Front. Agr. Sci. Eng. 2023, 10(4): 518–529 https://doi.org/10.15302/J-FASE-2023525

RESEARCH ARTICLE

CROP-LIVESTOCK INTEGRATION FOR SUSTAINABLE AGRICULTURE IN CHINA: THE HISTORY OF STATE POLICY GOALS, REFORM OPPORTUNITIES AND INSTITUTIONAL CONSTRAINTS

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KEYWORDS

crop-livestock integration, non-point source pollution control, nutrient cycling, policy intervention, sustainable development

HIGHLIGHTS

- This paper examines the historical evolution of crop-livestock integration in China with a specific focus on its role in mitigating non-point source pollution.
- Extensive examination of existing literature has unearthed the roots of crop-livestock integration dating back to the Western Zhou Dynasty (1046 to 771 BCE), ultimately culminating in a multifaceted and intricately interwoven system of rural development policies seen in contemporary China.
- This paper illuminates the diverse contributions of crop-livestock integration in different epochs of rural development within China, which contributes to a nuanced and more theoretically grounded comprehension of circular agriculture.

Received March 19, 2023;
Accepted October 25, 2023.

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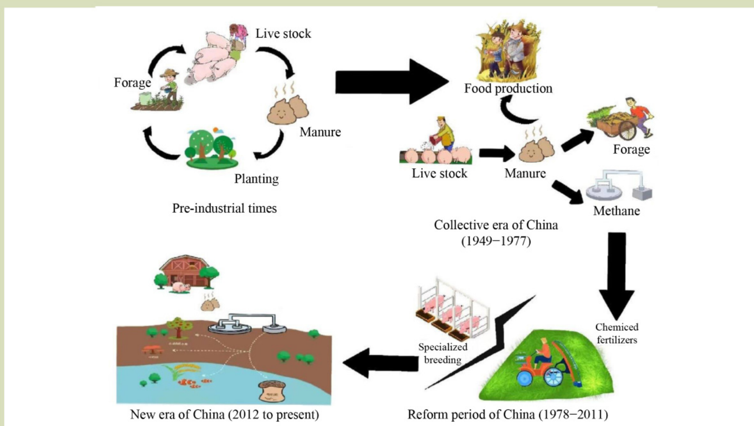
GRAPHICAL ABSTRACT



ABSTRACT

This paper examines the historical evolution of crop-livestock integration in China with a specific focus on its role in mitigating non-point source pollution. Extensive examination of existing literature has unearthed the roots of crop-livestock integration dating back to the Western Zhou Dynasty (1046 to 771 BCE), ultimately culminating in a multifaceted and intricately interwoven system of rural development policies seen in contemporary China. This paper identifies and characterizes four distinct stages in the historical trajectory of crop-livestock integration: the era of self-sufficient subsistence production in traditional times (1046 BCE to 1948); the period where crop-livestock integration emerged as a pivotal strategy for augmenting grain and meat production under collectivist policies (1949–1977); the phase marked by the industrialization and expansion of the livestock sector during the early years of economic reforms (1978–2011); and the present era in which crop-livestock integration is harnessed as a mechanism for pollution control and ecological preservation in contemporary China (2012 to present). This paper illuminates the diverse contributions of crop-livestock integration in different epochs of rural development within China, which contributes to a nuanced and more theoretically grounded comprehension of circular agriculture. This understanding has the potential to be leveraged to promote sustainable rural development in broader contexts.

1 INTRODUCTION

Crop-livestock integration, the practice of combining crop planting and livestock breeding, is recognized as a fundamental approach to fostering a circular and sustainable economy in agriculture[1]. Throughout the history of agricultural development in China, the concept of crop-livestock integration has been a pivotal in enabling the nation to sustainably provide for its expanding population, despite the constraints of limited arable land. Nevertheless, as agricultural production methods have evolved, the development of crop-livestock integration has undergone dynamic transformations. With the establishment of the People's Republic of China (PRC) in 1949, rapid economic growth and a burgeoning population have generated heightened demands for both the quantity and quality of food production[2]. While small-scale rural households continue to be central to agricultural production, the introduction of intensification and specialization has disrupted traditional crop-livestock integration, resulting in a range of challenges for non-point source pollution control. These issues encompass the improper use of mineral fertilizers, livestock-related manure pollution and significant misallocation of agricultural resources. Consequently, both agricultural resources and rural environments face substantial pressures[3].

Since 1978, the traditional self-sufficient model of crop-livestock integration has given way to profit-oriented agricultural enterprises, driven by both development policies and market forces. This significant shift has resulted in imbalances between the crop planting and livestock breeding sectors within agricultural production, along with disconnections between these two practices. Consequently, the circulation of resources between crop planting and livestock breeding has weakened, leading to pronounced soil and water pollution issues in China. Acknowledging the imperative of sustainable development, the Chinese central government incorporated the concept of ecological civilization into its national development and environmental protection agendas in 2012. Subsequently, a series of government policies has been implemented to provide state support for crop-livestock integration and the promotion of a circular economy. These policies encompass initiatives focused on non-point-source pollution mitigation, the encouragement of sustainable agricultural production and intensified efforts to combat pollution. However, the application of crop-livestock integration in agricultural production continues to grapple with numerous challenges.

Undoubtedly, the concept of the circular economy stands as a pivotal approach for achieving sustainable development and fostering rural revitalization in China. To gain a deeper insight into the evolution of crop-livestock integration in China[4], this study endeavors to scrutinize the political, economic and policy factors that have contributed to the adoption of crop-livestock integration at various junctures in China's rural development history.

2 CROP-LIVESTOCK INTEGRATION IN PREINDUSTRIAL TIMES

As human civilization advanced and agriculture developed, the exchange of substances and energy between crop planting and livestock breeding became increasingly significant[5]. Notably, in the Western Zhou Dynasty (1046 to 771 BCE), Chinese farmers instituted a fallow system that harnessed the power of green manures[1] to rejuvenate soil fertility and augment soil organic matter. Moving forward, during the Warring States period (770 to 221 BCE), farmers adopted a self-sufficient approach that intertwined crop planting and livestock breeding, with crop cultivation as the primary focus. In rural households, a diverse array of crops was cultivated alongside various livestock species, all contributing to the preservation of

[1] In agricultural methodologies, green manure is a crop that is deliberately cultivated and subsequently plowed into the soil to enhance soil fertility and augment organic nutrient content.

soil fertility. Even the legalist philosopher Xunzi prescribed that "it is the duty of rural households to augment land fertility through the use of manure". The Han Dynasty (202 BCE to 220) witnessed further refinement in farmer understanding of manure as a valuable fertilizer. Within the framework of crop-livestock integration, agricultural byproducts from crop production were utilized to feed livestock, while the labor and manure generated by livestock supported crop cultivation. The *Book of Fanshengzhi*, China's inaugural agricultural manual, underscored the indispensability of manure application, asserting that farmland could not sustain consecutive years of crop cultivation without manure, necessitating a fallow year for fertility restoration. Consequently, settled pig production became a prevalent practice during the Han Dynasty. The Northern Wei Dynasty (386 to 534) marked a notable development, as farmers devised more sophisticated techniques for producing organic fertilizer by employing livestock trampling to combine crop residues with cattle manure, exemplifying an early yet effective manifestation of crop-livestock integration. During the Tang Dynasty (618 to 907) and the subsequent Song Dynasty (960 to 1279), farmers gained a deeper appreciation of the benefits of manure in enhancing soil fertility and promoting crop growth, especially in land with less favorable soil conditions. The chapter on the coordination between manures and land in the *Agriculture Book* (*nongshu*) elaborated on techniques for utilizing manure to enable intensive farming on land with subpar fertility. This exemplified the meticulous attention Chinese farmers devoted to employing organic fertilizers as a means of transforming agrarian ecology.

During the Ming Dynasty (1368–1644) and the subsequent Qing Dynasty (1636–1912), Chinese farmers continued to advance their expertise in the utilization of manure fertilizers. The Book of *Xiu Qi Zhi Zhi* underscored the paramount importance of manure in maintaining soil fertility, emphasizing that "even though methods to enhance land fertility exist, land cannot prosper without the application of manure". It further asserted that "accumulating manure holds greater significance than accumulating gold". During this era, farmers persisted in refining their techniques for enhancing crop-livestock integration. For examples, in the Tai Lake region, farmers ingeniously employed mulberry leaves to raise sheep, utilizing sheep manure to cultivate mulberry trees. This circular nutrient approach extended to other facets of agriculture, such as using spiral shells and aquatic plants to feed fish, employing fish manure to fertilize mulberry trees, whose leaves were then employed to rear silkworms. Silkworm manure, in turn, was utilized to feed fish[6]. Similar instances of innovative crop-livestock integration, entailing the harmonious combination of crop cultivation with livestock and fishery production, were also prevalent in the Pearl River Delta and the Guanzhong region of present-day Shaanxi Province. These practices epitomized the resourceful and sustainable agricultural traditions of Chinese farmers during these dynastic periods, showcasing their deep understanding of the ecological interplay between different components of agricultural production (Fig. 1).

During preindustrial times, the development of crop-livestock integration in China was underpinned by two essential structural characteristics. Firstly, Chinese farmers adeptly harnessed local agricultural byproducts to diversify the sources of feed for their livestock. Given the constraints imposed by limited arable land in China, Considering China's limited arable land restrictions, relying solely on grain to support animal production is challenging. In response, Chinese farmers pioneered the integration of agricultural byproducts, including crop straws, leaves and grain brans, into animal diets. This innovative approach served to expand the available feed sources, reduce production costs, and mitigate pollution associated with livestock production. Secondly, Chinese farmers held a profound awareness of the inherent value of raising livestock to generate manure fertilizers for crop cultivation. The utilization of organic fertilizers to sustain soil fertility had constituted a foundational tenet of Chinese agriculture for millennia. Historically, farmers employed various methods of pen-raising sheep, pigs, or cattle to produce valuable manure fertilizers. The cyclic flow of nutrients and a commitment to environmental stewardship formed the bedrock of food productivity maintenance. Consequently, an array of distinct integration techniques evolved over time, drawing upon the creation and preservation of traditional knowledge and customs.

3 THE DEVELOPMENT CROP-LIVESTOCK INTEGRATION DURING THE COLLECTIVE ERA (1949–1977)

Following the establishment of the PRC, the nation embarked on a comprehensive set of initiatives aimed at addressing fertilizer shortages and enhancing the efficiency of grain production. One notable measure in this endeavor was the promotion of manure accumulation, coupled with the development of an extension system to facilitate crop-livestock integration. This initiative encouraged rural households and production teams to engage in livestock production to provide a vital source of manure fertilizers[7]. The state-led promotion of crop-livestock integration unfolded along three key dimensions.

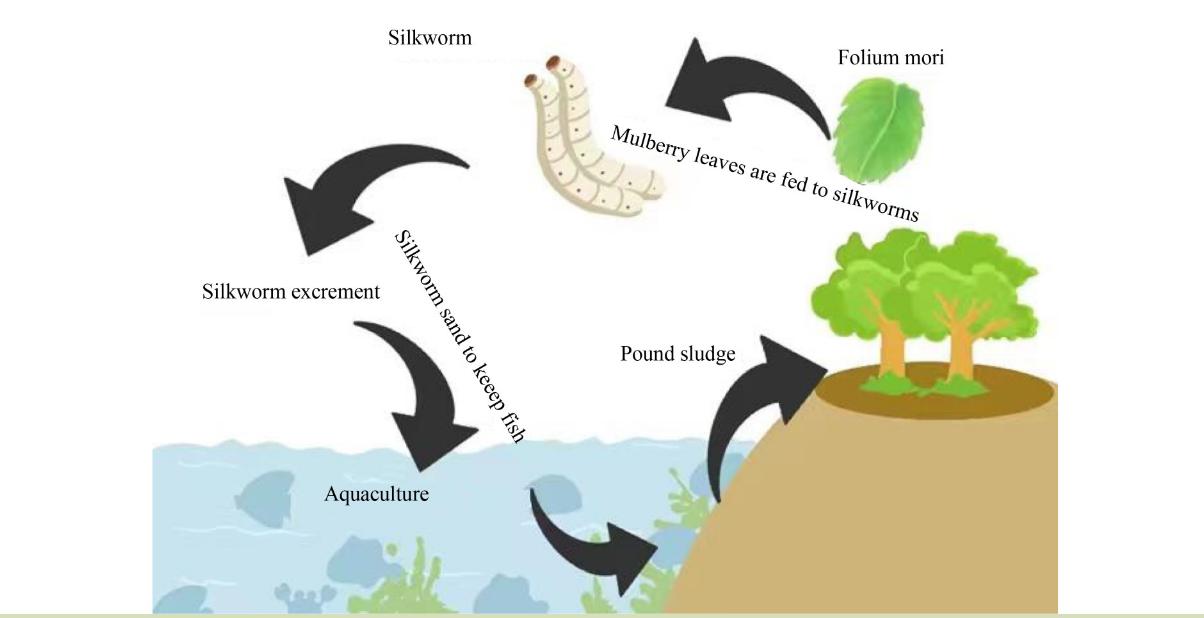


Fig. 1 Model of traditional crop-livestock integration.

The first dimension centered on the prioritization of mineral fertilizers to bolster agricultural productivity in addition to the wide application of manure. In the 1950s, Chairman Mao underscored the significance of fertilizers in agricultural production, ranking "reasonable fertilization" as the second point in his Eight-Point Charter for Agriculture[8]. From the 1950s through the 1970s, the government implemented a series of measures to promote the adoption of mineral fertilizers. These measures included the requirement for rural households to raise pigs in pens to accumulate manure, the timely provision of beancake[2] fertilizers to rural households, and the promotion of green manure practices. Additionally, the government advocated for local production and processing of mineral fertilizers, while imparting knowledge to farmers on how to apply mineral fertilizers judiciously based on the specific needs of their land and crops[9]. In most villages, an integrated approach was adopted, involving the collection and composting of manure, hays, soil, dry ashes and crop residues to manufacture fertilizers. These concerted efforts resulted in a significant increase in the adoption of mineral and organic fertilizers. By 1952, about 70% of China's arable land had adopted mineral and organic fertilizers, a figure that climbed to over 85% by 1957[10]. These initiatives, executed within the framework of the collective agricultural system, played a pivotal role in alleviating mineral fertilizer shortages and enhancing the efficiency of grain production in China.

The second dimension of the state-led promotion of crop-livestock integration revolved around agricultural policies designed to address the feed deficit. Upon the establishment of PRC, a grain shortage precipitated a feed crisis, prompting the Central Committee of the Communist Party of China and the State Council to issue the *Knowledge on Crop Planting and Livestock Breeding* in March 1957[11]. This policy advocated for the expansion of high-yield forage crops to bridge the feed gap. In the 1960s, China made strides in developing fermented feeds, algae feeds, and aquatic feeds. By the 1970s, Chinese agricultural practices incorporated the processing of roughages using basidiomycetes and cellulase, significantly enhancing feed utilization and strengthening the integration of crop-livestock systems[12]. By the late 1970s, the introduction of machinery such as feed mills and beaters for succulence feeds facilitated the mechanization of feed processing, further advancing research and development in this domain[13]. These endeavors played a pivotal role in alleviating the feed deficit and enhancing livestock production in China.

The third dimension of the state-led promotion of crop-livestock integration involved the establishment and dissemination of biogas projects in rural communities. To

[2] Beancake is a by-product obtained from soybean oil extraction and is commonly used for livestock breeding.

capitalize on the potential of livestock manure in enhancing soil fertility, China initiated the development of biogas projects, which received the highest political support from the Chinese central government[14]. By the mid-1970s, the number of biogas digesters in China had exceeded 7 million[15]. The state promotion of biogas digesters during the Collective Era laid a technical foundation for the application of circular economic principles in livestock manure management[16]. The rapid expansion of grain cultivation, bolstered by the application of mineral fertilizers, advancements in plant breeding, agricultural irrigation and other agricultural techniques contributed to a substantial increase in China's grain output from 113 billion kg in 1949 to 305 billion kg in 1978[17]. However, this rapid expansion created a feed supply deficit, leading to malnutrition and starvation of livestock. As crop production proved insufficient to support the growth of meat production, the inefficiencies inherent in traditional livestock production significantly dampened farmer motivation to engage in livestock production.

During this phase, China embraced a model of collectivist form of agricultural production, instituting a collective economic system and undergoing socialist transformation in rural areas, all in the pursuit of expanding food production. In 1951, China introduced three preliminary forms of agricultural communes: mutual aid groups, which were further categorized into temporary primary mutual aid groups and perennial mutual aid groups. In these groups, individual farmers voluntarily contributed their land as shares, pooled their livestock and tools within the community, engaged in collective labor, and distributed agricultural products based on their respective contributions. By 1952, China's agricultural mutual aid and cooperation organizations had made significant strides, with a total of 8 million mutual aid groups nationwide, involving 45 million participating farmers, constituting 40% of the total farming population. Additionally, more than 3600 primary cooperatives were established, with 59,000 enrolled farmers, accounting for 0.05% of the total number of farmers. Also, 10 senior cooperatives were formed. This model bears resemblance to the Soviet Union push for agricultural collectivization. In the latter part of 1929, the Soviet Union commenced collectivization efforts, creating numerous agricultural communes and instituting public ownership of most means of production. Nonetheless, distinctions existed in the development models employed by China and the Soviet Union. The Soviet Union primarily implemented a collective contracting system, whereas China entrusted agricultural production tasks to rural production groups. The more decentralized approach in China was proven effective in invigorating farmer initiatives to experiment, making the collectivist production model adaptable and malleable to local conditions, thereby facilitating the integration of crop and livestock production.

4 THE RIFT BETWEEN CROP PLANTING AND LIVESTOCK BREEDING IN CHINA'S AGRICULTURE DURING THE REFORM PERIOD (1978–2011)

In the early 1980s, China embarked on a momentous rural reform by dismantling the collectivist agricultural system. The Household Contract Responsibility System[3] was swiftly implemented nationwide, and the centralized system of unified purchase and sale[4] was abolished. However, during this period, the development conditions for rural farmers in China remained constrained. According to the poverty line standards established by China in 1978, an estimated 250 million people in rural areas lived below the poverty line, accounting for 26% of the total population, and the incidence of rural poverty had surged to 30%. Simultaneously, as living standards improved, dietary preferences underwent a corresponding evolution, with a notable increase in the demand for protein-rich foods. Statistics reveal a rapid growth in the consumption of livestock, poultry, and aquatic products in China, with per capita consumption of animal protein food rising from 11 kg per person in 1978 to 38 kg per person in 2002, reflecting an average annual growth rate of 9.8%[18].

Consequently, crop planting and livestock breeding became increasingly commercialized and specialized, giving rise to a diversified market system. However, as the industry expanded and business models evolved, a greater volume of manure was generated by industrialized and concentrated forms of livestock production, leading to significant pollution in watersheds and rural landscapes. Additionally, the rapid increase in mineral fertilizer production in China resulted in the widespread adoption of cost-effective mineral fertilizers, with usage reaching 12.7 Mt in 1980[19]. Fueled by institutional changes and technological advancements, China embarked on the modernization of its agricultural production, which, in turn,

[3] In the household responsibility system, farmers, using families as the primary unit, enter into contracts to obtain land and other means of production, as well as production assignments, from collective economic entities, predominantly villages and groups.

[4] "Unified purchase and sales" pertains to a procurement and distribution model that centralizes the acquisition and distribution of specific commodities, which hold significant relevance to both the national economy and the well-being of the populace.

disrupted the traditional crop-livestock integration. The industrial revolution ushered in new inputs and increased agricultural productivity but simultaneously severed the loop of substance exchange inherent in traditional crop-livestock integration[20,21]. As a result, crop planting and livestock breeding became fundamentally disconnected in several key aspects.

The first noteworthy development was the gradual transition from household-based animal production to specialized livestock production managed by professional operators. The flourishing market opportunities that emerged after 1982 spurred the growth of qualified specialized livestock breeders. By the end of 1984, the number of specialized animal production operators had surged to 450 thousand, and this figure further increased to 935 thousand by 1987[22]. During this period, China made strategic adjustments to the livestock-cropping ratio within its agricultural framework, advocating for diversified agricultural production with a central focus on livestock production. The evolution in animal production technology and operational models substantially bolstered the intensification of animal production practices while prompting many household operators to discontinue their involvement in animal production activities[23]. From 1985 to 2012, the average number of draft animals owned by households decreased from 0.57 to 0.26 per household (Fig. 2). Rural households increasingly specialized in various agricultural sectors. In recent decades, a growing influx of industrial and commercial capital was attracted to livestock production, giving rise to numerous medium to large livestock production enterprises[24]. Consequently, crop and livestock production became distinct and separate sectors, contributing to a stratification between small- and large-scale rural household operators and the discontinuation of traditional integrated crop and livestock production.

The second aspect of the disconnection between crop planting and livestock breeding stemmed from the significant expansion of mineral fertilizer usage in crop cultivation. The mechanization of agriculture and corresponding advancements in farming technology facilitated the proliferation of intensified cropping practices, resulting in an ever-increasing demand for mineral fertilizers. This led to a consistent yearly rise in the quantity of mineral fertilizers applied. In 1980, the total amount of mineral fertilizers applied in China, measured in terms of nutrient weight, stood at 12.7 Mt. By 2015, this figure had soared to a historic high of 60.2 Mt, representing a 3.74-fold increase. This trend is indicative of the gradual displacement of organic manures in farming practices, further segregating crop production from livestock production activities. In response to concerns regarding soil fertility and non-point source pollution, the Chinese central government has placed a strong emphasis on enhancing the processing capacity for organic fertilizers.

This transformation underscored the challenges inherent in reconciling the growing demands of intensified crop cultivation with the sustainable integration of livestock production, highlighting the need for more comprehensive approaches to agricultural practices and resource utilization. During this period, the expansion of specialized livestock production in China gave rise to a conflict over land resources between natural resource preservation and crop cultivation, as both sectors vied for land. This conflict engendered a detrimental cycle involving the ecological conditions, and crop and livestock production[25]. Simultaneously, the infusion of

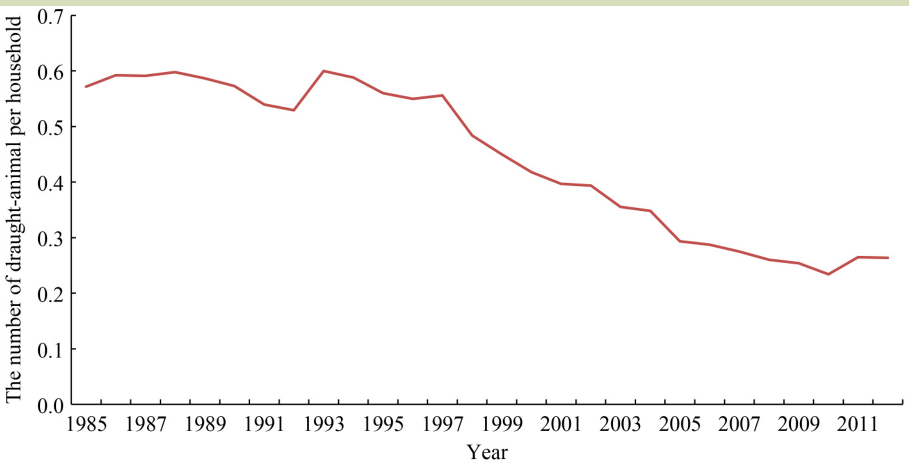


Fig. 2 Draft animals per household from 1985 to 2012 (Data source: China Agricultural Statistics Yearbook 1986 to 2013).

industrial and commercial capital into animal production operations resulted in the displacement of rural households by large-scale and specialized operators, leading to significant pollution stemming from livestock manure[26]. The pressing need for increased grain production and the escalating use of mineral fertilizers further reduced the application of livestock manure, exacerbating non-point source pollution and the deterioration of rural ecosystems. Also, since China’s economic reform and opening-up policies, the previously planned economy system has transitioned into a socialist market economy system. However, the corresponding market and regulatory framework could not be established overnight, resulting in an imperfect support mechanism for agricultural production. This also contributed significantly to the fragmentation of crop and livestock production. In summary, the disconnection between crop and livestock production evolved through two intertwined processes. First, specialized, and large-scale operators supplanted rural households in the animal production sector. Second, the widespread adoption of mineral fertilizers in farming rendered livestock manure obsolete in crop production. To address the socio-ecological challenges stemming from these interconnected processes, the Chinese government enacted a series of environmental and rural development policies, with the aim of achieving a balance between crop and livestock production, and mixed-use areas. These policies sought to reconcile the competing demands of agricultural production, ecological preservation, and sustainable rural development.

5 CROP-LIVESTOCK INTEGRATION AS STATE-MANDATED POLLUTION CONTROL MANDATES (2012 TO PRESENT)

The segregation of crop production from livestock production, coupled with heavy reliance on external inputs, has led to rapid increases in productivity. However, this growth has been accompanied by increasingly pronounced resource and environmental challenges. Excessive use of mineral fertilizers and pesticides, coupled with improper management of livestock manure, have resulted in issues such as soil degradation and water eutrophication. These problems not only undermine China’s agricultural competitiveness but also jeopardize its long-term sustainability[27]. Also, the declining environmental quality in agricultural production areas has had adverse effects on the living environment and health of residents. In 2011, the Ministry of Environmental Protection conducted a pilot survey of 364 villages nationwide, revealing considerable pollution in rural surface water, a 21.5% rate of soil samples exceeding contamination standards, and heavy soil pollution around areas such as garbage dumps, farmland, vegetable fields, and industrial zones[28]. Subsequently, in 2012, the principle of ecological civilization was integrated into China’s overarching development strategy, becoming an integral component of state planning across economic, political, cultural, social, and ecological domains. Since then, the Chinese government has launched unprecedented initiatives to embed the concept of ecological civilization into its environmental regulatory framework[5]. The objective of agricultural modernization in China shifted from a singular focus on achieving high yields to a comprehensive set of targets. The promotion of sustainable development in agriculture and the restructuring of the relationship between crop and livestock have emerged as vital pathways for implementing ecological civilization construction within the agricultural sector.

During this period, the Chinese government has continuously refined its policy objectives in response to economic, environmental, and demographic developments. Starting from 2012, the initial focus was on pollution control, addressing the environmental deficits that had accumulated over time. As the environmental situation gradually improved, the emphasis shifted toward the adoption of sustainable and efficient methods to drive transformation in agricultural development. Currently, and in the foreseeable future, with the introduction of the “Dual Carbon” goals, policy objectives have evolved to align with the synergistic reduction of pollution, mitigation of carbon emissions, and the promotion of sustainable development.

One of the primary strategies employed was the establishment of a manure utilization system with the explicit aim of reducing non-point source pollution. The results of China’s two most recent pollution censuses, conducted in 2007 and 2017, identified agricultural non-point sources as major contributors to water pollution. The animal production sector alone accounted for over 95% of COD (chemical oxygen demand) discharges and more than 50% of phosphorus discharges. Consequently, mitigating pollution from livestock production became a key focus of water pollution control efforts[29]. Also, the increased use of mineral fertilizers in crop cultivation led to

[5] From the *Resolution of the Central Committee of the Communist Party of China on the Significant Achievements and Historical Experience of the Party’s Centennial Struggle*, adopted at the Sixth Plenary Session of the Nineteenth Central Committee of the Nineteenth Central Committee of the Chinese Communist Party on November 11, 2011.

the release of substantial unabsorbed nitrogen into water bodies. As a response to environmental concerns, the Chinese central government has set ambitious policy objectives aimed at reducing mineral fertilizer application and reestablishing the nutrient exchange loop between crop planting and livestock breeding. This involves practices such as utilizing crop straws and livestock manure as organic fertilizers.

In 2014, *the Regulations on Preventing and Controlling Pollution from Large-scale Breeding Farm* were enacted, marking the first national regulation in China specifically focused on rural environmental protection. These regulations aimed to reinforce the primary responsibility of breeders for the resource utilization of animal manure. They introduced an incentive structure to encourage the comprehensive utilization of livestock manure and provided a legal framework for the transformation of manure from large-scale animal production operations into organic fertilizers. Subsequently, in 2015, the concept of sustainable development in agriculture was officially introduced, with its core and primary focus being the protection of water and soil resources, especially their ecological qualities that are fundamental in ensuring the quality and safety of agricultural products[30]. The Ministry of Agriculture put forth the “1+2+3” goal for sustainable agricultural development, which encompasses reducing overall water consumption for agriculture, minimizing the use of fertilizers and pesticides, and extensively utilizing animal manure and straw as resources, while also promoting the recycling of film mulch. To achieve these objectives, the Ministry of Agriculture initiated five major actions for sustainable agricultural development, which included initiatives such as animal manure recycling and the replacement of mineral fertilizers with manure in integrated fruit-vegetable-tea cultivation.

On the livestock production front, the government has allocated subsidy funds to equip large farms in counties with significant livestock production with waste recycling equipment and has invested in the construction of central manure plants at the county level. These initiatives have yielded significant results, with China achieving a comprehensive utilization rate of over 76% for livestock and poultry manure by the year 2021. Also, the matching rate of large-scale livestock and poultry manure treatment facilities and equipment reached an impressive 97%[31]. During this period of policy implementation, both large-scale crop and livestock production continued to grow. For instance, as illustrated in Fig. 3, between 2012 and 2020, the number of rural households engaged in livestock production with an annual output of fewer than 500 pigs decreased by 62%. In contrast, the number of animal production operators with an annual output exceeding 50,000 pigs witnessed a substantial increase of 196%.

From the perspective of crop production, the government has taken measures to encourage farmers to adopt manure instead of mineral fertilizers, with a specific focus on fruit, vegetable, and tea cultivation. In these targeted project areas, the government provides subsidies for the use of manure in crop production, or it directly purchases manure and distributes it to farmers free of charge. By implementing such initiatives, farmers can experience the benefits of using manure on soil and crop quality, thereby increasing their acceptance of this eco-friendly practice. This approach has yielded positive results, as evidenced by four consecutive years of negative growth in mineral fertilizer use from 2016 to 2020. In 2020, China’s total use of mineral fertilizers was 52.5 Mt, a significant decrease of 7.7 Mt, or 12.8%, compared to 2015. The second approach to reestablishing crop-livestock integration revolves around promoting sustainable development across various agricultural sectors. This shift toward ecological civilization was first introduced in the revised charter of the CPC during the Nineteenth National Congress of CPC in 2017. It emphasized the intrinsic value of clean water and green mountains. Subsequently, the *National Rural Revitalization Strategic Plan (2018–2022)* was issued in 2018 by the CPC Central Committee and the State Council. This plan outlined five revitalization actions, including a focus on rural ecological revitalization. Environmentally-friendly livestock production emerged as a pivotal component of the state rural development policies.

In the new era, crop-livestock integration has been actively promoted through government development plans and has been integrated into the industrialization and marketization of agriculture and rural economies. By 2019, China’s GDP per capita exceeded 10 thousand USD for the first time, and the demand for sustainable and high-quality agricultural products surged among Chinese residents. Supported by crop-livestock integration, the market for high-quality products has expanded rapidly to meet the needs of urban and rural consumers. Consequently, promoting the production of quality and affordable products, while also realizing the ecological value in agriculture, has become a crucial measure to advance crop-livestock integration within the framework of a market economy. In 2020, the Chinese Central government issued the *Opinions on Establishing and Improving the Mechanism to Realize Value in Ecological Products*, providing institutional support to transform environmental resources, including clean waters and green mountains, into invaluable assets that are integral to the functions of the socioecological system[32]. This signifies a concerted effort to align ecological principles with

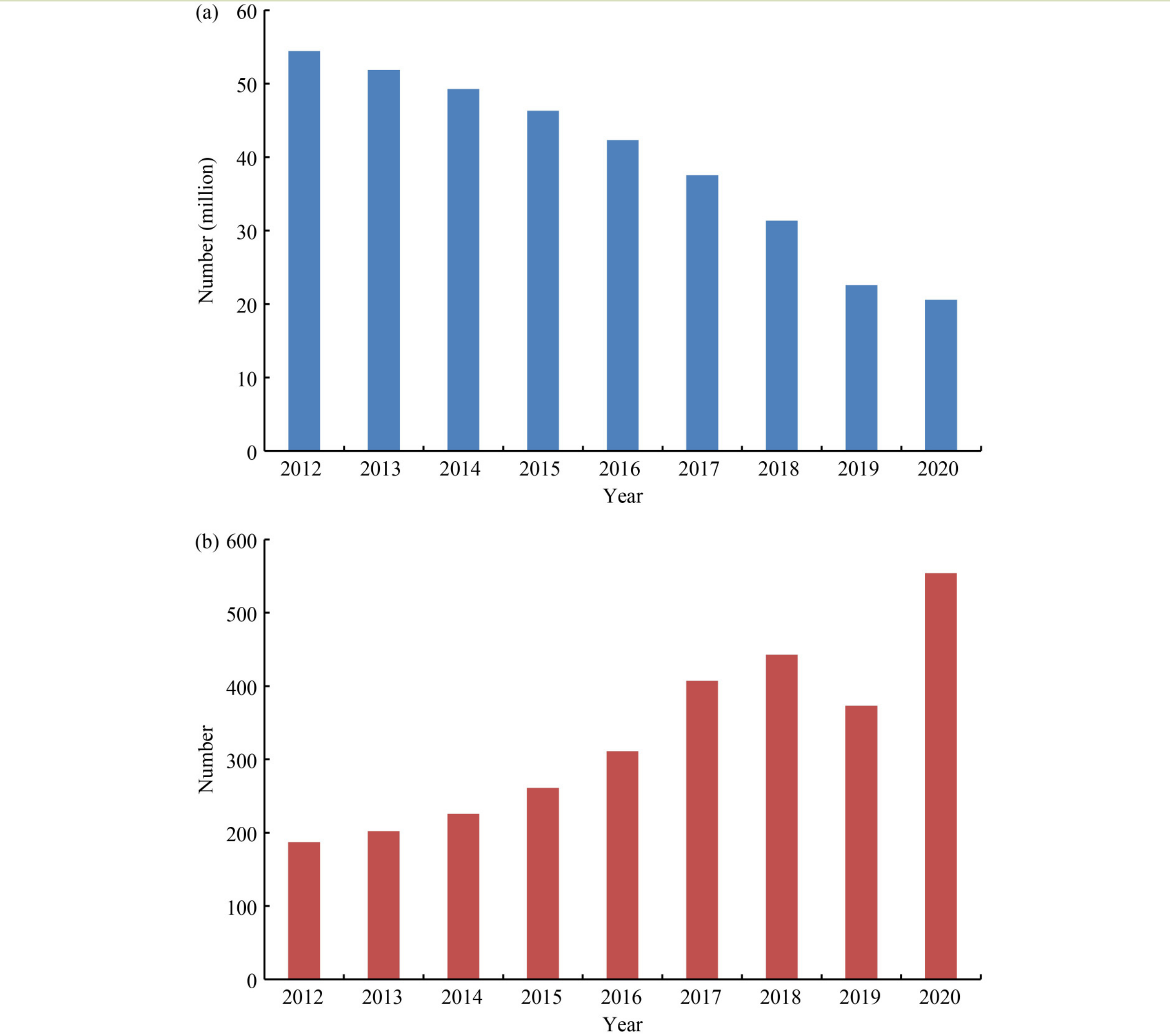


Fig. 3 Changes in the scale of pig production from 2012 to 2020. (a) The number (million) of rural households with the annual output of fewer than 500 pigs; (b) the number of breeding operations with the annual output of more than 50,000 pigs. Data source: China Agricultural Statistics Yearbook 2013 to 2021.

economic development and further promote the integration of crop and livestock production within the broader context of sustainable agriculture. In 2021, the Ministry of Agriculture and Rural Affairs of the People's Republic of China undertook a significant step by renaming the livestock manure utilization projects as the pilot projects for sustainable integration between crop planting and livestock breeding. These projects aimed to promote the local utilization of manure and facilitate the establishment of specialized service entities to support manure utilization. The overarching goal was to popularize scalable models of crop-livestock integration throughout the country. Since this transition, many provincial and local governments have taken the initiative to explore their own unique models for enhancing crop-livestock integration in their agricultural production.

For example, Zhejiang Province has developed pilot projects geared toward modernizing ecological and circular agriculture. Emphasizing coordination within counties as the foundation of their operations, the province has created a three-tier integration system based on resource and environmental capacity. This system comprises small integration within operators, medium integration within regions, and large integration within counties. Of note, the provincial government has been a pivotal facilitator, acting as an intermediary between farmers and livestock operators to enable the utilization of manure as organic fertilizer in both local and distant areas. Additionally, the provincial government has opened the doors for private capital to participate in the construction and operation of pollution control and waste utilization infrastructure within the livestock industry[33].

As the policies begin to take effect, there has been a noticeable reduction in pollution from the aquaculture industry. However, different regions have encountered a myriad of challenges when it comes to promoting crop-livestock integration. For livestock enterprises, despite government assistance in providing manure treatment equipment, the operation and maintenance of these devices can be cost-prohibitive. Also, there is a pervasive sense of distrust in the quality of organic fertilizers produced by livestock enterprises, coupled with the high cost of applying such fertilizers, which has led to a situation where the advancement of the use organic fertilization faces significant obstacles. This challenge is even more pronounced for liquid biogas slurry, as transportation poses additional logistical difficulties, further compounding the problem[34]. To address these ongoing issues, local governments have been continuously adjusting their approaches to facilitate a more effective implementation of integrated crop planting and livestock breeding. Heilongjiang Province represents another interesting adaptation of the central government crop-livestock integration policies. The province has developed services provided by third-party providers to maximize manure utilization and has established specific subsidies to promote manure management. Subsidies are allocated either to specific stages of the manure management process, such as collection, treatment and adoption in crop production, or they are granted throughout the entire process. A traceable subsidy allocation and management mechanism has been established in alignment with the flow of manure. By establishing connections between government guidance with commercial services, animal production with manure collection and treatment, and third-party service provision to farmers, more stakeholders are incentivized to participate in manure collection, treatment and utilization, thereby encouraging the expansion of comprehensive manure utilization services.

6 CONCLUDING REMARKS

Throughout the millennia, Chinese farmers have grappled with the challenge of limited arable land per capita while successfully maintaining land fertility and increasing agricultural productivity. A pivotal factor in their achievement has been the practice of crop-livestock integration, where crop and livestock production mutually reinforce each other. As traditional agriculture has evolved into a modernized system, the dynamic relationship between crop and livestock production has undergone several distinct phases. These stages include an era of integration in ancient and collectivist times, a period of separation during the opening of the market economy, and a phase of renewed coordination during the era of sustainable development. From its early and rudimentary stages, crop-livestock integration has matured into a comprehensive system that encompasses a wide array of policies, mechanisms, techniques and institutions. The current state of crop-livestock integration not only provides a theoretical and practical foundation for China's circular and sustainable economy in rural areas but also, in certain areas, offers effective pathways to advance agricultural and rural modernization.

Through considering the evolution of crop-livestock integration in China, it becomes evident that significant breakthroughs have been made in terms of mechanism construction, model innovation, technology upgrades and supportive measures. In the context of agricultural modernization, the establishment of a sustainable production system that prioritizes environmental considerations and aligns with resource capacities is of paramount importance. This approach helps mitigate the harm to agricultural resources and the environment that can result from the disconnect between crop and livestock production. From the perspective of the development of modern crop and livestock production, it is imperative that the government proactively fosters third-party socialized service organizations to provide manure return services, effectively bridging the gap between crop crop and livestock production. Additionally, by leveraging market mechanisms to promote the recycling and sustainable development of crop and livestock production, crop-livestock integration can contribute to realizing ecological values, aligning with the notion of ecological civilization. This holistic perspective underscores the importance of balancing agricultural productivity with environmental stewardship, setting the stage for a more sustainable and harmonious coexistence between agriculture and the natural world.

Acknowledgements

The research was supported by the National Social Science Foundation Youth Project "Research on the Realization Mechanism, Enriching People Effect and Path of Agricultural Carbon Reduction and Increase Value under the Background of Double Carbon Target" (22CJY030).

Compliance with ethics guidelines

Danmeng Feng, KouRay Mao, Yujie Yang, and Yu Hu declare that they have no conflicts of interest or financial conflicts to disclose.
This article does not contain any studies with human or animal subjects performed by any of the authors.

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