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The impact of farm size on agricultural sustainability

Chenchen Ren[a,b,#], Shen Liu[c,d,#], Hans Van Grinsven[e], Stefan Reis[f,g], Shuqin Jin[h], Hongbin Liu[d], Baojing Gu [a,i,*]

[a] Department of Land Management, Zhejiang University, Hangzhou 310058, People's Republic of China;

[b] Policy Simulation Laboratory, Zhejiang University, Hangzhou 310058, People's Republic of China;

[c] Aisino Corporation Inc., Beijing 100195, People's Republic of China;

[d] Key Laboratory of Nonpoint Source Pollution Control, Ministry of Agriculture, Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing 100081, China

[e] PBL Netherlands Environmental Assessment Agency, PO BOX 30314, 2500 GH The Hague, The Netherlands

[f] Centre for Ecology & Hydrology, Penicuik, EH26 0QB, United Kingdom

[g] University of Exeter Medical School, Knowledge Spa, Truro, TR1 3HD, United Kingdom

[h] Research Center for Rural Economy, Ministry of Agriculture of China, No. 56 Zhuanta Hutong, Xicheng District, Beijing 100810

[i] School of Agriculture and Food, The University of Melbourne, Victoria 3010, Australia

[#] Co-first authors

***Corresponding Author:**

Department of Land Management, Zhejiang University, Zijingang Campus, 866 Yuhangtang Road, Hangzhou 310058, PR China.

Email: bjgu@zju.edu.cn

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The impact of farm size on agricultural sustainability

Abstract

Farm size plays a critical role in agricultural sustainability. This may have far-reaching consequences for the economic and environmental performance of agricultural production, resulting, for instance, in an excessive use of mineral fertilizers. However, the magnitude of such effects and their main causes are not well understood, while being essential for effective policy development, especially for countries like China where the agricultural sector is still largely dominated by smallholder farms. In this paper, we review the current understanding of how farm size affects agricultural sustainability using China's crop farming as an example from economic, environment and social aspects. We analyze impacts from both a Chinese and a global perspective to identify intervention points to improve agricultural performance. We found that increasing farm size has a positive impact on farmer's net profit, as well as economic, technical and labor efficiency with mean coefficients 0.005, 0.02 and 2.25 in economic performance, respectively. Nevertheless, the relationships between farm size and overall productivity, total factor productivity and allocative efficiency are still not well understood and therefore require more research. Meanwhile, increase in farm size is associated with statistically significant decrease in fertilizer and pesticide use per hectare, showing clear benefits for environmental protection. In line with the experiences documented for the evolution of agricultural practices in developed countries, the expansion of large-scale farming is a critical path for modernizing agricultural production and ensuring sustainable food production from the social perspective. Measures concerning farm size should be implemented in an interaction between farmers and the government to promote the green development of agriculture.

Keywords: Environmental protection; Land fragmentation; Large-scale farming; Smallholder farms; Efficiency; Non-point pollution

1. Introduction

The world has achieved great success in increasing agricultural production and food security during past half century. It feeds over 7 billion global population with limited arable land. Grain yield increased from 1.2 to 3.7 tons ha^{-1} during the period from 1961 to 2017 (FAO, 2017). However, the world is also facing grand challenges. Hunger and malnutrition are still commonly found in Africa and Asia with the fact that a high proportion of population depends on local agriculture for their livelihoods (Zhang et al., 2013). Nowadays more than half of the nitrogen fertilizer used in agriculture is lost to the environment, wasting the resource, producing threats to air, water, soil and biodiversity (Lassaletta et al., 2014). To reduce these negative impacts and promote the sustainable development of agricultural production, many measures have been proposed such as increasing the use of modern technologies (Hašková, 2017), or the use of biochar (Smetanová et al., 2013; Maroušek et al., 2017).

However, few measures have so far considered farm size when it comes to agricultural development and related environmental sustainability. In fact, smallholder farms globally occupy up to 40% of agricultural areas (Lesiv et al., 2018). Smallholder farms typically are less than 2 ha, although the definition of smallholder used in national censuses varies considerably (Rigg et al., 2016). Smallholders can survive and grow because poverty decreases (Lipton, 2006), but small-scale farming can present a barrier for the sustainable development of agriculture, especially for countries with smallholders dominated. Previous studies have indicated that fertilizer use per hectare decreases with increasing farm size (Ju et al., 2016). Other factors of agriculture, such as productivity, efficiency and rural income, may also be closely related to farm size. Yet, previous studies usually focused on some of the factors mentioned above. A comprehensive and integrated picture on the impacts of farm size and their causes is so far lacking.

China is a typical region still dominated by smallholder farms, accounting for 35% of the 570 million world farms in 2014 (Lowder et al., 2014). It is mainly caused by the

Household Contract Responsibility System (HCRS), resulting in several parcels operated by each household instead of a non-divided farm, leading to land fragmentation. Land fragmentation is defined as the existence of a number of spatially separate plots of land which are farmed as single, which is a major problem in China (Tan et al., 2006). The average farm size in China remains to be comparatively small until today. Farm size traditionally expands with economic development (Adamopoulos and Restuccia, 2014), as demonstrated by examples for the United States of America (USA), France and other developed countries (Figure 1). However, China did not follow this rule because of policy distortion (Wu et al., 2018). The consequences can be observed today in many negative environmental impacts such as air and water pollution and low agricultural labor productivity (Chuanmin and Falla, 2016). And the fertilizer intensity per crop in China is about 3-fold higher than the world average, in total accounting for ~30% of global mineral fertilizer use with serious pollution (Jiao et al., 2016).

To identify and better understand the relationship between farm size and these problems, we reviewed papers related to farm size taking China as a typical example with the aim of giving a comprehensive and integrated picture of the impacts of farm size and their causes. We hypothesize that impacts of farm size will promote agricultural sustainability and test it by the analysis of existing literature taking crop farming as an example from both a Chinese and global view. Sustainable agriculture is defined as practices that meet current and future societal needs for food, for ecosystem services, and for healthy lives, and is achieved by maximizing the net benefit to society when all costs and benefits of the practices are considered (Tilman et al., 2002). There are still many countries dominated by small scale farming, and a better understanding of the role of farm size is relevant for future national and international agricultural policies.

2. Methods

In order to fully assess the impact of farm size on agricultural sustainability, we carried out a comprehensive review taking the following steps. Based on the facts presented within the introductory sections, relevant keywords were derived. We firstly reviewed published literature regarding the history of agricultural mechanization in some developed countries in order to fully understand the role of farm size, considering that two keywords were common for this subject (agricultural mechanization/sustainability, history/lessons). At the same time, we further searched on two keywords (China, agriculture) to analyze the evolution of farm size in China and its drivers as a typical case study. Next, in order to further enrich the review relevant key words for farm size were identified as used by experts in the field. In each research string, the keywords used to select papers were: "farm size" or "field size" or "large-scale farming" or "scale farm" or "land fragmentation" or "smallholders" or "small farmers". The search was carried out in “article title, abstract, keywords” and adding constraints concerning “document type” (“article” “article in press” and “review”) and “subject area” focusing on research areas related to farm size. Accordingly, we summarized three aspects related to farm size on agricultural sustainability, namely, economy, environment and society (policy). Finally, we selected papers for in-depth review based on the following criteria: (1) screening out various aspects related to farm size, the research object is crop farming; (2) clearly explaining relationship between farm size and each related aspect, and explicitly including information on the limitations of the respective study; (3) proposing feasible suggestions for existing problems; (4) prioritizing analytical papers with global implications. Besides, databases were aimed at ScienceDirect, Engineering Village, ISI Web of Science, and Google Scholar databases and some major international publishers, such as Elsevier, IEEE Xplore, Springer, and Wiley to ensure a comprehensive overview of relevant papers throughout the searching.

Based on these steps, this paper is structured as follows: (1) from the perspective of economy, we analyze the relationship between farm size and agricultural performance, including indicators such as total factor productivity (TFP), labor efficiency, technical efficiency, allocative efficiency and economic efficiency; (2) we discuss the environmental impacts as a function of farm size; (3) we review the historical development of agriculture in China from 1949 to 2016 and analyze its linkage with farm size; (4) and then we analyze the interaction between farmers and governments in the society and provide policy suggestions from Chinese and global perspective; (5) and finally, a distribution pattern of farm size in China is given with brief mechanism, followed by (6) conclusions.

3. Results and Discussion

3.1 The relationship between farm size and agricultural economy

Due to the indivisibility of capital such as fixed inputs on machinery and knowledge, average input cost per area of small-scale farms is difficult to reduce (Manjunatha et al., 2013). For large-scale farms, on the contrary, the fixed cost per land area managed is small (Carter, 1984), resulting in relatively higher production efficiency (Rios and Shively, 2005). In order to further measure the impact of farm size on production efficiency, we analyzed the following multiple concepts of efficiency, including productivity, TFP, labor efficiency, technical efficiency, allocation efficiency and economic efficiency (Xu and Jeffrey, 1998; Helfand et al., 2015). The definitions of these efficiencies are listed in Table 1.

Agricultural productivity as an indicator to measure the level of agricultural development has been studied widely (Benjamin and Brandt, 2002; Barrett et al., 2010), especially connected with farm size. However, their results are inconsistent. In earlier years, it was believed that increasing farm size did not necessarily lead to production increases; on the contrary, this may be an inverse relationship (Barrett et al., 2010). However, recent studies found that agricultural productivity increases with farm size (Wang et al., 2015). It seems that the perceived inconsistency regarding the relationship between productivity and farm size may arise due to other influencing factors, such as technology levels and economic development stage (Juliano and Ghatab, 2003; Henderson, 2015). Another important influencing factor is political context. Yet more research on this subject is still needed to better understand the key drivers and contributing factors.

TFP is mainly affected by technology (Avila and Evenson, 2004). The growth of TFP can substantially contribute to agricultural development (Jorgenson and Gollop, 1992). However, the relationship between TFP and farm size remains to be ambiguous. There is a strong positive relationship between TFP and farm size in the Corn Belt, USA (Key, 2018). On the contrary, TFP is higher for smaller farms than for larger ones in Malawi, Tanzania, and Uganda (Julien et al., 2018). This relationship can even be different between regions of the same country, such as observed for Brazil (Helfand et al., 2015). Thus, whether farm size essentially is related to the TFP on household level farms is still unclear (Restuccia and Santaeulalia-Llopis, 2015).

Labor efficiency is labor productivity (Li et al., 2013). Before the 1990s in China, when fertilizers, pesticides, and agricultural machinery were not widely available, affordable and used, farmers often invested more labor to increase agricultural production (Liu et al., 2018). This resulted in lower opportunity cost of laborers working in the agricultural sector (Deininger et al., 2014). Farmers could only devote their labor to agriculture, leading to a low level of labor efficiency (Benjamin and Brandt, 2002). Labor efficiency increased in recent years (Liu et al., 2018), because increased inputs of fertilizers and machinery increase the total production, while reducing labor input (Deininger et al., 2014). Meanwhile, economic growth attracted more rural workers to non-agricultural sectors and also reduced the labor input to agriculture. Labor efficiency increased with farm size by a factor of 2.25 due to the scale effects (Li et al., 2013). This explains the relatively lower labor efficiency in China with smallholders dominated compared to developed countries such as France and the USA, which have much larger farm sizes than China (Figure 2).

Technical efficiency can shed an insight into the assessment of whether input is excessive or not (Bojnec and Latruffe, 2013), and is an important integral part of the TFP. The degree of adoption of technology generally determines the level of efficiency. With the increase of farm size, the knowledge of farmers increases due to more input to training and studying that promotes the adoption of higher level of technologies (Syp et al., 2015). In general, one hectare increase in farm size increases technical efficiency scores in the range of 0.01-0.03 (Xu and Jeffrey, 1998; Bojnec and Latruffe, 2013).

Allocative efficiency can substantially influence TFP. However, there is not much research available on the relationship between farm size and allocative efficiency, hence the relationship between these factors remains ambiguous. For example, smallholder farms can achieve higher allocative efficiency (Xu and Jeffrey, 1998), which reflected by the fact that farm size has a negative effect on allocative efficiency (Bojnec and Latruffe, 2013).

Economic efficiency is related to farmers' profits. Generally, a one hectare increase in farm size results in a 0.005 increase in economic efficiency (Xu and Jeffrey, 1998; Bojnec and Latruffe, 2013). But it shows different results between plant types and regions (Xu and Jeffrey, 1998). It has been highlighted that an increase by one unit in in farm size leads to about an 8% decline in the average production cost (Lu et al., 2018).

3.2 Environmental consequences related to farm size

Agricultural non-point source pollution has been the global focus of attention in recent decades. Environmental pollution by agriculture stems mainly from chemicals such as synthetic fertilizers and pesticides (Niroula and Thapa, 2007), burning of crop residues (Yang et al., 2008) and animal waste (Guo et al., 2010). Over half of this applied fertilizer is in excess of plant nutritional needs and hence lost to the environment (Caires et al., 2016). As a result, substantial environmental and health impacts can be observed, e.g., eutrophication (Zhang et al., 2013), soil acidification (Guo et al., 2010) and air pollution (Wang et al., 2018). Therefore, each country has introduced corresponding laws to limit the use of chemical fertilizers. For example, the US Fertilizer Law stipulates the minimum guaranteed content of medium and trace element fertilizers (FAO). The European Union promulgated the "Nitrates Directive" that restricts the use of fertilizers outside the growing season and on steep slopes and near water courses, demand codes of Good agricultural practices to promote balanced fertilization and the maximum amount of nitrogen from manures is set at 170 kg·ha^{-1} (EPCEU, 1991; Van Grinsven et al., 2015). "Fertilizer Management Law" in Japan stipulates the corresponding specifications and standards for various types of common fertilizers such as the minimum or maximum amount of main ingredients should be included, and the maximum limit of harmful components to plants should be allowed (MAFF, 2014). However, China's fertilizer management belongs to different departments lacking a unified fertilizer supervision and management system. In 2011, 468 kg ha^{-1} of mineral fertilizer was applied on China's arable land, as compared to a world average level of 129 kg ha^{-1} (Figure 3). Meanwhile, the percentage of organic nutrients such as residues returned to agricultural land in China has declined from >95% in 1949 to <54% in 2005 (Ju et al., 2005). Fertilizer input and losses are assumed to double by 2050 compared to 2010 levels, if no measures to mitigate China's agricultural pollution are implemented (Gu et al., 2015).

Managing farm size can affect the environmental performance of farming through a range of different mechanisms. In general, 1% increase in farm size would cause a 1.8% decrease in the use of herbicides & pesticide and 0.3% decrease in fertilizer and pesticide use (Wu et al., 2018). Compared to small-scale farms, land used by large farms has 6-9% more soil organic carbon (SOC) stocks (Zhu et al., 2018), 48% less carbon dioxide emissions (Todde et al., 2018) and an 8%-28% carbon footprint reduction (Zhu et al., 2018). Meanwhile, the global warming potential, eutrophication potential, acidification potential, aquatic eco-toxicity and human toxicity impacts per unit area in large farms are 1.6-12.7% lower than that of small farms (Syp et al., 2015; Wang et al., 2017).

To produce more cereals, costs from both non-fixed (e.g. fertilizer) and fixed (e.g. machinery) inputs are both key factors (Figure 4). Smallholders tend to use excessive amounts of fertilizers and pesticides to maximize agricultural production (Ju et al., 2016). Due to the high costs of fixed inputs, smallholders would likely use more non-fixed inputs than fixed input to increase yields (Pishgar-Komleh et al., 2017; Wang et al., 2017). Meanwhile, many smallholder farmers have part-time jobs in urban areas especially for countries like China, and as a consequence are not able to invest more labor to improve their management practices due to the high opportunity costs of labor input and a small share of their total income stemming from agriculture. Therefore, in spite of implementation of soil testing and elimination of fertilizer subsides, we fertilizer use still increased in small-scale farms. In contrast, large-scale farms tend to have relatively more fixed inputs due to their scale effect, resulting in much cheaper fixed costs per unit cropland area if their total cropland area managed was large (Wu et al., 2018). These fixed inputs can save non-fixed inputs such as fertilizers and increase fertilizer use efficiency. Large-scale farm-holders are more sensitive to fertilizer prices and will intentionally use less mineral fertilizers to reduce production costs (Ju et al., 2016). Thus, large-scale farming has no direct impact on the environment, but provides a good platform for improving farmers' agricultural practices and lead to a positive impact on our environment.

3.3 History of agricultural development and its linkage with farm size in China

To comprehensively understand the role of farm size in the society, we firstly review the history of agricultural development and its linkage with farm size taking China as an example. Based on the socioeconomic development and related effects on agricultural performance, we divided agricultural development phases into six distinct periods: from 1949 to 2016: 1949-1977, 1978-84, 1985-93, 1994-98, 1998-2003, and 2004-2016, respectively (Figure 5). Each period is divided by policies or regulations promulgated or abolished with productivity or efficiency changes.

The first phase (1949-77) is a period where China underwent land reform, collectivization movement, the Great Leap Forward, and the Cultural Revolution (detailed in Table 2). After the land reform was successfully implemented by 1952, a collectivization movement started with an impressive success: agricultural production increased steadily from 1952-58 (Putterman and Skillman, 1993). However, with the collectivization changing from a voluntary to a compulsory movement with a lack of supervision, the agricultural production collapsed in the period 1959-61 (Feder et al., 1992). Since 1961, China's large-scale farming has stagnated, and agricultural production showed large variations until the end of Cultural Revolution in 1976.

The second phase (1978-84) was marked by the installment of the HCRS, which was set up as an alternative institution due to the recognized failure of the collectivization movement. It has been proven that the HCRS increased agricultural productivity significantly and accounts for half of the production growth during the period of 1978-1984 (Lin, 1991). Average farm size evolved from large scales under collectivization to small ones under the HCRS (Qu et al., 1995). Meanwhile, the Hukou system - formally implemented in 1958 - restricted the free migration of farmers from rural to urban areas, which reduce farmers' willing to transfer their farms, further enhancing small-scale farming emerging as a result of implementing the HCRS (Deininger et al., 2014).

During the third phase (1985-93), the economic system was reformed from plan-dominated to market-driven (Gong, 2018). Government started allowing products to be traded in the market freely (Yao, 1995), and gradually abolished the unified procurement approach (Zhang and Brümmer, 2011). Compared to the previous phase, agricultural production grew slowly due to the diminishing returns from the implementation of HCRS, in spite the introduction of some new technologies such as hybrid rice (Lin, 1991). The contribution of small-scale farming to agricultural production reached its peak during this phase.

In the fourth phase (1994-98), agricultural funding by the central government increased dramatically, facilitating the development of industrial-scale agriculture (Gong, 2018). To meet food security objectives and increase farmers' incomes, government raised the procurement prices of grain. Meanwhile, mineral fertilizer production (resulting in lower costs) and subsidies increased the affordability of fertilizers to farmers at all levels, leading to a further increase of agricultural productivity. But it also resulted in negative consequences, such as a drop in nutrient use efficiency and wide-spread environmental pollution (Fan et al., 2011). Labor elasticity began to decline at this stage, indicating less contribution of labor input to output, compared with other input factors (Gong, 2018).

The fifth phase (1998-2003) can be considered as a transition period marked by integrating rural development and overall economic reforms (Zhang and Brümmer, 2011). China faced a heavy economic burden because of excessive increases in grain stocks and the substantial debts accumulated by state-owned grain enterprises during this period (Zhang and Brümmer, 2011). China joined the World Trade Organization (WTO) in 2001, adding further pressures on the protectionist policies with regard to the Chinese agricultural sector and the elimination of the quota procurement system (Gong, 2018). However, the grain yield per hectare declined, with a continuing increase in fertilizer use during this period. In 2003, the arable land area per rural population available was only half that in 1949 (NBSC, 2006).

The sixth phase (2004-16) was labelled “San Nong” as a reference to agriculture, farmer and countryside (Gong, 2018). Chinese government released 19 “No. 1 Documents” focusing on agriculture by 2017. As a consequence, China started to abolish agricultural taxes in 2004 (Lohmar et al., 2009) and land transfer and large-scale farming were proposed in the No. 1 Document in 2009. A series of policies were implemented to raise farmer’s income and narrow the urban-rural gap. For instance, a reform of the Hukou system was listed as one of the key objectives in 2013. Various new agricultural technologies emerged during this period (Fan et al., 2011) and as a result, mechanization in agriculture increased 10 folds between 1978 and 2015 (DRSES, 2017).

In the context of this historical development of Chinese agriculture, we found an increasing degree of financial support for agriculture from Chinese government subsidies and improved levels of agricultural science and technology. Unfortunately, we also observe a substantial and rapid increase in the use of mineral fertilizers and significant drop in arable land per rural population availability (Figure 5). This leads to a decrease in the proportion of land >10 mu (15 mu = 1 hectare) managed by each household and as a result, land fragmentation is intensifying. We also found that technical efficiency remained generally stable from 1949 to 1984, after which it dropped substantially (Zhang and Brümmer, 2011). Meanwhile, a 3.6% drop of the TFP was also observed for the period after 1984 (Zhang and Brümmer, 2011). In fact, the agricultural technology level and the farm size are matched well in the second phase (Chen and Song, 2008). At a low level of technology, the optimal farm size that can be managed by a single household is small. It is one of the key reasons that agricultural productivity increased rapidly during that period.

Since the late 1970s, hybrid rice has been widely used (Lin, 1991) and agricultural science and technology have been improved substantially (Fan et al., 2011), benefiting agricultural productivity. Thus, the farm size per household managed should be increased. Unfortunately, the per capita arable land area in China declined dramatically over the past 30 years, which causes a mismatch between productivity and farm size, leading to efficiency loss and environmental pollution. Many studies suggested that TFP and technical efficiency can still be improved, indicating that innovations in technology, infrastructure and supporting policies can further improve agricultural production, without jeopardizing environmental protection (Chen et al., 2009). However, in the context of small-scale farms, the extension of technology use and improvement of infrastructure typically incur high implementation costs (Niroula and Thapa, 2005). On the other hand, the large number of smallholders make the effective dissemination of scientific information and latest technology and skills more difficult. A typical example is that the introduction of soil testing technology has not been widely adopted yet in China. In addition, due to the indivisibility of capital such as fixed inputs on machinery and knowledge, smallholders in China often benefit little from scale farming (Feder et al., 1992), resulting in high costs, low profit, and non-point pollution (Niroula and Thapa, 2005). It seems that farm size plays an important role on the problems arisen in agriculture during the past decades in China.

3.4 The role of farm size in a societal context over time

Reviewing the history of agricultural development in developed countries such as the USA, Japan, Israel and France, reveals that these countries achieved agricultural modernization in the last century with successes on large-scale farming, agricultural cooperation in production and sales, and agricultural mechanization. This suggests that increasing farm size may be a critical path for agricultural modernization. In addition to the role of the economy in promoting farm size, the development of large-scale farming in the USA and France is mostly driven by the market due to their models of private land ownership as scarcely populated countries. In contrast, for a densely populated country like Japan, it is a greater challenge to promote large-scale farming solely through market drivers. Hence, the Japanese government issued a series of preferential policies in the 1960s to promote scale farming. For example, regulation and subsidies were used to encourage farmers to consolidate land, and agricultural associations also provided a platform to help farmers to adopt large-scale farming. As a result, the total number of rural households rapidly decreased by 59.8% and farmers in the Hokkaido owning more than 10 ha lands increased from 4.7% to 43.2% between 1960 and 1995 (Zhang et al., 2014). Israel is a land state-owned country, indicating that land is owned by the country and will not be freely used and traded, just like China. It is famous for its irrigation, cultivation and sound science-technology systems. However, there is no way to spontaneously promote large-scale farming through market forces or incentives alone. Therefore, Israeli agricultural modernization mainly relied on government policies and financial support, e.g., developing agricultural infrastructure as well as using land intensively. Even so, the average farm size in Israel is much larger than that in China. Therefore, countries like China can learn from Israel's agricultural science and technology system and the way of intensive land use to improve their agriculture.

Based on reviewing the agricultural history of China and other developed countries, the role of increasing farm size needs to be reconsidered in order to enhance the modernization. We suggested the important role of farm size in a societal context over time by analyzing the interaction between Chinese farmers and the government (Figure 6). The willingness of farmers to transfer land or manage a large-scale farm depends on whether there is a sound transfer system and the availability of non-agricultural employment opportunities, as well as a social security system (Hung et al., 2007; Wang et al., 2016). As for the government, setting laws to safeguard property rights of farmers (Benjamin and Brandt, 2002), reducing restrictions imposed by the Hukou system (Liu et al., 2016; Long et al., 2016) and improving the land market by regulations and institutions are effective ways to consolidate land with proficient farmers (Juliano and Ghatab, 2003). Moreover, a sound science-technology system as it has been implemented e.g. in Israel for farmers is also important (Liu and Zhuang, 2000). This could improve the farmers' knowledge and result in the more efficient management of cropland. Other measures including agricultural insurance, agricultural cooperation and other financial support polices like credit services like in France and USA should also be taken into consideration.

4. The distribution of farms with different sizes and its driving forces

An illustration of the spatial distribution of China's scale farms in 2007 can be obtained from Figure 7, highlighting the low level of large-scale farming overall. Even with the small total number of large-scale farms in China, the differences between provinces are still very obvious. The number of larger scale farm in the southern hilly region and the western region of China is relatively small compared to higher numbers in the Northeast Plain and Inner Mongolia. Land fragmentation shown by the pie chart in the southern hilly region is consistently high. However, this does not generally apply to all provinces. For example, the number of scale farms in Xinjiang and Gansu Province is higher than average. The average farm size in each area is typically limited by the natural resource endowment, including total farm size, slope, terrain and so on. However, economic development, urbanization and technological development of an area also play an important role (Huang, 1973). This is reflected in a reduction in economy-wide productivity from 1 to 0.25 resulting in an increase in the share of employment in agriculture from 2.5% to 53%, a 21-fold reduction in average farm size, and a 25-fold reduction in agricultural labor productivity (Adamopoulos and Restuccia, 2014).

More research needs to explore the mechanisms behind this. Such future research can build on the use of models to quantify farms' suitability in various provinces, so as to reasonably advance large-scale farming. Improving the interactions between the Chinese national and provincial governments and farmers, utilizing a model as depicted in Figure 6, would make a difference not only regarding agricultural production, but also food security and national development.

5. Conclusions

This paper provides a comprehensive and integrated assessment of the drivers for and impacts of farm size. Our analysis shows that farm size has a substantial influence on agricultural sustainability from the aspect of economy, environment and society. At the same time, it highlights the importance of reducing agricultural non-point source pollution. In fact, some literature sources argue that small farmers can ensure food production through intensive farming with new technology (Zhang et al., 2016), but at substantial transaction costs. Agricultural sustainability can be improved based on a better understanding of the role of farm size especially for developing countries where small farms are still dominant. While we could not quantify all impacts of farm size in great detail, robust evidence from our work and existing studies suggests that addressing farm size is a critical way to promote development of sustainable agriculture. The fact that these assessments are incomplete means that our analysis may underestimate the social benefits of large-scale farming. More studies are needed to enhance the quantitative and qualitative understanding of the role of large-scale farming, and efforts to develop this approach should continue to move ahead with cautious optimism, while ensuring opportunities for adaptation as new and better information emerges.

References:

Adamopoulos T., Restuccia D., 2014. The Size Distribution of Farms and International Productivity Differences. Am. Econ. Rev. 104 (6), 1667-1697. https://doi.org/10.1257/aer.104.6.1667

Avila, A.F.D., Evenson, R.E., 2004. Chapter 72 Total Factor Productivity Growth in Agriculture: The Role of Technological Capital. Handbook of Agricultural Economics. 4 (09), 3769-3822. https://doi.org/10.1016/S1574-0072(09)04072-9.

Barrett, C.B., Bellemare, M.F., Hou, J.Y., 2010. Reconsidering Conventional Explanations of the Inverse Productivity-Size Relationship. J. Public Econ. 38 (1), 88-97. https://doi.org/10.1016/j.worlddev.2009.06.002.

Benjamin, D., Brandt, L., 2002. Property Rights, Labor Markets, and Efficiency in a Transition Economy: The Case of Rural China. Can. J. Econ. 35 (4), 689-716. https://doi.org/10.1111/1540-5982.00150.

Bizimana, C., Nieuwoudt, W.L., Ferrer, S.R., 2004. Farm size, land fragmentation and economic efficiency in southern Rwanda. Agrekon. 43 (2), 244-262. https://doi.org/10.1080/03031853.2004.9523648.

Bojnec, Š., Latruffe, L., 2013. Farm size, agricultural subsidies and farm performance in Slovenia. Land Use Policy. 32 (Supplement C), 207-217. https://doi.org/10.1016/j.landusepol.2012.09.016.

Caires, E.F., Filho, R.Z., Barth, G., Joris, H., 2016. Optimizing Nitrogen Use Efficiency for No-Till Corn Production by Improving Root Growth and Capturing NO3-N in Subsoil. Pedosphere. 26 (4), 474-485. https://doi.org/10.1016/S1002-0160(15)60058-3.

Carter, M.R., 1984. Identification of the Inverse Relationship between Farm Size and Productivity: An Empirical Analysis of Peasant Agricultural Production. Oxford. Econ. Pap. 36 (1), 131-145. https://doi.org/10.1016/0165-4896(84)90043-X.

Chen, Z., Huffman, W.E., Rozelle, S., 2009. Farm technology and technical efficiency: Evidence from four regions in China. China Econ. Rev. 20 (2), 153-161. https://doi.org/10.1016/j.chieco.2009.03.002.

Chen, Z., Huffman, W.E., Rozelle, S., 2011. Inverse relationship between productivity and farm size: The case of China. Contemp. Econ. Policy. 29 (4), 580-592. https://doi.org/10.1111/j.1465-7287.2010.00236.x.

Chen, Z., Song, S., 2008. Efficiency and technology gap in China's agriculture: A regional meta-frontier analysis. China Econ. Rev. 19 (2), 287-296. https://doi.org/10.1016/j.chieco.2007.03.001.

MNRC (Ministry of Natural Resources of the People's Republic of China), 2009. China's Statistical Yearbook of Land and Resources. Geological Publishing House. http://www.shujuku.org/statistical-yearbook-of-chinas-land-and-resources.html/ (accessed 13 June 2018).

Chuanmin, S., Falla, J.S., 2016. Agro-industrialization: A comparative study of China and developed countries. Outlook Agr. 35 (3), 177-182. https://doi.org/10.5367/000000006778536792.

Deininger, K., Jin, S., Xia, F., Huang, J., 2014. Moving Off the Farm: Land Institutions

to Facilitate Structural Transformation and Agricultural Productivity Growth in China. World Dev. 59 (Supplement C), 505-520. https://doi.org/10.1016/j.worlddev.2013.10.009.
Demetriou, D., Stillwell, J., See, L., 2012. Land consolidation in Cyprus: Why is an Integrated Planning and Decision Support System required? Land Use Policy. 29 (1), 131-142. https://doi.org/10.1016/j.landusepol.2011.05.012.
DRSES (Department of Rural Socio-Economic Survey, National Bureau of Statistics), 2017. China Rural Statistical Yearbook. China Statistics Press. http://data.cnki.net/Yearbook/Single/N2017100312/ (accessed 13 June 2018).
EPCEU (The European Parliament and the Council of the European Union), 1991. Council Directive (91/676/EEC) concerning the protection of waters against pollution caused by nitrates from agricultural. http://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:31991L0676&_from=EN/ (accessed 13 June 2018).
Fan, M., Shen, J., Yuan, L., Jiang, R., Chen, X., Davies, W.J., Zhang, F., 2011. Improving crop productivity and resource use efficiency to ensure food security and environmental quality in China. J. Exp. Bot. 63 (1), 13-24. https://doi.org/10.1093/jxb/err248.
FAO (Food and Agriculture Organization of the United Nations), 2017. FAOSTAT: FAO Statistical Databases. http://www.fao.org/faostat/en/#home/ (accessed 13 June 2018).
FAO (Food and Agriculture Organization of the United Nations), Oklahoma Fertilizer Act and Rules. http://www.oda.state.ok.us/forms/cps/faar.pdf.
Feder, G., Lau, L.J., Lin, J.Y., Luo, X., 1992. The Determinants of Farm Investment and Residential Construction in Post-Reform China. Econ. Dev. Cult. Change. 41 (1), 1-26. https://doi.org/10.2307/1154216.
Feng, Z., Liu, B., Yang, Y., 2005. A Study of the Changing Trend of Chinese Cultivated Land Amount and Data Reconstructing: 1949-2003. J. Nat. Resour. 20 (1), 35-43. https://doi.org/10.3321/j.issn:1000-3037.2005.01.006.
Gong, B., 2018. Agricultural reforms and production in China: Changes in provincial production function and productivity in 1978–2015. J. Dev. Econ. 132, 18-31. https://doi.org/10.1016/j.jdeveco.2017.12.005.
Gu, B., Ju, X., Chang, J., Ge, Y., Vitousek, P.M., 2015. Integrated reactive nitrogen budgets and future trends in China. Proc. Natl. Acad. Sci. U. S. A. 112 (28), 8792-8797. https://doi.org/10.1073/pnas.1510211112.
Guo, J.H., Liu, X.J., Zhang, Y., Shen, J.L., Han, W.X., 2010. Significant Acidification in Major Chinese Croplands. Science. 327 (5968), 1008. https://doi.org/10.1126/science.1182570.
Hašková, S., 2017. Holistic Assessment and Ethical Disputation on a New Trend in Solid Biofuels. Sci. Eng. Ethics. 23 (2), 509-519. https://doi.org/10.1007/s11948-016-9790-1.
Helfand, S.M., Magalhaes, M.M., Rada, N.E., 2015. Brazil's Agricultural Total Factor Productivity Growth by Farm Size. Inter-American Development Bank Working Paper No. 609 (IDB-WP-609), Washington DC.

http://dx.doi.org/10.18235/0000157.
Henderson, H., 2015. Considering Technical and Allocative Efficiency in the Inverse Farm Size-Productivity Relationship. J. Agr. Econ. 2 (66), 442-469. https://doi.org/10.1111/1477-9552.12086.
Huang, Y., 1973. On Some Determinants of Farm Size across Countries. Am. J. Agr. Econ. 55 (1), 89. https://doi.org/10.2307/1238669.
Hung, P.V., MacAulay, T.G., Marsh, S.P., 2007. The economics of land fragmentation in the north of Vietnam. Aust. J. Agr. Resour. Ec. 51 (2), 195-211. https://doi.org/10.1111/j.1467-8489.2007.00378.x.
Jabarin, A.S., Epplin, F.M., 1994. Impact of land fragmentation on the cost of production wheat in the rain-fed region of northern Jordan. Agr. Econ-Blackwell. 11, 191-196. https://doi.org/10.1016/0169-5150(94)00027-1.
Jiao, X., Lyu, Y., Wu, X., Li, H., Cheng, L., Zhang, C., Yuan, L., Jiang, R., Jiang, B., Rengel, Z., Zhang, F., Davies, W.J., Shen, J., 2016. Grain production versus resource and environmental costs: towards increasing sustainability of nutrient use in China. J. Exp. Bot. 67 (17), 4935-4949. https://doi.org/10.1093/jxb/erw282.
Jorgenson, D.W., Gollop, F.M., 1992. Productivity Growth in U.S. Agriculture: A Postwar Perspective. Am. J. Agr. Econ. 74 (3), 745-750. https://doi.org/10.2307/1242588.
Ju, X., Gu, B., Wu, Y., Galloway, J.N., 2016. Reducing China's fertilizer use by increasing farm size. Glob. Environ. Change. 41, 26-32. https://doi.org/10.1016/j.gloenvcha.2016.08.005.
Ju, X., Zhang, F., Bao, X., V, R., M, R., 2005. Utilization and management of organic wastes in Chinese agriculture: past, present and perspectives. Science China. 48 (2), 965-979. https://doi.org/10.1007/bf03187135.
Juliano, J.A., Ghatab, M., 2003. Can unobserved heterogeneity in farmer ability explain the inverse relationship between farm size and productivity. Economics Letters. 2 (80), 189-194. https://doi.org/10.1016/S0165-1765(03)00091-0.
Julien, J.C., Bravo-Ureta, B., Rada, N., 2018. Assessing farm performance by size in Malawi, Tanzania, and Uganda. Food Policy. S030691921830246X. https://doi.org/10.1016/j.foodpol.2018.03.016.
Kalantari, K., Abdollahzadeh, G., 2008. Factors Affecting Agricultural Land Fragmentation in Iran: A Case Study of Ramjerd Sub District in Fars Province. Am. J. Agric. Biol. Sci. 3 (1), 358-363.
Key, N., 2018. Farm size and productivity growth in the United States Corn Belt. Food Policy. S0306919218302471. https://doi.org/10.1016/j.foodpol.2018.03.017.
Lassaletta, L., Billen, G., Grizzetti, B., Anglade, J., Garnier, J., 2014. 50 year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland. Environ. Res. Lett. 9 (10), 105011. https://doi.org/10.1088/1748-9326/9/10/105011.
Lesiv, M., Laso Bayas, J.C., See, L., Duerauer, M., Dahlia, D., Durando, N., Hazarika, R., Kumar Sahariah, P., Vakolyuk, M., Blyshchyk, V., Bilous, A., Perez Hoyos, A., Gengler, S., Prestele, R., Bilous, S., Akhtar, I.U.H., Singha, K., Choudhury, S.B., Chetri, T., Malek, Ž., Bungnamei, K., Saikia, A., Sahariah, D., Narzary, W.,

Danylo, O., Sturn, T., Karner, M., McCallum, I., Schepaschenko, D., Moltchanova, E., Fraisl, D., Moorthy, I., Fritz, S., 2018. Estimating the global distribution of field size using crowdsourcing. Glob. Change Biol. 25 (1), 174-186. https://doi.org/10.1111/gcb.14492.

Li, G., Feng, Z., You, L., Fan, L., 2013. Re-examining the inverse relationship between farm size and efficiency. China Agr. Econ. Rev. 5 (4), 473-488. https://doi.org/10.1108/caer-09-2011-0108.

Lin, J.Y., 1991. The household responsibility system reform and the adoption of hybrid rice in China. J. Dev. Econ. 36 (2), 353-372. https://doi.org/10.1016/0304-3878(91)90041-S.

Lipton, M., 2006. Can Small Farmers Survive, Prosper, or Be the Key Channel to Cut Mass Poverty? Electron. J. Agric. Dev. Econ. 3 (1), 58-85.

Liu, G., Wang, H., Cheng, Y., Zheng, B., Lu, Z., 2016. The impact of rural out-migration on arable land use intensity: Evidence from mountain areas in Guangdong, China. Land Use Policy. (59), 569-579. https://doi.org/10.1016/j.landusepol.2016.10.005.

Liu, S., Wang, R., Shi, G., 2018. Historical Transformation of China's Agriculture: Productivity Changes and Other Key Features. China World Econ. 26 (1), 42-65. https://doi.org/10.1111/cwe.12228.

Liu, Z., Zhuang, J., 2000. Determinants of Technical Efficiency in Post-Collective Chinese Agriculture: Evidence from Farm-Level Data. J. Comp. Econ. 28 (3), 545-564. https://doi.org/10.1006/jcec.2000.1666.

Lohmar, B., Gale, F., Tuan, F., Hansen, J., 2009. China's ongoing agricultural modernization: challenges remain after 30 years of reform. Economic Information Bulletin.

Long, H., Tu, S., Ge, D., Li, T., Liu, Y., 2016. The allocation and management of critical resources in rural China under restructuring: Problems and prospects. J. Rural Stud. 47 (Part B), 392-412. https://doi.org/10.1016/j.jrurstud.2016.03.011.

Lowder, S.K., Skoet, J., Singh, S., 2014. What do we really know about the number and distribution of farms and family farms worldwide? Background paper for The State of Food and Agriculture 2014. ESA Working Paper No. 14-02. Rome, FAO.

Lu, H., Xie, H., He, Y., Wu, Z., Zhang, X., 2018. Assessing the impacts of land fragmentation and plot size on yields and costs: A translog production model and cost function approach. Agr. Syst. 161, 81-88. https://doi.org/10.1016/j.agsy.2018.01.001.

Manjunatha, A.V., Anik, A.R., Speelman, S., Nuppenau, E.A., 2013. Impact of land fragmentation, farm size, land ownership and crop diversity on profit and efficiency of irrigated farms in India. Land Use Policy. 31, 397-405. https://doi.org/10.1016/j.landusepol.2012.08.005.

Maroušek, J., Kolář, L., Vochozka, M., Stehel, V., Maroušková, A., 2017. Novel method for cultivating beetroot reduces nitrate content. J. Clean. Prod. 168, 60-62. https://doi.org/10.1016/j.jclepro.2017.08.233.

MAFF (Ministry of Agriculture, Forestry and Fisheries) (Japan), 2014. Fertilizer Regulations. http://elaws.e-

gov.go.jp/search/elawsSearch/elaws_search/lsg0500/detail?lawId=325AC0000000127/ (accessed 13 June 2018) (in Japanese).
NBSC (National Bureau of Statistics of China), 2006. Compilation of Statistical Data for the New China Fifty-five Years. http://www.bookask.com/book/1357743.html/ (accessed 13 June 2018).
NBSC (National Bureau of Statistics of China), 2017. China Statistical Yearbook. http://www.stats.gov.cn/tjsj/ndsj/ (accessed 13 June 2018).
Niroula, G.S., Thapa, G.B., 2005. Impacts and causes of land fragmentation, and lessons learned from land consolidation in South Asia. Land Use Policy. 22 (4), 358-372. https://doi.org/10.1016/j.landusepol.2004.10.001.
Niroula, G.S., Thapa, G.B., 2007. Impacts of land fragmentation on input use, crop yield and production efficiency in the mountains of Nepal. Land Degrad. Dev. 18 (3), 237-248. https://doi.org/10.1002/ldr.771.
Pishgar-Komleh, S.H., Akram, A., Keyhani, A., van Zelm, R., 2017. Life cycle energy use, costs, and greenhouse gas emission of broiler farms in different production systems in Iran-a case study of Alborz province. Environ. Sci. Pollut. R. 24 (19), 16041-16049. https://doi.org/10.1007/s11356-017-9255-3.
Putterman, L., Skillman, G.L., 1993. Collectivization and China's Agricultural Crisis. J. Comp. Econ. 17 (2), 530-539. https://doi.org/10.1006/jcec.1993.1041.
Qu, F., Heerink, N., Wang, W., 1995. Land administration reform in China: its impact on land allocation and economic development. Land Use Policy. 12 (3), 193-203. https://doi.org/10.1016/0264-8377(95)00003-V.
Restuccia, D., Santaeulalia-Llopis, R., 2015. Land Misallocation and Productivity. J. Public Econ. https://doi.org/10.2139/ssrn.2607103.
Rigg, J., Salamanca, A., Thompson, E.C., 2016. The puzzle of East and Southeast Asia's persistent smallholder. J. Rural Stud. 43, 118-133. https://doi.org/10.1016/j.jrurstud.2015.11.003.
Rios, A.R., Shively, G.E., 2005. Farm size and nonparametric efficiency measurements for coffee farms in Vietnam, Meeting, July 24-27, Providence, Ri. American Agricultural Economics Association (New Name 2008: Agricultural and Applied Economics Association), 2005.
Sikor, T., Ller, D.M., Stahl, J., 2009. Land Fragmentation and Cropland Abandonment in Albania: Implications for the Roles of State and Community in Post-Socialist Land Consolidation. World Dev. 37 (8), 1411-1423. https://doi.org/10.1016/j.worlddev.2008.08.013.
Smetanová, A., Dotterweich, M., Diehl, D., Ulrich, U., Dotterweich, N.F., 2013. Influence of biochar and terra preta substrates on wettability and erodibility of soils. Z. Geomorphol. 57 (1), 111-134. https://doi.org/10.1127/0372-8854/2012/S-00117.
Syp, A., Faber, A., Borzecka-Walker, M., Osuch, D., 2015. Assessment of Greenhouse Gas Emissions in Winter Wheat Farms Using Data Envelopment Analysis Approach. Pol. J. Environ. Stud. 24, 2197-2203. https://doi.org/10.15244/pjoes/39682.
Tan, S., Heerink, N., Kruseman, G., Qu, F., 2008. Do fragmented landholdings have

higher production costs? Evidence from rice farmers in Northeastern Jiangxi province, P.R. China. China Econ. Rev. 19 (3), 347-358. https://doi.org/10.1016/j.chieco.2007.07.001.

Tan, S., Heerink, N., Kuyvenhoven, A., Qu, F., 2010. Impact of land fragmentation on rice producers' technical efficiency in South-East China. NJAS-Wagen. J. Life Sci. 57 (2), 117-123. https://doi.org/10.1016/j.njas.2010.02.001.

Tan, S., Heerink, N., Qu, F., 2006. Land fragmentation and its driving forces in China. Land Use Policy. 23 (3), 272-285. https://doi.org/10.1016/j.landusepol.2004.12.001.

Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S., 2002. Agricultural sustainability and intensive production practices. Nature. 418 (6898), 671-677. https://doi.org/10.1038/nature01014.

Todde, G., Murgia, L., Caria, M., Pazzona, A., 2018. A Comprehensive Energy Analysis and Related Carbon Footprint of Dairy Farms, Part 2: Investigation and Modeling of Indirect Energy Requirements. Energies. 11 (2), 463. https://doi.org/10.3390/en11020463.

Van Grinsven, H.J.M., Bouwman, L., Cassman, K.G., van Es, H.M., McCrackin, M.L., Beusen, A.H.W., 2015. Losses of Ammonia and Nitrate from Agriculture and Their Effect on Nitrogen Recovery in the European Union and the United States between 1900 and 2050. J. Environ. Qual. 44 (2), 356. https://doi.org/10.2134/jeq2014.03.0102.

Wan, G.H., Cheng, E., 2001. Effects of land fragmentation and returns to scale in the Chinese farming sector. Appl. Econ. 2 (33), 183-194. https://doi.org/10.1080/00036840121811.

Wang, J., Chen, K.Z., Das Gupta, S., Huang, Z., 2015. Is small still beautiful? A comparative study of rice farm size and productivity in China and India. China Agr. Econ. Rev. 7 (3), 484-509. https://doi.org/10.1108/CAER-01-2015-0005.

Wang, M., Ma, L., Strokal, M., Chu, Y., Kroeze, C., 2018. Exploring nutrient management options to increase nitrogen and phosphorus use efficiencies in food production of China. Agr. Syst. 163, 58-72. https://doi.org/10.1016/j.agsy.2017.01.001.

Wang, X., Chen, Y., Sui, P., Yan, P., Yang, X., Gao, W., 2017. Preliminary analysis on economic and environmental consequences of grain production on different farm sizes in North China Plain. Agr. Syst. 153 (Supplement C), 181-189. https://doi.org/10.1016/j.agsy.2017.02.005.

Wang, X., Han, L., Huang, J., Zhang, L., Rozelle, S., 2016. Gender and Off-farm Employment: Evidence from Rural China. China World Econ. 24 (3), 18-36. https://doi.org/36. 10.1111/cwe.12156.

Wang, Z., Ma, K., Shi, C., 2011. Analysis of Substitute Relation Between Rural Labor and Agro-mechanism in Grain Production. Journal of Agricultural Mechanization Research. 25 (22), 157-161. https://doi.org/10.1021/ja00230a013.

Wu, Y., Xi, X., Tang, X., Luo, D., Gu, B., Lam, S.K., Vitousek, P.M., Chen, D., 2018. Policy distortions, farm size, and the overuse of agricultural chemicals in China. Proc. Natl. Acad. Sci. U. S. A. 115 (27), 7010-7015.

https://doi.org/10.1073/pnas.1806645115.
Xu, Q., 2013. Technical and Allocative Efficiencies and China's Grain Production-A Microcosmic Empirical Study Based on Data of Rural Households. Frontiers. (16), 84-95. https://doi.org/10.16619/j.cnki.rmltxsqy.2013.16.006.
Xu, X., Jeffrey, S.R., 1998. Efficiency and technical progress in traditional and modern agriculture: evidence from rice production in China. Agr. Econ.-Blackwell. 18 (2), 157-165. https://doi.org/10.1016/S0169-5150(98)80004-2.
Yang, X., Xu, Y., Huang, Q., Xu, M., Liang, Y., Hu, J., Ran, W., Shen, Q., 2008. Organic-link fertilizers and its relation to sustainable development of agriculture and protection of eco-environment. Acta. Pedol. Sin. 45 (5), 925-932. https://doi.org/10.1163/156939308783122788.
Yao, S.J., 1995. Agricultural Reforms and Grain Production in China. Palgrave Macmillan UK. 105 (431), 1083. https://doi.org/10.1007/978-1-349-23553-7.
Zhang, F., Chen, X., Vitousek, P., 2013. Chinese agriculture: An experiment for the world. Nature. 497 (7447), 33-35. https://doi.org/10.1038/497033a.
Zhang, S., Jiang, J., Luan, J., Lan, X., Fang, D., 2014. The Analysis and Inspiration of Scale Operation in Agricultural Process of United States and Japan. Issues in Agricultural Economy. 35 (1), 101-109.
Zhang, W., Cao, G., Li, X., Zhang, H., Wang, C., 2016. Closing yield gaps in China by empowering smallholder farmers. Nature. 7622 (537), 671. https://doi.org/10.1038/nature19368.
Zhang, Y., Brümmer, B., 2011. Productivity change and the effects of policy reform in China's agriculture since 1979. Asian-Pac. Econ. Lit. 25 (2), 131-150. https://doi.org/10.1111/j.1467-8411.2011.01307.x.
Zhu, Y., Waqas, M.A., Li, Y., Zou, X., Jiang, D., Wilkes, A., Qin, X., Gao, Q., Wan, Y., Hasbagan, G., 2018. Large-scale farming operations are win-win for grain production, soil carbon storage and mitigation of greenhouse gases. J. Clean. Prod. 172, 2143-2152. https://doi.org/10.1016/j.jclepro.2017.11.205.

Table 1 Definition of different efficiencies

Items	Interpretations
Total factor productivity (TFP)	TFP measures output growth that is deducted from the input of factors. TFP refers to the ratio of total investment to total output over a given period of time in a company, industry, or region. It often uses production functions of the Cobb-Douglas form to calculate TF (Li et al., 2013).
Labor efficiency	Same as labor elasticity (Benjamin and Brandt, 2002; Li et al., 2013), or the output of unit labor (Carter, 1984). Labor efficiency=Yield/Farm labor
Technical efficiency	Technical efficiency can be calculated with the non-parametric methods: Data Envelopment Analysis (DEA) (Bojnec and Latruffe, 2013) or stochastic frontier production function (Tan et al., 2010; Li et al., 2013). It is often expressed by the ratio of real output and frontier output, reflecting the extent to which people master and use a technology (Xu, 2013).
Allocative efficiency	The ability of choosing optimal input levels for given factor prices (Xu and Jeffrey, 1998; Benjamin and Brandt, 2002). It refers to the adjustment of inputs and outputs corresponding to prices after the determination of production technologies (Xu, 2013). Allocative efficiency is calculated with DEA using input prices and output (Bojnec and Latruffe, 2013). It includes components of cost minimization, revenue and profit maximization (Rios and Shively, 2005).
Economic	The state of allocative efficiency and technical efficiency achieved at

efficiency	the same time is called economic efficiency (Xu, 2013). The product of technical and allocative efficiency (Xu and Jeffrey, 1998; Bojnec and Latruffe, 2013). EE = AE×TE

Table 2 A Glossary of Political Terms in China

Terms	Explanations
Household Contract Responsibility System (HCRS)	The HCRS is the basic institution in rural China to allocate the majority of farmland to all rural households equitably.
Rural China	Rural China is relative to urban China. It refers to the agricultural area, which includes towns, villages and agricultural industry (natural economy and primary industry). The Hukou system - formally implemented in 1958 – further delineated the boundaries between rural and urban areas and restricted the free migration of farmers from rural to urban areas.
Hukou system	The Hukou system is a very specific Chinese household registration system that divides the Chinese population into two categories, rural and urban, and regulates rural-to-urban migration.
Land transfer system	Land transfer system refers to a platform that help farmers transfer their land to more capable farmers. It is an effective system to promote large-scale farming.
Land reform	Nationwide Land reform took place from 1950 until the spring of 1953.In all, 700 million mu of land (1 hectare=15 mu) and various means of production were redistributed among 300 million peasants who had been landless before.
Collectivization movement	In a process of collectivization that started in 1953, the farmers were first organized in so-called mutual help teams. Then these were gradually merged into lower agrarian cooperatives. As a result of the collectivization of the countryside, certain amenities and services that had until then been reserved for city dwellers, now came within reach of the rural population. During this period, the cropland was consolidated to some extent.
Great Leap	During the Great Leap Forward, lower forms of cooperatives would be

Forward	merged into huge People's Communes. The Great Leap Forward took two forms: a mass steel campaign, and the formation of the people's communes. As a result of the massive production drives in steel and agriculture, both the production and transport sectors had become severely dislocated, which disrupted the national economic order, wasted a lot of resources, and caused great losses.
Cultural Revolution	The Cultural Revolution is a series of campaigns, initiated by Mao, intended to transform China into a truly revolutionary country. The campaigns result effectively in a civil war.

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Table 3 Summary of variables affected by farm size

Variables	Large-scale farms	Small-scale farms	References
Average costs	–	+	(Jabarin and Epplin, 1994; Lu et al., 2018)
Machinery	+	–	(Wang et al., 2011)
New technology	+	–	(Tan et al., 2008)
Risk spreading	–	+	(Sikor et al., 2009; Demetriou et al., 2012)
Ecological variety	–	+	(Demetriou et al., 2012)
Chemical use	–	+	(Niroula and Thapa, 2007)
Land fragmentation	–	+	(Wan and Cheng, 2001; Kalantari and Abdollahzadeh, 2008)
Technical efficiency	+	–	(Xu and Jeffrey, 1998; Rios and Shively, 2005; Bojnec and Latruffe, 2013)
Economic efficiency	+	–	(Bizimana et al., 2004; Bojnec and Latruffe, 2013)
Labor efficiency	+	–	(Benjamin and Brandt, 2002; Adamopoulos and Restuccia, 2014; Li et al., 2013)
Allocative efficiency	Ambiguous		(Xu and Jeffrey, 1998; Bojnec and Latruffe, 2013)
Total Factor productivity	Ambiguous		(Restuccia and Santaeulalia-Llopis, 2015; Julien et al., 2018)
Production	Ambiguous		(Juliano and Ghatab, 2003; Chen et al., 2011; Wang et al., 2015)

Table 4 List of data sources in Figure 5

Items	Data sources	Year
Grain yield	Compilation of Statistical Data for the New China Fifty-five Years (NBSC, 2006)	1949-2004
	China Statistical Yearbook (NBSC, 2017)	2005-2016
Arable land area	A Study of the Changing Trend of Chinese Cultivated Land Amount and Data Reconstructing 1949-2003 (Feng et al., 2005)	1949-1995
	Compilation of Statistical Data for the New China Fifty-five Years (NBSC, 2006)	1996-1998
	Statistical Yearbook of China Land and Resources Statistics (MNRC, 2009)	1999-2008
	China Statistical Yearbook (NBSC, 2017)	2009-2016
Rural population	Compilation of Statistical Data for the New China Fifty-five Years (NBSC, 2006)	1949-2004
	China Statistical Yearbook (NBSC, 2017)	2005-2016
Fertilizer	China Statistical Yearbook (NBSC, 2017)	1949-2016

Table 5 A List of Abbreviation

Abbreviation	Full Name
CHIP	China Household Income Project
DRSES	Department of Rural Socio-Economic Survey, National Bureau of Statistics
EPCEU	The European Parliament and the Council of the European Union
FAO	Food and Agriculture Organization of the United Nations
HCRS	Household Contract Responsibility System
MAFF	Ministry of Agriculture, Forestry and Fisheries
MNRC	Ministry of Natural Resources of the People's Republic of China
NBSC	National Bureau of Statistics of China
SOC	Soil Organic Carbon
TFP	Total Factor Productivity
WTO	World Trade Organization

Figure 1 Comparison of farm size in different countries. Note: The left axis (green lines) refers to average farm size in France, Israel, USA, and high-income countries. The right axis (red lines) refers to China, Japan and low-middle-income countries. Country-level longitudinal data of average household arable land are from decennial national agricultural census during 1960-2000, compiled by Lowder et al. Farm size refers to the area of agricultural land, including land use for cultivation of crops and animal husbandry.

Figure 2 Comparison of labor efficiencies for different countries during 1964-1987. Data sources: Labor efficiency data are from Arnade.

Figure 3 Comparison of synthetic fertilizer input and wheat yield within different countries in 2011. Data sources: Data are from FAO (Food and Agriculture Organization of the United Nations) database of the United Nations. Most of the variables used for cross-country comparisons in the paper are compiled from the FAO database of the United Nations, available at http://www.fao.org/faostat/en/#data/QC. These variables include, for instance, consumption of NPK fertilizers, areas of arable land, yields of wheat. Figure A refers to the amount of N fertilizer applied to a unit of arable land and is calculated by dividing the total amount of N fertilizer applied in each country by the area of cultivated land. Figures B and C respectively show the application rates of P and K fertilizer per arable land. The calculation method is the same. D is intended to show the agricultural production in each country, taking wheat as an example. This picture clearly shows us that China's better agricultural production is accompanied by a very high chemical fertilizer application.

Figure 4 Input comparison between small-scale and large-scale farms. Fixed inputs refer to machinery, irrigation infrastructures, etc. Non-fixed inputs refer to chemical fertilizers, pesticide, seeds, etc. Large-scale and small-scale farms have different input preferences. Large-scale farms tend to prefer more fixed inputs, and small-scale farms have the opposite, preferring more non-fixed inputs. Therefore, under the condition of increasing the same output, the fixed input of large-scale farms will contribute more to the increase of production, while the small-scale farms will mostly use non-fixed inputs.

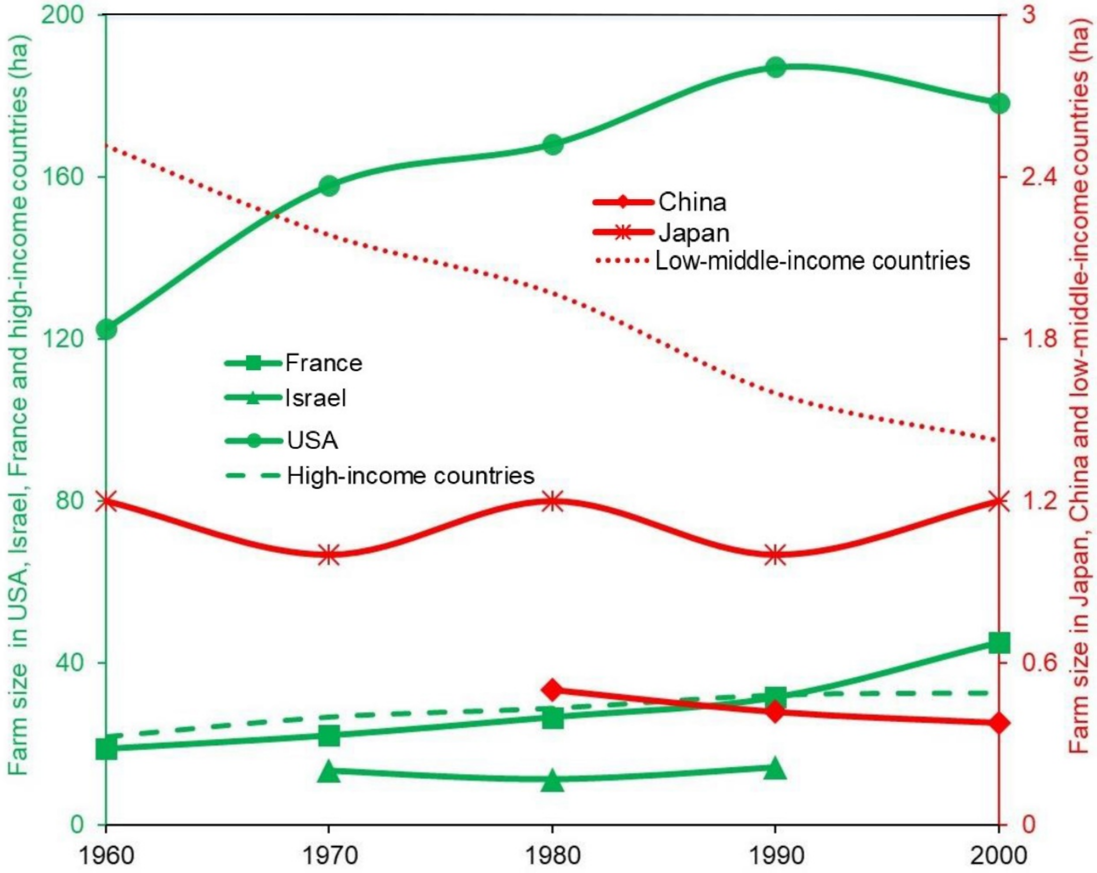
Figure 5 History of agricultural development and farm size changes from 1949 to 2016 in China. Left Y-axis: ha/rural population; right Y-axis: NPK fertilizer application and grain yield. Data sources are detailed in Table 4. Arable land area per rural population is based on the total cultivated area divided by the rural population. Rural population refers to the population living in rural areas, corresponding to the urban population. Fertilizer data is the amount of NPK fertilizer from China Statistical Yearbook divided by the arable land amount. Data of the farm size distribution pattern in the lower right corner comes from China Household Income Project (CHIP, 1988, 2002, 2008, 2013). It reflects a gradually decrease proportion of land >10 mu (15 mu = 1 hectare) per household in China since 1988. CHIP is available at http://ciid.bnu.edu.cn/chip/index.asp provided by China Institute for Income Distribution. It is a widely used nationally representative survey on households since 1988.

Figure 6 Relationship between government and farmers in China's agriculture. China's agriculture has always been constrained by economic development, local conditions, and the Household Contract Responsibility System (HCRS) as well as the Hukou system. For the Chinese government, after the establishment of policies, laws, and institutions, the state of agriculture is adjusted by providing subsidies, credit support, and education. Farmers provide feedback to the government by changes in productivity, profits, and environmental impacts. These are shown by farmers' investment costs e.g. for seed, chemicals and machinery. In such a process, China's agriculture is in the process of evolving from a smallholder-focused sector to modern, large-scale farming. However, under the constraints imposed by China's HCRS and the

Hukou system, coupled with the impact of economic drivers and local conditions, the process of increasing the share of large-scale farming in China is slow.

Figure 7 The distribution of China's scale farms in 2007. In this figure, we used data from the first national survey on pollution sources in China in 2007. The data includes a census of registered scale farms. The depth of the base map color indicates the number of scale farms in each province. Pie charts represent the proportion of parcels of different sizes. For example, the red slide of each pie chart refers to the proportion of parcels less than 10 mu in the province. The figure can show that in 2007, the national scale of operation was low and land fragmentation was serious.

Figure 1


Farm size in USA, Israel, France and high-income countries (ha)
200
160
120
80
40
0
Farm size in Japan, China and low-middle-income countries (ha)
3
2.4
1.8
1.2
0.6
0
1960
1970
1980
1990
2000
China
Japan
Low-middle-income countries
France
Israel
USA
High-income countries

813 **Figure 2**

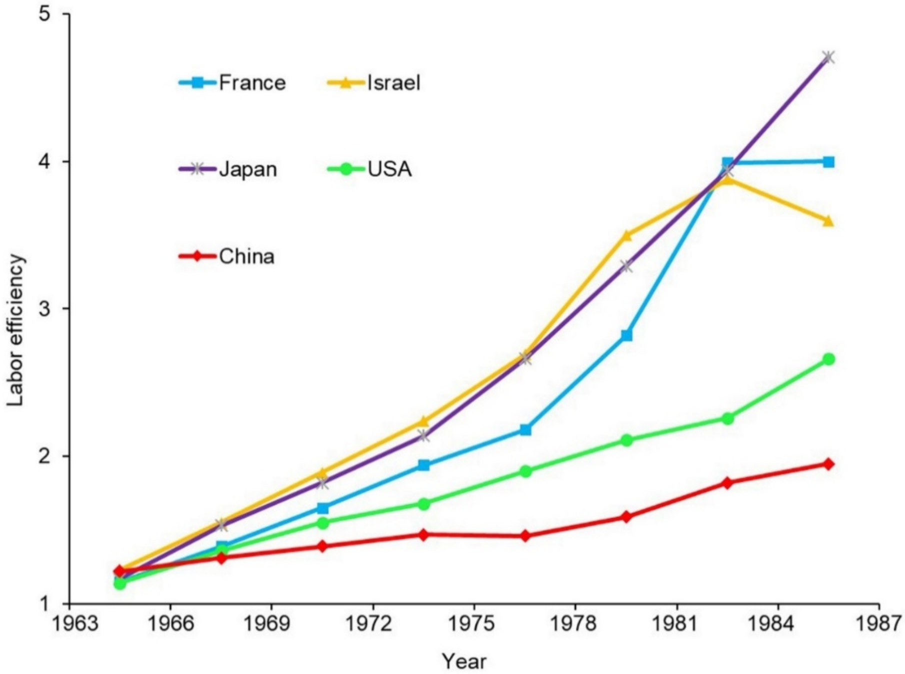


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Figure 3

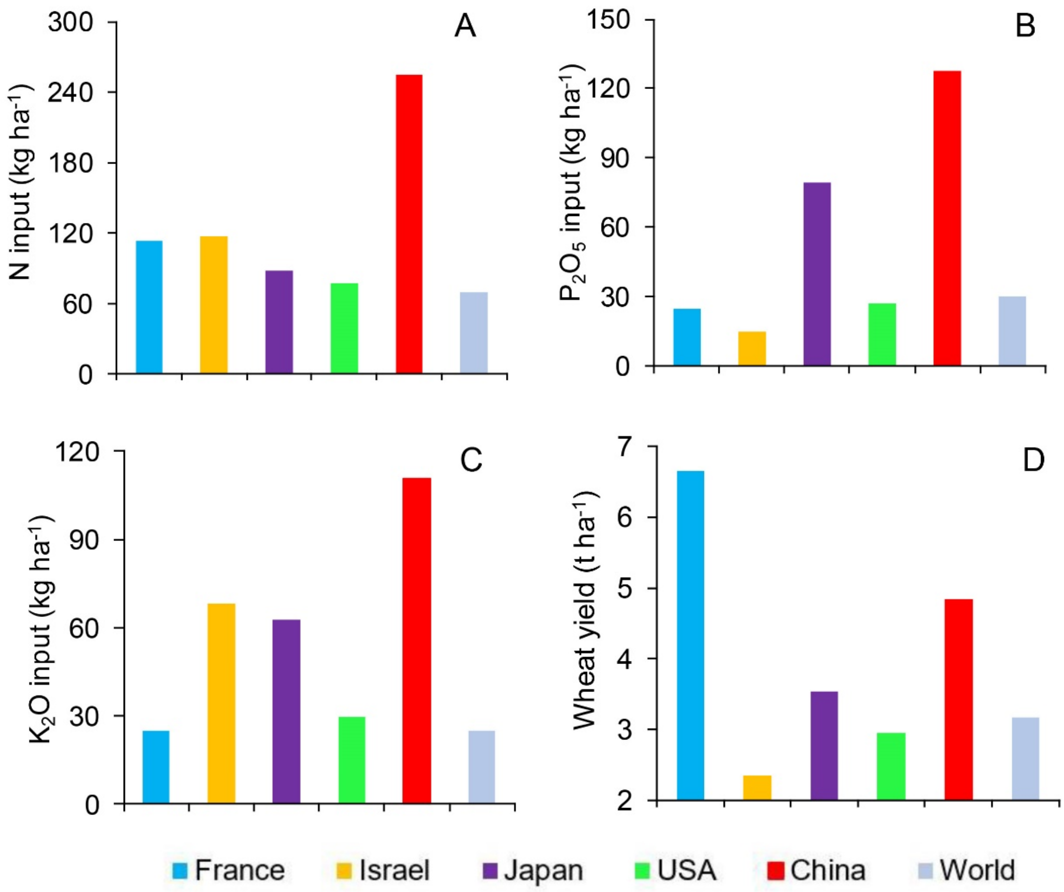
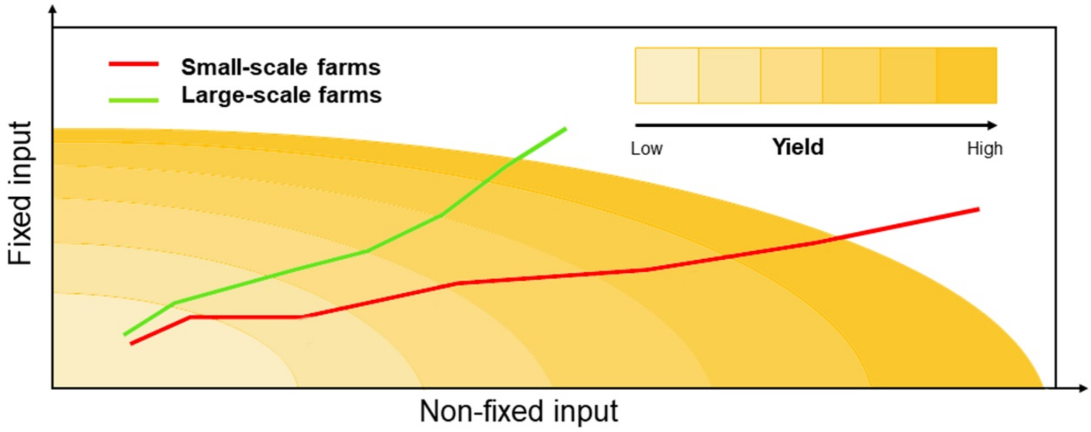
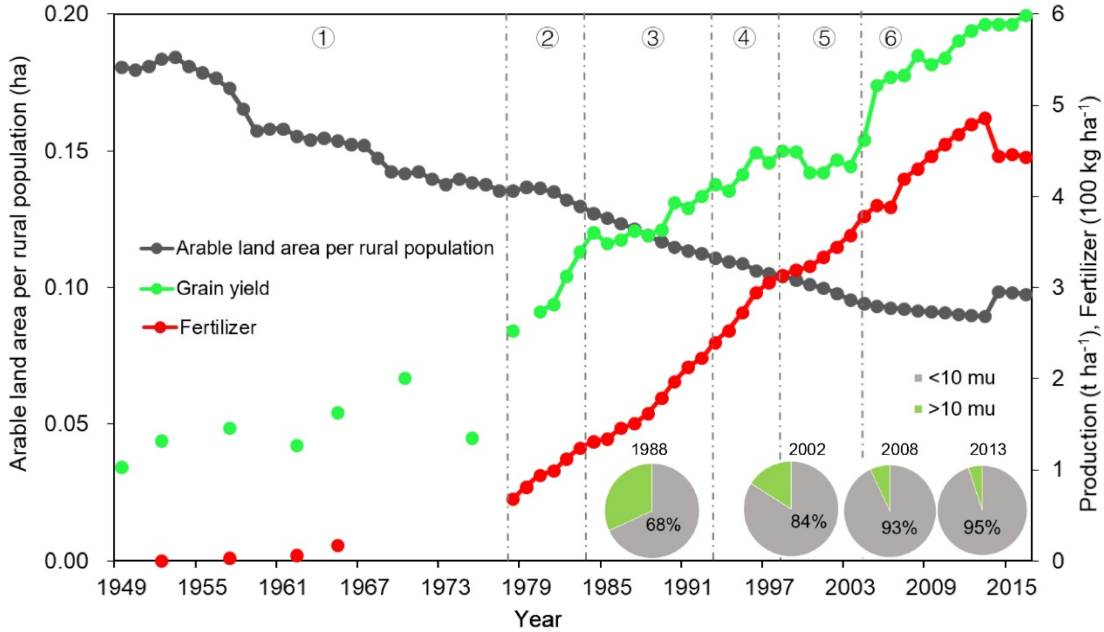

A
N input (kg ha-1)
300
240
180
120
60
0
B
P2O5 input (kg ha-1)
150
120
90
60
30
0
C
K2O input (kg ha-1)
120
90
60
30
0
D
Wheat yield (t ha-1)
7
6
5
4
3
2
France
Israel
Japan
USA
China
World

Figure 4


Small-scale farms
Large-scale farms
Low
Yield
High
Fixed input
Non-fixed input

823 **Figure 5**



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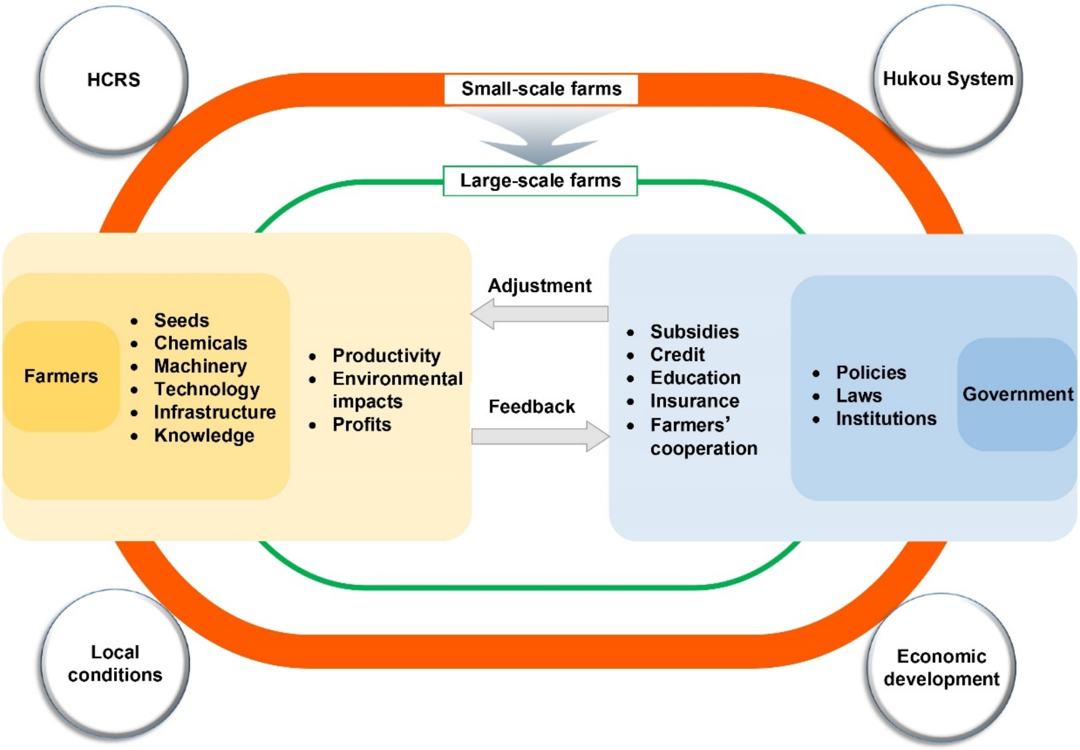
826 **Figure 6**



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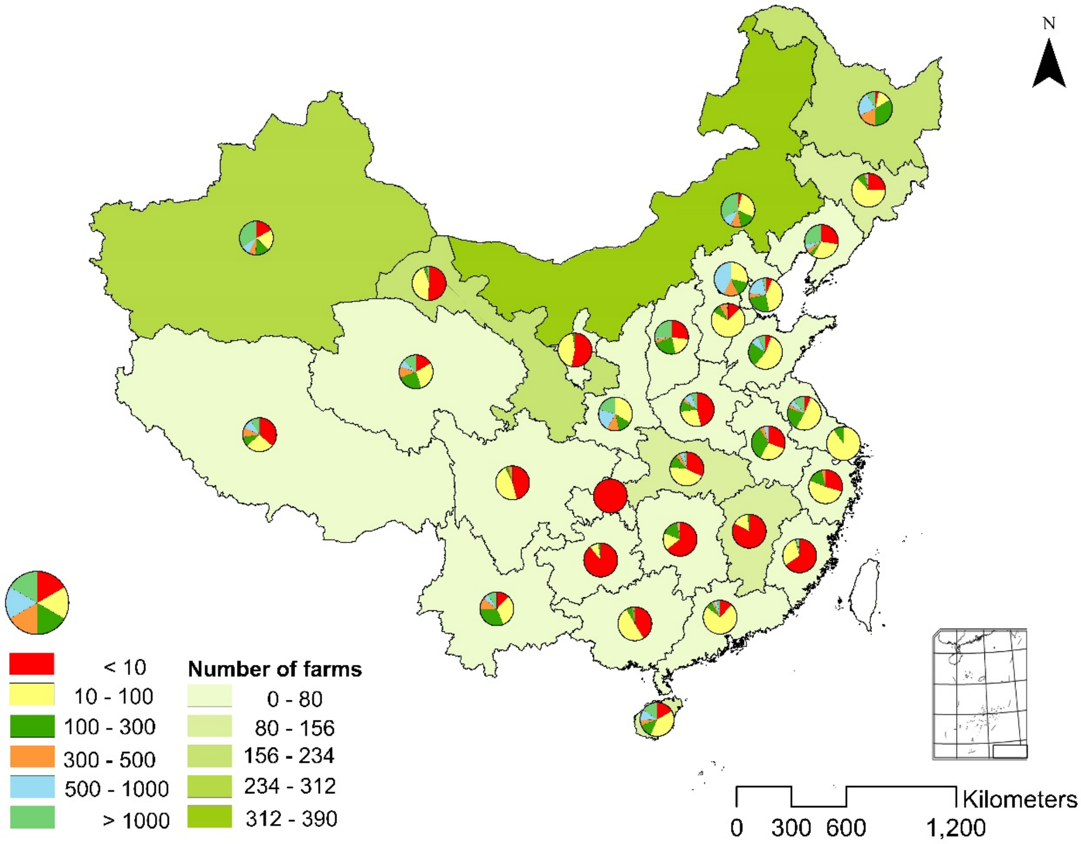
829 **Figure 7**



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Highlights

- Farm size plays an important role in the performance of agriculture.
- Increasing farm size shows clear benefits for environmental protection.
- Large-scale farming is a critical path for modernizing and sustaining agriculture.
- Smallholders prefer to use more non-fixed inputs to increase yields.