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Optimal manure utilization chain for distributed animal farms: Model development and a case study from Hangzhou, China

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ABSTRACT

Manure management is a concern for many livestock and poultry producers all around the world. Manure is generated, processed, transported, and utilized in various ways. Manure management requires the coordination of animal feeding operations (AFOs), centralized processing facilities (CPFs), and crop farms. Such a manure utilization chain is more than an individual farm scale, and it is a complex nexus between different production systems. In this study, the manure utilization chain, which recognizes manure management behaviors at different units of a region, was proposed to ensure sustainable manure utilization for distributed animal farms. The goal of this study was to develop a regional manure utilization chain (RMUC) model to minimize annual manure utilization costs by identifying the optimal manure flow patterns among AFOs, CPFs, and crop farms. The model was implemented to evaluate the manure utilization chain in Hangzhou, China. The results showed that the average solid manure logistics cost was CNY 20/ton (1 CNY ~ 0.14 USD), and the average slurry manure utilization cost was CNY 25.4/ton when the manure nutrients were adequately distributed. If the solid manure processing capacities of CPF were optimized, the average solid manure logistics cost would be reduced to CNY 8/ton. This paper also discusses the cost of executing the manure land application setbacks (the minimum distance required between manure application areas and sensitive areas). If Hangzhou followed manure land application restrictions of Illinois, U. S, the slurry manure utilization cost (CNY 65.8/ton) would be 2.59 times greater than the cost (CNY 25.4/ton) in the current scenario. Manure management would be more similar to other waste management and rely on centralized strategy instead of individual farm management.

1. Introduction

Modern animal feeding operations (AFOs) raise a larger number of animals in a small area. Unlike small scale or "free-range" farms, such a production model has confined hundreds or more single species animals, fostered advances in breeding and mechanics, and reduced the production cost (Hu et al., 2017). The development of the AFO in China started in 2006. Over the past 14 years, this industry experienced rapid development with little environmental regulations, however it has been more recently hampered by strengthened environmental regulations (Bai et al., 2019b). AFOs are clustered in a particular region to leverage the advantages of climate, processors, transportation access, labor, and market. However, the spatial cluster presents challenges for manure management in the local community, such as air pollution and water eutrophication (Moller et al., 2007b; Martens and Böhm, 2009; Mathot et al., 2020). Recently, the size of individual AFOs is increasing and present new challenges, such as the surplus of manure nutrients, high transportation cost of manure, and the decreasing willingness of farmlands to accept manure fertilizer (Case et al., 2017; Sharara et al., 2017; Makara and Kowalski, 2018). Since 2015, Chinese governments have forbidden livestock production in some regions in order to prevent water pollution from animal manure. The number of slaughtered pigs decreased by 46 million head per year from 2014 to 2017 (Bai et al., 2019a). Ensuring an effective manure utilization chain is necessary for environmental well-being and sustainable food supply.

Animal manure from AFOs is generated, processed, transported, and utilized in various ways and involves hundreds or thousands of units in a

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Nomenclature

Indices	*Description*
i	Animal feeding operations (AFOs).
k	Manure waste types (slurry = 0, liquid = 1).
d	Manure processing facility and wastewater treatment sites (CPFs).
j	Crop-farming villages.

Input data set	*Description*
DMSP	The distance matrix from AFO site i to CPF site d (km).
DMSC	The distance matrix from AFO site i to crop-farming village j (km).
DMPC	The distance matrix from CPF site d to crop-farming village j (km).
DS	Manure spreading distance in crop-farming village j (km).
AS	Amount of manure k that produced from AFO site i (ton).
ASs	Amount of solid manure that produced from AFO site i (ton).
STC	Total solid concentration of manure k that produced from AFO site i (%).
SVC	Volatile solid concentration of manure k that produced from AFO site i (%).
NC	Nitrogen concentration of manure k that produced from AFO site i (%).
PC	Phosphorus concentration of manure k that produced from AFO site i (%).
CND	Nitrogen demand of crop-farming village j (ton).
CPD	Phosphorus demand of crop-farming village j (ton).
caps	The processing capacity of solid manure at CPF site d (ton).
capl	The processing capacity of slurry and liquid manure at CPF site d (ton).

Decision variables	*Description*
CAPs	The optimal processing capacity of solid manure at CPF site d (ton).
CAP^{LO}	The optimal processing capacity of slurry and liquid manure at CPF site d (ton).
XDs	Amount of solid manure transported to CPF d from AFO site i (ton).
XD	Amount of slurry manure k transported to CPF site d from the AFO site i (ton).
XJ	Amount of slurry manure k transported to crop-farming village j from AFO site i (ton).
XJD	Amount of liquid fertilizer that transported to crop-farming village j from CPF site d (ton).
XPD	Amount of liquid fertilizer processed by waste treatment plant at CPF site d (ton).

Symbol	*Quantity*
CAP^{LB},CAP^{UB}	The lower bound and upper bound of the processing capacity of slurry manure at CPF site d (ton).
Copl	Annual unit cost for slurry manure processing at CPF site d (CNY/ton)
Ccol	Unit collection cost of slurry manure at CPF site d (CNY/ton).
Clo	Unit distribution cost of liquid effluent at CPF site d (CNY/ton).
Copps	Opportunity cost for solid manure processing at CPF site d (CNY/ton).
Coppl	Opportunity cost for slurry manure processing at CPF site d (CNY/ton).
Rs	Unit revenue of selling solid manure (CNY/ton).
Rl	Unit revenue of slurry manure at CPF site d (CNY/ton).
PAS	Amount of collected slurry manure at CPF site d (ton).
PSTC	Total solid concentration of influent slurry manure at CPF site d (%).
PSVC	Volatile solid concentration of influent slurry manure at CPF site d (%).
PNC	Nitrogen concentration of influent slurry manure at CPF site d (%).
PPC	Phosphorus concentration of influent slurry manure at CPF site d (%).
K	Kinetic coefficient.
GF	Gas production factor of influent slurry manure in CPF site d (m^3 CH_4/m^3).
EAS	Amount of effluent at CPF site d (ton).
ENC	Nitrogen concentration of effluent produced from CPF site d (%).
EPC	Phosphorus concentration of effluent produced from CPF site d (%).

Parameters	*Description*
Bo	The maximum rate of biogas production (CH_4/kg SV).
Ccs	Annualized capital cost for solid manure processing (CNY /ton).
Ccl	Annualized capital cost for slurry manure processing (CNY/ton).
Ctfs	Fixed transportation cost for solid manure (CNY /ton).
Ctfl	Fixed transportation cost for liquid and slurry manure (CNY/ton).
Ctvs	Variable transportation cost for solid manure (CNY/ton km).
Ctvl	Variable transportation cost for liquid and slurry manure (CNY/ton km).
Co_{AD}	Unit operational cost of the anaerobic digestion process (CNY/ton).
Co_{waste}	Unit operational cost of waste treatment (CNY/ton).
Cops	Unit processing cost of solid manure (CNY/ton).
r_{gas}	Unit price of natural gas (CNY/m^3).
r_{OF}	Unit price of organic fertilizer (CNY/ton).
CF_{OF}	Mass conversion factor for solid manure to organic fertilizer (ton/ton).
ε_N, ε_P	Nitrogen and Phosphorus loss in manure land application.
SE	Separation efficiency for solid, nitrogen, and phosphorus.
$T_{digester}$	Digester temperature (°C).
HRT	Hydraulic retention time (days).

local manure utilization chain. In this sense, manure utilization chain management is a set of actions to guide the manure from the source to the end-users needing nutrients (Poffenbarger et al., 2017; Sharara et al., 2018). For local communities that do not have intensive animal production, manure utilization mainly focuses on individual AFO practices. Manure is either applied to self-owned croplands or cooperated crop farms, which merely damage the local environment. Manure management restrictions and actions include on-site pollution control (heavy metals, nutrient run-off, and pathogens) and nutrient management plans (Villalba et al., 2019; Pagliari et al., 2020). While some regions do not have sufficient croplands for manure application, the complexity of manure utilization becomes more than an engineering problem, as it requires higher level planning that accounts for the cluster effect of manure generation and utilization (Flotats et al., 2009; Takahashi et al., 2020).The manure utilization could be collective and centralized in order to include a set of decisions such as manure collection patterns, location selection, and field distribution. Understanding the complexity of the manure utilization chain in a region can guide the design of manure management infrastructures, as well as the strategical planning of natural resources and pollution controls.

The animal manure utilization chain includes two stages or four stages, depending on the manure utilization mode and manure commercial value, as shown in Fig. 1. The solid manure produced by poultry or sheep has higher nutrient concentration and is valuable for processing, transportation, and utilization (Sharara et al., 2018). The fertilizer facility collects solid manure from AFOs to make organic fertilizer that meets organic fertilizer standards (M-FP) (Fig. 1a). The reliable solid manure sources, lower procurement, and transportation costs are the critical factors for a successful organic fertilizer operation (Kunz et al., 2009; Sharara et al., 2018). The slurry manure produced by swine and cattle has high moisture contents (>85% as excreted) and low nutrient density, which is more difficult to treat and transport (Li et al., 2014). Fresh manure is processed either at a farm or at a centralized facility. Depending on the housing types and manure processing technology, the composition of slurry manure varies from facility to facility (Moller et al., 2002). As shown in Fig. 1(b), slurry manure is stored at the animal farms and used by local crop farms. The unused portion is shipped to a centralized processing facility (CPF) for further processing: energy (M-EP), fertilizer (M-FP), or wastewater (WP) (Rehl and Müller, 2011). The treatment of manure wastewater into irrigation water is costly (Wang and Serventi, 2019). The effluents from M-EP and M-FP are utilized as liquid fertilizer. Compared to solid manure processing, the slurry manure utilization chain is more complex because the cost is related to nutrient concentration, cropland availability, application method, and transportation distance (Mayerle and de Figueiredo, 2016). Crops are the end-users of processed manure products (Hutchings et al., 2013), and the nutrient demands of crops (nitrogen, phosphorus, and potassium) vary by seasons, crop types, climate conditions, and application approaches. An organized and optimized manure utilization chain can improve the nutrient utilization efficiency, reduce the logistics costs, and sustain the manure supply and demand in a region.

From a stakeholder perspective, economic cost is one of the most critical factors for determining a manure utilization chain. Research indicates the importance of labors and logistics for manure utilization (Poffenbarger et al., 2017; De Menna et al., 2018). To guide sustainable manure utilization, many local governments have introduced compensation policies, tax rules, and regulations (He et al., 2016; Mackenzie et al., 2017). For example, an analysis performed in Wisconsin, USA, estimated the minimum sale price of granulated manure (Sharara et al., 2018). One research demonstrated that a random parameter logit model can be used to analyze farmer preferences for animal pollution control policies (Pan et al., 2016). The standard values of most proposed policies, such as setback distance, tax rates, and subsidy, are estimated from a set of parameters and based on the statistical average or median scenario. Few studies have included the interactions and trade-off between animal producers and manure users to the calculation (Sharara et al., 2018). Some studies have also discussed the impacts of environmental policies on individual farm profit, but no research has quantified individual farm responses to regional manure operations (Zheng et al., 2013; Poffenbarger et al., 2017).

This study aimed to construct and optimize a regional manure utilization chain that demonstrates the animal manure flows between AFOs, CPFs, and crop farms under the scope of sustainability. The modeling methodology enables the rapid configuration of the manure utilization chain and supports the evaluation process of various economic, technical, and environmental objectives. The planning and

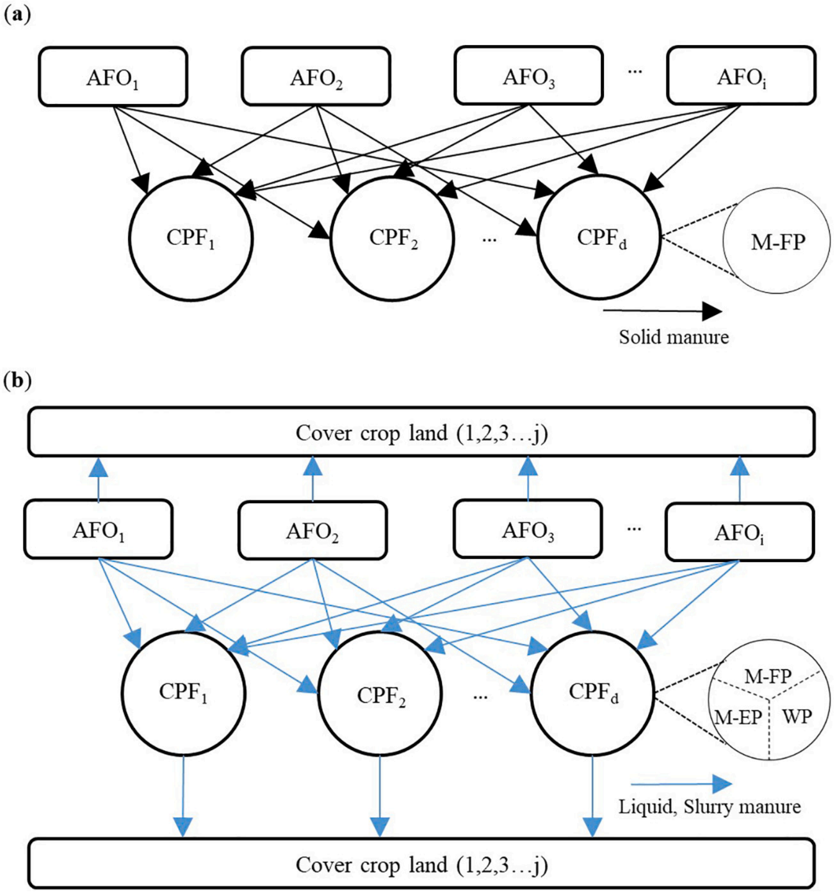

Fig. 1. Animal feeding operations (AFOs), centralized processing facility (CPFs), and crop lands make up a manure utilization chain. CPFs process manure to energy (M-EP), fertilizer (M-FP), or wastewater (WP) The solid manure utilization chain (a) involves a two-stage utilization chain and slurry manure utilization chain (b) involves a four-stage utilization chain.

decisions of regional management and resource allocation are subject to rational agreement of each unit in the manure utilization chain, which balances the sustainability needs and economic outcomes (Ribaudo et al., 2003; Nguyen et al., 2012). Especially for regions with intensive animal production, a decision-support tool can be helpful in many areas, such as distance between manure application areas and sensitive areas, construction of centralized manure processing facility, and the benefits of new technology and strategy (Martens and Böhm, 2009; Qiu et al., 2017; De Menna et al., 2018). This model can be used to inspect configuration (numbers and capacities of facilities, transportation routes, crop farms), quantify the performances (economic returns, available manure application lands, nutrient utilization efficiency), and analyze the synergies and trade-offs among different objectives (Groot et al., 2012; McDonald et al., 2019).

The regional manure utilization chain (RMUC) model enabled the geographical information system (GIS) to estimate the land suitability and nutrient demands for liquid manure land application. The land suitability evaluation allowed for multi-criteria strategies in regional planning and is capable of environmental, economic, and aesthetic constraints for land use (Huang et al., 2010). A case study was performed in Hangzhou, China, demonstrate the RMUC model functionality. The Hangzhou government was used to evaluate the *ecological plan* that had both closed breeding operations and setup prohibition zones since 2014. The *ecological plan* has not been complete because the local environmental capacity bears a heavy burden on animal husbandry. In recent years, the increasing demand for meat in urban area challenges the *ecological plan*. There is an urgent need to improve manure management policies. In addition to prohibition zones, the scenario discussed case study answers proposed by "what-if" questions to analyze how setback distances (distance between manure application areas and sensitive areas) affect the manure utilization configuration and the total cost. The modeling results and scenario discussion can provide evidence to decision-makers and indicate possible future research directions.

2. Methodology

2.1. Problem formulation

The scope of this paper is to depict a system where animal manure is either processed or used by different facilities or the end-users, but it is not to be disposed of without being utilized. The manure utilization chain consists of two parts: (i) the manure collection chain for organic fertilizer and (ii) the manure utilization chain for the slurry and liquid-portion of manure. An efficient manure collection chain involves the CPFs at optimal locations with enough capacity to reduce the manure collection cost for solid manure. A sufficient manure utilization chain allocates the manure nutrients to the crop farms and excessive manure to CPFs at a relatively lower cost, as shown in Fig. 2. Other CPF products, such as solid fertilizer, treated water, and sludge, can be sold in the organic market to be used as irrigation water and treated by other waste treatment plants. The fates of these products would not affect the decision of local manure utilization.

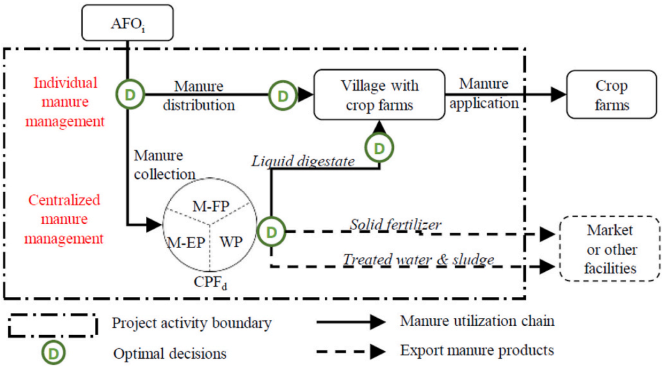

Fig. 2. System boundaries.

With the information from manure supply (AFOs), manure demand (crop farms), and logistic networks, RMUC models could construct an optimal logistics configuration for manure and manure-based products under certain constraints. For a solid manure collection chain, the objective is to minimize the regional manure utilization cost for all units in solid manure treatment. For the slurry manure utilization chain, this study focuses on solving one particular problem formulation: the units in slurry manure utilization chain, such as AFOs and CPFs, decide their flow patterns based on their local objectives (minimization of manure operational cost but do not focus on the minimization cost of the whole chain). This formulation guarantees the operational-level decisions for AFOs and CPFs are made independently based on their benefits, as described above. This design ensures the various stakeholders decide on sustainability goals and face the consequences from that decision but not the irrational global optimal results (Klotz et al., 2018). In this sense, the RMUC model can depict the co-benefits and trade-offs between units in different stages for possible configuration schemes.

2.2. Overview of the RMUC model

The RMUC model integrated information analysis and optimization tools to provide optimal mass and nutrient flows in the animal manure utilization chain. The integration of data processing models, optimization models, and analysis models could effectively address the issues of a large production system (Lin et al., 2014). In this study, the Animal Husbandry and Veterinary Bureau of Hangzhou provided animal production records and manure management records of AFOs and CPFs in Hangzhou. The records of AFOs includes physical addresses, animal types, animal inventory, manure handing system, solid-liquid separation system, annual manure production, annual solid-portion manure production, and annual liquid-portion manure production. The information from CPFs used in this study includes physical addresses, solid manure processing capacity, and liquid manure process capacity. The spatial-related data was provided by the Urban Planning and Land Resources Bureau of Hangzhou.

There were three sub-modules to prepare the necessary information: land application module, transportation distance module, and manure characteristic module (Fig. 3). The land application module summarizes the land-use information from crop farm polygons to village-level units (crop-farming village: the smallest unit in manure utilization chain) through geographical information system (GIS), and it calculates the nutrient demands (nitrogen and phosphorus) by average crop yield, land area, and the reference value for nutrients removed by the harvest of agricultural crops. The average crop yields are obtained from the 2019 Hangzhou Agricultural Census (Zhejiang Bureau of Statistics, 2019). The land area can be estimated from land suitability analysis in GIS by user-defined parameters, such as setback distances to living space, rivers, and roads. The reference value for nutrients removed by the harvest of crops was derived from the plant database of the Natural Resource and Conservation Service of the United States Department of Agriculture (USDA-NRCS, 2000).

The transportation distance module estimated the shortest route and distance through the application programming interface (API) that connected the address of units in the manure utilization chain to online map-service providers. As shown in Fig. 3, the physical address of each unit in the manure utilization chain (AFOs, CPFs, crop-farming village) is converted to a geospatial location. The geospatial locations of starting and ending points were then sent to the online map-service providers (google map) to estimate the shortest route and distance.

The manure characteristics module estimated the nutrient contents (nitrogen and phosphorus) and total solid content of manure and manure products. The fresh manure excreta parameters and nutrient contents of different animals are the standard values in China (Wang

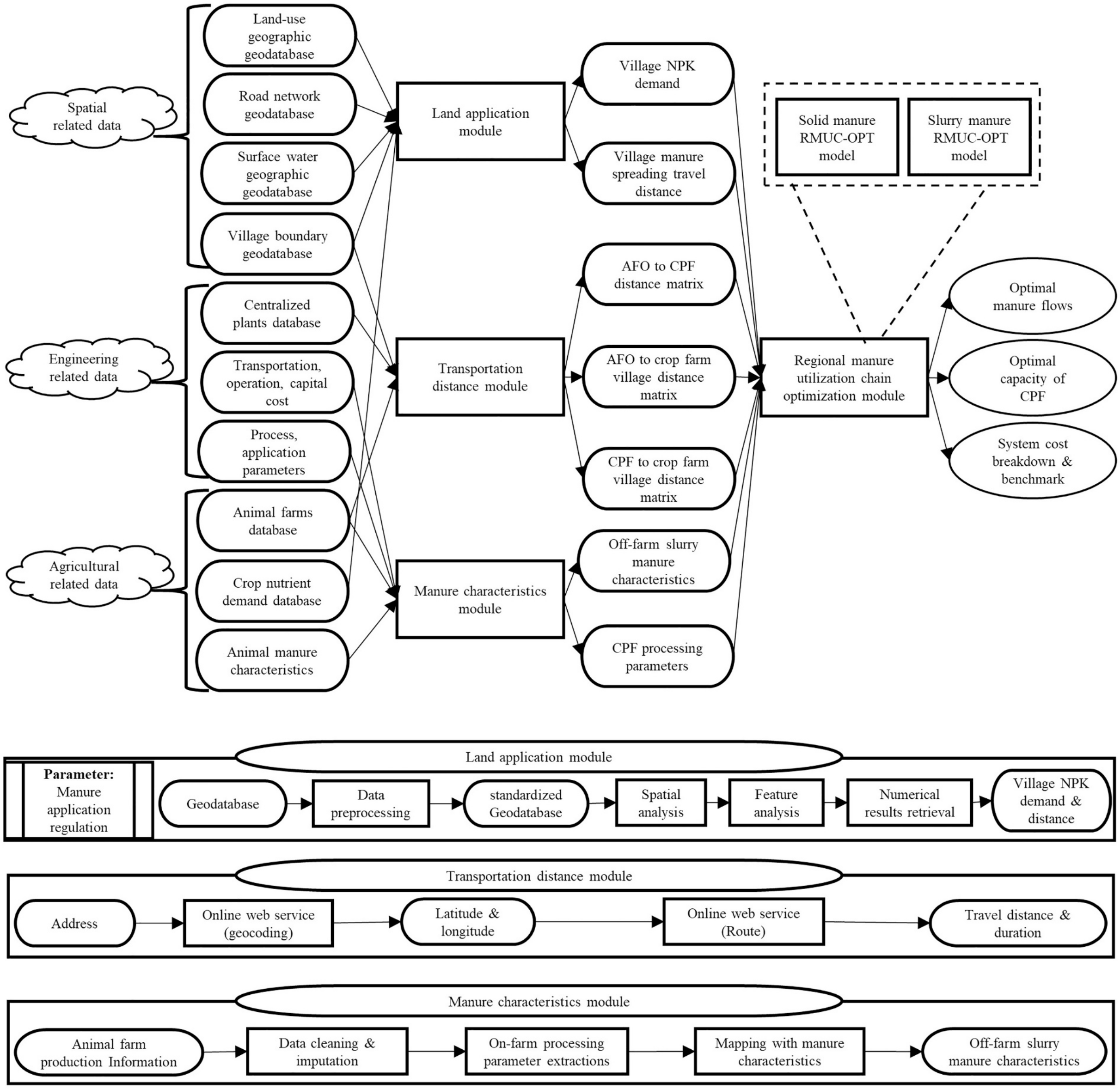

Fig. 3. The components of the regional manure utilization chain (RMUC) model and the data flow.

et al., 2006). The total solids content and nutrient contents of animal manure were scaled from reference values by assuming the manure nutrients could be diluted with the dilution ratio of fresh manure weight to the reported manure weight. The manure composition might vary substantially. However, due to the comparative nature of this study, it was deemed reasonable to assume a deterministic value for this parameter. Table A.2 presents the values for the operational parameters to calculate the manure nutrient flows and losses, which are documented in the references.

Subject to user-defined scenarios, the required information for input data was prepared through the models described above and stored in a spreadsheet file format. The GIS data sources, and processing assumptions are listed in the Appendix. A list of set names, decision variables, and parameters used in the model is provided in the "Nomenclature" section. All capital cost and operational cost values of CPFs were obtained from local contractors and standardized to the annualized costs. Table A.2 presents the values of the economic parameters used in computational experiments. The optimization module (RMUC-OPT) could read spreadsheet files to initialize parameters and constraints. The RMUC-OPT models were formulated as mixed-integer linear programming (MILP) that included two optimization models: solid manure RMUC-OPT model and slurry manure RMUC-OPT model. The MILP is solved using the Gurobi solvers. The results were stored in the Excel spreadsheet for further visualization of the maps through ArcGIS.

2.3. Solid manure RMUC-OPT model

The optimization model objective is to minimize the total cost composed of solid manure logistics, solid manure processing, excessive solid manure penalty, and opportunity costs (Eq. (1)). The decision variable related to the objective function is the amount of solid manure flow from AFOs to CPFs (*XDs)* and the processing capacity of solid manure at candidate CPF sites (*CAPs*). The inputs determined by the users include AFO solid manure (*ASs*), current solid manure processing capacities at candidate CPF sites (*caps*), and distance matrices from AFOs to CPFs (*DMSP*). Transportation costs are a function of both variable and fixed costs. Variable costs reflect transportation costs associated with distances, which are a function of unit variable cost (*Ctvs*), the amount of manure, and the transportation distance. Fixed cost does not vary with transportation distance and is a function of unit fixed cost

(*Ctfs*) and amount of manure, which includes loading and unloading costs. The solid manure processing cost is linearly dependent on unit operational cost (*Cops*) and solid manure processing capacity. Two equality constraints (h_1 *and* h_2) guarantee all solid manure from AFOs is adequately collected by CPFs.

Moreover, the decisions associated with expanding or reducing the processing capacity at each facility site will result in penalty cost or opportunity cost (f_d, Eq. (4)). The excessive manure penalty cost is the additional annualized capital cost for the manure exceeding the current capacity (Ccs: annualized unit capital cost). The opportunity cost is the loss of potential gain if the optimal solid manure processing capacity is lower than the current capacity. This value is estimated from unit revenue (*Rs*), unit operational cost (*Cops*), and the difference between the optimal solid manure process capacity and current manure processing capacity.

$$\begin{aligned} &\underset{i,d}{Min}\sum_i\sum_d (Ctfs + Ctvs\times DMSP_{id})XDs_{id} \\ &+\sum_d Cops\times CAPs_d + \sum_d f_d(CAPs_d, caps_d) \\ &\qquad s.t. \\ &\qquad h_1 : \sum_d XDs_{id} = ASs_i \\ &\qquad h_2 : \sum_i XDs_{id} = CAPs_d \\ &\qquad g_1 : CAPs_d \geq 0 \\ &\qquad g_2 : XDs_{id} \geq 0 \end{aligned} \tag{1}$$

$$Rs = r_{OF}CF_{OF} \tag{2}$$

$$Copps = Rs - Cops \tag{3}$$

$$f_d = Ccs\times max(CAPs_d - caps_d, 0) - Copps\times min(CAPs_d - caps_d, 0) \tag{4}$$

2.4. Slurry manure RMUC-OPT model

The optimization of the slurry manure utilization chain uses the sequential optimization approach based on the analytic target cascading structure (ATC), which includes three modules as shown in Fig. 4. The CPF location module is the upper-level module, which simulates CPF locations and capacities in the decision-making process. The AFO logistics optimization module is a lower-level module and optimizes the optimal slurry manure flows for each AFO. The CPF logistics optimization module is a lower-level module and simulates the optimal flows of liquid effluents. The analysis module summarizes the characteristics of the influent slurry manure for each CPF and calculates operational parameters and economic parameters for each CPF based on the collected influents. Given the input data sets and parameters, the first step is to run the AFO optimization logistics modules without capacity constraints. The crop nutrient demands, available croplands, and manure collection costs are updated to the upper-level module (CPF location module). Slurry manure processing amounts are sent to the upper-level modules (CPF logistics optimization module). The CPF logistics optimization module optimizes liquid fertilizer distributions and sends the cost factors to the upper-level module. The CPF location module takes the lower-level module responses and optimizes the locations and capacities of all given CPF sites. Then, the optimal decisions serve as the capacity constraints of the AFO logistics module for another iteration. The iterations continue until convergence is reached, which is the optimal capacities for all given CPF sites.

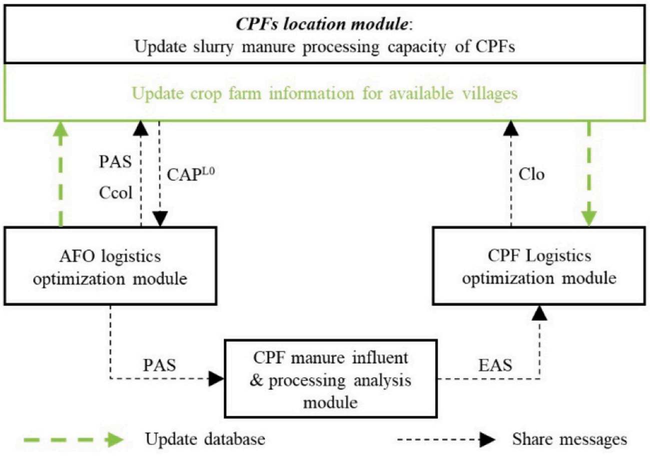

Fig. 4. Analytic target cascading (ATC) structure of slurry manure RMUC-OPT model.

The ATC was used to build a slurry manure RMUC-OPT model, which is the system design approach that enables a top-level design target to be cascaded down to lower levels of the modeling hierarchy (Kim, 2001). The ATC structure can simulate the decision-making process regarding the strategic-level and tactic-level decisions. Meanwhile, this structure maintains the feasibility of each submodule and optimizes the problem in a collaborative way. The multilevel optimization methods have been well studied and are applied in many large-scale industrial systematic optimization problems, such as aero-elastic optimization and smart grid design (Chell et al., 2019).

2.4.1. CPF location module

The CPF location model is the upper-level module. The objective is to minimize the total facility cost composed of operational, manure collection, waste treatment, and liquid fertilizer distribution costs. Slurry manure availability (*PAS*) and unit collection cost (*Ccol*) are the responses of the AFO logistics optimization module. Unit CPF distribution cost (*Clo*), unit processing cost (*Copl*), and unit opportunity cost (*Coppl*) are the responses from the CPF logistics optimization module. The decision variables (CAP^{L0}) associated with expanding or reducing current capacities (*capl*) at each facility site result in a penalty charge or opportunity cost. The excessive manure penalty cost is the additional cost of the manure exceeding the current capacity (*Ccl*: the unit cost of processing excessive slurry manure). The opportunity cost is the loss of potential gain if the optimal slurry manure processing capacity is lower than the current capacity.

$$\begin{aligned} &\underset{d}{Min}\sum_d \left[\begin{array}{l} (Clo_d + Copl_d + Ccol_d)CAP_d^{L0} \\ +Ccl\max\left(CAP_d^{L0} - capl_d, 0\right) \\ -Coppl_d\min\left(CAP_d^{L0} - capl_d, 0\right) \end{array}\right] \\ &\qquad s.t. \\ &\qquad h_1 : CAP_d^{LB} = \min(PAS_d, capl_d) \\ &\qquad h_2 : CAP_d^{UB} = \max(PAS_d, capl_d) \\ &\qquad g_1 : CAP_d^{LB} \leq CAP_d^{L0} \leq CAP_d^{UB} \\ &\qquad g_2 : \sum_d CAP_d^{L0} \leq \sum_d PAS_d \end{aligned} \tag{5}$$

2.4.2. AFO logistics optimization module

The AFO logistics optimization model objective is to minimize the logistics cost of slurry manure from AFOs to crop farm villages and to CPFs. The decision variables related to AFO slurry manure transportation costs are the amount of slurry manure going to the crop-farming village (*XJ*) and to CPFs (*XD*). Slurry manure availability (*AS*), the transportation distance matrix (*DMSC* and *DMSP*), distance for manure spreading in the crop-farming village (*DS*), and the nutrient demands of crop farms (*CND*, *CPD*) are the inputs of the module. The equality constraints (h_1) guarantee that all slurry manure from AFOs is adequately shipped to CPFs or crop-farming villages. The control constraint (g_1) ensures the slurry manure shipped to CPFs is less than the capacity that is optimized at the upper-level module (CAP^{L0}). Since nutrient requirements at each crop-farming village are different, the nutrients supply (N and P) to the crop-farming villages should be limited to the nutrient demands (g_2 and g_3). The parameters of nutrient loss during manure application (ε_N, ε_P) are the values from a reference (Hutchings et al., 2013). The unit manure collection cost (*Ccol*) of each CPF equals the total manure collection cost divided by the amount of collected manure.

$$\begin{gathered}
\underset{i,k,d,j}{Min}\sum_i\sum_j\sum_{k=1,2}\left[Ctfl + Ctvl \times \left(DMSC_{ij} + DS_j\right)\right]XJ_{kij} \\
+\sum_i\sum_d\sum_{k=1,2}(Ctfl + Ctvl \times DMSP_{id})XD_{kid} \\
s.t. \\
h_1 : \sum_j XJ_{kij} + \sum_d XD_{kid} = AS_{ik} \\
g_1 : \sum_k\sum_i XD_{kid} \le CAP_d^{L0} \\
g_2 : 0.01 \times (1 - \varepsilon_N) \times \sum_i\sum_k NC_{ik}XJ_{kij} \le CND_j \\
g_3 : 0.01 \times \left(1 - \varepsilon_p\right) \times \sum_i\sum_k PC_{ik}XJ_{kij} \le CPD_j
\end{gathered} \tag{6}$$

$$Ccol_d = \frac{\sum_i\sum_{k=1,2}(Ctfl + Ctvl \times DMSP_{id})XD_{kid}}{\sum_i\sum_{k=1,2}XD_{kid}} \tag{7}$$

2.4.3. *CPF manure influent & processing analysis module*

The CPFs were expected to store, handle, and process manure for predetermined fertilizer or energy products in order to provide a consistent format and reduce logistics challenges. A classic CPF treatment, as shown in Fig. A.1, was used in this study. The component flows from AFOs to CPFs, such as mass flows (*PAS*), total solid content (*PSTC*), total volatile solid content (*PSVC*), total nitrogen content (*PNC*), and total phosphorus content (*PPC*) will be calculated by analysis module (Eqs. A.1 to A.6). A biogas production factor (*GF*) and effluent nutrient contents (*EAS, ENC, EPC*) were estimated based on the operational parameters and nutrient partitions (Fig. A.2), which were described in the literature (Moller et al., 2007a; Suresh et al., 2009; Hutchings et al., 2013). The local crop farms will use the liquid effluent of CPFs. The unit processing cost and the opportunity cost of CPFs (*Ccopl, Coppl*) are calculated by Eqs. (A.11) to (A.13).

2.4.4. *CPF logistics optimization module*

Similar to the AFO logistics optimization module, the decision variables related to liquid effluents of CPFs are the amount of liquid fertilizer to crop farm village (*XJD*) and the amount of slurry manure processed by the waste treatment plant (*XPD*). Model inputs include the transportation distance matrix (*DMPC*), manure spreading distance matrix (*DS*), and the nutrient demands of crop farms (*CND*, *CPD*). The equality constraint (h_1) guarantees all liquid digestate from CPFs are adequately used by crops, and unused portions presenting certain pollution risks will be treated at the wastewater treatment process. Since nutrient requirements at each crop-farming village are different, the supply of the nutrients to the crop-farming villages should be limited to the nutrient demands based on the agronomic standards (g_1 and g_2). Unit CPF distribution costs (*Clo*) of each CPF equals to the total manure utilization cost divided by the effluents.

$$\begin{gathered}
\underset{d,j}{Min}\sum_d\sum_j\left[Ctfl + Ctvl \times \left(DMPC_{dj} + DS_j\right)\right]XJD_{jd} + \sum_d Co_{waste}XPD_d \\
s.t. \\
h_1 : \sum_j XJD_{jd} + XPD_d = EAS_d \\
g_1 : 0.01 \times (1 - \varepsilon_N) \times \sum_d DNC_d XJD_{jd} \le CND_j \\
g_2 : 0.01 \times (1 - \varepsilon_P) \times \sum_d DPC_d XJD_{jd} \le CPD_j
\end{gathered} \tag{8}$$

$$Clo_d = \frac{\sum_j\left[Ctfl + Ctvl\left(DMPC_{dj} + DS_j\right)\right]XJD_{jd} + Co_{waste}XPD_d}{EAS_d} \tag{9}$$

2.5. *Case study in Hangzhou, China*

The Hangzhou metropolitan area, capital of Zhejiang province in China, is about 16,596 km^2 and has a population of over 20 million, as shown in Fig. 5. The landscape of Hangzhou is characterized by mountainous topography, where over 65% of the total area is hills and mountains, 8% of the area is water bodies, and plains account for 26.4% (Qiu et al., 2017). An overlay analysis between the standard criteria maps in Table A.1 indicated that the village with arable lands and forest lands account for 63% of all towns in the Hangzhou metropolitan area, and all of them have surface waters, such as river, lakes, and wells. The major crops in this area are rice, corn, wheat, tubers, and soybean, which account for 16% of the total area. Hangzhou also has a large production of fruit and tea. The common fruits are citrus, pears, peaches, red bayberry, persimmons, and grapes that accounts for 2.5% of the total area. Some other agricultural products, such as vegetables, bamboo, and mulberry, take up 0.8% of the whole area (Zhejiang Bureau of Statistics, 2019). The available area for manure application is only a small portion of total lands because of the geological conditions, environment, and social concerns. Most arable lands that are along the river or lakes were developed for agriculture purposes, such as rice farming and fishery. The arable lands have easier access to the water source, and the nutrients are more likely to pollute the Qiantang river system, which is the largest river in Zhejiang province and passes through Hangzhou metropolitan area (Huang et al., 2010).

Based on the records from the Animal Husbandry and Veterinary Bureau of Hangzhou, there are 822 AFOs and 32 CPFs in the Hangzhou metropolitan area. Over the past few decades, the animal production industry in Hangzhou has significantly increased due to market growth and the improvement of nutrients, housing, and mechanics in animal husbandry. As shown in Fig. 6, most livestock farms, especially for swine, sheep, and cattle farms, are still small-scale or medium-scale. Poultry industry grows rapidly, and some farms have changed to large-scale. All livestock and poultry farms are confined and specialized animal feeding operations. The annual manure production is 3.2 million tons (liquid and slurry: 2.4 million tons; solid manure: 0.75 million tons). The slurry manure production from swine and dairy farms accounts for 89% of total slurry manure production in Hangzhou, as shown in Fig. A3.

Hangzhou has 30 certified manure specific CPFs and two waste treatment facilities. Among 32 certified CPFs, 19 CPFs that can convert solid manure into organic fertilizer, and 18 CPFs that could process slurry manure. The current manure processing capacity of CPFs is 1.46 million tons (M-FP: 0.75 million tons, M-EP: 0.71 million tons). 5 CPFs have processing capacity for both solid manure and slurry manure. 2 CPFs have the waste treatment capacity to annually process a total of 95 million tons of liquid manure for irrigation water. The solid manure processing capacities of CPFs are commensurate with the solid manure production of animal farms. However, only 30% of slurry manure can be processed by CPFs (Hangzhou Bureau of Agriculture, 2018). The local regulation prohibits the direct land-application of raw manure. Slurry manure generated from AFOs in Hangzhou is produced, collected, processed, and stored at their farms for a period. In most cases, the

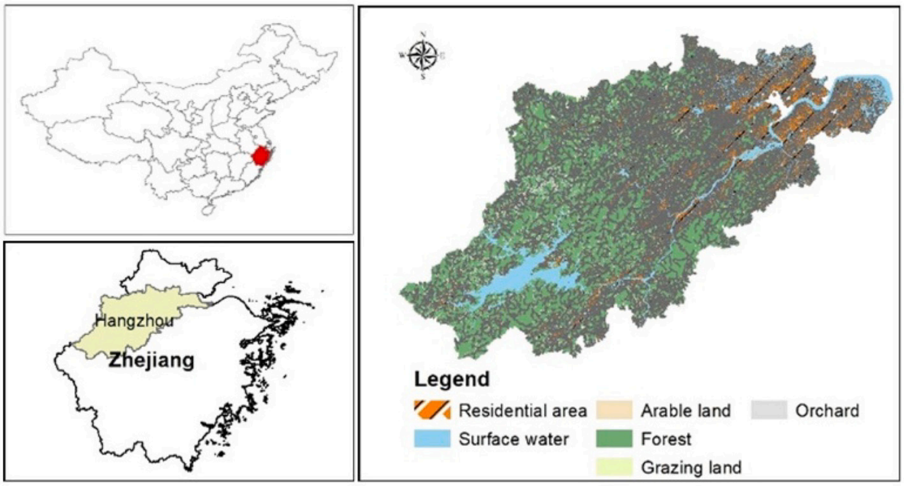

Fig. 5. Location map of the study area (Hangzhou, China).

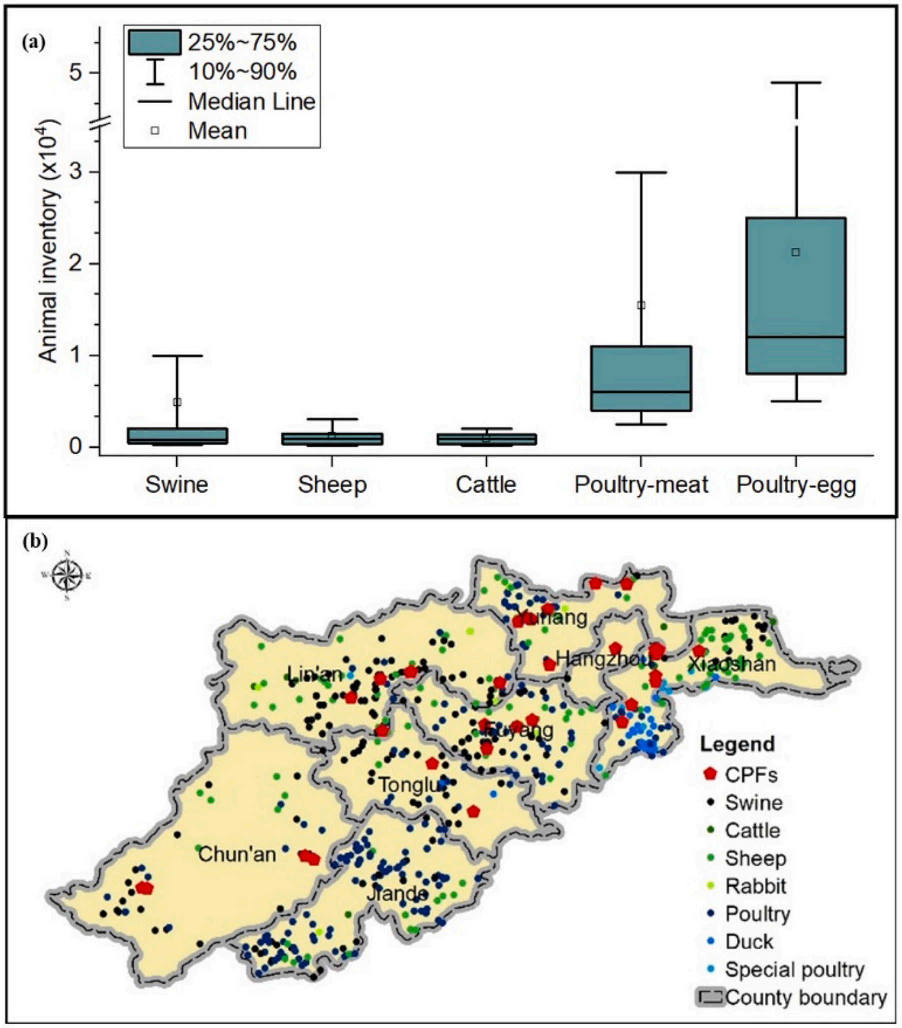

Fig. 6. (a) Statistic summary of animal inventory records from Animal Husbandry and Veterinary Bureau of Hangzhou and (b) location of animal farms and centralized manure processing facilities in Hangzhou, China.

procurement cost of slurry manure is zero or negligible. If the land application cost and logistics cost exceed the nutrient values for slurry manure, slurry manure would be recognized as waste instead of fertilizer for both AFOs and CPFs.

2.6. Scenario analyses

To illustrate the use of the RMUC model, a manure utilization chain in Hangzhou was chosen as a baseline scenario. In Hangzhou, the available lands for manure fertilizer application are classified and summarized (unit: administrative village) into four classes: arable land, forest land, grazing land, and orchards. Most villages are distributed between the valley of mountains and hills. Currently, manure application practices suggest that tank trucks carry the liquid manure fertilizer, get to the target arable lands or orchards, and spread liquid fertilizer by pressurized guns along the roads and trails. Commercial orchards can store liquid manure fertilizer. Only the arable lands on the roadside can use liquid manure products because of a lack of infrastructure and no large equipment access. The baseline case was to analyze the manure utilization infrastructures and calculate the utilization cost for current solid manure utilization and slurry manure utilization. In addition to the baseline, the sensitivity analysis was conducted to illustrate how manure utilization cost changed with the economic parameters.

The RMUC model was also applied to evaluate the current manure utilization chain in Hangzhou. A scenario analysis was conducted to allow the solid manure from AFOs to be shipped to the closest CPFs without capacity constraints. A scenario analysis was also conducted to assess the impact of a setback policy change on the configuration of slurry manure utilization chain. The manure application setbacks of Illinois (USA) were compared as the initial trial for policymaking.

3. Results and discussion

3.1. Baseline scenario in Hangzhou, China

To understand the manure utilization chain configuration, the logistics of both solid manure and slurry manure utilization were optimized by the RMUC model. The optimal solid manure processing capacities range from 7000 tons/year to 140,000 tons/year. The optimal logistics cost was CNY 20/ton, and the average transportation distance was 40 km for solid manure. The solid manure collection distance for CPFs varies from 5 km to 89 km. As shown in Fig. 7(a), some CPFs with high procurement demands had to collect the solid manure across the district boundary for the CPFs. The optimal logistics expenditure accounts for up to 12% of total cost. Especially in the Jiande district, many

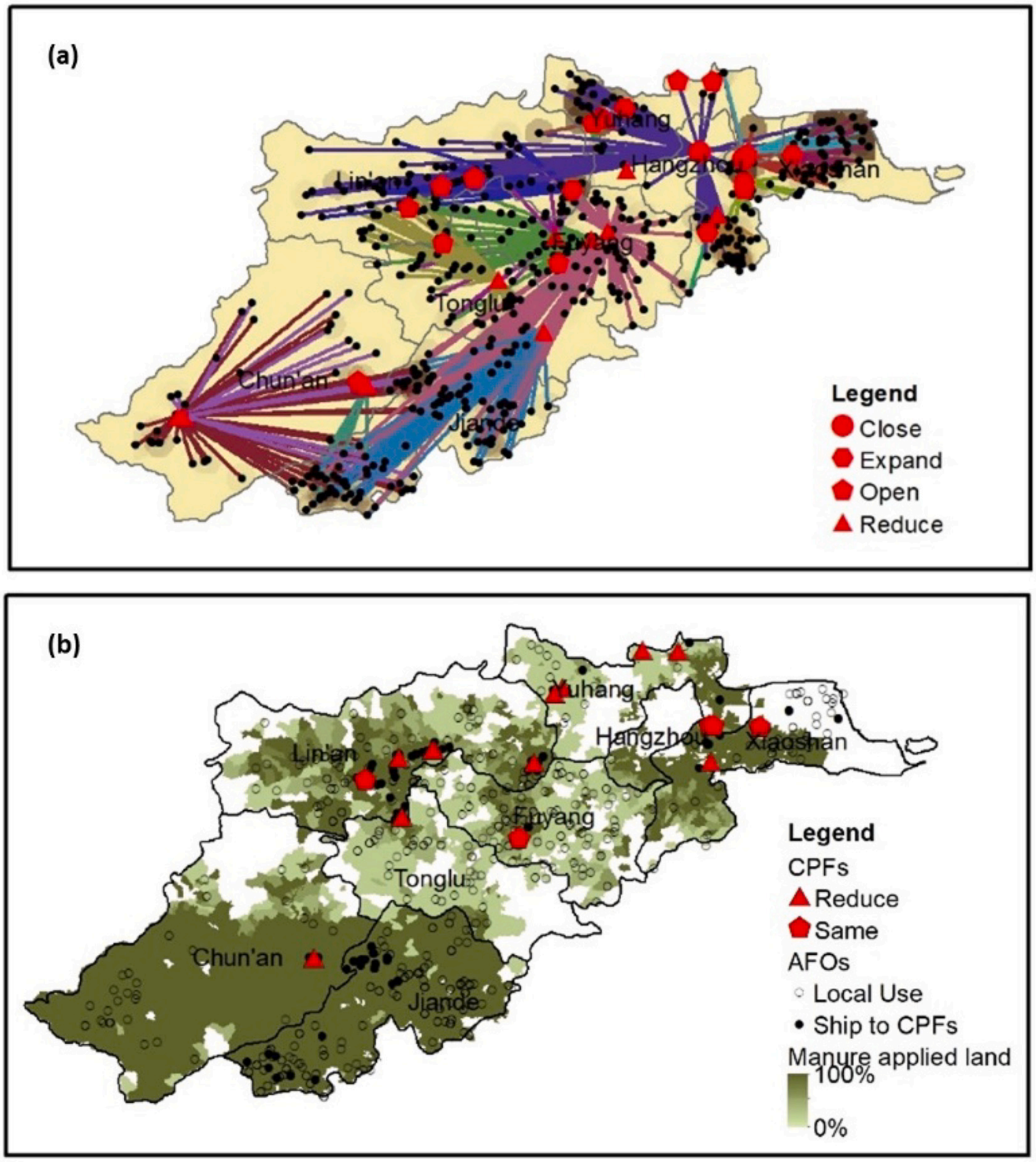

Fig. 7. The optimal manure supply-chain configuration with (a) solid manure business (b) slurry manure business.

AFOs were generating solid manure, but none of the CPFs were in this district or close to the district border, thus requiring allocation of the CPFs to reduce the logistics cost.

Slurry manure utilization involves land application stages. In theory, any lands covered by crops can utilize manure fertilizers. However, the available area for manure application is only a small portion of total lands because of the geological conditions, environment, and social concerns. For slurry manure, the optimal utilization cost was CNY 25.4/ton, and the average travel distance (from supply to end-users) was 15.7 km. The optimal results indicated that 11 CPFs should reduce their capacity, 3 CPFs needed waste treatment process, and the manure processing capacity ranged from 778 tons/year to 301,000 tons/year. As shown in Fig. 7(b), 82% of AFOs applied 68% of manure fertilizer in nearby villages. Among 2050 villages with different crop growth, 78% of villages followed the phosphorus-limited manure applications, and 22% of villages followed the nitrogen-limited manure application. The optimal average liquid fertilizer and CPF effluent usage for a single village was 1089 tons.

3.2. *Sensitivity analysis of economic parameters*

The sensitivity analysis results quantify changes in each economic parameter based on the optimal manure utilization cost while others are kept at the same constant level. The results indicate that the variable transportation cost had the most significant impact on solid and slurry manure utilization costs. Increasing or decreasing 10% of variable transportation costs would increase or decrease the solid manure logistics costs by 8%. As shown in Fig. 8, a 10% increase of the variable transportation cost would increase unit utilization cost by 4%. The processing cost of slurry manure (*Cops*, Co_{AD}) had much more impact on unit utilization cost. However, the results showed that a 10% variation in processing cost would not affect the slurry manure utilization chain configuration. The optimal results are more sensitive to some parameters, such as variable transportation cost, capital costs, and waste treatment costs. For example, increasing or decreasing the waste treatment cost by 10% would result in 3% less or more slurry manure be processed by waste treatment instead of shipping to the crop fields.

3.3. *Scenario analysis of CPF solid manure capacity*

The CPF candidate locations were fixed, while the solid manure processing capacity limit was relaxed compared with the baseline scenario. The optimal results showed 30 CPFs involved in solid manure utilization, and their capacities ranged from 240 tons/year to 214,000 tons/year. Solid manure was shipped to the nearest CPFs. The optimal average transportation cost of solid manure was CNY 8/ton, and the average manure collection distance was 20 km. Fig. 9 compares CPF capacities for the baseline scenario and revealed that 5 CPFs were selected for expanding processing capacities; 12 CPFs were selected for reducing processing capacities; 2 CPFs that did not have location advantages should be closed; 11 CPFs that did not have solid manure processing operations in the past were selected for servicing the neighbor animal farms.

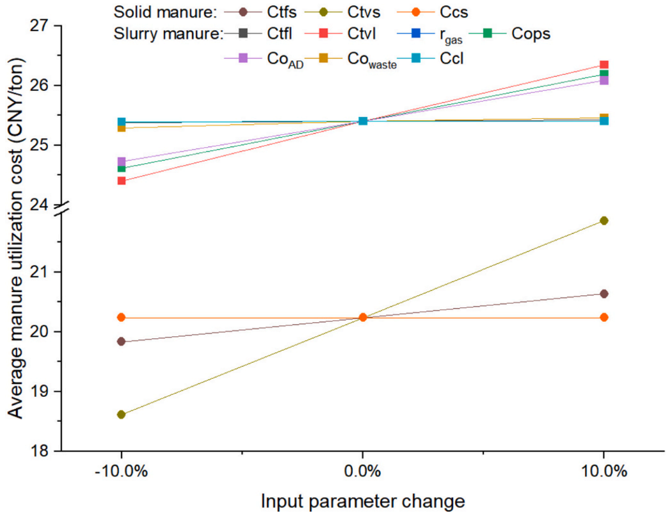

Fig. 8. Global sensitivity analysis of manure utilization chain optimization at baseline scenario.

3.4. *Scenario analysis of the manure application setbacks on slurry manure utilization*

Hangzhou has policies for AFO locations but lacks land application restrictions. Regarding the environmental concerns, over 50% of arable lands are within range of surface water boundary less than 90 m away. To quantify the impact of land application, the impact of the manure application setbacks of Illinois (USA) was evaluated, which restricts the distance for land application of manure to down-gradient surface water is 200 ft (~60 m); Within a quarter mile (400 m) of a residence, fertilizer must be injected or incorporated (Illinois Environmental Protection Agency, 2003). In this study, we assumed the setback distance to the residential area (400 m) and to the surface water (60 m) with current manure application practices. The land suitability analysis indicates only 7.4% of arable lands and 24.5% of operated orchards are available for manure application under this restriction.

In general, land application restrictions suggest that less land is available for manure application, and more farming villages and CPFs would become involved in slurry manure utilization. As shown in Fig. 10, the percentages of slurry manure applied to the villages nearby AFOs were reduced from 68% to 14%, and the percentage of slurry manure that was processed by CPFs increased from 32% to 86%. With land application restriction, the optimal results indicated 7 CPFs should reduce their capacity, all CPFs need a waste treatment process, and the manure processing capacity ranged from 621 tons/year to 1,250,000 tons/year. The optimal results suggested that the application policy significantly impacted slurry utilization patterns in the southeast districts. Over 98% of villages that had available lands were full capacity. The waste treatment process processed around 80% of the manure. The optimal results suggested more and larger CPFs process the excessive manure under the Illinois land application policies. In the Xiaoshan district, most arable lands were not suitable due to open water setback restrictions. Most of the slurry manure was converted to irrigation water instead of liquid fertilizer.

The manure nutrient utilization pattern for the scenario using Illinois land application policy was very different from the baseline scenario utilization pattern. The nitrogen and phosphorus losses included gas emissions during manure utilization and runoff during the land application, respectively (Oenema et al., 2007; Hutchings et al., 2013). Considering the Illinois land application policy, less nitrogen and phosphorus were released to the environment because of reduced land application practices as shown in Fig. 11. The baseline scenario had better nitrogen and phosphorous efficiency when compared to the scenario with Illinois land application policy. As shown in Table 1, the baseline scenario's nutrient value was 60% higher than the value of the scenario with the Illinois land application policy. More nitrogen was removed by waste treatment, and more phosphorous was exported to other agricultural production systems as solid fertilizer in the scenario with Illinois land application setbacks. The land application setbacks reduced the environmental capacity of nitrogen and phosphorus. The waste treatment process removed the excess nitrogen and phosphorus from the local agricultural production system. In other words, the deterministic factor for the manure management to be effective "nutrient utilization" or to be "waste treatment" was not the intensive manure production criteria but rather the manure land application.

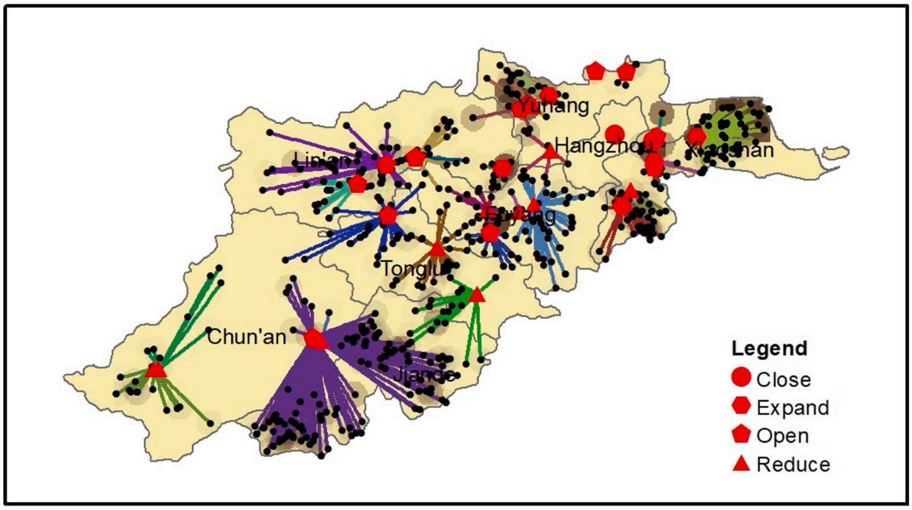

Fig. 9. The optimal solid-manure supply-chain configuration with relaxed solid processing capacity constant $\text{cap}_d = 0$ at Eq. (1). Colored lines represent the AFOs that are severed by CPFs.

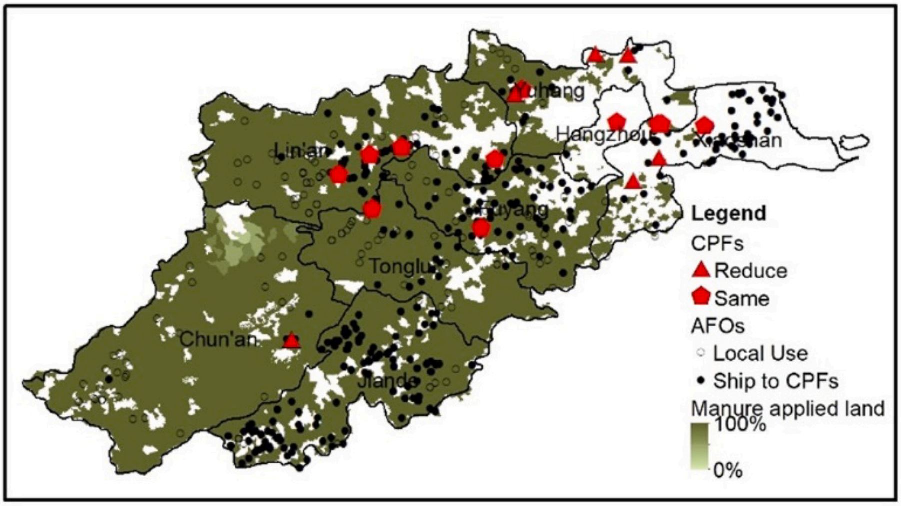

Fig. 10. The optimal configuration of slurry manure utilization chain at Illinois manure application setbacks.

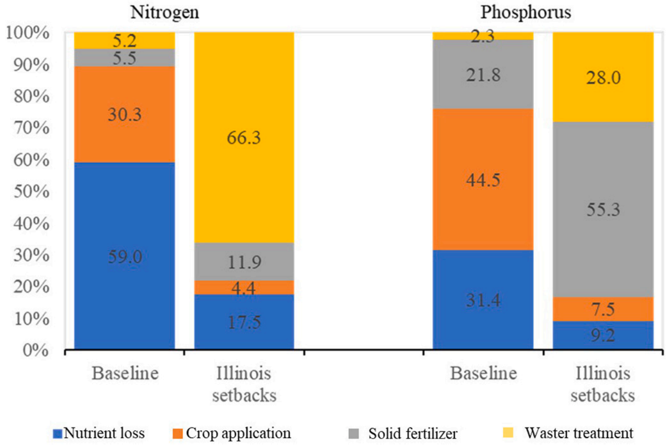

Fig. 11. The fate of animal manure nitrogen and phosphorus input.

Table 1
Slurry manure utilization costs with and without land application setbacks.

	Baseline scenario		With land application policy	
	Total cost (Million CNY)	Average (CNY per ton)	Total cost (Million CNY)	Average (CNY per ton)
AFO local use	11.3	6.9	4.8	14.2
AFO to CPFs	6.5	8.4	32	15.4
CPFs processing	35.3	49.6	87.2	45.5
CPFs local use	6.2	10.2	0.0085	7.8
CPFs waste treatment	2	18	34.5	18
Average utilization cost	61.3	25.4	158.5	65.8
NP utilization value*	13.7		8.5	

[*] Nitrogen (P_N) and phosphorus (P_P) are used by crops or concentrated into a solid fertilizer.

The total utilization cost of applying manure land application policy was 2.59 times greater than the total cost at the baseline. The optimal results (Table 1) showed that the average cost for AFO local manure utilization was increased from CNY 6.9/ton to CNY 14.2/ton. The average cost for CPFs collection was increased from CNY 8.4/ton to CNY 15.4/ton. The average travel distance (from supply to end-users) for slurry manure was decreased from 15.7 km/ton to 4.3 km/ton. The savings of total CPF expenditure outweighed the increased transportation cost, which suggested the utilization pattern that was mainly a “centralized strategy” instead of an “individual-farm strategy.”

3.5. *Guidance for animal manure management in Hangzhou*

Based on the analysis results mentioned above, the Hangzhou *Ecological Plan* with respect to manure management can be adapted to present more precise strategies that can balance the development of animal husbandry and environmental protection at a lower cost. In fact, the production cost of organic fertilizer in Hangzhou is relatively high compared to the average cost in China. The government is providing subsidies to some CPFs to collect and process the slurry manure. In the RMUC models, the constraints guaranteed that the application of both nitrogen and phosphorus be less than the nutrient requirement of crops. The estimation of manure utilization cost can be used as evidence to determine the economic support that would help AFOs and CPFs use manure in a sustainable way.

The scenario analysis of manure application on slurry manure utilization indicates that the total cost of slurry manure utilization under the Illinois setback-policy is much more expensive than the baseline, due to abundant river systems. The slurry manure utilization chain is susceptible to manure application policy in Hangzhou. Pollution risks of different setback-distances should be discussed in future research. Moreover, land suitability analysis shows that only small portions of arable lands are categorized to manure applicable lands with current manure application methods. Improving the manure application infrastructure in crop-farming villages through different mechanisms, such as storage and pumping stations, will increase the environmental capacity of recycling manure nutrients.

The following suggestions are provided to reduce the manure utilization cost and address manure management issues. According to the information from the Animal Husbandry and Veterinary Bureau of Hangzhou, the water usage of AFOs vary significantly from individual to individual: the worst 10% of broiler farms generate 7.8 times more manure than the median level farms, and the worst 10% of sheep farms produce 6.8 times more manure than the median level farms. Reducing water usage might decrease the logistic pressure of manure utilization. The transportation of slurry manure occurs from AFOs to CPFs, AFOs to crop-farming villages, and CPFs to crop-farming villages. Such a high transportation cost suggests that pipeline pumping could be an intriguing alternative for shorter-distance slurry transport, which needs further evaluation. Electric vehicles can also be an alternative to reduce the logistics cost and greenhouse gas emission.

A lack of information about manure nutrients is one barrier to recycling nutrients to agricultural land. Many organizations and agricultural extension groups recommend a regular analysis of manure samples to maximize nutrient efficiency and minimize the nutrient loss to the environment (Zhu et al., 2004; Marino et al., 2008). In this study, we used the information from Animal Husbandry and Veterinary Bureau of Hangzhou and assumed deterministic values of manure nutrient composition to provide comparative analysis under different scenarios. However, the uncertainty analysis and improved data-acquisition are required to apply the RMUC models in more accurate calculation of economic costs and regular supervision of regional manure utilization behaviors. The RMUC models can be further implemented to quantify how the strategies can minimize the utilization cost and improve local configurations of the manure utilization chain.

4. Conclusions

This study developed a regional manure utilization chain (RMUC) model to minimize the animal manure utilization cost by selecting the optimal decisions of manure transport between animal feeding operations (AFOs), centralized manure processing facilities (CPFs), and crop farms. The baseline case was set to the current economic parameters, animal production levels, and manure utilization configurations. The optimal results indicated that the average solid manure logistics cost was CNY 20/ton, and the average transportation distance was 40 km. For slurry manure, the average manure utilization cost was CNY 25.4/ton, CPFs process and reallocate 32% of slurry manure, and the average travel distance was 15.7 km.

The scenario analysis indicated that the current solid manure CPF configuration had the potential to be improved. Our study suggests that optimizing the solid manure processing capacities of CPFs could reduce 70% of the transportation cost. Optimal solid manure supply chain should include an increased number of smaller CPFs. The scenario analysis indicated that the current slurry manure utilization pattern could be significantly changed if the manure land application policy was implemented like in Illinois, USA. Considering Illinois manure fertilizer land application restrictions, the total utilization cost of slurry manure would be 2.59 times greater than the total cost for the baseline scenario. Around 53% of AFOs will change from individual manure management patterns to centralized manure management patterns. We recognized the regional slurry manure management should be better described as “waste management” instead of “nutrient management”.

The proposed RMUC model compared the regional manure utilization costs and included the manure management pattern of AFOs (individual or centralized), the manure processing pattern of CPFs (manure to fertilizer or energy or irrigation water), and liquid fertilizer land-application pattern (N-based or P-based) of the manure utilization chain in Hangzhou, China. However, the uncertainty analysis and improved data-acquisition are required to apply the RMUC models in more accurate calculation of economic costs and regular supervision of regional manure utilization behaviors. Our study can be used to comparatively analyze the economic value of some sustainable trajectories (reduce water usage, improve manure transportation, accurate measurement of manure compositions) that guide AFOs and CPFs to manage manure. The results can support the strategical actions of industries and governments.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2020.102996.

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