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Typology of farms and spatial patterns on the North China Plain to support crop–livestock integration

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KEYWORDS

Land use, agricultural landscape, decoupling, cluster analysis

HIGHLIGHTS

- Six farm types were identified in Quzhou county using farm-level data to capture local farm diversity.
- Current crop and livestock production systems are spatially decoupled with subregional specialization.
- A large potential exists to improve farm management by reducing mineral fertilizer use and increasing resource exchange between farms.
- The pattern of farm types is a result of agricultural policies.
- New policies are needed to coordinate and facilitate integrated crop–livestock systems with a proper animal-to-cropland ratio at local level.

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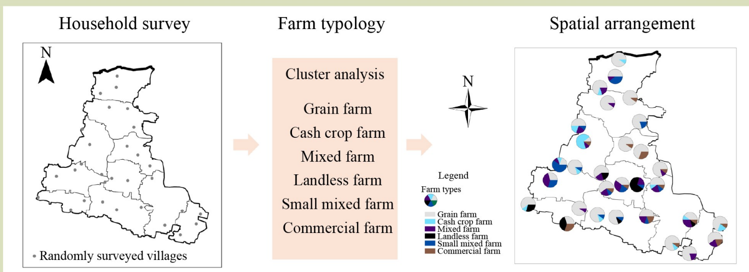
GRAPHICAL ABSTRACT



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ABSTRACT

The benefits of integrated crop–livestock systems (ICLS) have been widely discussed, but their application remains limited. The effects of agricultural characteristics and spatial distribution in a landscape on the development of ICLS are not well understood. This study aimed to better understand the current specialization of farming systems to support ICLS development, by capturing the diversity of farms and their spatial distribution patterns. It developed a spatially explicit farm typology and map of the proportion of types throughout the study area, using a 300-households survey data set from Quzhou, a typical agricultural production county on the North China Plain. Also, it identified six distinct farm types characterized by the degree of specialization, management and farm size. Environmentally and socioeconomically oriented variables were used to further quantify farm types. Three features in these farm types were identified as being relevant in the context of ICLS, that is overuse of fertilizer, the decoupling of crop and livestock production, and a strong dependence of specialized livestock farms on feed import. Farm types were unevenly distributed across the study area, indicating regional specialization and a spatial decoupling of crop and livestock production. The paper discusses driving forces behind the different farm types and their implications for ICLS. New guiding policies are needed to limit strong regional specialization and facilitate ICLS to ensure a balanced crop-to-livestock ratio and distribution at a subregional scale. Overall, this study may help to contextualize future ICLS designs to local conditions and support agricultural transition policies and rural development on the North China Plain.

1 Introduction

Across many regions in the world, agriculture has specialized and intensified to achieve economies of scale in increasingly competitive global markets, particularly as labor availability decreases due to economic development and urbanization[1,2]. In China, the adoption of reform and opening up policies has accelerated the specialization and intensification of agriculture, enabling the production of competitive goods to meet substantial local and global market demands[3]. Additionally, rapid industrialization has provided farmers with greater access to low-cost input resources, further driving agricultural specialization and intensification. However, this shift has come at a significant cost, through extensive environmental degradation and the depletion of natural resources[1,4]. Agricultural production is now recognized as a major driver of the transgression of multiple planetary boundaries[5,6], highlighting the urgent need for more sustainable practices.

In recent decades, the demand for food in China, in particular livestock products, has increased rapidly, associated with a strong economic growth[7]. A strong trend toward specialization and intensification in livestock production can be observed, driven by increased demand from the large and fast-growing middle- and upper-classes in the population, and supported by the introduction of new and more productive animals breeds and technologies[8]. Many mixed farms, where livestock was held on farm backyards, have been replaced by large feedlots with extremely high animal density. In this process, crop and livestock production are increasingly decoupled at household level[9]. The decoupling significantly disrupts nutrient cycling, resulting in, for example, a reduced fraction of manure that is recycled and used on cropland. At the same time, crop production in China has become increasingly dependent on synthetic fertilizers, accounting for about one-third of the global total nitrogen fertilizer consumption[10]. Due to subsidies and a lack of science-based information, the relatively low cost of synthetic fertilizers has stimulated farmers to apply excessive amounts to avoid any risk of yield limitation[11]. This practice has resulted in significant nutrient surpluses, with associated risks of leaching and other environmental emissions. The nitrogen use efficiency of synthetic fertilizers in China remains below 50%. Simultaneously, the average manure recycling rate is below 50%, primarily due to the decoupling of crop and livestock systems because of specialization[12]. As a result, the environment significantly deteriorated, leading to negative consequences for human health. For example, nitrate from agricultural runoff and leaching decreases water quality and causes eutrophication of ground- and surface-water[13]. This can result in toxic algae blooms in Chinese lakes and rivers, and even green tides in the Chinese sea, thus posing serious risks for biodiversity and human health[14,15]. Also, the large ammonia emissions significantly contribute to $PM_{2.5}$ pollution[16], causing air quality problems.

The decoupling of crop and livestock production strongly contributes to low nutrient use efficiency[17,18]. Previous studies suggested integration of crop and livestock systems (ICLS) has clear potential to increase nutrient circularity and contribute to agricultural sustainability[19–21]. To achieve this potential, crop and animal production needs to be balanced at the regional scale. Some studies concluded that a massive relocation of livestock within China is needed to geographically balance livestock numbers with feed supply, as well as manure production with crop nutrient demands at local or regional levels[17,22]. These studies predominantly focused on regions neglecting the farm level and other stakeholders. They did not provide specific strategies for specific regions. It is crucial to include the farm level, as key decision-making units, to understand drivers of specialization in a regional analysis. This allows for a comprehensive understanding of potential challenges, revealing detailed resource allocations and assessing the impacts of interventions on local stakeholders. This understanding can inform local and regional policymakers in the development of context-specific policies aimed at ICLS.

Farm size, spatial proximity of farms, sociodemographic characteristics of farmers and diversity of farm types are important in crop–livestock integration[17,19,23,24]. There is a considerable heterogeneity across or within counties in terms of farm structure, management practices, farms' assets, farm diversity and environmental characteristics[25]. Quantifying the type of farming systems, their spatial distribution and farmer characteristics is an essential step toward effective policies that enable ICLS. How to design ICLS to specific regions that differ in farm diversity, spatial distribution of farm types and farmer characteristics is currently unknown for many regions, including the North China Plain.

In many regions worldwide, including China, there is a profound lack of farm level data to better inform policymakers, resulting in ineffective policies with low acceptance among the diverse farmer population[25,26]. Characterizing and mapping farm types can capture the diversity of farms and the spatial distribution of farm types. Farm typologies are extensively used in many studies to analyze the diversity of farming systems in different rural areas[27–30]. To better inform ICLS-oriented policies and developments, an enhanced understanding on the spatial distribution of farm types is needed. We introduce a spatially explicit typology aimed at achieving four primary objectives. In this context, a spatially explicit farm typology refers to the classification of farms into homogeneous groups based on common characteristics while explicitly accounting for their geographic location and spatial context. The first objective is to capture the diversity of farms by using farm-level data from a survey. The second objective is to quantify the regional farm diversity and spatial arrangement of farm types over the study area. Third, we elaborate on the role of agricultural policies on the farm typology evolution. Last, we discuss how identified farm types, and their distribution may help to contextualize future ICLS designs for local conditions and can support agricultural transition policies on the North China Plain.

2 Materials and methods

2.1 Case study area

The case study focused on Quzhou County, an administrative division of Handan City in Hebei Province, centrally located on the North China Plain. In Quzhou County, 72% of the total area is dedicated to crop production, and the county ranks first in Hebei Province for the number of laying hens[31]. Hebei Province itself is one of China's largest agricultural areas and ranks third nationally in egg production[32]. Given Quzhou's intensive food crop and egg production, its representativeness is evident through shared agricultural characteristics with Hebei Province. The county shares key sustainability challenges with the North China Plain, including low resource-use efficiency, groundwater depletion and rural poverty[33,34], further reinforcing its relevance as a study area. Additionally, Quzhou serves as a pilot demonstration zone for the national promotion of ICLS and agricultural green development[35]. Quzhou encompasses 342 villages across 10 townships, covering a total area of 677 km^2, with 525 km^2 of cropland as the dominant land use[31]. There are three main rivers (Fuyang, Zhizhang and Laosha Rivers), providing water for extensive irrigation systems. Winter wheat, summer maize, cotton and vegetables are main crops, while animal production is dominated by pigs, laying hens, sheep and beef cattle.

In Quzhou County, 86% of the residents live in the rural area, categorized as the rural population by the Hukou system[31]. The classification of population into rural and urban categories is based on the Hukou system, a unique household registration system in China. Residents classified as the rural population are entitled to own rights to croplands in rural areas, engaging in agriculture for their livelihood. Consequently, Quzhou is characterized by a substantial rural population actively engaged in agriculture.

2.2 Selection of farms

To establish a representative sample of farms from Quzhou County, a random selection process was applied using ArcGIS Pro 3.3.2[36]. Three villages from each of the 10 townships were randomly chosen (Fig. 1). The ArcToolbox feature "Create Random Points" feature was used for this purpose. Three random points were generated in each township, with a minimum distance of 1.5 km between points to prevent clustering. Subsequently, nearest villages were identified by overlaying these points with the Quzhou map. Within each selected village, 10 farm households were randomly chosen for the survey. A survey team, comprising three members, was assigned to visit farms. Each person headed in a different direction from the village center to conduct three to four face-to-face interviews. Data was collected from a total of 300 surveyed farm households.

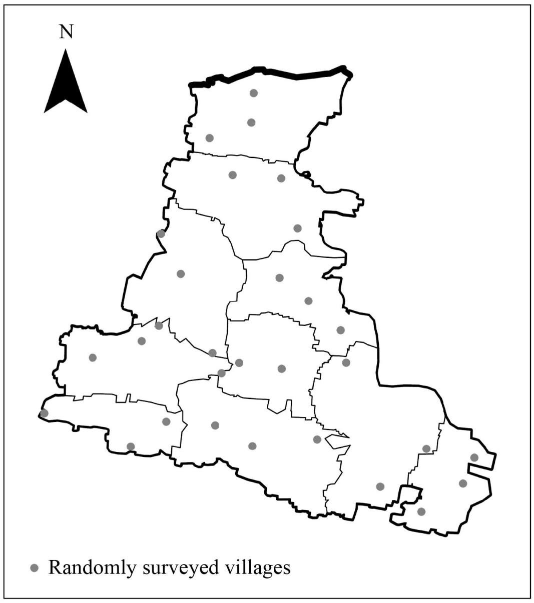

Fig. 1 Quzhou County and villages randomly selected for farm survey (审图号: 冀邯 S(2025)001 号).

2.3 Survey

The farm survey was conducted in December 2022, using a structured questionnaire (Table S1), consisting of three parts. The first part covered information about farm structure including total land area, the number of fields and field locations, types of crops and animals, specialization (specialized in crop or animal types or mixed), crop area and number of animals. The second part covered socioeconomic characteristics including family size, age of household head, the number of years of education of household head and sources of family income (from farming alone and/or off-farm activities). Given that our survey was conducted during the lockdown period of the COVID-19 pandemic, most farmers were at home and restricted from taking off-farm part-time jobs. Consequently, we asked whether farmers had off-farm jobs or would choose to engage in off-farm work when there were no lockdowns. The third part covered farming practices information including amounts of fertilizer application ($kg \cdot ha^{-1}$), sources and amounts of feed and manure, whether farmers exchange materials with one another, whether manure is applied on croplands, and if farmers sell on-farm produced manure.

The questionnaire was tested on 10 farmers (including specialized animal farmers, smallholder crop farmers and village heads) prior to the official start of the survey. During the test, we revised the questionnaire to ensure that questions would be easy for farmers to understand and answer. Also, some questions were removed due to inconsistency with the actual context. In the study area, most households have their fields in close proximity to the village. Farmers were reluctant to reveal exact field locations. We therefore used the village center to represent the farm locations. The three interviewers were trained prior to the survey and had experience with farm surveys.

2.4 Data analysis

We first developed a spatially explicit farm typology, based on farm-structure-related variables. In a second step, we incorporated new stratifying variables related to farming practices and socioeconomic information to further refine and categorize the initial farm typology, providing a more comprehensive understanding of the identified farm types. Table S1 provides a detailed description of farm-structure-related variables, farming practice variables and socioeconomic variables. In addition, all farms visited were classified. The proportion of each farm type in each sampled village was calculated and spatially represented on the maps.

The data was processed and analyzed in R version 4.3.0[37]. The farm type distribution map (Fig. 2) was made by ArcGIS Pro 3.3.2[36]. Prior to analysis, the Shapiro-Wilk test was used to test if continuous data was normally distributed and Levene's homogeneity of variance test was used to evaluate homogeneity of variance. If assumptions about the normal distribution and homogeneity of variance were not met, a non-parametric Kruskal–Wallis test was used to compare group means, followed by multiple pairwise comparisons. For categorical variables, independence was tested using the Chi-square test (or Fisher's exact test) followed by pairwise comparisons with Bonferroni-Holm correction.

We used the clValid package[38] to test cluster quality among five algorithms: hierarchical cluster analysis, partition around the medoids, divisive analysis, K-means and model-based clustering[29]. The indicators of cluster quality are compactness, connectedness and separation, which can be assessed by the Dunn index, silhouette width and connectivity[39–41]. The performance of these algorithms is presented in Fig. S1. Given that minimizing connectivity and

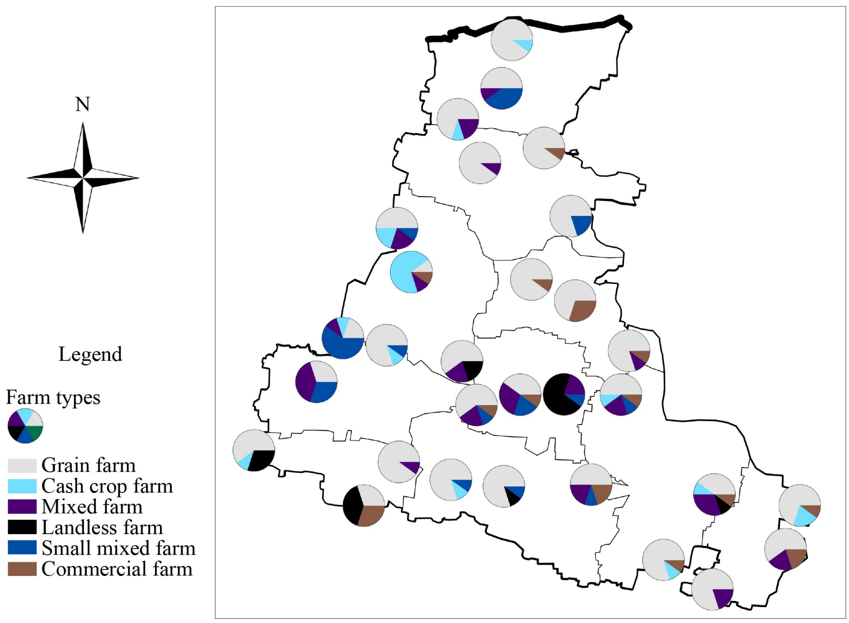

Fig. 2 Proportion of farm types in sampled villages (审图号: 冀邯 S(2025)001 号).

maximizing both the Dunn index and the silhouette are expected, the results showed that hierarchical cluster analysis was the most suitable method for our data. Hierarchical clustering with complete linkage was performed using the R package "cluster"[42]. Gower's distance was used as the dissimilarity coefficient in the clustering process, because it is capable of handling various data types[30].

3 Results

3.1 Farm type definition

Six distinct clusters were identified (Fig. S2). Accordingly, the 300 farms were classified as grain farm, cash crop farm, mixed farm, commercial farm, small mixed farm and landless farm, representing respectively, 61%, 6.7%, 11.3%, 6.7%, 8.3%, and 6% of the farms, respectively (Table 1). The six types are summarized below.

Type 1 (grain farm): This farm type included specialized grain farmers (*N* = 183; 61%) with about 99% of their land area allocated to grain production. The farm area was on average 0.8 ha with four fields, which is intermediate compared to the other types. **Type 2 (cash crop farm)**: In this type, households specialized in cash crops with 65% of land area used for such crops (mainly cotton and apple production) (*N* = 20; 6.7%). The percentage of land used for grain production was minor, averaging only 5.2%. In addition, this type had an intermediate number of fields (3.5), but the average land area was smallest (0.5 ha) of all types. **Type 3 (mixed farm)**: This type comprised mixed farms including grain and poultry production (*N* = 34; 11.3%). Farmers allocated most of their land (95.8%) to grain production and had 0.8 ha on average. The average number of livestock units was 151. In addition, the number of fields of this type was intermediate with three fields. **Type 4 (commercial farm)**: This type comprised commercial farms that focused on grain and cash crop production (*N* = 20; 6.7%), with a similar proportion of land allocated to grain (49%) and cash crops (51%). Compared to other types, the farm size was relatively large (1.2 ha) with five fields. **Type 5 (small mixed farm)**: This type consisted of small mixed farms, including grain and pig or beef cattle production (*N* = 25; 8.3%). Farmers allocated 100% of their land (0.8 ha) to grain production. Pig farming was dominant with 68% of the farms and 32% of the farms had beef cattle. The average of 31 livestock units was markedly less than those in types 3 and 6. **Type 6 (landless farm)**: This type was characterized by specialized landless farms (*N* = 18; 6%), with poultry (94%) or pig production (6%). The average number of livestock units was 345, which is significantly larger than for the other types.

Table 1 Means of selected structural and socioeconomic variables for each farm type, the percentage of farms producing poultry, pigs, or beef cattle and percentage of farmers whose income completely depends on farming within each farm type

Item	Farm types					
	Grain	Cash crop	Mixed	Commercial	Small mixed	Landless
The number of farms	183	20	34	20	25	18
Percentage of farms (%)	61	6.7	11.3	6.7	8.3	6
Farm-structure-variables						
Mean number of fields[1]	4^{bc}	3.5^{ab}	3.2^{a}	5^{c}	2.5^{a}	–
Mean total land area (ha)[1]	0.8^{b}	0.5^{a}	0.8^{b}	1.2^{c}	0.8^{b}	–
Mean area with grain (%)[1]	98.7^{c}	5.2^{a}	95.8^{b}	48.8^{a}	100^{c}	–
Mean area with cash crops (%)[1]	1.3^{a}	94.8^{b}	4.2^{a}	51.2^{b}	0^{a}	–
Mean livestock units[1]	–	–	151^{b}	–	30.8^{a}	345^{c}
Farms producing poultry (%)[2]	–	–	100^{b}	–	0^{a}	94.4^{b}
Farms producing pig (%)[2]	–	–	0^{a}	–	68^{b}	5.6^{a}
Farms producing beef (%)[2]	–	–	0^{a}	–	32^{b}	0^{a}
Socioeconomic variables						
Number of years of education[1]	7.1^{a}	6.7^{a}	8.5^{b}	7.2^{a}	8.8^{b}	9.8^{c}
Family size (people)[1]	4.9^{a}	4.2^{a}	4.3^{a}	5^{a}	4.1^{a}	3.5^{a}
Age of household head[1]	59^{a}	59.5^{a}	56.9^{a}	57.1^{a}	55.8^{a}	59.8^{a}
Households with single income (%)[2]	21.3^{a}	30^{ab}	32.4^{ab}	55^{bc}	24^{a}	77.8^{c}

Note: [1] Assumption of normality by Shapiro–Wilk tests was not met for these variables, therefore the non-parametric Kruskal–Wallis test was conducted, followed by post-hoc pairwise comparisons. [2] According to a smaller sample size (less than 1000), Fisher's exact test is more accurate than the Chi-square test. Therefore, Fisher's exact test followed by multiple pairwise comparison was conducted. $^{a-d}$ Types with no overlap in letters are significantly different ($P < 0.05$).

3.2 Typology characterization

3.2.1 Socioeconomic characterization

The average age of the household head was similar for all farm types, that is, between 55 and 60 years (Table 1). The landless farms had a smaller family size (3 people) than the others. Additionally, the number of years of education of mixed, small-mixed and landless farmers was between 8 and 10, and significantly higher compared to other types. Among grain, cash, mixed and small mixed farms, 20% to 30% of households engage in off-farm jobs for additional income. In contrast, 50% to 80% of households in commercial and landless farms rely solely on farming for their income.

3.2.2 Farming practice characterization

The analysis of phosphorus and nitrogen management across different farm types revealed significant differences in mineral fertilizer, feed and manure management practices (Table 2). In terms of phosphorus management, grain farms had the highest mean P application through mineral fertilizers at 92 $kg\cdot ha^{-1}\cdot yr^{-1}$, followed by mixed and small mixed farms, while cash crop and commercial farms reported lower rates. Landless farms had the highest mean P in purchased feed at 4920 $kg\cdot ha^{-1}\cdot yr^{-1}$, followed by mixed farms reporting 1850 $kg\cdot ha^{-1}\cdot yr^{-1}$. No P was obtained from feed from neighbors across all farm types. Small mixed farms had the highest mean organic fertilizer P on croplands (137 $kg\cdot ha^{-1}\cdot yr^{-1}$), while mixed farms had the lowest (11 $kg\cdot ha^{-1}\cdot yr^{-1}$). Manure P production and export were highest in landless farms at 3.78 $t\cdot ha^{-1}\cdot yr^{-1}$, with mixed farms also showing significant rates.

For nitrogen management, mixed and small mixed farms had the highest mean N application through mineral fertilizers, with 416 and 422 $kg\cdot ha^{-1}\cdot yr^{-1}$, respectively, while cash crop and commercial farms reported lower rates. Landless farms had the highest mean N in purchased feed with 30.7 $t\cdot ha^{-1}\cdot yr^{-1}$,

Table 2 Phosphorus and nitrogen applications in mineral fertilizer, feed and manure management for each farm type

Farming practice variable	Farm types					
	Grain	Cash crop	Mixed	Commercial	Small mixed	Landless
Phosphorus						
Mineral fertilizer management						
Mean P application ($kg·ha^{-1}·yr^{-1}$)[1]	91.7^b	65.4^a	80.8^{ab}	69.8^a	80.5^{ab}	-
Feed management						
Mean P in purchased feed ($kg·ha^{-1}·yr^{-1}$)[1]	–	–	1850^b	–	573^a	4920^c
Mean P in feed from neighbors ($kg·ha^{-1}·yr^{-1}$)[1]	–	–	0	–	0	0
Manure management						
Mean organic fertilizer P on croplands ($kg·ha^{-1}·yr^{-1}$)	45.7	46.2	11	35.2	137	–
Mean organic fertilizer P from neighbors	0	0	0	0	0	–
Mean manure P production ($kg·ha^{-1}·yr^{-1}$)	–	–	1289	–	272	3780
Mean manure P export ($kg·ha^{-1}·yr^{-1}$)	–	–	1246	–	233	3780
Nitrogen						
Mineral fertilizer management						
Mean N application ($kg·ha^{-1}·yr^{-1}$)[1]	397^b	311^a	416^b	260^a	422^b	–
Feed management						–
Mean N in purchased feed ($kg·ha^{-1}·yr^{-1}$)[1]	–	–	13,300^b	–	2450^a	30,720^c
Mean N in feed from neighbors ($kg·ha^{-1}·yr^{-1}$)[1]	–	–	0	–	0	0
Organic fertilizer management						
Mean organic fertilizer N on croplands ($kg·ha^{-1}·yr^{-1}$)	127	150	59	120	97	–
Mean organic fertilizer N from neighbors	0	0	0	0	0	–
Mean manure N production (kg/ha/year)	–	–	7700	–	2077	20,365
Mean manure N export ($kg·ha^{-1}·yr^{-1}$)	–	–	3440	–	1000	9230

Note: [1] Assumption of normality by Shapiro-Wilk tests was not met, therefore the non-parametric Kruskal–Wallis test was conducted, followed by post-hoc pairwise comparisons. [a–d] Types with no overlap in letters are significantly different ($P < 0.05$)

followed by mixed farms reporting 13.3 $t·ha^{-1}·yr^{-1}$. No N was obtained from feed from neighbors across all farm types. Cash crop farms had the highest mean organic fertilizer N on croplands at 150 $kg·ha^{-1}·yr^{-1}$, while mixed farms had the lowest use with 59 $kg·ha^{-1}·yr^{-1}$. Manure N production and export were highest in landless farms (20 $t·ha^{-1}·yr^{-1}$ and 9 $t·ha^{-1}·yr^{-1}$), with mixed farms also showing significant rates.

3.3 Spatial distribution of the farm types

Figure 2 provides a visual representation of the distribution of farm types across the sampled villages, revealing distinct patterns in their spatial arrangement. Grain farms were nearly evenly spread across the county and emerged as the dominant type in most surveyed villages, at proportions typically ranging from 0.3 to 0.9. Cash crop farms were more concentrated in the northern and south-western areas with much lower proportions, generally at a proportion less than 0.7. Mixed farms were concentrated in the southern and central parts of the county at proportions up to 0.4. Commercial farms were distributed in the south-eastern part of the county at proportions up to 0.3. Small mixed farms were concentrated in a few locations in the center and north part of the county at proportions up to 0.6. Lastly, landless farms were mostly found in the center and southern regions of the county at proportions up to 0.7.

4 Discussion

In the study area, we identified six major farm types, where about two-thirds of the farms specialized in grain production, which were evenly distributed throughout the study area. Additionally, there were some large-scale landless farms and mixed farms specialized in grain, poultry, pigs and beef cattle production, which were spatially clustered in a relatively small area. A small number of farms were mixed, combining both animal and crop production. The results provide a detailed picture of farm types and their spatial distribution. From the farm typology, we identified three main problems and obstacles toward a more sustainable agricultural development in the study area, that is, the overuse of mineral fertilizer, limited material exchange between farms, and dependence on externally supplied feed. Here, we first discuss these three problems (Sections 4.1 and 4.2), followed by a discussion on driving forces behind these farm types (Section 4.3). Finally, the development of sustainable options for farmers and policymakers is discussed (Section 4.4).

4.1 Overuse of mineral fertilizer in crop farms

Our findings indicate that all farms, particularly grain farms and mixed farms with grain production, applied excessive amounts of fertilizer. According to interviewed farmers, the average nitrogen application from synthetic fertilizers was about 400 $kg \cdot ha^{-1}$, with an additional 126 $kg \cdot ha^{-1}$ from manure. These rates are significantly higher than the recommended 320 $kg \cdot ha^{-1}$ for a wheat-maize double cropping system to achieve optimal yields, as demonstrated in a 12-year long-term field experiment on the North China Plain (160 $kg \cdot ha^{-1}$ for wheat and 165 $kg \cdot ha^{-1}$ for maize)[43]. Similarly, phosphorus application followed the same trend, with grain and mixed farms applying between 80 and 91 $kg \cdot ha^{-1}$ P, substantially exceeding the 66 $kg \cdot ha^{-1}$ P required to sustain optimal wheat-maize yields without yield reduction[44]. It is remarkable that while mixed farms have abundant amounts of manure, they still heavily rely on mineral fertilizers. This could be attributed to lack of knowledge and nutrient management skills, and limitations related to storage capacity, available application techniques or manure treatment technologies. We found that on average, farm sizes were generally less than 1 ha. To increase yield, smallholder farmers tend to use mineral inputs (e.g., mineral fertilizer), without expensive machinery[45]. The lack of machinery can contribute to fertilizer abuse, that is, farmers opting for hand broadcasting when irrigating, which tends to result in larger losses when compared to mechanized application of fertilizer[46].

4.2 Decoupled livestock and crop production at the farm and regional level

The proportion of mixed farms in the study area was less than 20% of the total number of farms, highlighting a decoupling of livestock and crop production at the household level as found in earlier studies[9,17]. A direct exchange between farms was relatively rare in our case study area. For example, none of grain farms used manure from animal farms and no nitrogen or phosphorus in the feed was obtained from neighboring crop farms. This regional decoupling may cause intensification of livestock production without considering the capacity of nearby croplands to produce feed and to use manure. This is more likely to increase the risk of large nutrient surpluses in the region, leading to large losses to the environment[17] whereas decoupling aggravates the dependence on mineral fertilizers for crop farmers.

The decoupling of crop and livestock also increases the dependence on feed imports. In Quzhou County, landless farms imported all their feed from outside the study area instead of sourcing it from other farms in the region (e.g., feed produced by grain farms). Similarly, mixed farms, when faced with insufficient on-farm produced feed, opted to import feed to meet their requirements. We found that mixed farms and landless farms can reach herd sizes of up to about 150 and 345 LU respectively, demanding much more feed than their farms' production capacity. Consequently, areas where many of such farms are located have a substantial import of animal feed. Large feed imports disrupt regional nutrient cycling, causing resource depletion in the areas exporting feed and accumulation in the areas importing feed through livestock manure[17]. Regions with large manure surpluses are characterized by large nutrient losses with ammonia emissions and nitrate leaching[47].

4.3 Agricultural policies associated with the observed typology

The North China Plain is the most important wheat-growing region in China, contributing to about two-thirds of the total wheat production[32]. As such, it is essential for securing the national food supply. In our study area, grain farm (primarily wheat-maize systems) was the dominant farm type, accounting for 61% of the farms. This aligns with the critical role of North China Plain as China's main agricultural area. The North China Plain is the most important wheat-maize production region in the country, contributing 59% and 26% of national wheat and maize production, respectively. Quzhou County, our study area, is a significant agricultural area within the North China Plain, making the prevalence of grain farms in our findings logical.

The dominance of grain farms in Quzhou is closely associated with national agricultural policies aimed at ensuring food security. The farmland protection policy[11], that is, the 1.8 Billion Mu Red Line Policy introduced in 2006, targeted at ensuring that China maintains at least 120 Mha of arable land for agricultural production. After introduction of the policy, China's farmland remained above 120 Mha, reaching 127 Mha in 2022[32]. In addition, the 1.55 Billion Mu Permanent Basic Farmland Policy, introduced in 2008, strictly forbids permanent basic land use for non-agricultural purposes and prioritizes farmland for grain production to enhance national food security. In Quzhou, the influence of the latter policy is evident, as the proportion of land used for grain production relative to the total land area has exceeded 50% since 2005 (Fig. 3)[31]. Vegetables, cotton and oil crops are permitted within crop rotations or intercropping systems, but this is not common in the area. Possible reasons for not growing these crops include the advanced age of grain farmers in the study area (averaging 60 years old) and their limited education (an average of 7 years), which makes it difficult for them to manage these labor-intensive practices.

Additionally, policy incentives have significantly contributed to the dominance of grain farming. In 2004, the government introduced the Direct Grain Subsidy scheme[48], allocating 15 billion yuan annually to support grain farmers. This was followed in 2006 by the General Input Subsidy scheme, designed to offset fertilizer costs for grain farmers, which eventually reached 107 billion yuan annually (Fig. 4).

Farms with fragmented fields were prevalent in our study area. Strong land fragmentation is primarily influenced by the Household Contract Responsibility System (HCRS)[49]. The HCRS in China ensures even land allocation among households in villages by categorizing fields based on varying soil, proximity to road and well, and drainage conditions. Each household receives a randomly allocated share of fields from each category, with the share size depending on the number of household members[49]. Due to the high population density and limited land availability, farm sizes remain small, averaging around 0.5 ha. Also, our results show the proportion of households relying solely on farming income ranged from 21% to 78%, which indicates that many farmers opted to do part-time jobs outside agriculture. This is the outcome of Rural Revitalization Strategy policy[50]. A key component of the Rural Revitalization Strategy is to create off-farm employment opportunities in rural areas, increasing farm incomes through urbanization[50]. In our study area, we observed that many farmers have indeed taken on off-farm jobs. However, this has also raised concerns. Most migrant workers are around 40 years old on average and have about 8 years of education[32]. In

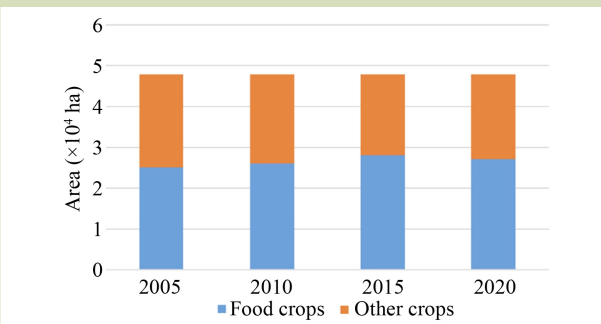

Fig. 3 Area of land used for food and other crops.

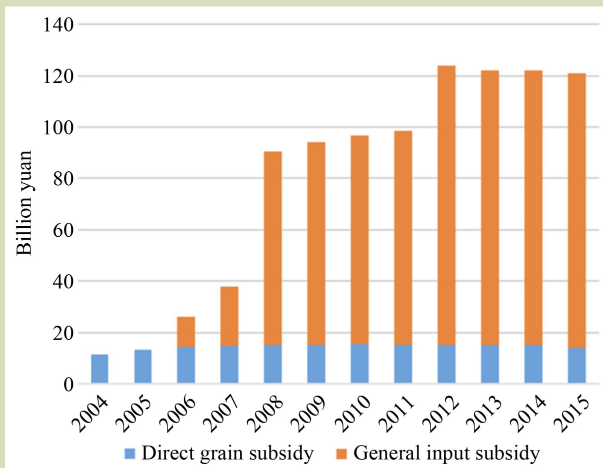

Fig. 4 Monetary value of agricultural subsidies. Reproduced from Huang and Yang[11], with permission from Elsevier.

our study area, older and less-educated farmers are left to continue farming, with an average age of 60 years with only 7 years of education. This creates a barrier to transitioning from grain-based agriculture to high-value and diversified agricultural systems in Quzhou[51]. Also, the Hukou system is an important constraining factor. Rural migrants working in cities, either as laborers or self-employed in the informal urban sector, have very limited access to urban social services[52]. As a result, during the busy farming season, many farmers choose to cultivate their contracted land in the village as a form of insurance. This, in turn, can hinder the process of land consolidation and land leasing.

Economic growth, coupled with governmental policies (i.e., Animal Husbandry Law of the People's Republic of China 2005) and incentives also stimulated livestock production and specialization[8]. In our study area, about 25% of the farms produced animal products which was a larger proportion than cash-crop and commercial farms. Some larger-scale and even landless farms dominated by poultry were also observed. This is because the Quzhou Government regards poultry production an important industry to overcome poverty, and it allocates substantial subsidies to poultry farmers (e.g., reduced construction costs of feedlots). In 2018, the Chinese government introduced the Rural Revitalization Strategy, emphasizing *one county-one industry* as a key element to enhance regional competitive advantages and establish modern agricultural systems. In response to this policy, Quzhou County formulated the Agricultural Industrialization Development Plan, prioritizing egg production[53]. As part of this plan, Nanliyue Town, located near the center of Quzhou County, was designated as a focal area for egg production. This development is reflected in Fig. 2, showing a significant proportion of landless and mixed farms in this area. However, compared with the proportion of grain farms, livestock farms are less abundant in Quzhou County. This can be attributed, in part, to the farmland protection policy, which prevents farmlands to be used for construction including housing for livestock. In addition, the aging of farmers and low education also contribute to this. We found that most farmers are relatively old, ranging from 55 to 60 years old, which is consistent with the general trend in many regions worldwide including China[54], adding to the problem of labor productivity, succession, innovation and new technology adoption.

4.4 Implications for agricultural policies and integrated crop–livestock system development

A typology is a useful tool, not only for capturing farm diversity but also for comprehensive environmental assessments[55]. For our study, we introduced and analyzed environmental indicators for each farm type, revealing the poor environmental performance of the farming systems in the study area. This understanding of the diversity of farms and farming management strategies can help in designing future policies aimed at addressing these issues more effectively and comprehensively. The typology helps identifying which farms have large potential for resource exchange (e.g., feed and manure) based on their specialization and geographic distribution. For example, the dominant grain farms may serve as key nodes for manure use or feed provision, while the mixed farms and landless farms can be important manure suppliers to crop farms. In addressing the overuse of fertilizers in grain farms, it is crucial to encourage farmers to adopt balanced fertilization strategies. To this end, government interventions, such as providing free soil testing services and reducing fertilizer subsidies, can contribute significantly. For farms with substantial livestock production, it is essential to focus on manure management, and to enable manure storage and perhaps processing infrastructure.

ICLS requires collaboration between specialized farms, which differs from mixed systems at farm level having both animals and crops on a single farm[20]. ICLS can take three forms[56]: (1) coexistence: exchange of products between farms; (2) complementarity: exchange of products with strategic planning (e.g., adapted crop rotation); and (3) synergy: strong integration between farms with resource sharing and planning (e.g., land sharing and extending crop rotations). All ICLS offer many environmental benefits[57,58], but it presents significant challenges in relation to planning, coordination, transition costs, local agricultural situation and farmer awareness[20,56]. Our study revealed a distinct pattern of farming systems in Quzhou County, which can inform the design of locally adapted crop and livestock integration strategies. First, in our study area, agriculture intensification and specialization are evident, paralleled by the substantial increases in gross domestic product of the nation, agricultural productivity and urbanization over recent decades. Many crop farms have intensified through substantial fertilizer application, but they have not increased in farm size. Livestock farms have expanded and intensified through feed imports and specialized by focusing on single livestock species. This unbalanced development of crop and livestock farms in terms of farm size sets the study area apart from many others around the world. In many developed countries, farm size shows a positive relationship with GPD, agricultural productivity and urbanization[52] but this was not observed in our study. This unique development trajectory can be largely attributed to the HCRS and Hukou system. This context has important implications for the development of effective policies for ICLS. First, Chinese crop farms are small and direct exchanges of products and land between many crop farmers, and a single large livestock farmer is challenging. Therefore, new guiding policies are required to facilitate collaboration between farms, such as encouraging crop farmers to cooperate or form cooperatives to enable easier product exchange and to organize land sharing with livestock farms.

Second, regional specialization is an issue. Many landless farms and mixed farms appeared clustered in relatively small areas with a high risk of nutrient surplus because manure production exceeds the carrying capacity of the nearby croplands. The manure production and crop nutrient needs can be balanced by reducing the livestock density in specific areas and relocating livestock farms to regions dominated by grain farming, thus enhancing the coupling between livestock and croplands[22]. Third, we found few farms exchange products with other local farms (e.g., feed and manure), suggesting potential to better utilize local resources and contribute to regional circularity. Some governmental facilitation is crucial to achieve ICLS, such as subsidies for transfer hubs[59], manure processing and storage facilities (e.g., compaction, solid-liquid separation and thermal conversion)[60] and transport options. In addition, supportive policies, such as encouraging local feed production and developing feed processing and storage facilities, seem to be needed.

5 Conclusions

In this study of a representative county of the North China Plain, we used a spatially explicit farm typology approach based on farm-level interviews to capture the diversity of farms and reveal the spatial arrangement of farm types in the study area. Six major farm types featured: grain, cash crop, mixed, commercial, small mixed and landless farms. The farm types were not evenly distributed across the study area, indicating regional specialization with a spatial decoupling of crop and livestock production. Farm management strategies were suboptimal with an overuse of chemical fertilizer. In the study area, only a small proportion of farms utilized local manure resources, suggesting limited manure recycling and application on cropland, combined with a strong dependency of specialized livestock farms on feed imports.

ICLS can effectively enhance circularity by building synergistic relationships between crop and livestock production. Our study indicates that a balanced ratio of crop areas and livestock numbers with an even spatial distribution within the region is a key aspect of ICLS. This allows for efficient recycling of nutrients and enhances regional agricultural circularity. In addition, improved fertilizer and manure management will likely reduce nutrient losses to the environment. Driven by the Chinese dietary shift toward more animal-based products, the number and scale of livestock farms will likely further increase. To improve circularity, the location of livestock farms matters and feed demand should match the capacity of surrounding croplands to produce feed and use manure.

Agricultural policies and farmer sociodemographic characteristics are important for current management strategies, hindering future agricultural transitions. Although the local government stimulated specialized livestock industries for poverty alleviation, grain production remains dominant because of farmland protection policies. The Household Contract Responsibility System leads to strong land fragmentation and small farm sizes, limiting options for ICLS as it is difficult to coordinate collaboration of many crop farms with a single large livestock farm. We conclude that new guiding policies are needed to coordinate specialization and facilitate ICLS to ensure a proper animal-to-cropland ratio at local level. The typology described here allows for policy scenario development to explore different configurations of resource flows that align with ICLS principles, enhancing nutrient cycling and reducing environmental impact.

Supplementary materials

The online version of this article at https://doi.org/10.15302/J-FASE-2025640 contains supplementary materials (Table S1; Figs. S1–S2).

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Compliance with ethics guidelines

Yuhang Sun, Antonius G. T. Schut, Yong Hou, Nico Heerink, and Martin K. van Ittersum 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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