs), and the integrated irrigation and fertilization system. Of these, ca. 60% received training on fertilizer use reduction, compared to 34% of the non-reduced group. They also obtained higher knowledge scores for maize farming (2.9 points) and basic fertilization (4.1 points) compared to 2.5 and 2.8 points for the opposite group. This suggests that such training and agricultural extension services had a positive impact on shaping farmers' behavior. Of the total 305 farmers who received trainings on fertilizer use reduction, the vast majority report that the trainings were organized by the local agronomic stations (86.7%). The rest includes universities and research institutes (6.5%), retailers (3.6%), as well as cooperatives, county agricultural bureaus and agricultural committees (3.2%).

As shown in Fig. 3a, replacing conventional fertilizers with formulated fertilizers is the most common scientific fertilization method farmers adopted (50.0%). Application of formulated fertilizers based on soil testing is one of the precision fertilization techniques and is the core of the scientific fertilization system in China (C. Chen et al., 2014). Started in 2005, the formula fertilization technique has been widely promoted nationwide (Luo et al., 2013). However, due to its knowledge-intensive nature, the adoption rate of formulated fertilizers usually depends heavily on the availability of training programs (Zhao et al., 2016). In our sample, of the 134 households that adopted formulated fertilizers in 2018, 71% received training in the same year.

Replacing conventional fertilizers with SRFs or CRFs is another common approach reported (34.3%), followed by replacing with organic fertilizers (8.2%). While the usage of organic fertilizers is often limited by the availability of farm livestock and labor, the application of SRFs and CRFs is largely constrained by the high price despite their proven benefits (Chalk et al., 2015; Morgan et al., 2009; Xiao et al., 2019). Additionally, 4.5% of the respondents applied the integrated irrigation and fertilization system, through which they could efficiently apply fertilizers via the irrigation system.

Of the 443 households that did not reduce conventional fertilizers, only 8.3% were constrained by farm resources and inputs (see Fig. 3b), including imperfect machines and equipment (4.4%), high associated costs (2.9%) and poor quality of the fertilizers (1.0%). Most of the concerns are related to awareness and knowledge. About 40% reported that they did not know how to reduce conventional fertilizers, and 31.2% were concerned about the decline in maize yields. One in five believed that reducing the use of conventional fertilizers was unnecessary. It is noteworthy that 49.0% of respondents who listed limited agricultural inputs as a major constraint to reducing conventional fertilizer use received training. Among those who did not reduce due to lack of awareness and knowledge, this figure dropped to 33.2%. This again demonstrates the positive effects of such training programs. Nevertheless, effectiveness of those trainings should be still improved and enhanced.

4.2.3. Factors influencing farmers' decisions to reduce conventional fertilizer use

We use a logistic regression model to examine potential factors

Table 3
Results of the linear regression analysis.

	log_TotalFert	PK ratio	log_MaizeYield	Total knowledge score
Constant	5.864*** (0.105)	0.293*** (0.068)	8.812*** (0.064)	4.546*** (0.582)
log_Farm size	−0.027** (0.013)	0.000 (0.010)	0.021** (0.010)	0.338*** (0.072)
croptype1 (cash + grain)	−0.001 (0.038)	0.103*** (0.031)	0.062*** (0.021)	/
crop_structure2 (Intercropping) [a]	−0.163 (0.131)	−0.164** (0.075)	0.110** (0.048)	/
crop_structure3 (Rotation)	−0.045(0.094)	−0.072 (0.053)	0.000 (0.039)	/
Land parcel	0.040 (0.030)	0.027 (0.028)	−0.056** (0.022)	/
Soil fertility2 (Medium) [b]	0.046* (0.029)	−0.006 (0.024)	−0.047** (0.021)	/
Soil fertility3 (Low)	0.039(0.041)	−0.008 (0.049)	−0.251*** (0.049)	/
Soil texture2 (loam) [c]	0.045(0.036)	0.053 (0.032)	0.108*** (0.031)	/
Soil texture3 (clay)	0.054(0.036)	−0.004 (0.034)	0.087*** (0.032)	/
Age of household head	/		/	0.004 (0.009)
Edu0 (No formal education) [d]	/		/	−0.362(0.301)
Edu2 (Junior high)	/		/	0.660 *** (0.171)
Edu3 (Senior high/secondary school)	/		/	1.114*** (0.613)
Edu4 (Above high school)	/		/	0.440 (0.621)
Village_cadre1	/		/	0.355** (0.180)
Main activity2 (Off-farm only) [e]	/		/	−0.842** (0.368)
Main activity3 (off-farm + agriculture)	/		/	−0.312 (0.210)
Main activity4 (no job)	/		/	−0.563 (0.734)
Main activity5 (others)	/		/	0.243 (0.349)
Regional fixed effects	Yes	Yes	Yes	Yes
N	555	566	668	584
adjusted R-squared	0.118	0.042	0.200	0.230

Note: *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. Robust standard errors appear in parentheses.

[a] Reference group for *crop structure* is monoculture.

[b] Reference group for *soil fertility* is high.

[c] Reference group for *soil texture* is sandy.

[d] Reference group for *education* is primary school.

[e] Reference group for *main activity* is farming only.

associated with farmers' decision to reduce conventional fertilizer use. The Wald test results show that the aspects of the socio-economic background of the household head, maize farming condition and training and knowledge have a significant impact on the farmers' decision-making process (see Table 4). More specifically, household head being a village cadre, farm size, soil productivity, participation in training and farmers' knowledge of maize cultivation have a positive effect on the decision to reduce conventional fertilizer use.

Various studies have reported a negative association between the age of the household head and the decision to adopt more environmentally conscious technologies (e.g. Jia et al., 2013; Qi et al., 2021). This is believed to be caused by older farmers being more risk averse, less flexible concerning changes and therefore hesitant to accept new technologies (Daxini et al., 2018). However, in our study, this negative relationship was not significant.

The Wald test indicates that farmers' education level had no significant impact on farmers' decision to reduce conventional fertilizer use. However, our results suggest that the household head holding a village cadre position contributes to the decision to reduce conventional fertilizer use ($p < 0.1$), with the odds of the reduction increased by 61%. In addition to the previously mentioned better access to agricultural inputs and information, being a village leader can also be considered as a component of social capital. Arunrat et al. (2017) highlighted that social capital is a key factor leading to the adoption of new technologies by farmers, as it can help strengthen experience sharing and farmers' confidence. Wang et al. (2014) also confirmed the positive relationship between farmers' adoption decisions and social capital, as the latter can provide help and information to farmers through social networks.

In terms of maize growing conditions, farm size is found to be a key factor associated with an increased probability of reduced conventional fertilizer use. A 1% increase in farm size contributes to a 27% increase in the odds of reduced conventional fertilizer use in maize cultivation. This finding is in line with results presented in Table 3, where a significantly negative effects of farm size on fertilizer inputs are found. One plausible explanation is that the costs associated with replacing conventional fertilizers with more effective scientific fertilization techniques are relatively low for larger farms. As noted by Chen et al. (2011), adopting a new technology usually requires fixed costs of learning and experimentation. Thus, the returns on the adoption are positively correlated with farm size. In addition, since household heads on larger farms usually have better knowledge of fertilizer application and maize cultivation (see Table 3), their environmental awareness and "know-how" may motivate them to adopt better crop management techniques. The results of the logistic analysis also support the notion that higher maize cultivation knowledge scores positively influence the decision to reduce conventional fertilizer use ($p < 0.1$). Last but not least, larger farms usually have better infrastructure, such as machinery and irrigation, which makes it easier to apply scientific fertilization techniques (Ren et al., 2021).

The perceived soil productivity is also significantly associated with the decision to reduce conventional fertilizer use ($p < 0.05$). Farmers on farms with low soil productivity are significantly more hesitant to reduce the use of conventional fertilizers than those on farms with high soil productivity. This may be due to farmers' fear that reducing the use of conventional fertilizers would lead to lower agricultural outputs (see Fig. 3b).

In terms of the aspect of training and knowledge, the results again emphasize their significant positive impacts on farmers' production behavior. The participation in trainings on fertilizer reduction increased the odds of reduced conventional fertilizer use by 264% ($p < 0.01$). Similar results have been also reported by Suvedi et al. (2017), Liu et al. (2019) and Huang et al. (2012).

4.3. Robustness check

To perform robustness checks and capture the potential effects of overall farm scale (total sown area) and rural land rental on maize production, we add the categorical variables *farm scale* and *rented_land* and re-estimate the models. The classification of farm scale is given in Table 2. The variable *rented_land* is defined as 1 = the farm cultivated land rented from elsewhere; 0 = no rented land. This step allows us to discuss the role of farm size (maize sown area) in maize production, in

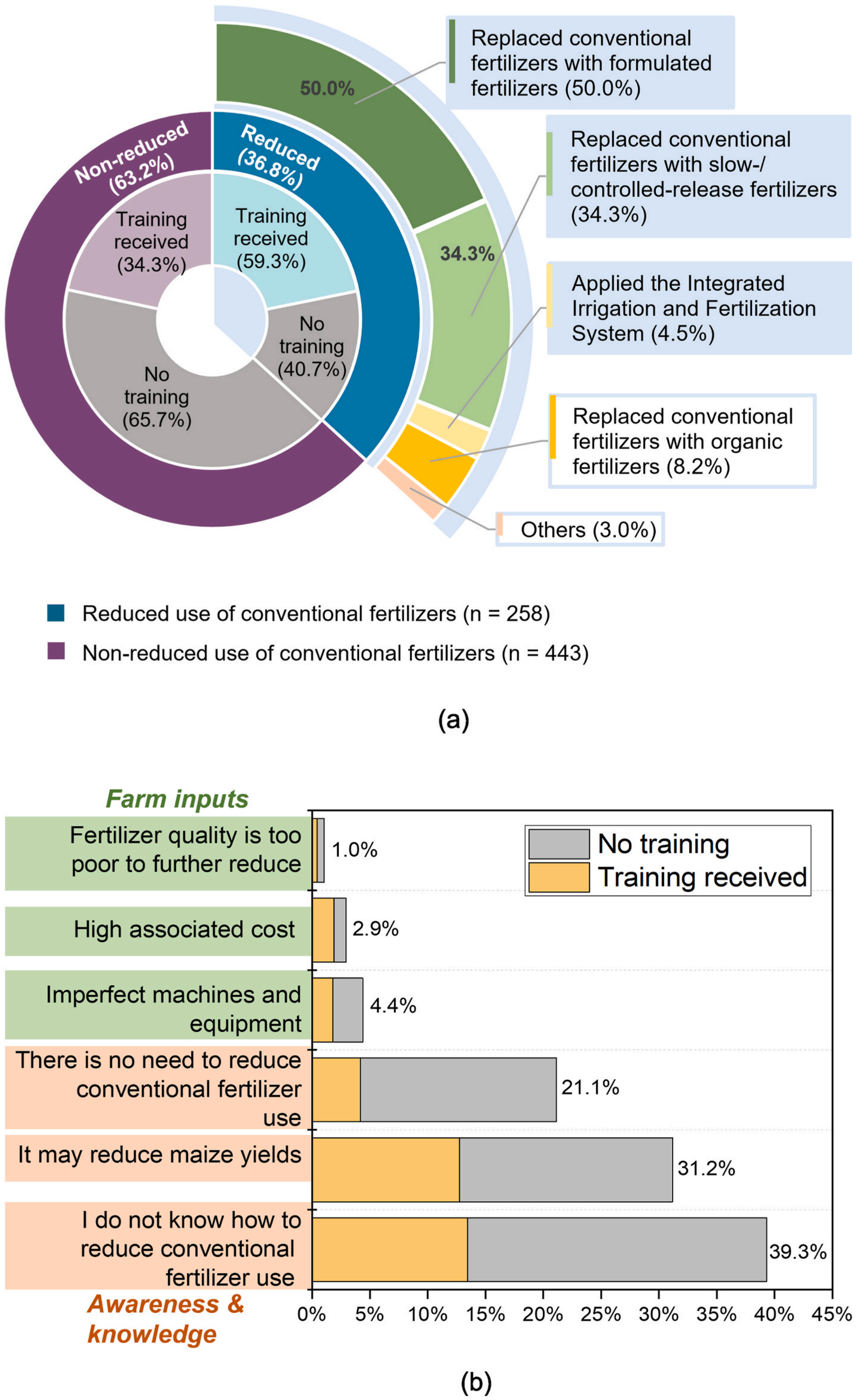

Fig. 3. (a) Distribution of households with reduced and non-reduced use of conventional fertilizers, and the main strategies farmers adopted to reduce conventional fertilizer use (b) Reasons reported by farmers who did not reduce conventional fertilizer use.

relation to the dynamic development of the whole farm. Results of the robustness check are presented in Table S3 and S4 in the Supplementary materials.

Results of the robustness checks show that the significant negative association between farm size and fertilizer use persists. The significant positive effects of farm size on maize yield and on farmers' total knowledge score also hold (Table S3). Not surprisingly, compared to farmers who only cultivate their own land, those who rent land from elsewhere achieved higher knowledge scores ($p < 0.1$). One possible explanation is that farmers would only take additional risks by renting more land if they perceive themselves as skilled farmers. There is no significant effect of the overall farm scale on fertilizer use intensity and farmers' knowledge scores in maize production. However, compared to small-scale farms, maize yield is significantly lower on large-scale farms ($p < 0.05$). One possible explanation is the higher crop diversity on large farms (see Table 2). As farmers are likely to invest more labor resources

Table 4
Results of the logistic regression model.

	Coefficient	Std. Error	t-statistic	Wald	Odds ratio
Constant	−1.458	1.009	−1.445	–	0.23
Household head					
Gender1	−0.272	0.437	−0.622	0.380	0.76
Age	−0.010	0.012	−0.824	0.679	0.99
Education[a]				3.964	
Edu0 (No formal education)	−0.899	0.550	−1.637	–	0.41
Edu2 (Junior high)	0.055	0.245	0.225	–	1.06
Edu3 (Senior high/ secondary school)	−0.051	0.317	−0.161	–	0.95
Edu4 (Above senior high)	−0.549	0.770	−0.713	–	0.58
Village_cadre1	0.476*	0.258	1.849	3.401*	1.61
Family economic situation					
Income level[b]				3.530	
Income_level1 (Superior)	0.559	0.546	1.024	–	1.75
Income_level2 (Upper middle)	0.409	0.325	1.257	–	1.51
Income_level4 (Lower middle)	0.267	0.278	0.961	–	1.31
Income_level5 (Inferior)	0.410	0.367	1.118	–	1.51
Grain_income	0.480	0.379	1.268	1.591	1.62
Private car	−0.105	0.248	−0.423	0.179	0.9
Maize farming condition					
log(MaizeArea)	0.240**	0.117	2.053	4.277**	1.27
Landparcel1	−0.218	0.276	−0.789	0.620	0.8
Soil productivity[c]				6.201**	
SP_1 (High)	0.938**	0.467	2.009	–	2.55
SP_2 (Medium)	1.046**	0.441	2.372	–	2.85
Training and knowledge					
Fert_training1	1.293***	0.238	5.430	31.197***	3.64
Maize_Score	0.197*	0.108	1.832	3.379*	1.22
Regional fixed effects	Yes				

[a] Reference group for *education* is primary school.
[b] Reference group for *Income level* is medium.
[c] Reference group for *soil productivity* is low.

in profitable cash crops, less attention would be paid to grain crops such as maize. Nevertheless, as suggested by Wu et al. (2018), while grain yields may be lower on larger farms, the overall labor productivity is significantly higher.

The results of **Eq. (2)** also largely hold after the robustness check (Table S4). The Wald test again confirm that village cadre position, soil productivity, training, and knowledge of maize cultivation have significant effects on farmers' decisions to reduce conventional fertilizer use. The effect of farm size is no longer significant ($p = 0.132$). This can be attributed to a higher standard error in this model specification, probably due to the fact that the added variables are correlated with farm size. Nevertheless, the coefficient estimate and the odds ratio of the farm size variable remains almost unchanged.

4.4. *Achieving sustainable grain production in China: a comprehensive approach is needed*

Starting from 2015, Chinese authorities have introduced a series of measures and strategies to reduce the use of chemical fertilizers. These measures include the reduction or elimination of subsidies for fertilizer production, transportation and value added taxes (VAT) (e.g. NDRC, 2016, 2015; STA, 2015), as well as regulations on the use of fertilizers in crop production (e.g. MoA, 2015). Since then, overall fertilizer application rates have been declining and nutrient management has improved. However, our results suggest that until 2019, excessive fertilizer use still persists in maize cultivation in northern China. Specifically, the average N input in maize cultivation reaches 262 kg N ha^{-1}. This is well above the simulated optimum input of 206 kg N ha^{-1}, beyond which the yield response of maize would be marginal (Li et al., 2019). Considering that fertilizer overuse can also lead to yield loss and reduce crop quality in some cases (Albornoz, 2016), it is critical to reduce fertilizer inputs to ensure the sustainability of grain production in China.

We find that smallholder farmers' lack of "know how" is strongly associated with over-fertilization in maize production. In addition to socio-economic backgrounds such as education level and occupation, household heads form larger farms are shown to have better knowledge in terms of fertilizer application and maize cultivation, and are more likely to adopt environmentally conscious production techniques. As reflected in maize production, increasing farm size is significantly associated with reduced fertilizer use and increased yield. Our study reveals the linkages between on-farm resources, the socio-economic context of the farm, and farmers' knowledge and perceptions in maize production. We believe that to achieving sustainable grain production in China, a comprehensive approach covering various aspects is needed.

Firstly, as mentioned in several studies, increasing farm size by land consolidation would contribute to the sustainability of food production in China (Duan et al., 2021; Ju et al., 2016; Ren et al., 2019; Zhang et al., 2021). However, farm expansion should be supported by adequate government inputs and institutions, such as training as well as agricultural infrastructure and subsidies. The former will equip farmers with improved crop management strategies, while the latter will assist in the implementation of modern technologies such as integrated irrigation and fertilization system. It is worth mentioning that further subsidies for fertilizers should be specific and prudent, i.e., supportive policies should be allocated to the adoption of scientific fertilizer application methods, such as SRFs and CRFs, rather than maintaining the low prices of conventional chemical fertilizers. As Wang et al. (2022) predicted, reforming China's fertilizer policy by eliminating nitrogen fertilizer subsidies would help reduce nutrient losses and pollution in the short and long term.

Secondly, the current agricultural extension programs - especially for smallholder farmers - should be further strengthened. Our results indicate that one-third of farmers still lack "know-how" after completing fertilizer reduction trainings (Figs. 3b), and 74% of them are smallholders. A viable model for empowering smallholder farmers is through the Science and Technology Backyard (STB) platform. The STB involves agricultural scientists and students living in villages among farmers, working closely with them, and transferring knowledge (Jiao et al., 2019). Studies have shown that significant yield and productivity improvements were achieved through the STB platform (Shen et al., 2013; Yang, 2016; Zhang et al., 2016). The STB platform would also enable farm-level nutrient bookkeeping, making it possible to calculate nutrient balance on farms and further improve nutrient use efficiency (Wielemaker, 2019). To date, the STB model has been replicated and implemented in many provinces in China (Shen et al., 2013). However, continuous efforts and investments should be made to further develop and adapt the model in order to meet the needs of more than 800 million farmers of China.

Thirdly, intra/inter-village social networks should be used and enhanced to transfer knowledge and scientific fertilization techniques. In our study, social capital - reflected as holding a village cadre position - is shown to have a significant positive impact on farmers' knowledge and environmental-conscious farming decisions. Mobilizing social capital to strengthen agricultural extension services would be a cost-effective and efficient way to improve the effectiveness of trainings. The findings of Qi et al. (2021) also suggest that farmers are more likely to adopt the advice of those around them, i.e., friends, family, and acquaintances, rather than formal extension agents.

Finally, further emphasis should be placed on the promotion of formulated fertilizers and on the cooperation between research institutions and fertilizer companies. Our results indicate that formulated fertilizer is the most readily adopted scientific fertilization technique by farmers. Li and Ma (2021) also confirmed the positive impact of formulated fertilizer adoption on farmers' income. However, its application depends to a large extent on the availability of training. As proposed by Shen et al. (2013), a "regional recommendations with local adjustment" should be established, where scientists develop several "key formulas" for specific regions and farmers can fine-tune nutrient ratios according to their soil conditions. Fertilizer enterprises could then produce the compound fertilizers according to the key formulations and make these available in regional markets. In this context, it is possible to reduce the reliance of formulated fertilizer promotion on training programs.

5. Conclusions

The application of chemical fertilizers has played an important role in sustaining food production in China. However, China is also at serious risk of the environmental consequences of overuse of chemical fertilizers. Using cross-sectional survey data of 774 maize-producing farms in Northern China in 2018, we investigate the role of farm size in maize production and how it relates to farmers' fertilizer application strategies. Our results show that despite the recent declines in fertilizer application rates across China, excessive fertilizer use persists in maize cultivation. On average, farmers applied 380 kg ha^{-1} chemical fertilizers in maize cultivation and harvested 8055 kg ha^{-1} of maize grain. This is much higher than the recommended fertilizer use of about 277 kg ha^{-1} for the corresponding yield level (MoA, 2018). We find that farm size has a negative effect on chemical fertilizer use and a positive effect on maize yield ($p < 0.05$). More specifically, each 1% increase in farm size is associated to a 0.03% decrease in fertilizer use and a 0.02% increase in maize yield. A key factor leading to reduced fertilizer use among larger farms is the relatively high level of knowledge and awareness among the household heads. Our results show that farmers on large farms achieved significantly higher knowledge scores in terms of fertilizer application and maize cultivation. They are also more likely to attend agricultural trainings and adopt scientific fertilization techniques, such as formulated and slow-/controlled-release fertilizers, compared to smallholder farmers. Beside farm size, trainings and farmers' knowledge, having a family member holding a position as a village cadre is associated with reduced conventional fertilizers. This seems to confirm the positive influence of social networks on knowledge transfer.

Based on our findings, this study presents in-depth practical and political implications for more sustainable grain production in China. However, the available data impose some limitations that should be noted. First, we restrict our analysis to five provinces including Shandong, Henan, Hebei, Jilin and Heilongjiang to represent maize production in northern China. Nevertheless, Inner Mongolia and Liaoning are also two strong maize producers in northern China and should ideally also be taken into account to make the sample more representative. Second, the survey relied on self-reported behaviors, which may have led participants to give "socially desirable" responses (Floress et al., 2018). This may be particularly true for the village cadres, who may feel social pressure to provide desirable answers about reducing fertilizer use. Third, relying on cross-sectional data limited us from controlling for unobserved heterogeneity. Future studies can account for this using panel data to minimize unobservable effects.

Credit author statement

Xiaomin Yu: Conceptualization, Data curation, Methodology, Writing – original draft, Visualization. **Karsten Schweikert**: Methodology, Software, Formal analysis, Writing – Review & Editing. **Yajuan Li:** Data curation, Writing – Review & Editing. **Ji Ma**: Data curation, Writing – Review & Editing, Supervision. **Reiner Doluschitz:** Conceptualization, Writing – Review & Editing, Supervision.

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.

Data availability

Data will be made available on request.

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Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2022.116347.

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Supplementary Materials

Table S1 Questions and the corresponding points concerning farmers' maize farming skills and basic fertilization knowledge

Question	Answer	Point
Maize farming skills		
Do you know which maize varieties are suitable for the local area?	0 = I don't know any;	(0)
	1= know one or two varieties and their characteristics;	(0.5)
	2 = know more than three varieties and their characteristics.	(1)
"Increase planting density by reducing plant height" can help increasing the maize yield. Would you be willing to improve your maize farming accordingly? Why?	0 = No (too risky);	(0)
	1 = Yes (with appropriate reasons);	(1)
	2 = Others (text description).	(0 or 0.5)
At what period of time should maize chemical control be carried out?	0 = I don't know;	(0)
	1 = before vegetative 6 (V6) stage;	(0)
	2 = at V6 to V8 stage (plant height ca. 50-60 cm);	(0.5)
	3 = after V8 stage.	(1)
How do you determine if your maize is ripe?	1 = when others start harvesting;	(0)
	2 = when the bracts turn white;	(0.5)
	3 = when the kernels become hard;	(0.5)
	4 = when the kernel milk line disappears;	(1)
	5 = when the black layer of the kernels appears.	(1)
What is the most important reason for your choice of maize harvest time?	1 = my maize is ripe;	(1)
	2 = seeing others begin to harvest;	(0)
	3 = while the family members who are working or going to school are home;	(0.5)
	4 = the combine harvester is approaching my field;	(0.5)
	5 = the weather;	(0.5)
	6 = others (text description).	(0 or 0.5)
Basic fertilizer application knowledge		
What is your idea of fertilization?	1 = the more fertilizer applied, the better;	(0)
	2 = fertilizer application should depend on the crop growth;	(0.5)
	3 = fertilizer application should depend on what is lacking in the soil;	(1)
	4 = others (text description).	(0 or 0.5)
Do you know the meaning of N – P2O5 – K2O in compound fertilizer?	0 = No	(0)
	1 = Yes	(1)
Do you know the meaning of 24-12-12 on the fertilizer bag?	0 = No	(0)
	1 = Yes	(1)
Do you know how to convert the pure nutrient application rate to the fertilizer application rate?	0 = No	(0)
	1 = Yes	(1)

Do you know that fertilizer over use can lead to environmental or health problems?	0 = No	(0)
	1 = Yes	(1)

Table S2 Demographic information and major farm characteristics of the sampled households on scientific fertilization.

Variables	Non-reduced	Reduced	Total sample
Number of households	443 (63.2%)	258 (36.8%)	701
Information of the household head			
Gender (% of respondents)			
Male = 1	89.6%	90.7%	90.0%
Female = 0	10.4%	9.3%	10.0%
Age	60.5 (9.4)	57.4 (10.0)	59.4 (9.7)
Education level (average years of education)	7.4 (3.3)	8.5 (2.9)	7.9 (3.2)
Village cadre (% of respondents)			
Yes = 1	15.8%	28.2%	20.4%
No = 0	79.9%	67.1%	75.2%
Main occupational activity (% of respondents)			
Farming only = 1	71.3%	72.9%	71.2%
Off-farm work only = 2	7.0%	4.3%	6.0%
Farming and off-farm work = 3	13.3%	12.0%	12.8%
No job = 4	1.6%	0.39%	1.1%
others = 5	2.3%	4.7%	3.1%
Household economic status			
Income level (% of respondents)			
Superior = 1	2.5%	7.8%	4.4%
Upper middle = 2	10.6%	12.8%	11.4%
Medium = 3	56.9%	55.8%	56.5%
Lower middle = 4	19.6%	15.9%	18.3%
Inferior = 5	10.4%	7.8%	9.4%
Grain income ratio	0.27 (0.30)	0.37 (0.33)	0.31 (0.32)
Private car (%of respondents)			
Yes = 1	33.4%	34.9%	34.0%
No = 0	66.6%	65.1%	66.0%
Major farm characteristics			
Farm scale (% of respondents)			
Small = 1	75.4%	57. 4%	68.8%
Medium = 2	16.0%	23.3%	18.7%
Large = 3	8.6%	19.4%	12.6%
Maize area (ha)	1.18 (2.72)	5.50 (20.44)	3.55 (24.2)
Maize yield (kg ha^{-1})	7836.4 (1830.3)	8408.3 (1827.0)	8045.6 (1848.4)
Fertilizer input (kg ha^{-1})	380.4 (121.4)	375.4(104.9)	378.6 (115.6)
Land fragmentation (% of respondents)			
Multiple=1	76.1%	81.8%	78.2%
one = 0	23.9%	18.2%	21.8%
Perceived soil productivity (%of respondents)			

High = 1	27.3%	29.8%	28.2%
Medium = 2	62.5%	64.3%	63.2%
Low = 3	9.0%	5.4%	7.7%

Table S3 Results of the robustness check - corelation analysis.

	log_TotalFert	PK ratio	log_MaizeYield	Total knowledge score
Constant	5.852 *** (0.107)	0.291 *** (0.074)	8.836 *** (0.069)	5.008 *** (0.618)
log_Maize area	-0.049 ** (0.020)	0.003 (0.016)	0.045 *** (0.016)	0.330 *** (0.114)
Farm scale2 (medium) [a]	0.045 (0.037)	-0.017 (0.035)	-0.035 (0.032)	-0.287 (0.227)
Farm scale3 (Large)	0.146 * (0.082)	-0.015 (0.065)	-0.123 ** (0.053)	-0.286 (0.417)
rented_land1	-0.056 (0.039)	0.024 (0.034)	0.0180 (0.027)	0.373 * (0.226)
croptype1 (cash+grain)	-0.004 (0.040)	0.104 *** (0.033)	0.075 *** (0.024)	
crop_structure2 (Intercropping) [b]	-0.172 (0.133)	-0.152 ** (0.076)	0.100 ** (0.048)	
crop_structure3 (Rotation)	-0.043 (0.097)	-0.060 (0.053)	-0.003 (0.040)	
Landparcel1	0.046 (0.031)	0.019 (0.028)	-0.065 *** (0.023)	
Soil fertility2 (Medium) [c]	0.015 (0.026)	-0.005 (0.023)	-0.043 ** (0.020)	
Soil fertility3 (Low)	0.030 (0.061)	-0.056 (0.047)	-0.150 *** (0.057)	
Soil texture2 (loam) [d]	0.047 (0.036)	0.045 (0.033)	0.122 *** (0.034)	
Soil texture3 (clay)	0.058 (0.037)	-0.008 (0.034)	0.089 *** (0.033)	
Village_cadre1				0.379 ** (0.181)
Age				0.006 (0.009)
Edu0 (No formal education) [e]				-1.008 *** (0.300)
Edu2 (Junior high)				-0.598 *** (0.172)
Edu3 (Senior high/ secondary school)				0.440 ** (0.199)
Edu4 (Above high school)				-0.215 (0.608)
Main activity2 (Off-farm only) [f]				-0.808 ** (0.366)
Main activity3 (off-farm + agriculture)				-0.262 (0.219)
Main activity4 (no job)				-0.578 (0.717)
Main activity5 (others)				0.248 (0.348)
Regional fixed effects	Yes	Yes	Yes	Yes
N	544	555	653	571
adjusted R-squared	0.118	0.039	0.163	0.238

Note: *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. Robust standard errors appear in parentheses.

[a] Reference group for *farm scale* is small;

[b] Reference group for *crop structure* is monoculture;

[c] Reference group for *soil fertility* is high;
[d] Reference group for *soil texture* is sandy;
[e] Reference group for *education* is primary school;
[f] Reference group for *main activity* is farming only.

Table S4 Results of the robustness check - logistic regression analysis.

	Coefficient	Std. Error	t-statistic	Wald	Odds ratio
Constant	-1.447	1.083	-1.336		0.24
Household head					
Gender1	-0.257	0.454	-0.566	0.315	0.77
Age	-0.010	0.012	-0.807	0.652	0.99
Education[a]				4.036	
Edu0 (No formal education)	-0.937*	0.553	-1.694		0.39
Edu2 (Junior high)	0.030	0.249	0.121		1.03
Edu3 (Senior high/ secondary school)	-0.040	0.320	-0.124		0.96
Edu4 (Above senior high)	-0.597	0.793	-0.752		0.55
Village_cadre1	0.457*	0.260	1.755	3.066*	1.58
Family economic situation					
Income level[b]				3.411	
Income_level1	0.617	0.561	1.100		1.85
Income_level2	0.435	0.328	1.324		1.54
Income_level4	0.229	0.284	0.808		1.26
Income_level5	0.352	0.376	0.937		1.42
Grain_income	0.575	0.387	1.485	2.184	1.78
Private car	-0.014	0.252	-0.054	0.003	0.99
Maize farming condition					
log(MaizeArea)	0.272	0.183	1.484	2.266	1.31
rented_land1	-0.055	0.314	-0.175	0.031	0.95
Farm scale[c]				4.280	
FS_2 (medium)	0.411	0.323	1.270		1.51
FS_3 (Large)	-0.353	0.611	-0.578		0.70
Landparcel1	-0.187	0.286	-0.653	0.425	0.83
Soil productivity[d]				5.493*	
SP_1 (High)	0.917*	0.471	1.946		2.50
SP_2 (Medium)	0.993**	0.444	2.238		2.70
Training and knowledge					
Fert_training1	1.268***	0.241	5.254	29.116***	3.55
Maize_Score	0.208*	0.109	1.909	3.671*	1.23
regional fixed effects			Yes		

[a] Reference group for *education* is primary school;
[b] Reference group for *Income level* is medium;
[c] Reference group for *farm scale* is small;
[d] Reference group for *soil productivity* is low.

Chapter 5 General Discussion

This dissertation aims to provide a comprehensive and systematic understanding of chemical fertilizer use and management in China at the national, regional, farm and household levels, which will contribute to China’s sustainable nutrient management. At the national level, the study provides a quantitative literature review of the development of chemical fertilizers in China (Chapter 2), where hypothesis (1) “*Despite recent declines in the application rate of chemical fertilizers, high nutrient surpluses persist in China with regional variations*” is confirmed. This section of the study also partially serves as the theoretical and data basis for the analysis that follows. At the regional level, the study examines the relationship between fertilizer nutrient surpluses and regional economic development, which provides a deeper perspective on recent progress in reducing fertilizer application in China and the challenges ahead (Chapter 3). In this section, hypothesis (2) “*The relationship between fertilizer N and P surpluses and regional economic development follows a typical Environmental Kuznets curve (EKC) trajectory – an inverted U-shaped curve*” is confirmed. At the farm and household level, the study focuses on maize farmers in northern China to understand the role of farm characteristics, farmers' knowledge, perceptions, and socioeconomic context in farmers' fertilizer use strategies (Chapter 4). In this section, hypotheses (3) “*Small farms tend to overuse fertilizers in maize production in China compared to large farms without further improving yields*” and (4) “*The lack of knowledge and awareness among small farmers is the main reason for their excessive use of chemical fertilizers*” are confirmed.

Due to the cumulative nature of the dissertation, the results and methods of each analysis have been discussed in the corresponding chapter. Yet, this chapter presents an overarching discussion that ties together the major findings of each chapter, provides deeper insights and discusses these results in the broader context of the relevant literature. Specifically, the chapter begins with a discussion of the development of China's fertilizer policy and its implications for fertilizer use in the context of achieving national grain self-sufficiency. Second, a comprehensive assessment of China's recent performance in reducing fertilizer use is presented using indicators generated in Chapters 2 through 4. Since the data used in Chapter 2 only cover up to 2018, updates and recalculations of selected indicators are also included. This is followed by a discussion of potential factors that hinder the sustainable management of fertilizers in China. Then, the conclusions of the study and policy recommendations for sustainable fertilizer management in China are presented. The chapter ends with the contributions and limitations of this study.

5.1 The trade-off between food self-sufficiency and the environment: China’s highly subsidized chemical fertilizers

Food self-sufficiency has been a key priority for the Chinese government for decades (Simelton, 2011). More specifically, in October 1996, the government announced that China would produce 95% of the grain it consumes (Information Office of the State Council, 1996; Zhan, 2017). In order to achieve grain self-sufficiency and contribute to China's food security, the Chinese government has implemented a series of supportive policies and measures over the past decades to expand domestic grain production capacity (Y. Li et al., 2014; Niu et al., 2022). An important aspect of these measures is the effort to mobilize the fertilizer industry as well as subsidies for farmers to increase their purchasing power for industrial fertilizers (S. Li et al., 2014; Y. Li et al., 2013).

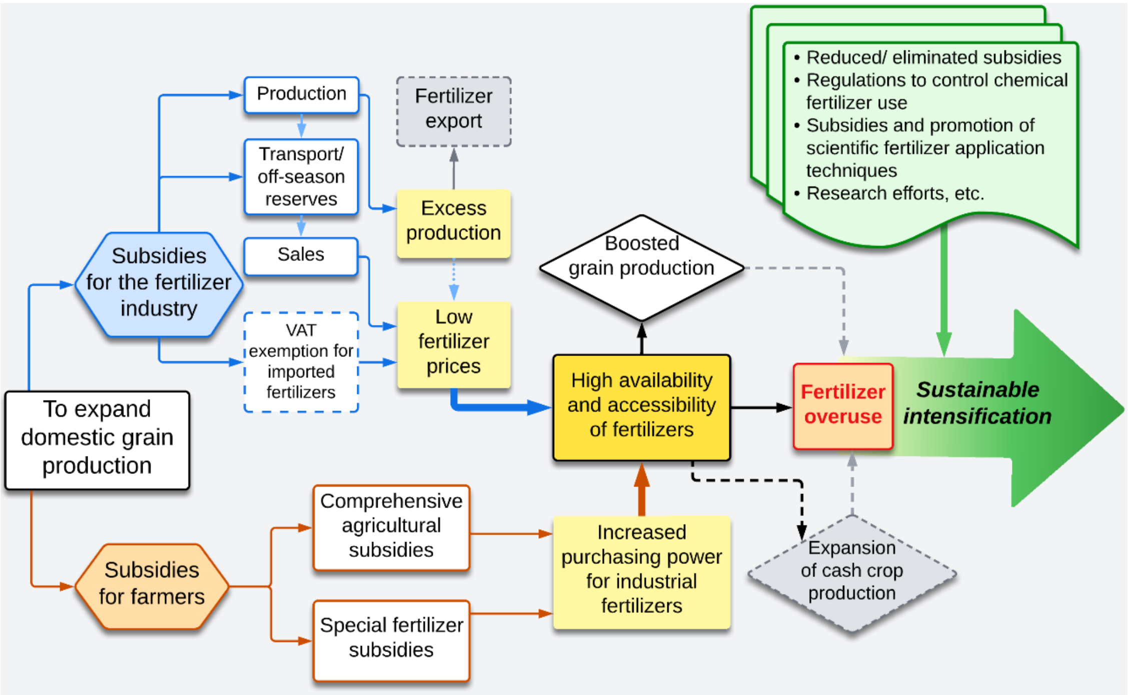

Figure 1 *Roadmap for the development of fertilizer-related policies in China and their implications. Adapted from Li (2014).*

Figure 1 shows the roadmap for the development of fertilizer-related policies in China and their implications. Beginning in the 1980s, the Chinese government implemented a series of policy supports for farmers and the fertilizer industry to improve the availability and accessibility of chemical fertilizers (Chapter 2). This has led to artificially low fertilizer prices, which on the one hand brought economic benefits to fertilizer suppliers and farmers, and on the other hand directly led to excessive use of chemical fertilizers in the coming years (Cui and Shoemaker, 2018; Y. Li et al., 2013). It was estimated that until the early 2010s, farmers and fertilizer suppliers benefited from the preferential fertilizer subsidy policy to the tune of 2.2 billion and 5.3 billion CNY, respectively (S. Li et al., 2014). Meanwhile, the Chinese government also tried to promote the marketing of agricultural products, which was seen as a further incentive to mobilize farmers for food production (Y. Li et al., 2014). As a result, from the 1980s to the 2000s, China experienced a rapid expansion of food production that allowed the country to feed its large and still growing population (Chapter 2). In the 2000s, the production of cash crops began to expand and massive amounts of arable land was used to grow vegetables, fruits, etc. (Su et al., 2016). This has accelerated the rise in fertilizer consumption due to the high profitability of cash crops and their nutrient-intensive nature (Xinyu Zhang et al., 2013). Nowadays, maize, vegetables and fruits are the major drivers of chemical fertilizer consumption in China (Xiaohui Chen et al., 2018). In addition to having a grain self-sufficiency ratio (SSR) of 98.5% (Zhu, 2022), China has also become the world's largest producer of a wide range of agricultural products (Chapter 2).

China's growth in food production has been accompanied by the excessive use of chemical fertilizers (Cui and Shoemaker, 2018). This has not only led to a diminishing marginal rate of return, but also to serious environmental consequences (Chapter 2) and hindered the sustainable development of the regional economy (Chapter 3). Several scholars have emphasized that correcting distortions in fertilizer prices is one of the key ways to reduce non-point source pollution from agriculture (Bai et al., 2019; Sun et al., 2012), and shifting some of the subsidies to the non-fertilizer sector would be an effective way to redistribute welfare (S. Li et al., 2014). Beginning in the 2010s, the Chinese government introduced a series of gradual measures to phase out fertilizer-related subsidies and control the use of chemical fertilizers (see Table 1 of Chapter 1). The academic community has also made efforts to guide farmers' fertilizer use strategies and raise their environmental awareness (Chapter 4).

However, there has never been a simple solution to the dilemma between food productivity and the environment, especially for a developing country like China, where agriculture is dominated by 200 million small farmers (Huang et al., 2012). Despite the great attention and effort given to sustainable agricultural intensification in recent years, chemical fertilizers still play an important role in sustaining China's current food production. In 2021, due to rising prices for bulk raw materials for fertilizer manufacturing and instability in international markets, fertilizer prices in China have risen significantly - especially for nitrogen fertilizers, with urea prices reaching their highest level in the last 10 years (China Business Network, 2021). To compensate for the high prices of fertilizers and other production materials, in July 2021, the Chinese government decided to grant a one-time subsidy totaling CNY 20 billion to grain farmers (MoA, 2021). In August 2022, another 10 billion CNY was provided to grain farmers to support domestic food production (MoA, 2022).

5.2 Assessing China's recent performance in reducing fertilizer use

In Chapter 2, the annual growth rates of chemical fertilizer use and nutrient surpluses were estimated for each province in China. The results show that 83% and 93% of the provinces have achieved the goal of zero growth in these two aspects by 2019, respectively. Since the data used in Chapter 2 are up to 2018, here the discussion incorporates the most recent data (up to 2020) into the calculations and updates Tables 2 and 3 of Chapter 2. The updated tables are presented in the Appendixes as **Tables A2** and **A3**.

The most recent data show that by 2021, all Chinese provinces have achieved the zero growth goal for fertilizer use (NBS, 2022a). From 2019 to 2020, provinces in the southwest and northwest enjoyed the highest rates of fertilizer use reduction, at 6.6% and 6.3%, respectively. They also had the highest reductions in fertilizer nutrient surpluses, with 8.1% in the Northwest and 7.5% in the Southwest (NBS, 2022a). Compared to these provinces, fertilizer use declined more slowly in the provinces in NCP and NECP, averaging 3.5%. Besides Beijing (657 kg ha^{-1}), provinces with the highest fertilizer consumption are located in the southeast coast, where cash crop production is intensive. This include Hainan (657 kg ha^{-1}), Fujian (641 kg ha^{-1}) and Guangdong (506 kg ha^{-1}).

However, despite having achieved the goal of zero growth in fertilizer use nationwide, cointegration regression analysis (Chapter 3) shows that there is still a linear increase between fertilizer nutrient surpluses and GRP per capita in seven Chinese provinces, suggesting that pollution from fertilizer use will become more severe as the economy grows. Therefore, to provide a comprehensive assessment of China's recent performance in reducing fertilizer consumption, the discussion here combines three indicators from Chapters 2 and 3 of the study for assessment. These include estimates of fertilizer inputs and fertilizer nutrient surpluses per hectare of cropland at the provincial level (Chapter 2, incorporating the most recent data available), and the grouping results of the EKCs (Chapter 3).

More specifically, a province is considered to be in *Group A* if: 1) the province's fertilizer use and fertilizer surpluses have declined for **five consecutive years**; and 2) the province has **reached** the EKC turning point between its fertilizer surpluses and its per capita GRP. Provinces in *Group A* are believed to have made good progress in reducing fertilizer use and are moving toward sustainable agricultural intensification. A province belongs to *Group B* if: 1) the province's fertilizer use and fertilizer surpluses have declined for **five consecutive years**; but 2) the province still exhibits a **positive relationship** between its fertilizer surpluses and its per capita GRP. Provinces in *Group B* have made some progress in reducing fertilizer use, but the tension between fertilizer pollution and economic growth in these provinces is likely to become more pronounced as the economy grows. Last but not least, if a province does not meet any of the requirements, it is in *Group C*. More efforts and attention must be given to these provinces to control their fertilizer consumption and improve nutrient management. A summary of the assessment method and results is presented in **Table A4** in the Appendixes.

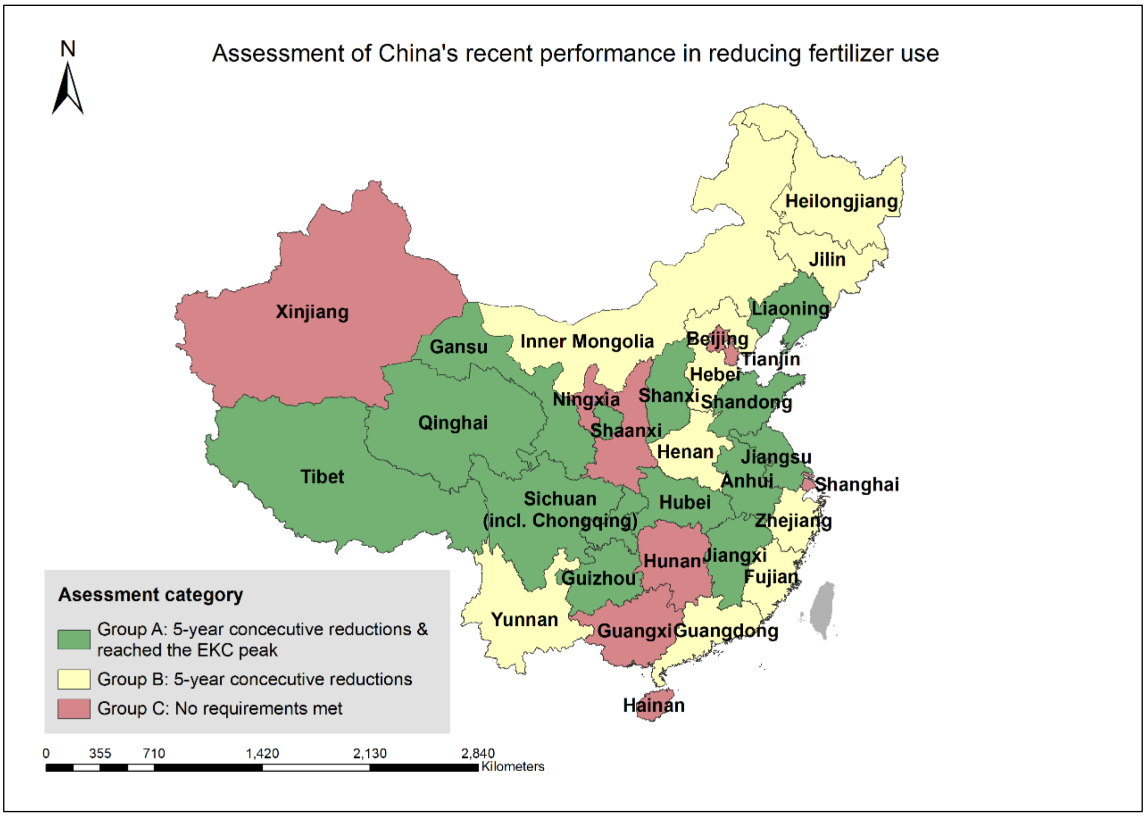

Figure 2 *Assessment of China's recent performance in reducing chemical fertilizer use.*

Figure 2 shows the spatial distribution of the provinces in Group A, B and C. Assessment results show that 12 out of 30 provinces in China belong to Group A. These provinces cover most of central China and hold 43% of China's total cultivated land area (NBS, 2022a), indicating general progress in reducing fertilizer use in China. In contrast to the Group A provinces in central China, most of the provinces in Groups B and C are located either in the far north or in the far south of China. These provinces share at least one of the following three characteristics: economic dependence on crop production; intensive cash crop cultivation; and multiple cropping seasons (Chapter 2 and 3). These characteristics are also considered to be some of the major barriers to sustainable fertilizer management in China, which will be discussed in detail in Chapter 5.3.

5.3 Potential factors hindering sustainable fertilizer management in China

5.3.1 Rural-urban migration and the small farm size

Several recent studies have suggested that small farm size is one of the major barriers to sustainable agricultural intensification in China today (e.g., Chen et al., 2011; Dawe, 2015; Sheng et al., 2019). This argument is supported by the findings in Chapter 4, where farm size was found to have a negative effect on fertilizer use and a positive effect on yield and farmers' knowledge score in maize production in northern China. Potential reasons behind these findings can be summarized in two main aspects.

First, in recent decades, China's land management practices have shifted from labor-intensive to capital-intensive (Y. Zhang et al., 2020). This was led by the vast transformation of China's labor market due to rural-urban migration and urbanization - in 2015, the size of the rural-urban migration in China reached 250 million people, more than three-quarters of the population of the United States (Bairoliya and Miller, 2021). As a result, agricultural inputs such as machinery, irrigation systems, and agrochemicals have begun to play an important role in compensating for the decline in agricultural labor (Ebenstein et al., 2011). However, in China, farm mechanization and modernization are often limited by the historical land fragmentation and small farm size (Chen et al., 2011; Sheng et al., 2019), resulting in a lack of fixed inputs for smallholder farmers (Ren et al., 2021). In this context, maintaining crop yields through the use of highly subsidized chemical fertilizers becomes the “low-hanging fruit” of the smallholders in China, despite the environmental concerns associated with fertilizer nutrient overload (Ren et al., 2021; Xin, 2022).

Second, household heads of small farms are often characterized by their older age and lower education levels (Chapter 4). These characteristics are often considered to have negative impacts on farm management practices, farmers' knowledge and environmental awareness (Yu, 2014). The data used in Chapter 4 show that household heads of small-scale farms are on average older (60 years old) and less educated (7.7 years of education - junior high school) compared to those of medium and large-scale farms (see **Table 1**). They also score lower in knowledge of maize cultivation and fertilizer application and are less likely to participate in agricultural training or adopt scientific fertilization techniques (Chapter 4). On the one hand, it can be argued that older people are often hesitant to expand their farms because they are risk averse (Daxini et al., 2018), leading to the phenomenon that small farms are usually operated by older farmers. This may be particularly true for subsistence older farmers, who suffer from social security deficiencies (Gong et al., 2016; Qu et al., 2012). On the other hand, farmers on small-scale farms may lack incentives to adopt new technologies or learn new skills because of the correspondingly higher fixed costs (Gong et al., 2016; Ren et al., 2021). The typical "business-as-usual" approach of the small farms may be outdated and inconsistent with the goal of sustainable intensification.

Table 1 *Selected descriptive statistics of the survey data used in Chapter 4.*

Variables	**Small-scale [a] farms**	**Medium-scale farms**	**Large-scale farms**	**Total sample**
Number of households	524 (67.7%)	149 (19.3%)	101 (13.0%)	774
Age of the household head [b]	60.5 (9.2)	59.1 (9.6)	51.8 (8.9)	59.4 (9.7)
Education level of the household head (years) [c]	7.7 (3.1)	8.0 (3.3)	9.0 (3.0)	7.9 (3.2)
Decision to reduce conventional fertilizer use in maize cultivation (% of respondents)				
Yes=1	28.2%	40.3%	50.0%	33.3%
No=0	63.7%	47.7%	37.6%	57.2%
Total knowledge score	5.4 (1.9)	5.9 (2.0)	7.0 (1.7)	5.7 (1.9)
Basic fertilization score	2.9 (1.4)	3.2 (1.5)	3.8 (1.2)	3.0 (1.4)
Maize cultivation score	2.6 (1.0)	2.7 (1.1)	3.2 (1.0)	2.7 (1.1)

[a] The classification method of farm scale can be found in Table 2 of Chapter 4.

[b and c] These results were not included in Chapter 4.

5.3.2 The dependence of some regional economies on cash crop production

The spatial distribution of Chinese industry can be observed by the share of the secondary sector economy in the total domestic economy of each province. According to the National Bureau of Statistics (NBS) of China, in 2021, four provinces on the eastern coast accounted for more than one-third of China's total secondary sector economy, including Jiangsu (11.5%), Guangdong (11.1%), Shandong (7.4%) and Zhejiang (6.9%) (NBS, 2022a). Apart from Shandong, these provinces also had the highest GDP per capita of all provinces (NBS, 2022a), reflecting a relatively high level of industrialization and economic development.

In contrast to the economically developed provinces in the eastern coastal region, some areas of China still rely heavily on the primary sector of the economy, especially crop production. These areas are generally characterized by a high ratio of gross output value of crop production (GVC) to the total GRP and a low per capita GDP (Chapter 3), indicating the dependence of their economies on agriculture and making the reduction of fertilizer use a major challenge. These areas include major grain-producing regions such as Henan, Hebei in the NCP and Jilin and Heilongjiang in the NECP, as well as provinces with a high proportion of cash crops, such as Xinjiang, Hainan and Guangxi (Chapter 2). As shown in **Figure 2**, most of these provinces are classified in Groups B and C in the overall assessment of reducing fertilizer use, reflecting their relatively slow progress in fertilizer reduction.

Studies have shown that until the 1980s, grain crops accounted for almost 90% of China’s total fertilizer consumption in order to ensure national food security (Xiaohui Chen et al., 2018; Y. Li et al., 2014). In the 2000s, land use for cash crops, i.e., sugar crops, oil seeds, fiber crops, tobaccos, rubber, vegetables and fruits, began to expand drastically (Xiaohui Chen et al., 2018; Yang et al., 2016). Due to their profitability and high yield response to fertilizers (He et al., 2015; Ma et al., 2016), chemical fertilizer consumption for cash crops in China has become more prominent (Kahrl et al., 2010). This has led to high nutrient surpluses in cash crop producing regions such as southeast and northwest of China (see **Figure 5** in Chapter 2). The former is a major producer of tropical fruits and vegetables with multiple cropping seasons, while the latter has a large amount of cultivated land for fiber and oilseeds (Chapter 2).

Nowadays, China’s “grain baskets” – the mid- and lower reaches of Yangtze River, the NECP and the NCP – contribute about two-thirds of total grain production each year (Y. Li et al., 2014). Although excessive fertilizer use still occurs in grain production in

China - for example, in maize production in northern China, farmers apply on average 37% more fertilizers (380 kg ha^{-1}) than recommended (Chapter 4) - fertilizer nutrient surpluses are generally lower in grain-producing areas than in areas with a high proportion of cash crops (Chapter 2). In addition, grain cultivation in China has slowly moved toward large-scale production with improved infrastructure and machinery (Ren et al., 2021), showing great potential for sustainable intensification. However, cash crops such as fruits and vegetables are still predominantly grown on a small scale and are labor and capital intensive (Zhang et al., 2020). This makes it more challenging to reduce fertilizer use in cash crop production than in grain production.

As mentioned in Chapter 3, the five large cash crop producing provinces along the Southeast coast (Hainan, Guangxi, Guangdong, Fujian and Zhejiang) continue to show linear growth between fertilizer nutrient surpluses and GRP per capita. On the contrary, the provinces in China’s “grain baskets” region have either reached the turning point of the EKC or are approaching it. This highlights the improvements in reducing fertilizer use in grain-producing regions and the significant challenges in balancing cash crop production and the environment in some areas of China.

5.3.3 The interface between practice and science: more effort needed

The importance of education and training in translating science into innovative practices in agricultural production has been highlighted in many studies (Cui and Shoemaker, 2018; Kernecker et al., 2021). For example, in some countries in the European Union, the Agricultural Knowledge and Innovation System (AKIS) involving farmers, researchers and other actors has proven its important role in facilitating communication and interaction to drive agricultural innovations (Knierim et al., 2015). In Germany, the promotion of smart agriculture also requires adequate extensions to bring together multiple stakeholders and enhance interaction (Knierim et al., 2019; Munz et al., 2020).

In recent years, considerable efforts have been made by Chinese academia to foster collaboration between practice and science with the aim of reducing fertilizer use and improving nutrient use efficiency. Typical examples include the continuous effort to breed crop cultivars with high nutrient use efficiency (e.g., D. Li et al., 2021; Weiß et al., 2021) and the commercialization of the advantages cultivars; the “Soil Testing and Fertilizer Recommendation” program sponsored by the MoA of China from 2005 to 2010, where 160 million grain farmers were involved (Y. Li et al., 2013); and the promotion of the STB platform, which enables agricultural scientists to work directly on the farm and transfer scientific farming knowledge to the farmers (Jiao et al., 2019; Yang, 2016).

However, despite these efforts, China still has a long way to go before it can effectively and systematically provide scientific advice to hundreds of millions of Chinese farmers (W. Zhang et al., 2013). In fact, studies have shown that even in developed countries like Germany, the scaling up of scientific or smart agricultural technologies faces barriers from multiple dimensions and requires continuous effort and investment (Kernecker et al., 2021; Knierim et al., 2019). Furthermore, as pointed out by several scholars, China's current agricultural extension system suffers from a number of weaknesses (Gao et al., 2020; Smith and Siciliano, 2015). These include, *inter alia*, hierarchical and redundant institutional structures, unqualified extension agents in remote areas (Smith and Siciliano, 2015) and a lack of capacity to interact effectively and flexibly with farmers (Gao et al., 2020).

As indicated in Chapter 4, the results of the farm household survey in northern China show that while extension services have a significant positive impact on farmers' fertilizer use strategies ($p<0.01$), the interface between practice and science is still weak and should be strengthened. This latter argument can be illustrated from two aspects. Firstly, the coverage of the current extension services in the study region is not enough. From 2017 to 2018, only 43% of the interviewed farmers participated in trainings on reducing fertilizer application (Chapter 4). Considering that the Chinese government has implemented several regulations and policies to control fertilizer use since 2015 (Chapter 2), the coverage of relevant extension services is far from satisfactory. Secondly, the effectiveness of the trainings is not sufficient. Of the farmers who participated in the trainings, 21% reported that they still did not know how to reduce conventional fertilizer use, and only half actually adopted scientific fertilizer application techniques in their maize production (see Figure 3 in Chapter 4).

Chapter 4 provides evidence for the positive aspects of the training program and reveals its potential problems. In investigating the role of agricultural extensions in farmers' fertilizer use strategies, Chapter 4 and other regionally focused studies (e.g., Lin et al., 2022; Qi et al., 2021; Qiao et al., 2022) can serve as case studies and contribute to a comprehensive picture in this context.

5.3.4 The shrinking and aging of China's rural population

China’s population is expected to reach its peak in the coming three years (United Nations, 2018; Ye, 2022). In 2021, China’s population hit 1.41 billion, including 914 million urban and 498 million rural inhabitants (NBS, 2022a). However, the natural growth rate of the population in China has been declining for six consecutive years – from 6.53 ‰ in 2016 to 0.34 ‰ in 2021, and the Gross Dependency Ratio (GDR)[1] has increased from about 34% in the early 2010s to 46.3% in 2021 (NBS, 2022a). Although in 2021, the Chinese government introduced a universal three-child policy to promote a balanced population in the long run, China's fertility rate is likely to continue to decline (Yang et al., 2022). And the gap between the number of rural and urban residents is expected to continue to widen in the coming decades (see **Figure 3**) (United Nations, 2018).

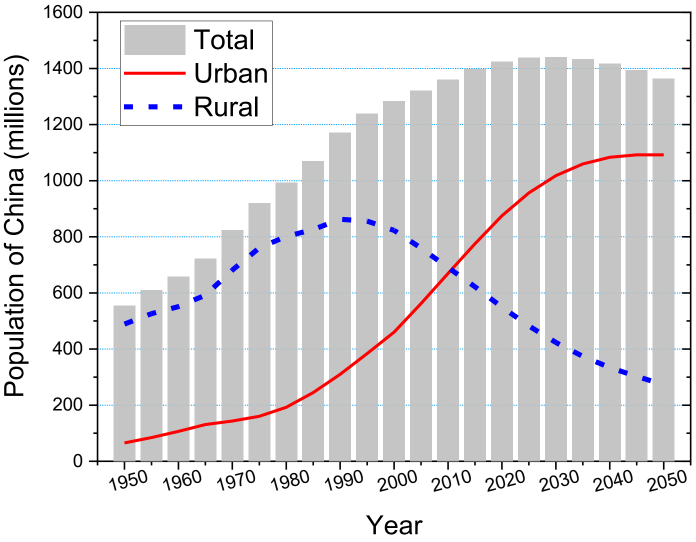

Figure 3 *Changes in rural–urban population in China from 1950 to 2050. Data source: United Nations, (2018)*

Cui and Shoemaker (2018) note that as China's population peaks, the pressure on domestic grain production will level off accordingly and they are thus “…*cautiously optimistic about the future of China’s food security*”. However, given the statistics of rural and urban population distribution and the increasing number of GDRs, the question of who will produce food in the countryside will take the stage (Cui and

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[1] Gross Dependency Ratio (GDR) is the ratio of the non-working-age population to the working-age population, expressed as a percent. The indicator generally describes the number of non-working-age people to care for per 100 working-age people and reflects the basic relationship between population and economic development from a demographic perspective (NBS, 2022a).

Shoemaker, 2018; Liu and Zhou, 2021). And the question that follows closely will be how these people will be able to produce enough food sustainably.

As mentioned in Chapter 5.3.1, China’s rapid urbanization has brought a large number of rural residents into urban areas, leading to a reduction in the rural labor force. However, in addition to the decline in the quantity of the rural population, rural-urban migration has also led to a decline in the quality of the rural labor force (Liu and Zhou, 2021). Well-educated rural residents generally have better job opportunities in the non-agricultural sector, which has led to a gradual decrease in the education level of the agricultural population (Gao and Li, 2022). Data from the China Family Panel Studies (CFPS[2]) show that in 2012, only 8% of the rural workforce (16 years and older) had a senior high school degree or above, compared to 20% of the urban workforce. Aging is also a more serious problem in rural China than in urban areas. Zeng and Wang (2014) demonstrated that assuming China’s fertility policies remain unchanged, the proportion of the population aged 65 years or older in the total population would reach 26% and 15% in 2030 and 51% and 25% in 2050 in rural and urban areas, respectively. In addition, the health status of older people in rural China is generally worse than that of urban citizens (Qu et al., 2012).

Liu and Zhou (2021) identified the aging and weakening of farmers as one of the key factors that threaten China's future food security. This is because, in addition to having a lower working capacity (Liu and Zhou, 2021), older farmers are also more likely to increase their fertilizer use to compensate for their reduced productivity, leading to a higher chance of fertilizer overuse (Lin et al., 2022). Furthermore, older farmers are generally seen to be more hesitant to adopt new environmentally conscious farming techniques due to risk aversion (Y. Li et al., 2021; Qi et al., 2021). In Chapter 4, although regression analysis showed no significant effect of age on farmers' decision to reduce fertilizer use in northern China, farmers who did not reduce their conventional fertilizer use were on average older (60.5 years) and had a lower level of education (7.4 years) compared to the opposite group (57.4 years and 8.5 years of formal education, see Table S2 in Chapter 4). All of these aspects create additional challenges for China to feed its future generations and achieve sustainable fertilizer management.

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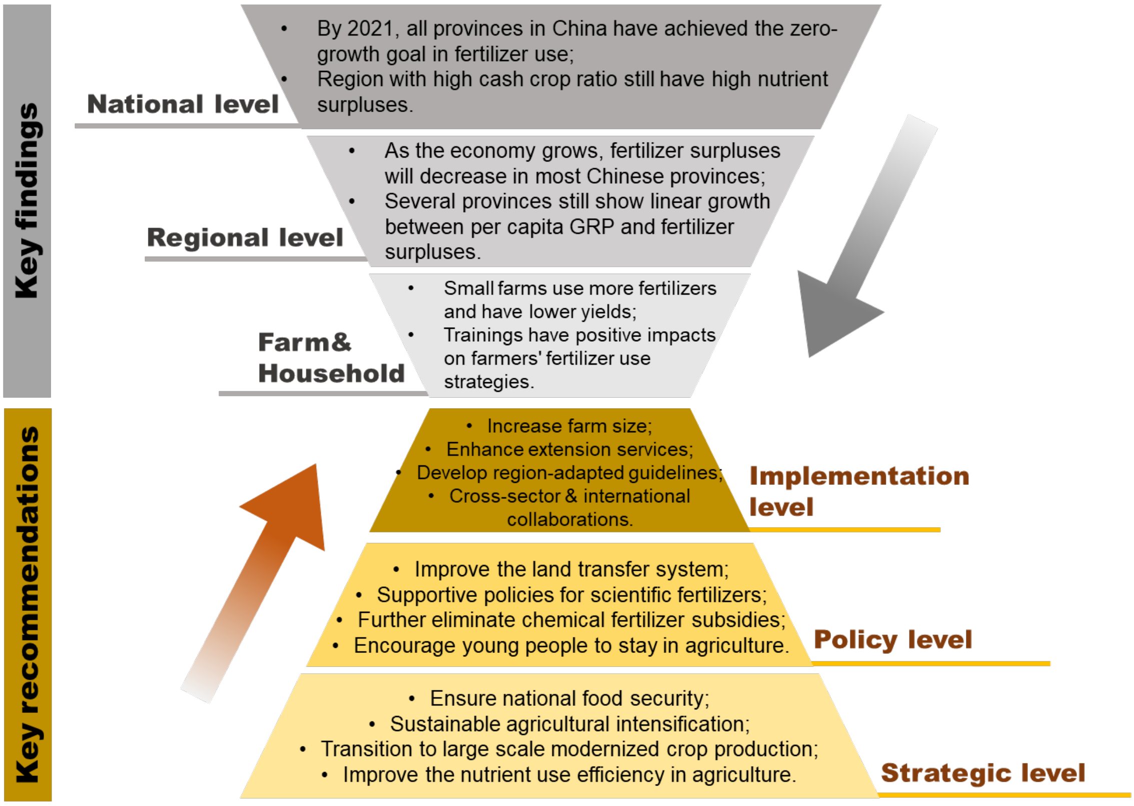
[2] China Family Panel Studies (CFPS) is funded by 985 Program of Peking University and carried out by the Institute of Social Science Survey of Peking University. (https://www.isss.pku.edu.cn/cfps/en/index.htm)

5.4 Conclusions and recommendations: the way forward for sustainable nutrient management in China

Overall, this dissertation confirms China’s recent progress in reducing chemical fertilizer use and sheds light on the current and future challenges that China faces in sustainable nutrient management. This can be reflected in the following conclusions. **First**, by 2021, all Chinese provinces have reached zero growth in fertilizer use and fertilizer N and P surpluses. However, regions with a high proportion of cash crops still suffer from high nutrient surpluses (Chapter 2, incorporating the most recent data available). **Second**, with further economic growth, the fertilizer surpluses will decrease in most Chinese provinces, indicating a moderating of the tension between economic development and the environment. Yet, seven provinces still exhibit a linear increase between per capita GRP and fertilizer nutrient surpluses (Chapter 3). **Third**, small farms tend to overuse fertilizers in maize cultivation without further increasing yields. Current extension programs have a positive impact on fertilizer use strategies and environmental awareness among farmers in northern China, however, the coverage and effectiveness of training should be improved (Chapter 4). As elaborated in Chapter 5.3, key factors impeding sustainable fertilizer management in China include: small farm size, which limits the application of modern agricultural inputs other than chemical fertilizers; the economic dependence on cash crops in some areas; the weak interface between farmers' practices and scientific production guidelines; and the shrinking and aging of China's rural labor force.

Based on these findings, recommendations to contribute to sustainable nutrient management in China can be made at three levels (**Figure 4**). At the **national strategic level**, the focus should remain on maintaining a high level of grain SSR to ensure national food security. At the same time, there should be a gradual transition to large-scale modernized crop production that promotes sustainable agricultural intensification. One the one hand, farm expansion will help strengthen the role of agricultural fixed inputs, such as machinery, advanced knowledge and management, and irrigation infrastructure in crop production and eliminate dependence on chemical fertilizers. On the other hand, it will also alleviate the pressure from the shrinking rural labor force. Consequently, the overall nutrient use efficiency and labor efficiency of agriculture will be improved. In addition, there is a need to support infrastructure improvements in key grain-producing areas, including the mid- and lower reaches of Yangtze River, the NECP and the NCP (Y. Li et al., 2014). In particular, the livelihoods and infrastructure of smallholder farmers should be supported to address their lack of fixed inputs (Ren et al., 2021).



- By 2021, all provinces in China have achieved the zero-growth goal in fertilizer use;
- Region with high cash crop ratio still have high nutrient surpluses.

- As the economy grows, fertilizer surpluses will decrease in most Chinese provinces;
- Several provinces still show linear growth between per capita GRP and fertilizer surpluses.

- Small farms use more fertilizers and have lower yields;
- Trainings have positive impacts on farmers' fertilizer use strategies.

- Increase farm size;
- Enhance extension services;
- Develop region-adapted guidelines;
- Cross-sector & international collaborations.

- Improve the land transfer system;
- Supportive policies for scientific fertilizers;
- Further eliminate chemical fertilizer subsidies;
- Encourage young people to stay in agriculture.

- Ensure national food security;
- Sustainable agricultural intensification;
- Transition to large scale modernized crop production;
- Improve the nutrient use efficiency in agriculture.

Figure 4 *An overview of the key findings and key recommendations of the study.*

At the **policy level**, the focus should be on the following four aspects. **(1)** The land transfer system should be improved to facilitate farm expansion and large-scale operation (Li, 2014). This can be achieved, for example, by optimizing the incentives of China's existing rural land property system (Peng et al., 2020), and internalizing and marketizing land costs through land contracting cooperation and land custody (Yu Liu et al., 2019). Agricultural socialized services can also be used as a means to promote operation scale (Huan et al., 2022). **(2)** Supportive policies should be given to the manufacturing, transport and use of scientific fertilizers. The rail transport incentive for slow-release fertilizers implemented in 2021 (NDRC, 2021) is a good example in this regard. However, incentives should also be considered for other scientific fertilizers and for farmers who adopt scientific fertilization techniques. **(3)** Subsidies for conventional chemical fertilizers should be further eliminated. To compensate for possible sharp increases in fertilizer prices due to fluctuations in international markets, a one-time subsidy to farmers at the right time may be a good solution. Such one-time subsidies have been implemented in 2021 and 2022, respectively (MoA, 2022, 2021).

Nevertheless, its impact on farmers' production strategies should be noticed and studied. **(4)** Supportive policies should be developed to encourage young people to stay in agriculture. Since young people are generally better educated and more open to advanced technologies and management practices, their participation will foster the process of sustainable agricultural intensification.

At the **implementation level**, in addition to increasing farm size, significant attention should be given to strengthening the interface between practice and science. Continuous efforts and investments should be made in agricultural extension programs, such as the nationwide promotion of soil testing and the STB platforms (Jiao et al., 2019; Yong Liu et al., 2019). It is important to note that the design of extension programs should always be aligned with farmers' preferences and needs, and that the approach should be holistic and involve the whole farm (Smith and Siciliano, 2015). One possible way to achieve this ambitious goal is to provide extension services through social media or mobile applications (Gao et al., 2020; STB, 2022). For example, Gao et al. (2020) developed a new agricultural extension model using WeChat public account, considering the current popularity of mobile phones and short videos. In this case, all family members have access to extension materials, rather than just the head of the household. Gao et al.'s findings show that the new extension model increases the adoption rates of a selection of agricultural technologies (Gao et al., 2020). In addition, region-adapted guidelines or reference maps for fertilizer use should be established, which should include a) recommended application rates for various crops based on regional soil testing; b) recommended types of organic fertilizers and the corresponding application methods based on regional characteristics; and c) strict upper limits for fertilizer application rates, in particular for cash crops. Last but not least, cross-sectoral and international collaborations, e.g. between scientific institutions, fertilizer manufacturers and/or extension agencies, should be supported to improve current commercial fertilizer products, fertilizer application guidelines and qualifications of extension personnel.

It is worth noting that Beijing, Tianjin, Shanghai, Hunan, Guangxi, Hainan, Shaanxi, Ningxia and Xinjiang should pay particular attention and make efforts to reduce fertilizer consumption. In the overall assessment of the study, these provinces are considered to have made the least progress in responding to recent calls to reduce chemical fertilizer applications.

5.5 Contributions and limitations of the study

This dissertation contributes to a comprehensive assessment of historical and current trends in fertilizer use and management in China. Potential barriers to sustainable nutrient management in China are identified and investigated, based on which policy recommendations from the national strategic level, the policy level and the implementation level are proposed. This dissertation utilizes data from various sources, including open-source data from NBS, China Statistics Yearbooks, FAOSTAT, the World Bank and CFPS; published data in the literature, including NUE data derived from Zhang et al. (2015) and S. Li et al. (2013), and PUE data kindly provided by Zhang et al. (2019); and, farm household survey data from the 2019 National Scientific Fertilization Survey (NSFS). Using a combination of data from different sources and an interdisciplinary approach, this study allows for a systematic and in-depth understanding of chemical fertilizer use and management in China from multiple levels and perspectives. Therefore, the findings of this dissertation can serve as a robust decision support and scientific basis for policy makers, stakeholders and researchers in this field.

Sustainable management of chemical fertilizers, or more broadly, the field of sustainable nutrient management, is a systematic, multidisciplinary and broad research topic. The limitations of this study lie mainly in the fact that it mostly deals with the topic from a socio-economic perspective, without establishing in-depth and farm-level connections with other research areas such as natural sciences. Moreover, the farm and household level analysis of the study employed only panel data from 2019 and therefore failed to build comparisons with the previous years. With time series data from farms and households observed in this study, it would be possible to gain more insight into the development of fertilizer use strategies adopted by farmers over the years.

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Appendixes

Table A1 Summary of major fertilizer-related policies in China since 2015.

Issuing date	Title	Reference
Mar. 2015	Action plan for zero growth in fertilizer use by 2020	(MoA, 2015)
Jul. 2015	Guidance from the Ministry of Industry and Information Technology on promoting the transformation and development of the fertilizer industry	(MIIT, 2015)
Aug. 2015	Notice on the Resumption of VAT Policy on Chemical Fertilizers	(STA, 2015)
Apr. 2016	Implementation Plan for Promoting the Integration of Irrigation and Fertilizer (2016-2020)	(MoA, 2016)
Nov. 2016	The National Development and Reform Commission on the promotion of market-based reform of gas prices for fertilizers	(NDRC, 2016)
May 2016	Action plan for the prevention and control of soil pollution	(The State Council, 2016)
Feb. 2017	Key work arrangement of agricultural non-point source pollution control of 2017	(MoA, 2017a)
Feb. 2017	Action plan for substituting mineral fertilizer with organic fertilizers from fruit/vegetable/tea	(MoA, 2017b)
Mar. 2017	Implementation opinions on “Action plan for soil pollution control” from the Ministry of Agriculture	(MoA, 2017c)
Jun. 2017	Opinions on the acceleration of resource utilization of livestock and poultry wastes	(The State Council, 2017)
Feb. 2019	Yangtze River “three phosphorus” special investigation and rectification action implementation plan	(MoEE, 2019)
Mar. 2019	Announcement on policies related to deepening VAT reform	(STA, 2019)
Dec. 2019	Tentative import tariff rates and other adjustment programs of 2020	(The State Council, 2019)
Sept. 2021	Notice on the implementation of preferential rail transportation policy for agricultural fertilizers such as slow-release fertilizers	(NDRC, 2021)

Table A2 Fertiliser N and P surpluses (kg ha^{-1}) of 30 provinces of mainland China (Chapter 2), incorporated with the latest data from 2019 to 2020.

	Year	1987-1990	1991-1994	1995-1998	1999-2002	2003-2006	2007-2010	2011-2014	2015-2018	2019-2020
Northeast	Liaoning	98.8	125.5	149.5	145.5	154.5	166.1	169.0	159.9	147.0
	Jilin	67.1	85.3	101.5	95.7	104.7	106.1	113.9	106.2	95.5
	Heilongjiang	29.8	45.9	54.6	52.2	54.4	56.0	60.8	58.5	50.2
Northcentral	Beijing	121.4	173.1	222.7	248.8	287.5	269.3	310.3	389.8	374.6
	Tianjin	61.1	86.8	151.0	191.6	280.2	351.8	320.7	257.8	213.3
	Hebei	88.2	125.6	166.7	175.8	192.4	211.7	215.0	205.7	185.1
	Shanxi	70.9	99.3	124.3	130.6	147.0	165.5	175.5	167.7	157.7
	Shandong	118.3	165.6	199.0	214.7	236.7	241.0	230.3	210.0	184.7
	Henan	86.0	133.0	167.7	190.7	206.8	239.3	261.0	257.1	236.0
Middle and lower reaches of Yangtze River	Shanghai	194.9	220.5	215.1	246.6	229.0	195.1	159.8	167.8	151.5
	Jiangsu	148.7	191.4	239.2	255.2	261.3	317.2	246.7	222.9	203.9
	Zhejiang	130.9	139.9	153.6	164.6	203.9	245.9	252.1	236.2	190.1
	Anhui	97.8	120.5	160.8	165.5	167.1	174.7	180.9	178.1	160.3
	Jiangxi	74.5	91.7	105.1	105.3	124.0	124.3	124.6	116.2	94.8
	Hubei	111.7	150.2	203.9	203.5	239.3	267.3	261.6	219.6	181.6
	Hunan	87.8	103.3	117.0	122.5	138.2	149.9	146.7	140.4	126.2
Southeast	Fujian	160.3	189.9	219.4	242.9	272.1	309.9	366.7	396.4	331.9
	Guangdong	160.4	186.8	197.7	201.5	236.8	287.5	306.3	311.0	262.4
	Guangxi	85.9	106.1	123.9	133.7	160.6	193.7	208.2	211.0	198.8
	Hainan	93.9	107.5	133.0	168.6	272.4	311.6	323.5	358.7	332.6
Southwest	Sichuan (incl. Chongqing)	88.4	109.2	122.3	136.7	145.1	164.4	163.8	153.1	131.7
	Guizhou	63.9	83.0	86.7	91.4	97.8	103.0	103.5	94.6	76.4
	Yunnan	72.7	97.0	116.7	118.3	143.9	161.6	180.7	184.9	153.8
	Tibet	41.4	57.1	85.8	81.4	112.7	142.5	146.8	140.5	101.8
Northwest	Inner Mongolia	37.2	53.5	72.3	80.6	105.4	132.7	141.9	143.6	128.4
	Shaanxi	69.6	112.7	155.2	176.4	209.4	229.1	306.0	303.1	254.0
	Gansu	51.9	75.8	100.4	114.0	125.2	140.9	145.5	137.7	116.7
	Qinghai	51.7	72.3	78.8	89.8	96.2	104.9	109.7	104.9	65.0
	Ningxia	74.0	98.4	130.0	146.1	140.5	153.2	167.5	163.4	134.5
	Xinjiang	59.1	89.3	125.5	129.2	149.1	190.8	206.3	203.8	183.9

Table A3 Average annual growth rates of fertilizer use and N and P surpluses of 30 provinces in China, for 2013 to 2015, 2016 to 2018 (Chapter 2), incorporated with the latest data from 2019 to 2020.

		Avg. Annual Growth Rate > 1%	**0 < Avg. Annual Growth Rate < 1%**	**Negative avg. Annual Growth Rate**
2013–2015	Fertilizer input (kg ha^{-1})	(13): Beijing, Tibet, Hainan, Xinjiang, Fujian, Inner Mongolia, Qinghai, Yunnan, Gansu, Guangdong, Ningxia, Guangxi, Shanghai	(6): Shanxi, Jilin, Henan, Hebei, Zhejiang, Jiangxi	(11): Shaanxi, Heilongjiang, Guizhou, Anhui, Sichuan (incl. Chongqing), Hunan, Liaoning, Jiangsu, Shandong, Tianjin, Hubei
	Fertilizer N and P surpluses (kg ha^{-1})	(11): Beijing, Tibet, Hainan, Fujian, Qinghai, Xinjiang, Inner Mongolia, Yunnan, Guangdong, Gansu, Ningxia	(2) Shanghai, Guangxi	(17): Henan, Shanxi, Hebei, Jiangxi, Zhejiang, Shaanxi, Heilongjiang, Sichuan (incl. Chongqing), Guizhou, Anhui, Liaoning, Jilin, Hunan, Jiangsu, Shandong, Tianjin, Hubei
		Avg. Annual Growth Rate > 1%	**0 < Avg. Annual Growth Rate < 1%**	**Negative Annual Avg. Growth Rate**
2016–2018	Fertilizer input (kg ha^{-1})	(2): Beijing, Shanghai	(3): Hunan, Anhui, Hainan	(25): Guangxi, Liaoning, Shaanxi, Henan, Jilin, Heilongjiang, Hebei, Shanxi, Jiangsu, Ningxia, Shandong, Sichuan (incl. Chongqing), Yunnan, Inner Mongolia, Fujian, Hubei, Guangdong, Zhejiang, Xinjiang, Jiangxi, Guizhou, Gansu, Qinghai, Tianjin, Tibet
	Fertilizer N and P surpluses (kg ha^{-1})	(1): Beijing	(1): Shanghai	(28) the rest
		Avg. Annual Growth Rate > 1%	**0 < Avg. Annual Growth Rate < 1%**	**Negative Annual Avg. Growth Rate**
2019–2020	Fertilizer input (kg ha^{-1})	(0)	(0)	All provinces
	Fertilizer N and P surpluses (kg ha^{-1})	(0)	(0)	All provinces

Table A4 Summary of assessment methods and results of China's recent performance in reducing fertilizer use.

Group	Requirements	Results
Group A	- the province's fertilizer use and fertilizer surpluses have declined for **five consecutive years**; - the province has **reached** the EKC turning point between its fertilizer surpluses and its per capita GRP	**Northeast:** Liaoning **Northcentral:** Shanxi, Shandong **Middle and lower reaches of Yangtze River:** Jiangsu, Anhui, Jiangxi, Hubei **Southeast:** *none* **Southwest:** Sichuan (incl. Chongqing), Guizhou, Tibet **Northwest:** Gansu, Qinghai
Group B	- the province's fertilizer use and fertilizer surpluses have declined for **five consecutive years**; - the province still exhibits a **positive relationship** between its fertilizer surpluses and its per capita GRP	**Northeast:** Jilin, Heilongjiang **Northcentral:** Hebei, Henan **Middle and lower reaches of Yangtze River:** Zhejiang **Southeast:** Fujian, Guangdong **Southwest:** Yunnan **Northwest:** Inner Mongolia
Group C	No requirements are met.	**Northeast:** *none* **Northcentral:** Beijing, Tianjin **Middle and lower reaches of Yangtze River:** Shanghai, Hunan **Southeast:** Guangxi, Hainan **Southwest:** *none* **Northwest:** Shaanxi, Ningxia, Xinjiang

References for the Appendixes

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Summary

Over the past few decades, China’s grain production has expanded drastically. On the one hand, this has eliminated food shortages and allowed China to feed its huge and still growing population. On the other hand, the rapid growth in grain productivity has come at a heavy cost. Excessive fertilizer use has led to a variety of negative consequences that threaten national food security and environmental sustainability. Since the 2010s, the Chinese government and academia have made considerable efforts to reduce the consumption of chemical fertilizers and improve nutrient management. These include a wide range of regulations to control or guide chemical fertilizer use, policies to eliminate subsidies for the fertilizer industry, and nationwide promotion of scientific fertilizer application methods. In response to these efforts, China's overall fertilizer application rate has been declining since 2016. However, China still applies far more fertilizers than its crops need, and the current crop Nitrogen Use Efficiency (NUE) and Phosphorus Use Efficiency (PUE) in China are both below the global average. Therefore, reducing dependence on chemical fertilizers for crop production and sustainably feeding a large population remains a key challenge for China.

This dissertation aims to contribute to sustainable nutrient management in China by providing a comprehensive and in-depth understanding of fertilizer use and management at the national, regional, farm and household levels. In the first study (Chapter 2), a systematic review of the historical development and current status of chemical fertilizer use and management in China at the national level is presented. In addition, fertilizer nutrient surpluses are estimated for 30 provinces in China and the regional and temporal variations are visualized. In the second study (Chapter 3), the relationship between fertilizer nutrient surpluses and the regional economy at the provincial level is examined within the framework of the Environmental Kuznets curve (EKC) hypothesis. A panel cointegration approach is employed, using time-series data from 1988 to 2019. In the third study (Chapter 4), the research focus is further narrowed to the farm household resolution. Using cross-sectional survey data from 774 maize-growing farms in northern China in 2019, the study investigates the role of farm characteristics, farmers' knowledge, perceptions, and socioeconomic context in farmers' fertilizer use strategies.

The studies confirm that by 2021, China has reached zero growth in fertilizer use and fertilizer nutrient surpluses at the national and regional level. However, regions with a high proportion of cash crops, such as the southeast coast and northwest, still suffer from high nutrient surpluses. Furthermore, in circa 2012, China has reached its EKC turning point between fertilizer nutrient surpluses and GDP per capita. With further economic growth, the fertilizer surpluses in most Chinese provinces will decrease, indicating a moderating of the tension between economic development and the environment. Looking at the farm and household level, the study shows that in northern China, small farms are more likely to overuse fertilizers in maize cultivation without further yield improvement. Current extension programs have had a positive impact on farmers’ fertilizer use strategies and environmental awareness; nevertheless, the coverage and effectiveness of trainings should be improved.

In summary, the dissertation identifies the following key factors that impede sustainable chemical fertilizer management in China: small farm size; regional economic dependence on cash crops; the large discrepancy between farmers' practices and scientific production guidelines; and the shrinking and aging of China's rural labor force. To address these aspects, the dissertation proposes recommendations at the national strategic level, policy level and implementation level, respectively. The findings and recommendations of this dissertation can serve as a robust decision support and scientific basis for policy makers, stakeholders and researchers in the field of sustainable nutrient management in China.

Zusammenfassung

In den letzten Jahrzehnten ist die Getreideproduktion in China drastisch gestiegen. Einerseits hat dies die Nahrungsmittelknappheit beseitigt und China in die Lage versetzt, seine riesige und wachsende Bevölkerung zu ernähren. Andererseits wurde der rasche Anstieg der Getreideproduktivität mit einem hohen Preis bezahlt. Der übermäßige Einsatz von Düngemitteln führte zu einer Reihe negativer Konsequenzen, die die nationale Ernährungssicherheit und die ökologische Nachhaltigkeit bedrohen. Seit den 2010er Jahren haben die chinesische Regierung und die Wissenschaft erhebliche Anstrengungen unternommen, um den Einsatz von chemischen Düngemitteln zu reduzieren und das Nährstoffmanagement zu verbessern. Dazu gehören eine Vielzahl von Vorschriften zur Kontrolle und Steuerung des Einsatzes von chemischen Düngemitteln, Maßnahmen zur Abschaffung von Subventionen für die Düngemittelindustrie und die landesweite Förderung wissenschaftlicher Methoden zur Verwendung von Düngemitteln. In Folge dieser Bemühungen ist die Gesamtmenge des verwendeten Düngers in China seit 2016 rückläufig. Allerdings wird in China immer noch weit mehr Düngemittel ausgebracht als nötig und die derzeitige Stickstoffnutzungseffizienz (NUE) und Phosphornutzungseffizienz (PUE) in China liegen beide unter dem weltweiten Durchschnitt. Daher bleibt die Verringerung der Abhängigkeit von chemischen Düngemitteln für die Pflanzenproduktion und die nachhaltige Ernährung einer großen Bevölkerung eine zentrale Herausforderung für China.

Diese Dissertation soll einen Beitrag zum nachhaltigen Nährstoffmanagement in China leisten, indem sie einen umfassenden und tiefgehenden Einblick über den Düngemitteleinsatz und -management auf nationaler, regionaler, betrieblicher und Haushaltsebene gewährt. Die erste Studie (Kapitel 2) gibt einen systematischen Überblick über die historische Entwicklung und den derzeitigen Stand der Nutzung von chemischen Düngemitteln in China auf nationaler Ebene. Darüber hinaus werden die Düngeüberschüsse für 30 Provinzen in China berechnet und die regionalen und zeitlichen Schwankungen dargestellt. In der zweiten Studie (Kapitel 3) wird die Beziehung zwischen

Düngemittelüberschüssen und der regionalen Wirtschaft auf Provinzebene im Rahmen der Umwelt-Kuznets-Kurve (EKC) Hypothese untersucht. Es wird ein Panel-Kointegrationsansatz mit Zeitreihendaten von 1988 bis 2019 verwendet. In der dritten Studie (Kapitel 4) wird der Forschungsschwerpunkt weiter auf die Ebene der landwirtschaftlichen Haushalte eingegrenzt. Unter Verwendung von Querschnittserhebungsdaten von 774 Maisbetrieben in Nordchina aus dem Jahr 2019 untersucht die Studie den Einfluss verschiedener Faktoren auf die Einsatzstrategie von Düngemitteln wie betriebliche Merkmale, Wissen und Auffassungen der Landwirte und sozioökonomischer Kontext.

Die Studien bestätigen, dass China seit 2021 auf regionaler und nationaler Ebene ein Nullwachstum beim Düngemitteleinsatz und bei Düngemittelüberschüssen erreicht hat. Jedoch leiden Regionen deren Produktion einen hohen Anteil an Cash Crops aufweist, wie die Südostküste und der Nordwesten, immer noch unter hohen Düngemittelüberschüssen. Darüber hinaus hat China um das Jahr 2012 den EKC-Wendepunkt zwischen Düngemittelüberschüssen und BIP pro Kopf erreicht. Mit weiterem Wirtschaftswachstum werden die Düngemittelüberschüsse in den meisten chinesischen Provinzen abnehmen, was auf einen Nachlass des Spannungsverhältnisses zwischen wirtschaftlicher Entwicklung und Umwelt hindeutet. Beim Betrachten einzelner Betriebe und Haushalte zeigt die Studie, dass in Nordchina kleine Betriebe zum übermäßigen Verbrauch von Düngemittel, welcher sich nicht in Ertragssteigerungen widerspiegelt, neigen. Die derzeitigen Beratungsprogramme haben sich positiv auf die Strategien und das Umweltbewusstsein der Landwirte beim Düngemitteleinsatz ausgewirkt. Die Reichweite und Wirksamkeit von Schulungen sollte jedoch verbessert werden.

Zusammenfassend werden in der Dissertation die folgenden Schlüsselfaktoren identifiziert, die ein nachhaltiges Management chemischer Düngemittel in China behindern: geringe Betriebsgröße, regionale wirtschaftliche Abhängigkeit von Cash Crops, starke Diskrepanz zwischen den Praktiken der Landwirte und der wissenschaftlichen Produktionsrichtlinien sowie Chinas schrumpfende und alternde ländliche Arbeitskräfte. Um die oben genannten Probleme anzugehen, werden in dieser Dissertation Vorschläge für eine nationale Strategie, für die Politik und für deren Realisierung vorgetragen. Die Ergebnisse und Vorschläge dieser Dissertation können politischen Entscheidungsträgern, Interessengruppen und Forschern im Bereich des nachhaltigen Nährstoffmanagements in China als fundierte Entscheidungsgrundlage und wissenschaftliche Basis dienen.

Curriculum vitae

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Education

10/2018 – 12/2022	Doctoral candidate in the Sino-German International Research Training Group "Adaptation of maize-based food-feed-energy systems to limited phosphate resources" (AMAIZE-P) University of Hohenheim, Institute of Farm Management, Germany
10/2014 – 07/2018	M.Sc. in Organic Agriculture and Food System University of Hohenheim, Germany
02/2016 – 06/2016	Erasmus exchange University of Ghent, Belgium
09/2010 – 06/2014	B.Sc. in Nutritional Sciences Shandong University of Traditional Chinese Medicine, China

Practical Experience

09/2021 – 06/2022	Research assistant in the Sino-German Project “Process Improvement for Resource-amended Treatment Systems” (PIRAT) Institute 520f, University of Hohenheim, Germany
04/2019 – 06/2019	Coordinator of a student excursion, where 45 German visitors travelled in China for a week Institute 410c, University of Hohenheim, Germany
07/2017 – 07/2018	Lab assistant for soil analysis Institute 490e, University of Hohenheim, Germany
10/2016 – 06/2017	Student assistant in the Sino-German Project “Sustainable Rubber Cultivation in the Mekong Region” (SURUMER) Institute 490e and 520f, University of Hohenheim, Germany
07/2016 – 12/2016	Internship in the Einhorn sustainable condom project Einhorn products GmbH (Berlin), Malaysia & Germany

07/2012 - 08/ 2012	AIESEC Intern at Discordant Families of Kenya (NGO) Nairobi, Kenya

Language skills

Chinese (mandarin)	Native
English	C1 (Proficient)
German	B2 (Advanced)

07 December 2022, Hohenheim

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Annex 3

Declaration in lieu of an oath on independent work

according to Sec. 18(3) sentence 5 of the University of Hohenheim's Doctoral Regulations for the Faculties of Agricultural Sciences, Natural Sciences, and Business, Economics and Social Sciences

1. The dissertation submitted on the topic

Towards sustainable chemical fertilizer management in China:
………………………………………………………………………………………
from theory to farm household
……………………………………………………………………………………....

is work done independently by me.

2. I only used the sources and aids listed and did not make use of any impermissible assistance from third parties. In particular, I marked all content taken word-for-word or paraphrased from other works.

3. I did not use the assistance of a commercial doctoral placement or advising agency.

4. I am aware of the importance of the declaration in lieu of oath and the criminal consequences of false or incomplete declarations in lieu of oath.

I confirm that the declaration above is correct. I declare in lieu of oath that I have declared only the truth to the best of my knowledge and have not omitted anything.

Place, Date	Signature