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Does livestock manure recycling among acquaintance networks decouple crop and livestock production? Evidence from rural China

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Abstract: Livestock manure serves as a vital source of organic fertiliser, with efficient utilisation being crucial for sustainable agricultural development. However, with the development of specialised high-input agriculture, livestock manure recycling (LMR) is currently inefficient and leading to the imbalance between surplus manure and croplands. This study theoretically and empirically investigates whether LMR among acquaintance networks influence the crop–livestock integration (CLI) production. Based on survey data of swine farmers in rural China, the estimates indicate that LMR among acquaintance networks enhances the degree of CLI but may result in over-application of manure. Conversely, LMR with outside villagers or organisations is more likely to reduce the degree of CLI, possibly leading to under-application of manure. The motivation behind farmers' LMR plays a crucial role. Furthermore, the study indicates that formal institution can break the constraints of acquaintance networks on LMR and restructure the crop-livestock relationship beyond the household level. Our findings emphasise that LMR within rural China's acquaintance networks are in a transition phase, exhibiting both relational and market orientation characteristics. It is currently essential to maintain the balance between crop and livestock production, advance the development of LMR social services when designing LMR policies, and to leverage the complementary roles of informal and formal institutions.

Keywords: crop-livestock integration; formal institution; rural networks; swine farmers

China is the world's largest market for animal products and the leading consumer of compound fertilisers, accounting for about one-third of global nitrogen fertiliser consumption. Traditionally, livestock manure was the primary source of additional nutrients, crucial for maintaining soil fertility and crop yield in Chinese farming systems. However, its recycling has decreased, leading to resource wastage and environmental damage (He et al. 2016). According to the 'Second National Pollution Source Census Bulletin (2017)', chemical oxygen demand, nitrogen, and phosphorus emissions from agricultural sources account for 69, 55, and 80% of the total emissions in China, respectively. Livestock manure, 3.8 billion tons annually, generates 32 million tons of pure nutrients, approximately 50% of the total nutrient input from chemical fertilisers in China (Feng

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et al. 2023). However, the average ratio of livestock manure recycling (LMR) is lower than 40% in China, indicating that over half of manure nutrients are lost to the environment (Ma et al. 2022). Reducing these nutrient losses has become a significant challenge for China in the context of achieving the Sustainable Development Goals. Studies show that the proportion of rural households practicing crop–livestock integration (CLI) has declined sharply from 71% in 1986 to only 12% in 2017 (Jin et al. 2021). Compared to households engaged only crop planting, the CLI households apply less compound fertiliser and more manure per cropland area. However, in one-third of CLI households, manure production has exceeded the nutrient requirement of their croplands (Han et al. 2023). The decoupling of livestock and crop production decreases soil organic matter and nutrient cycling rates, resulting in the return rates of nitrogen and phosphorus elements in livestock manure to croplands being only 30% and 48%, respectively (Bai et al. 2016). These facts indicate that CLI at the household level is inefficient, and rebuilding the links between livestock and croplands at a regional scale offers vital opportunities for the sustainable intensification of agriculture in China.

The natural characteristics of livestock manure makes large-scale transport impractical, necessitating the use of local croplands for manure self-elimination and nearby recycling to achieve its external economy (Asai et al. 2018). Thus, it is important to consider the acquaintance network in rural China, especially the constraint effects and behavioural differentiation induced by different circles within the acquaintance network (Qiu et al. 2020). In China's collectivist state, the collectivist tradition results in the 'difference order pattern' (cha xu ge ju) of trust. This difference order pattern of trust results in the allocation of resources within acquaintance networks, which is one of the most common approaches to accumulating social capital to buffer natural or social risks. For this reason, as an intra-village resource, livestock manure is accompanied by high levels of interpersonal trust due to the long-term interchange of relational assets (Qiu et al. 2021). The nature and high transport cost of manure also prevent large-scale movement, making local arable land usage for manure self-degradation and fertilisation of nearby croplands an inevitable choice for farmers (Zhang et al. 2019). This creates the inner circle of the manure return network. In contrast, market trading in the form of commercial organic fertilisers has become another possible option. Although it expands beyond the LMR scope, it remains peripheral to the acquaintance networks of LMR due to the high production threshold of commercial organic fertilisers. As shown in Figure 1, the LMR networks determined by the geographic relationship and the recycling radius contains two types of utilisation: inner circle among acquaintances and outer circle involving market transactions. The former is supported by the reciprocal mechanism of acquaintance networks and aims to minimise manure treatment costs, while the latter arises from market competition for scarce resources and aims to maximise agricultural profitability, explaining the decoupling of crop and livestock production under the LMR networks constraints.

Extant literature shows that, farmers' behaviour is typically analysed from the perspective of expected costs and benefits, focusing on the comparison of marginal costs and marginal benefits (He et al. 2020). However, in China's collectivist state, farmers' LMR practices reflect inherent natural laws and deeper sociological causes. Few studies have analysed the impact of LMR among acquaintance networks on the crop–livestock relationship in rural China. In this paper, we investigate the impact and mechanism of LMR networks on the degree of CLI. Additionally, we seek to alleviate the constraints of acquaintance networks on CLI through formal institution and to rebuild the crop–livestock relationship beyond the household level. Referring to extant studies, the contribution of this paper mainly reflected in two aspects: first, we expand the practice of LMR from the household level to re-

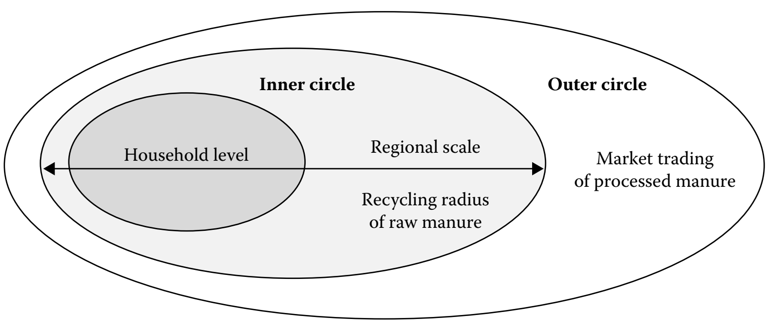

Figure 1. Inner and outer circle of LMR networks

LMR – livestock manure recycling
Source: Authors' own processing

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gional scale through acquaintance networks in rural China, enriching the spatial range of CLI within the LMR radius. Second, we discuss three scenarios of CLI based on the nutrient-balanced agriculture: 'insufficient manure', 'appropriate manure', and 'surplus manure'. This framework clarifies the reasons for the decoupling of crop and livestock production, and outlines the pathways for rebuilding CLI beyond the household level.

Theoretical analysis and hypothesis

Impact of LMR on CLI. China's No. 1 central document of 2024 advocated for farmer to adopt circular agriculture and implement CLI. Similar environmental regulations have also applied to some other countries. The U.S. Comprehensive Nutrient Management Plan (CNMP), which was enacted in 1999, is a flexible approach that combines self-monitoring and government regulation to restrain the pollution control behaviour of farms by guiding them to choose the appropriate manure management methods according to local conditions (Savage and Ribaudo 2013). However, the surge in specialised and large-scale farming has rendered CLI inefficient and unsuitable, given the current dynamics between livestock and crops (Pan et al. 2021). This situation has exacerbated the imbalance between surplus manure and croplands, which requires ascertaining whether the LMR demand of breeders and the cropland supply of neighbouring growers can be effectively matched. Given this, this section presents the theoretical framework for investigating the relationship between livestock farmer's LMR networks and the degree of CLI. As discussed in the introduction, leveraging the inner and outer circles of the LMR networks connects farmers with different LMR forms, identifies farmer's LMR decisions under different target constraints, and explores the degree of CLI induced by different LMR networks.

First, LMR in the inner circle among acquaintance is typically mediated by geographical or kinship relationships, resulting in lower transaction costs. Livestock manure is an important source of organic fertiliser for crop production. Transporting manure for free to neighbours or other crop farmers with geographical ties can ensure the soil quality and fertility, increase crop yield and income, and help livestock farmers accumulate social capital and reputation to cope with natural or social risks. Evidently, LMR among acquaintance networks inherently includes an 'implicit contract' of resource exchange and benefit sharing. Additionally, LMR among acquaintance networks based on geographical ties has a low degree of marketisation with most transactions occurring through informal verbal agreements. Due to the small manure output of these small-scale livestock farmers and their limited production endowments, such as agricultural labour and capital, manure is primarily used to maintain personal relationships and rural social networks, leading to a high degree of local integration of crop and livestock farming. However, plots fertility, soil conditions, and crop types within a village can vary significantly, resulting in different manure absorption capacities per unit cropland. Without scientifically calculating the carrying capacity of the cropland and managing manure nutrients plans, long-term manure application to the same plot could lead to surplus manure and damage to crop production (Basnet et al. 2002).

Second, LMR in the outer circle mainly relies on market transaction. Large-scale livestock farmers with substantial manure output and strong production endowments tend to commercialise livestock manure and seek sales channels in the form of organic fertiliser. This mainly includes selling to crop farmers from other villages, organic fertiliser production enterprises, and other organisations. Most transactions occur through formal contracts. Once market price signals come into play, a clear supply and demand structure between buyers and sellers is established (Qiu et al. 2022). The primary purpose of LMR in the outer circle is to generate profit. Market transactions need enhanced the contractual norms, including detailed contracts specifying the usage period, application frequency, application amount, and transaction price of the manure. Due to the scarcity of livestock manure and high transaction costs, the degree of CLI remains relatively low. In recent years, increasing environmental constraints and stricter livestock farming regulations in rural China have given large-scale farming entities with high manure production and strong waste treatment capabilities a comparative advantage in the market transaction of livestock manure, leading to decouple of crop and livestock production.

H_1: LMR within the inner circle among acquaintance enhance the degree of CLI, while LMR in the outer circle with market transaction decrease the degree of CLI.

Mechanism analysis: the role of farmers' LMR motivation. The LMR forms reflects the manure recycling motivations of livestock farmers. Maximisation of agricultural profit is taken as the primary goal when they choose LMR in the outer circle with market

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transaction, while minimisation of manure treatment costs is taken as the primary goal when they choose LMR in the inner circle among acquaintance. Therefore, farmers' LMR motivation mediate the influence of LMR networks on the degree of CLI.

As shown in Figure 2, the closer the geographical relationship, the more likely livestock manure is used to maintain interpersonal relationships and strengthen rural acquaintance networks. Small-scale livestock farmers, motivated by minimising manure treatment costs, gradually show a trend of CLI as they increasingly rely on organic manure to replace chemical fertiliser. In contrast, large-scale livestock farmers who choose LMR in the outer circle with market transaction are more likely to rely on market mechanisms as the relationship between the trading parties becomes more distant, aligning with the principle of market efficiency. When higher market prices and lower transaction costs make the net income from manure commercialisation exceeds that from crop production, livestock farmers will have higher income expectations from LMR. Therefore, LMR in the outer circle is determined by market mechanisms and transaction price, with the motivation to maximise agricultural profits potentially leading to the decoupling of crop and livestock production. Conversely, LMR in the inner circle among acquaintance is determined by the goal of minimising manure treat costs, which may lead to surplus manure return to croplands. Studies indicate that more than one-third of livestock farmers currently recycle surplus manure to croplands in quantities exceeding the environmental carrying capacity.

H_2: Farmers' LMR motivation, as reflected by LMR forms, mediate the influence of LMR networks on the degree of CLI.

MATERIAL AND METHODS

Survey data

The data comes from the 'Modern Agriculture (Swine) Industrial Technology System Industry Economic Survey' conducted by the research team in Jiangsu Province, rural China, between July and August 2022. Pigs are one of the most widely raised livestock in China, and pig manure, as an important source of organic fertiliser, has fertiliser characteristics that are well-suited for various crops and soils (Bai et al. 2019). Jiangsu Province is a typical agricultural region with a well-developed livestock industry, particularly in pig farming, providing a rich sample for this study and offering valuable insights for other regions to promote LMR. The research adopted a combination of stratified hierarchical sampling and random sampling methods. In the first stage, considering the distribution of pig farming in Jiangsu Province (mainly concentrated in Central and Northern Jiangsu), farm size structure (favouring medium-sized farms), and business models (including a few large-scale farms run by enterprises), 8 counties in Northern Jiangsu, 7 counties in Central Jiangsu, and 3 counties in Southern Jiangsu were selected as samples. In the second stage, 3–4 experimental townships were randomly selected from each of the 18 sample counties. In the third stage, with the assistance of local livestock and veterinary departments, 4–5 pig farms were randomly selected from each sample township as survey subjects, and face-to-face interviews were conducted with the farm owners. Finally, 346 valid samples of pig breeders were obtained with an effective response rate of 88.06%. Among pig breeder samples, 43 pig farms (12.43% of total samples) from Southern Jiangsu, 65 pig farms (18.79% of total sam-

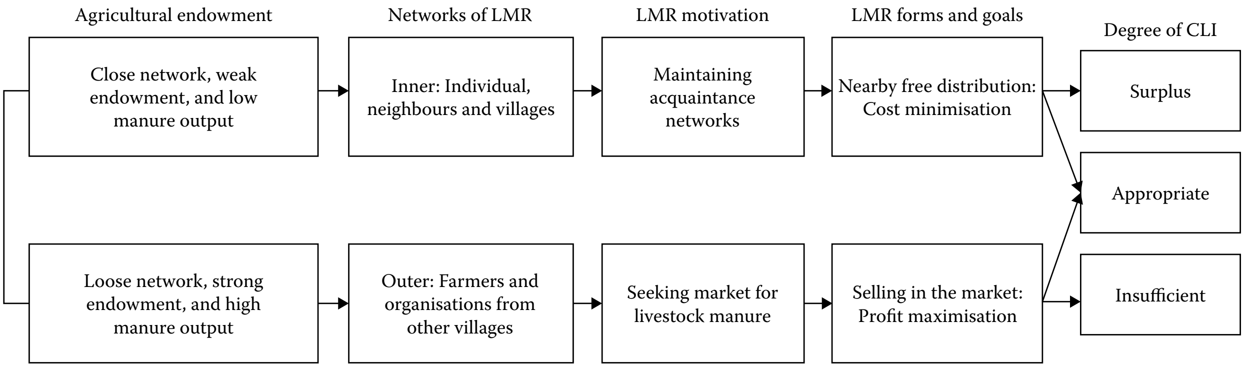

Figure 2. Theoretical framework of LMR networks affecting the degree of CLI

CLI – crop-livestock integration; LMR – livestock manure recycling

Source: Authors' own processing

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ples) from Central Jiangsu, and 238 pig farms (68.78% of total samples) from Northern Jiangsu (Table 1).

Variables selection

Dependent variable. The dependent variable is the degree of CLI, which is measured by the amount of pig manure recycled to cropland per ha. Following Wang et al. (2024), the degree of CLI was estimated by Emission Coefficient Method (ECM) [Equation (1)].

In Equation (1), the fattening pig stock (heads) includes both the current stock and the number of pigs marketed in 2021. The average rearing period is measured by the average fattening days recorded in the questionnaire. The LMR area of cropland includes both the cropland leased by the pig farmer and the nearby cropland. The daily manure production coefficient per fattening pig (m^3) refers to the 'Technical Guide for the Construction of Manure Treatment Facilities for Livestock and Poultry Farms (Households)' issued by the Ministry of Agriculture and Rural Affairs (Document No. 19, 2022). Additionally, farmers may adopt different manure treatment methods, each corresponding to a different LMR ratio. The LMR ratio is obtained through a questionnaire that asks the proportion of all manure treatment methods that ultimately flow to the cropland. Additionally, based on the recommended soil carrying capacity values for different crops provided in the 'Technical Guide for Calculating the Carrying Capacity of Livestock and Poultry Manure on Land' by the Ministry of Agriculture and Rural Affairs (Document No. 19, 2022), three CLI scenarios were discussed: 'insufficient manure', 'appropriate manure', and 'surplus manure'.

Independent variables. The dummy variable for LMR acquaintance networks is the main independent variable in our analysis. Whether LMR networks are defined as acquaintance (inner circle of networks) depends on judgment of the farm household. Neighbours and the crop farmers within the same village, due to their closer geographical relationship, are classified as the inner circle of LMR networks. Conversely, crop farmers from other villages and external organisations are classified as the outer circle of LMR networks. The dummy variable for LMR forms is the main intermediate variable in our analysis. Whether livestock manure is given to neighbouring crop farmers or sold to the market reflects the livestock farmer's LMR motivation to either minimise manure handling costs or maximise operational profits.

Control variables. Personal, family, production, and county characteristics are also controlled for (see Table 2). Personal characteristics include the farmer's years of formal education, and awareness of the environmental impact of livestock manure. These variables reflect the individual environmental awareness of the farmers. Existing studies have shown that farmers' environmentally friendly production behaviours increase

$$Degree\ of\ CLI = \frac{amount\ of\ pigs \times average\ rearing\ period \times daily\ manure\ production\ coefficient\ per\ fattening\ pig \times recycling\ ratio}{LMR\ area\ of\ croplands} \quad (1)$$

CLI – crop-livestock integration, *LMR* – livestock manure recycling

Table 1. Statistics of sample size by regions

Region	City	County	Samples	Proportion (%)
Southern	Nanjing	Lishui	19	5.49
	Changzhou	Wujin	14	4.05
	Suzhou	Wujiang, Changshu	10	2.89
Central	Nantong	Haimen	20	5.78
	Yangzhou	Gaoyou	22	6.36
	Taizhou	Taixing	23	6.65
Northern	Huai'an	Huaiyin, Jinhu, Xuyi	53	15.32
	Yancheng	Fu'ning, Binghai, Xiangshui, Sheyang, Jianhu	87	25.14
	Suqian	Shuyang, Sihong, Suyu	11	3.18
	Lianyungang	Guanyun, Donghai	87	25.14
Total			346	—

Source: Authors' estimates from survey data, 2022

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Table 2. Variables definition and descriptive statistics (n = 346)

Variables	Definitions	Mean	SD
Degree of CLI	the natural logarithm of the amount of LMR to farmland (m^3/ha)	3.5716	2.1920
Networks of LMR	individual or neighbours = 1, farmers and organisations from other villages = 0	0.8410	0.3662
Farmer's LMR motivation	LMR forms: nearby free distribution = 1, selling in the market = 0	0.0896	0.2860
Education	years of formal education	10.3382	3.2788
Family members serving as village officials	no = 0, yes = 1	0.2254	0.4180
Awareness of the environmental impact of livestock manure	no = 1, small = 2, moderate = 3, significant = 4, huge = 5	3.9017	0.9779
Agricultural labours	number of family members engaged in agricultural production	2.7312	1.1559
Household assets	number of cars owned by family members	3.0323	1.5245
Social capital	the natural logarithm of expenditure on weddings and funerals in 2021 (USD)	8.7349	1.0779
Clan capital	clan ancestral halls in the village (no = 0, yes = 1)	0.1619	0.3688
Breeding scale	free-range = 1, small-scale = 2, middle-scale = 3, big-scale = 4	2.2824	0.8524
Organisational form	family farming = 0; corporate farming = 1	0.4393	0.4964
Farmer's experience	years engaged in pig farming	13.6936	9.3430
Training	times participated in manure management training per year	2.3121	1.9834
Pilot county for green circular agriculture	no = 0, yes = 1	0.4364	0.4961

CLI – crop–livestock integration; LMR – livestock manure recycling
Source: Authors' estimates from survey data, 2022

with the improvement of their personal awareness (Obubuafo et al. 2008). Family characteristics include whether family members serve as village officials, agricultural labours, and household assets reflected by the number of cars owned by family members. These variables reflect the fiscal situation of the farmer's family. Additionally, family characteristics also include social capital, reflected by expenditures on participating in weddings and funerals, and clan capital, reflected by the presence of clan ancestral halls in the village (Greif and Tabellini 2010). Production characteristics include scale, organisational form, farmer's experience reflected by years engaged in pig farming and the number of times participated in manure management training per year (Pan et al. 2016). County characteristics are reflected by whether the county is selected as a pilot for green circular agriculture by government.

Table 3 presents the results of the descriptive analysis of LMR amount under different LMR networks and LMR forms. The LMR networks of livestock farmers mainly consist of their own or neighbouring crop farmers, focusing on an inner circle of networks. The LMR forms are typically nearby free distribution, aiming to minimise the cost of LMR. These farmers exhibit higher LMR rates and amounts compared to those who engage in LMR through the outer circle with market transaction, indicating a consistency between the LMR networks and the degree of CLI.

Estimation strategy

First, the estimation model for the impact of LMR networks on the degree of CLI is as follows:

$$Y_i = \beta_0 + \beta_1 P_i + \beta_2 Z_i + \varepsilon_i \quad (2)$$

where: Y_i – the degree of CLI computed by Equation (1); P_i – the LMR networks, which takes a value of 1 if farmers LMR among acquaintance networks and 0 otherwise;

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Table 3. LMR amount under different LMR networks and LMR forms

Items	Groups	LMR rate (%)	LMR amount (m^3/ha)	Proportion (%)
LMR networks	individual or neighbours	90.18	281.70	84.10
	farmers and organisations from other villages	59.46	249.75	15.90
LMR forms	nearby free distribution	85.55	282.77	91.00
	selling in the market	52.74	214.14	9.00

LMR – livestock manure recycling
Source: Authors' estimates from survey data, 2022

Z_i – a vector of the control variables (personal, family, production and county characteristics); β_0 – a constant term; β_1 and β_2 – the estimated parameters; ε_i – a residual term, which is assumed to be normally distributed.

Second, the estimation model for the mechanism test of farmers' LMR motivation is as follows:

$$\begin{cases} M_i = \chi_0 + \chi_1 P_i + Z_i \chi_2 + \varepsilon_i \\ Y_i = \gamma_0 + \gamma_1 M_i + Z_i \gamma_2 + \varepsilon_i \\ Y_i = \kappa_0 + \kappa_1 P_i + \kappa_2 M_i + Z_i \kappa_3 + \varepsilon_i \end{cases} \quad (3)$$

where: M_i – the farmer's LMR motivation reflected by LMR forms, which takes a value of 1 if farmers use nearby free distribution and 0 otherwise; x_0, γ_0, κ_0 – constant terms; x_1, γ_1, κ_1, κ_2, and x_2, γ_2, κ_3 – the estimated parameters; ε_i – a residual term, which is assumed to be normally distributed.

It is possible that endogeneity exists in the estimation of Equations (2 and 3). Therefore, we use theinstrumental variable (IV) method for our estimates, following previous studies. Two indicators, LMR networks and farmer's LMR forms of other livestock farmers at the village level, serve as the IVs for LMR networks and farmer's LMR motivation. First, LMR at the village level exhibits clustering effects, which may assimilate the individual farmer's LMR and is not influenced by individual farmer. Second, the degree of CLI is a result of individual farmer's LMR and is not directly affected by LMR at the village level. In other words, LMR at the village-level impacts the degree of CLI only through influencing their individual LMR.

Because the dependent variables in Equations (2 and 3) are ordinal indicators, an extended regression model (eregress) is used to estimate the parameters without accounting for the endogeneity problem. To test for endogeneity, we use the IV method. Specifically, the extended ordered probit regression model (eoprobit) is used in Equation (3), following Botezat and Pfeiffer (2014). Eoprobit fits an ordered probit regression model that accommodates any combination of endogenous covariates, non-random treatment assignment, and endogenous sample selection. Continuous, binary, and ordinal endogenous covariates are allowed. Treatment assignment may be endogenous or exogenous.

RESULTS

Impact of LMR networks on the degree of CLI

Table 4 presents the estimation results for Equation (2), i.e. the impact of acquaintance networks of LMR on degree of CLI. The results of a Durbin–Wu–Hausman (DWH) test indicate no endogeneity problem in our analysis; the results of the Kleibergen-Paap rk LM test and weak IV test show that the IVs were chosen appropriately. The results in column (2) show that pig farmers engaged in LMR within their acquaintance networks have a higher degree of CLI than those who utilise LMR through market transaction. Specifically, LMR within acquaintance networks positively affects the degree of CLI at the 5% significance level. It is widely recognised that LMR within acquaintance networks is often accompanied by non-market characteristics such as zero transaction costs and verbal agreements. As suppliers of livestock manure, pig farmers lack market-driven incentives to profit from providing small amounts of manure free to nearby crop farmers. Their primary purpose for LMR is to seek neighbours' help in manure disposing and avoid government-imposed environmental penalties. Crop farmers, as demanders of livestock manure, show a high enthusiasm due to its benefits in improving soil quality and crop yield, leading to a situation where the small amount of manure produced by free-range or smaller-scale pig farmers often falls short of demand.

Among the control variables, longer education periods and higher awareness of the environmental impact of livestock manure are associated with a greater

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Table 4. Impact of acquaintance networks of LMR on degree of CLI

Variables	Degree of CLI	
	OLS (1)	eregress (2)
LMR among acquaintance networks	0.386 (0.367)	5.982**(2.791)
Education	0.101** (0.042)	0.106*** (0.040)
Family members serving as village officials	0.392 (0.294)	0.414 (0.284)
Awareness of the environmental impact of livestock manure	0.208* (0.126)	0.202* (0.122)
Agricultural labours	0.234** (0.094)	0.247*** (0.092)
Household assets	–0.007 (0.052)	–0.008 (0.053)
Social capital	–0.393*** (0.131)	–0.395*** (0.128)
Clan capital	0.095 (0.363)	0.077 (0.351)
Breeding scale	1.061*** (0.212)	1.104*** (0.205)
Organisational form	–0.631** (0.314)	–0.699** (0.294)
Farmer's experience	–0.002 (0.064)	–0.001 (0.063)
Training	0.039*** (0.014)	0.040*** (0.013)
Pilot county for green circular agriculture	–0.323 (0.231)	–0.375 (0.228)
Constant	7.977*** (1.460)	8.629*** (1.453)
R^2	0.209	–
Wald test	–	76.020***
Log pseudolikelihood	–	–701.569
DWH test	0.149	
Kleibergen-Paap rk LM test	11.331***	
Weak IV test	11.647	

***, ** and *significance at the 1%, 5%, and 10% level, respectively; CLI – crop-livestock integration; DWH – Durbin–Wu–Hausman; eregress – extended regression model; IV – instrumental variable; LMR – livestock manure recycling; OLS – ordinary least squares

Source: Authors' own results obtained using Stata16

degree of CLI, indicating that farmers' CLI increases with improved personal awareness. Additionally, there is a positive relationship between family agricultural labour and the degree of CLI. Engaging in both farming and breeding requires more labour, which may affect the degree of CLI. However, there is a negative relationship between family social capital and the degree of CLI. A possible reason is that families with richer social capital face fewer constraints when choosing LMR networks, increasing their likelihood of earning profits through market transactions. Additionally, the larger the farming scale are associated with more frequent participation in manure management training and the higher degree of CLI. However, corporate farming negatively impacts CLI. Due to environmental regulations and the expansion of leading enterprises in recent years, many free-range and small-scale farmers have gradually exited the industry, while the number of farmers cooperating with enterprises has significantly increased (Jiang et al. 2023). Some enterprises centrally process and transport the livestock manure of cooperating farmers, preventing it from being recycled to nearby croplands, thereby reducing the degree of CLI.

Mechanism test: the role of farmers' LMR motivation

Table 5 presents the estimates for Equation (3), i.e. the mechanism of farmers' LMR motivation. The results in column (1) show that pig farmers with LMR in the inner circle among acquaintance have higher motivation for nearby free distribution to minimise manure treat cost. The results in column (2) shows that nearby free distribution of manure by pig farmers positively affects the degree of CLI at the 5% significance level. This indicates that farmer's LMR motivation also have an important impact on the degree of CLI. Furthermore, the results in columns (3) and (4) show that the impact of LMR networks on the degree of CLI is no longer significant after introducing both two variables of LMR networks and LMR motivation. This indicates that LMR motivation of pig farmers has become an important mechanism through which LMR networks influence the degree of CLI.

Robustness tests I: Recalculating the degree of CLI

To further test the robustness of our analysis, we constructed a new dependent variable. In Table 4 and 5, the dependent variable for calculating

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Table 5. Impact of acquaintance networks and LMR motivation on degree of CLI

Variables	Farmer's LMR motivation	Degree of CLI		
	eprobit (1)	eregress (2)	OLS (3)	eregress (4)
LMR among acquaintance networks	2.635*** (0.150)	–	0.226 (0.350)	0.235 (0.350)
Farmer's LMR motivation	–	10.524** (3.971)	0.902** (0.385)	5.998** (2.672)
Control variables	yes	yes	yes	yes
Constant	–3.565*** (0.928)	8.384*** (1.388)	7.801*** (1.500)	7.637*** (1.410)
R^2	–	–	0.223	–
Wald test or *F*-test	369.320***	65.360***	5.260***	65.930***
Log pseudolikelihood	–218.812	–672.943	–	–672.717
DWH test	0.701	0.014	–	0.015
Kleibergen-Paap rk LM test	10.565***	7.093***	–	6.308***
Weak IV test	10.451	8.962	–	8.122

*** and **significance at the 1% and 5% levels, respectively; CLI – crop-livestock integration production; DWH – Durbin–Wu–Hausman; eoprobit – extended ordered probit regression model; eregress – extended regression model; IV – instrumental variable; LMR – livestock manure recycling; OLS – ordinary least squares

Source: Authors' own results obtained using Stata16

the number of pigs raised includes the year-end stock of 2021, which is used to estimate the daily manure production. However, the fattening period of pigs in the year-end stock might not have reached the average number of days required, leading to an overestimation of daily manure production. We reprocessed the dependent variable as follows: we excluded the year-end stock of pigs that did not reach the average number of fattening days required for market readiness, recalculated the number of pigs raised, and the daily manure production and the degree of CLI. The estimation results using the new dependent variable in Table 6 are similar to the results in Table 4. Overall, using the new dependent variables confirms the robustness of our analyses.

Robustness tests II: Propensity score matching (PSM) estimation

To further check the robustness of our analysis and test endogeneity, we estimate Equations (2 and 3) using the PSM. However, PSM does not account for the fact that the propensity score is estimated, leading to biased standard errors estimation. Therefore, we follow the approach of Abadie and Imbens (2016) and use 'A–I' robust SE estimation. The PSM results in Table 7 are similar to the results in Table 4 and Table 5. In general, the PSM results also confirm the robustness of our analyses.

Further analysis I: Decoupling of CLI under the LMR networks

The CLI not only requires improving the efficiency of LMR but also demands implementing appropriately scaled livestock farming and suitable manure recycling based on the carrying capacity of the croplands and regional conditions (Martin et al. 2016). Regarding the carrying capacity of farmland, is it better for livestock farmers to return as much manure to the fields per acre as possible? The surveyed areas are primarily double-cropping regions, where crop farmers mainly produce rice and wheat in two seasons. Therefore, the manure absorption potential of the farmland is twice that of single-crop production. We refer to the recommended values of cropland carrying capacity for different crops provided in the Ministry of Agriculture and Rural Affairs' 'Technical Guidelines for Calculating the Land Carrying Capacity of Livestock and Poultry Manure' (using the average cropland carrying capacity for paddy and wheat). Based on croplands carrying capacity for manure absorption (converted to pig equivalent as the unit of measurement), we discuss the following three scenarios: 'insufficient manure' (actual pig equivalent per acre < 1), 'appropriate manure' (actual pig equivalent per acre between 1 and 2), and 'surplus manure' (actual pig equivalent per acre > 2). Specifically:

$$Average\ carrying\ capacity\ per\ acre\ cropland = \frac{(amount\ of\ pigs \times LMR\ ratio)}{(croplands\ area \times 2)} \tag{4}$$

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Table 6. Robustness check I: Recalculating the degree of CLI

Variables	Degree of new CLI		
LMR among acquaintance networks	4.051** (2.001)	—	0.560 (0.346)
Farmers' LMR motivation	—	5. 081* (3.076)	4.685* (3.002)
Control variables	yes	yes	yes
Constant	7.467*** (1.309)	7.362*** (1.288)	7.243*** (1.293)
Wald test	32.460***	26.380**	28.690**
Log pseudolikelihood	–819.318	–753.887	–752.471
DWH test	0.035	0.014	0.101
Kleibergen-Paap rk LM test	10.350***	7.188***	6.475***
Weak IV test	10.231	7.036	7.303

***, ** and *significance at the 1%, 5% and 10% levels, respectively; CLI – crop-livestock integration production; DWH – Durbin–Wu–Hausman; IV – instrumental variable; LMR – livestock manure recycling

Source: Authors' own results obtained using Stata16

Table 7. Robustness check II: PSM estimation

Variables	Farmers' LMR motivation	Degree of CLI	Degree of CLI
LMR among acquaintance networks	0.159*** (0.051)	0.952*** (0.331)	–
Farmers' motivation	–	–	0.665*** (0.088)

***significance at the 1% level; A–I (Abadie–Imens) robust SEs are shown in parentheses; CLI – crop-livestock integration production; LMR – livestock manure recycling; PSM – propensity score matching

Source: Authors' own results obtained using Stata16

In the model estimation, the values of –1, 0, and 1 are assigned to 'insufficient manure', 'appropriate manure', and 'surplus manure', respectively, and an extended ordered probit model (eoprobit) is employed. The estimation result in Table 8 column (1) shows that pig farmers with LMR within their inner circle among acquaintance leads to surplus manure. The result in column (2) shows that, compared to selling manure in the market, nearby free distribution also results in surplus manure. Additionally, column (3) indicates that, LMR within acquaintance networks may cause surplus manure due to the nearby free distribution form of LMR. In contrast, LMR in the outer networks can lead to insufficient manure due to market-based selling. Both insufficient manure and surplus manure recycling to croplands can be detrimental to production and environment. Therefore, while the government works to curb the decoupling of crop and livestock production, it should also be wary of the secondary pollution caused by surplus manure overloading croplands (Ma et al. 2022).

Further analysis II: Rebuilding CLI under the formal institutions

As discussed above, the constraints of LMR networks may lead to 'insufficient manure' or 'surplus manure' recycle to croplands, making the rebuilding of CLI an inevitable policy choice. The current LMR acquaintance networks will inevitably transform with the intervention of formal institutions. The 'Green Circular Agriculture Pilot Work' [Nong Ban Nong (2021) No. 10] issued by the Ministry of Agriculture and Rural Affairs primarily supports specialised service organisations and market entities providing LMR services. The policy aims to encourage social capital to connect large-scale livestock farmers needing manure treatment with professional large-scale crop farmers in need of manure fertiliser. Through contractual agreements, these entities provide services such as collection, storage, fertiliser processing, transportation, distribution, and field application of livestock manure. The policy aims to cultivate an LMR services market and promote the restructuring of CLI through multi-party collaboration.

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Table 8. Impact of farmer's acquaintance networks and farmer's motivation on degree of CLI

Variables	Carrying capacity of farmland		
	(1)	(2)	(3)
LMR among acquaintance networks	1.926** (0.609)	–	1.228 (1.320)
Farmers' LMR motivation	–	1.391* (0.867)	0.812*** (0.223)
Control variables	yes	yes	yes
Wald test	42.110***	47.840***	61.060**
Log pseudolikelihood	–418.829	–305.912	–297.352

***, ** and *significance at the 1%, 5%, and 10% levels, respectively; CLI – crop-livestock integration production; LMR – livestock manure recycling

Source: Authors' own results obtained using Stata16

Table 9. Grouped estimation based on pilot county

Variables	Degree of CLI	
	non-pilot counties (n = 210) (1)	pilot county (n = 136) (2)
LMR within acquaintance networks	6.755* (3.712)	3.567 (3.745)
Control variables	yes	yes
Constant	9.332*** (1.600)	8.965*** (2.450)
Wald test	66.63***	56.22***
Log pseudolikelihood	–367.955	–320.032

*** and *significance at the 1% and 10% levels, respectively; CLI – crop-livestock integration production; LMR – livestock manure recycling

Source: Authors' own results obtained using Stata16

Based on the list of green circular agriculture pilot counties in Jiangsu Province, the research sample is divided into pilot counties and non-pilot counties. The grouped estimation results, reflecting the heterogeneous impact of LMR networks on the degree of CLI, are shown in Table 9. The impact of LMR is significantly positive in non-pilot counties but not significant in pilot counties, indicating that acquaintance networks still play a significant role in CLI in non-pilot counties. However, this impact becomes insignificant with the implementation of the pilot policy. The pilot policy has played a crucial role in establishing market mechanisms for manure transactions in villages, fostering market entities, and regulating resource allocation. The constraints of LMR networks on CLI were disrupted under the formal institutions, consequently promoting the shift from personalised LMR to marketisation LMR. This reflects the weakening of informal institutional constraints manifested in LMR networks by formal institutions, thereby aiding the transformation and reshaping of CLI beyond the household level in a market-oriented and contractual manner (Becker 1974).

DISCUSSION

Fertilising croplands with livestock manure are currently the primary and most effective resource utilisation methods (Han et al. 2023). However, the proportion of China's farmers engaged in integrated crop-livestock farming has sharply declined from 71% in 1986 to 12% in 2017, and the utilisation rate of livestock manure was only 76% in 2021 (Feng et al. 2023). This decline not only generates contradictions between surplus manure and croplands but also brings environmental consequences. On one hand, due to the limited cropland area available for manure disposal, the cropland nutrient system will be in a surplus state. The larger the manure surplus, the greater the environmental pollution risk, leading to an overload on the surrounding croplands (Pan et al. 2023). On the other hand, most greenhouse gas emissions reportedly arise from livestock manure management systems, yet emissions are significantly lower when these manures are recycled onto croplands (Pratt et al. 2015). In view of this, policy makers still face several challenges in facilitating an appropriate CLI from three perspectives:

i) Maintaining an appropriate livestock farm scale and balance between crop and livestock production. The current development of livestock farming overly emphasises scale and economic efficiency, which has intensified the decoupling of crop and livestock production, resulting in multiple negative effects. The government should regulate these practices and promote LMR efficiency. On the one hand, scientific calculations should determine the carrying capacity of croplands, appropriate farming scales should be allocated, and the number and scale of farms in restricted farming areas should be strictly controlled to develop moderate-scale farming. On the other hand, standards for the timing and amount of manure returned to the fields should be established, and nutrient management of manure and field nutrient management plans should be implemented to promote CLI. This will help fully utilise the nutrients in manure and prevent secondary pollution caused by repeated surplus manure application on the same cropland.

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ii) Cultivating LMR social service entities and markets. Formal institutions are promoting the transformation of China's rural society from the perspective of resource allocation. They are gradually dismantling the LMR network under informal institutions while reshaping CLI through contractual and market-based approaches. However, the lack of LMR social service entities and markets has made it difficult to match the supply and demand of livestock manure, hindering the development of manure trading market beyond the household level. The government should strengthen the industry chains and social service organisations as intermediaries to organically connect crop and livestock production. Through the collaboration and matching of specialised production entities, a multi-party interest linkage mechanism can be established to rebuild CLI beyond the household level.

iii) Leveraging the complementary roles of informal and formal institutions. In the early stages of promoting LMR, informal institutions can capitalise on their 'local advantages' in guiding and regulating farmers' behaviour. However, it is crucial to recognise the phased nature and limitations of informal institutions, including social trust. For instance, LMR acquaintance networks may lead to under-application or over-application of manure in farmland. As rural factor markets continue to develop and the division of labour deepens, the personalised nature of resource allocation will inevitably lose its dominant role. In later stages of promoting LMR, formal institutions should take the leading role by fostering markets for village resources, such as livestock manure, and cultivating corresponding socialised service providers. This approach strengthens the incentives and constraints imposed by formal institutions on resource allocation and environmental governance in villages, thereby addressing the deficiencies of informal institutions in providing effective incentives and constraints.

Of course, this study also has its limitations. First, the extant studies on CLI use 0–1 binary variables to indicate whether farmers adopt CLI or not (Bao et al. 2024), but there are obvious limitations. However, the innovatively use of the Emission Coefficient Method (ECM) to estimate the degree of CLI also might exist self-reported bias. It has been shown that there are many factors affecting emission coefficient of livestock manure during production, such as livestock and poultry breeds, growth cycle, feed composition and environmental factors. We have selected the reference value recommended by the Chinese agricultural department to minimise self-reported data bias. Second, the regional specificity that might limit generalisability of the study. Our survey came from rural areas in South-eastern China, and the sample selected hog farmers and did not include other livestock and poultry farmers. This may limit the generalisability of the conclusions due to the large differences between the northern and southern regions as well as feeding conditions. These limitations provide implications for future research, which might pay more attention to exploring the shock of the regional and livestock breed differences on the LMR, especially the adjustment of CLI strategies for livestock farmers.

CONCLUSION

The emergence of informal institutions is based on social identity and shared cognition, which regulate human society. Informal institutions still play an irreplaceable role in regulating human behaviour today because implementing formal institutions is costly. However, the enforcement of formal institutions is still indispensable for the standardisation and marketisation of human behaviour. This paper investigates the interaction between the informal institutions reflected by LMR networks and formal institutions reflected by pilot policy in rural China. It aims to elucidate the decoupling of crop and livestock production under the constraints of LMR networks while proposing a pathway for restructuring CLI. We found that LMR networks significantly impact the degree of CLI through farmers' LMR motivation. LMR within the inner circle of networks enhance the degree of CLI, while LMR in the outer circle of networks with market transaction decrease the degree of CLI. Further analysis indicates that the long-term LMR in the outer circle of networks with market transaction can lead to insufficient manure recycle to the croplands, resulting in decoupling of CLI. In contrast, frequent LMR in the inner circle among acquaintance can exceed the land's carrying capacity, leading to surplus manure recycling. Both scenarios ultimately hinder agricultural production and the environment. Heterogeneity analysis reveals that the informal institutions represented by acquaintance networks are being replaced by formal institutions embodied in government pilot policies. This transition helps overcome constraints and rebuild CLI beyond the household level. The conclusions emphasise that, LMR within rural China's acquaintance networks are in a transition phase, exhibiting both relational and market orientation characteristics. While strengthening the role

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of the formal institutions in the resource allocation and environmental governance in villages, attention should also be paid to guiding the market-oriented transformation of the rural resource allocation.

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