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A Transportation Network Optimization Model for Livestock Manure under Different Terrains Considering Economic and Environmental Benefits

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Abstract: Optimizing the path of livestock manure used for farmland is a hugely significant issue, which not only improves the utilization efficiency of manure but also reduces the cost of the transportation of manure. However, some factors such as different terrains and the density of surrounding farmland may lead to more difficulty in further improving the resource utilization rate. Therefore, this paper aims to establish a transport network optimization model for a complex livestock manure distribution scheme. Using basic information from livestock and poultry farms, cultivated land, water areas and forestland in Xinzhou District, Wuhan City, Hubei Province, the relationship between farmland and livestock farms is divided into farm-intensive and water-intensive farmland areas by using the Voronoi diagram subdivision method. Then, according to the supply–demand balance of manure and crop demand, an optimization model is proposed to discuss the manure return scheme for these two types of terrain. The results show that our model can help significantly improve manure utilization efficiency under different terrain situations, which is proposed comprehensively, considering the economic and environmental benefits.

Keywords: regional division; manure returning to the field; distribution plan optimization; economic loss evaluation

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1. Introduction

With the development of its economy, China has become the country with the highest rate of livestock and poultry breeding in the world [1,2]. Statistical data shows that China raises 20 billion livestock and poultry every year and produces more than 3 billion tons of manure per year [3]. However, the unreasonable disposal of livestock manure is closely related to the natural environment where rural residents live. It usually brings serious environmental problems, such as the eutrophication and microbial contamination of water [4] and air pollution from harmful gases such as NH3 [5]. Therefore, how to reasonably dispose of livestock manure is an important research issue.

Since livestock and poultry manure are good for improving the soil quality of farmland [6] and reducing the accumulation of heavy metals such as Cd and Pb in rice grains [7], they are generally recommended to be returned to farmland for crop production in China, which can bring significant social benefits. To improve the utilization efficiency of livestock manure, many policies and regulations have been issued by the Chinese government. The resource utilization rate of livestock and poultry waste reached more than 76% by 2021 [8]. However, some factors may lead to more difficulty in further improving the resource utilization rate.

Firstly, livestock and poultry manure are usually returned nearby [9,10]. The reason is that the transportation fee of livestock manure is larger than that of chemical fertilizers; therefore, the farther the transportation distance of livestock manure, the lower the enthusiasm of farmers to apply livestock manure [11].

Secondly, the risk of livestock manure pollution to the surrounding environment will be significantly increased if there is not enough farmland around used for livestock manure return [12].

Lastly, different terrains, such as weir ponds, woodlands, swamps, construction land and other landforms, around the livestock farms and farmland, would have varying degrees of influence on manure transportation [13,14]. Unreasonable manure transfer will increase the energy consumption of transportation in the process of returning manure to the field [15].

Thus, it is necessary to establish a suitable optimization model to optimize the return path of manure from livestock and poultry farms to crop farmland, which can be adjusted according to the conditions of the surrounding environment, including the terrains and farmland areas in a certain region.

Through the optimization model, we aim to reduce the transportation cost of livestock manure from livestock farmland to crop farmland and increase the reasonable utilization of livestock manure, ensuring that the amount of livestock and poultry manure used for farm crops does not exceed the demand. The key contributions of this study can be summarized as follows.

(1) Taking, for example, Xinzhou District of Wuhan City, Hubei Province in China, some important information, including the spatial distribution of livestock and poultry farms, the crop demand of livestock manure, and the special terrains such as water areas and woodlands that hinder the transport of manure, were mined and extracted using statistical methods and the Voronoi diagram method.
(2) Considering the influence of the surrounding environment on the livestock and poultry manure returned, such as special terrains and farmland area, a transportation optimization model is comprehensively proposed, considering the economic and environmental benefits.

The remainder of this paper is organized as follows. Section 2 provides an overview of the literature regarding the research on livestock and poultry manure and optimal models. In Section 3, data and methods are presented in detail. The results are shown in Section 4. In Section 5, the discussion and future work are included. Finally, this study is concluded in Section 6.

2. Literature Review

This paper aims to optimize the path of livestock manure used for farmland. The reason for this is that integrating cropland and the livestock industry is a sustainable development model for the world, which not only promotes the utilization of manure, but also reduces the input of chemical fertilizers and decreases environmental pollution [16].

The existing research mainly focuses on the analysis and evaluation of manure's pollution potential to the surrounding environment using the livestock manure nitrogen load on farmland (LMNLF) [17–25] or the improved LMNLF based on livestock farm positioning [10]. However, the use of manure is affected by the transportation cost, land availability, crop and soil needs, transport logistics and farmers' reluctance to use manure instead of inorganic fertilizer [26,27]. This phenomenon not only exists in China, but also in other countries such as the USA [26], Ukraine [28] and Cambodia [27].

Therefore, some studies are devoted to how to improve the resource utilization efficiency of livestock and poultry manure in a certain region. For example, Matthias and Jutta [29] developed a model to determine the maximal profitable manure transport distance; Ghafoori et al. [30] proposed liquefying manure and adopting pipeline transportation instead of vehicle transportation, and Banik et al. [31] thought that manure–biochar incubation enabled biochar to stabilize carbon and several nutrients of manure [31]. However,

few works fully considered the role of the geographical environment in improving the resource utilization efficiency of livestock and poultry manure, especially the different terrains around livestock farms and farmland, which also increase the difficulty of manure transportation [13,14]. Therefore, this paper proposes an optimal transportation model of livestock manure from the aspect of influencing factors on livestock transportation, such as terrains, the demand of cropland and the location of farms, etc.

Fortunately, a great amount of research has been produced on transportation network optimization models [32–35], such as a bi-level programming model [36,37] and a fuzzy robust stochastic optimization model [38,39]. Moreover, most of these studies focused on multi-objective mathematical models. For example, the multi-objective MINLP for solid waste management (CSWM) [40], an integrated multi-objective optimization model in a coal mining industry using the analytic hierarchy process and data envelopment analysis techniques [41], and a new multi-objective mathematical model for the hub location and routing problem under uncertainty in flows, costs, times, and the number of job opportunities [42].

The above models are aimed at minimizing the total transportation cost and maximizing regional or environmental development, but few studies are published concerning the transportation optimization of manure returned to farmland. Therefore, this paper also aims to build an optimization model of livestock manure transportation that integrates economic and environmental benefits.

However, some differences are obvious between our problem and those in the existing literature. The absorptive capacity of farmland, the transportation distance and terrains are all important factors for the optimization model. Because in some areas, there are many livestock farms but only a small amount of farmland; in some other areas, the reverse applies. Far distances mean more cost and people usually choose to give up returning manure to farmland. Water is also an obstacle to transportation, but it is usually next to farmland. So, how to describe them in the proposed model is a hard task.

3. Materials and Methods

To establish a transportation optimization model for manure returned to farmland, it is important to distinguish different farmland types within districts, such as the farm-intensive type and the water-intensive type, because this is strongly related to the returned manure efficiency. In this section, data from Xinzhou District of Wuhan City, Hubei Province in China, is collected and analyzed. Then, farmland types are divided by the hierarchical clustering method and the Voronoi diagram method. Based on the geographical characterization, a transportation optimization model for manure returned to farmland, considering economic and environmental factors, is proposed in Section 3.5.

3.1. Research Area

The research area in this study is Xinzhou District of Wuhan, which is located on the north bank of the middle reaches of the Yangtze River. This region has a total area of 1500.66 square kilometers, most of which is cultivated land. Xinzhou District is adjacent to Huangpi District in the west and Hongshan District in the south; its latitude and longitude range are roughly between 114°30′–115°5′ E and 30°35′–30°2′ N. The terrain slopes from the northeast to the southwest; the northeast is the low hills and hills, the central part is the hills and plains, and the southwest is the riverside, riverside plain, river and lake waters. The land elevation is between 20 and 100 m.

3.2. Data Collection and Preprocessing

The remote sensing monitoring data of China's land use in Hubei Province in 2020 were acquired from the website of the Resources and Environment Science and Data Center. The data are 1 km raster grid data, generated through manual visual interpretation, based on Landsat 8 remote sensing images and land-use remote sensing monitoring data from 2015. First, the land-use classification raster grid data of Xinzhou District were cut out from

the land-use classification raster grid data of Hubei Province, and then the longitude and latitude coordinates and information on the areas of cultivated land and various terrains in Xinzhou District were obtained. Then, to explore the impact of special terrains on the economic benefits of manure transportation, the longitude and latitude data of water areas (canals, lakes, reservoirs, potholes and ponds) and woodlands (forestland, shrubs) were extracted. The latitude and longitude coordinates of all the livestock and poultry farms were obtained from the 2017 survey results, as were the livestock and poultry manure collection and use data of each farm throughout the year.

3.3. Hierarchical Clustering of Farmland in Xinzhou District

To distinguish the geographical environment types, the clustering analysis function of SPSS software was used to determine the hierarchical clustering of farmland in Xinzhou District. The hierarchical clustering method is a hierarchical and bottom-up clustering algorithm [43]. Starting from the bottom layer, this algorithm ends when all the data points are merged into a class by merging the most similar clusters to form a cluster in the upper level [44]. Based on the longitude and latitude data of all the farms in Xinzhou District, the aggregation coefficients were calculated, and their variation curves observed. The number of clustering categories was determined by the elbow criterion, and systematic clustering was implemented. After completion, the farms, water areas and woodlands within 2 km of each farmland were searched and classified into categories, and the basic distribution of each agricultural element was counted.

3.4. Region Division and Classification Based on Voronoi Diagram

After hierarchical clustering and classification, several regional centers in each category were selected and a Voronoi diagram was constructed by the Delaunay triangulation method for each specific region division. Voronoi diagrams, also known as Dirichlet diagrams or Tyson polygons, can divide continuous spaces into corresponding spheres of influence, according to the spatial distribution of facilities, which have been widely applied in the power division of urban service areas [45] and the location selection of logistics centers [46], etc. Then, according to the distribution of various agricultural elements in each region, the regions were divided into farm-intensive types and water (woodland)-intensive types.

3.5. Optimization Model of Manure Transportation

After the regions were divided and classified, an optimization model of manure transportation was built that integrates economic benefits, environmental benefits and topographic hindrance factors. First, the symbols of this part are defined and explained as shown in Table 1.

Table 1. Symbolic description of the model construction part.

Symbols	Illustrations (Unit)
x_i	The fertilizer amount required by the *ith* farmer (t)
y_i	The manure amount required by the *ith* farmer (t)
Q	Nitrogen content in nitrogen fertilizer (g/kg)
P	Nitrogen content in manure (g/kg)
v	Price of manure transportation and pretreatment (Yuan/t·km)
L	Distance of manure transportation (km)
ω	Unit price of fertilizer (Yuan)
x_{ij}	The amount of manure from the *ith* farm to the *jth* farmland (t)
f_{ij}	Economic benefit of x_{ij} from the *ith* farm to the *jth* farmland (Yuan)
S_1	Benefits from manure substitute fertilizer (Yuan)
S_2	Manure transportation cost (Yuan)
S	Total economic benefits (Yuan)
d_{ij}	Transport distance from the *ith* farm to the *jth* farmland (km)

Table 1. *Cont.*

Symbols	Illustrations (Unit)
q	The maximum load vector of manure
p	The yield vector of manure in the farm
u	Obstacle coefficient of terrain
s_j	Gains from the jth farmland (Yuan)
ω_1	Weight of economic benefits
ω_2	Weight of environmental benefits

3.5.1. Manure Amount Required to Replace Chemical Fertilizer (in Terms of Nitrogen)

The unreasonable application of nitrogen fertilizer can lead to the loss of nitrogen to the environment through runoff, leaching, ammonia volatilization, nitrification–denitrification and other ways, resulting in water and air pollution. However, the combined application of organic fertilizer can effectively reduce nitrogen loss [47]. Therefore, this paper adopted the calculation method of replacing nitrogen fertilizer with manure. Since the nitrogen content in nitrogen fertilizer and in manure are known, to achieve the same crop benefits with manure and chemical fertilizer, the required manure amount can be calculated according to the required amount of chemical fertilizer for each farmer, i.e.,

$$y_i = \frac{x_i \times Q}{P} \tag{1}$$

3.5.2. Analysis of Economic Benefits of Manure Returning to Field

The economic benefit of returning manure to farmlands is considered as the money that can be saved by farmers in the process of replacing fertilizer with manure. Therefore, it can be divided into two parts: the first part is benefit S_1, which is brought by replacing chemical fertilizer; the second part is the amount of manure transportation costs S_2 [11]. Ignoring the transportation costs of chemical fertilizers, the total benefit is

$$S = S_1 - S_2 \tag{2}$$

where $S_1 = wx_i$ and $S_2 = vLy$.

3.5.3. Manure Transportation Model Combining Economic and Environmental Benefits

Assuming that there are m farms and n farmlands in a region, the distance matrix D is first calculated, and the manure transportation matrix X is initialized, i.e.,

$$D = \begin{pmatrix} d_{11} & \cdots & d_{1n} \\ \vdots & \ddots & \vdots \\ d_{m1} & \cdots & d_{mn} \end{pmatrix}_{m \times n}, X = \begin{pmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{pmatrix}_{m \times n} \tag{3}$$

Then, the total manure amount of the jth farmland is finally obtained as $\sum_{i=1}^{m} x_{ij}$, and the total manure amount exported by the ith farm is $\sum_{j=1}^{n} x_{ij}$. Our aim is that the optimal results should meet the requirements of the farmlands as much as possible, and the total output should also not be greater than the total manure production of the farm.

In optimizing the economic benefits of farmlands, it is necessary to make full use of the manure; that is, the goal of optimization is to maximize the weighted sum of $\sum_{j=1}^{n} s_j$ and $\sum_{i=1}^{m}\sum_{j=1}^{n} x_{ij}$. The optimization model is

$$\begin{cases} \max \omega_1 \sum_{j=1}^{n} s_j + \omega_2 \sum_{i=1}^{m}\sum_{j=1}^{n} x_{ij} \\ \sum_{i=1}^{m} x_{ij} \le q_j, j = 1, 2, \cdots, n \\ \sum_{j=1}^{n} x_{ij} \le p_i, i = 1, 2, \cdots, m \\ s_j = \sum_{i=1}^{m} f_{ij}, j = 1, 2, \cdots, n \end{cases} \tag{4}$$

The optimization model comprehensively considers the economic benefits and environmental benefits, which has advantages with the single-objective optimization model [48] for the logistics process of satisfying the nutrient needs of crops by means of livestock manure.

3.5.4. Obstacle Coefficient

The judgment method for judging whether a certain terrain k has an obstruction impact on the manure transportation between the *ith* farm and the *jth* farmland is to obtain the map spot area g_k of a certain terrain k from ArcGIS and calculate the linear distance h from the terrain k to the link between the *ith* farm and the *jth* farmland. If

$$\sqrt{\frac{g_k}{\pi}} \le h \tag{5}$$

then it is determined that the manure transportation between these two places will have a great impact; thus, the distance between them is multiplied by the obstruction coefficient of the terrain.

3.5.5. Solving by Genetic Algorithm

The genetic algorithm (GA) is a method to search for the optimal solution by simulating the natural evolutionary process [49]. This method takes all the individuals in a population as the object and efficiently searches a coded parameter space through selection, crossover and mutation [29]. In this paper, binary parameter encoding, which is loaded in the toolbox of MATLAB software, was adopted. The transportation matrix corresponding to the average manure transportation from the farm to the farmland within 2 km was taken as the initial population, and the fitness function is the opposite of the total benefit function. A detailed analysis was performed, focused on the farm-intensive area (the longitude and latitude ranges are E114.759–E114.8 N30.75–N30.78) and the water (woodland)-intensive area (the longitude and latitude ranges are E114.59–E114.64 N30.55–N30.7), and a heat map was drawn to compare the changes in the global benefits after optimization and before optimization.

4. Results

4.1. Data Collection, Clustering and Region Division

With the method described in Section 3.2, the results can be seen in Figure S1, which is in the Supplementary Materials. Xinzhou District is segmented from Shapefile data of Wuhan City in Figure S1a, and part of Xinzhou District is cut out from Landsat 8 land-use raster grid data in Hubei Province, which is shown in Figure S1b. Then, by transformation with the surface turning point tool, the elements of Xinzhou District were extracted, and Figure S1c presents the scatterplot with the livestock farm data.

Taking all the farmlands in Xinzhou District as sample points, the aggregation coefficients of 1 to 100 clusters were calculated with SPSS software. It was found that the aggregation coefficient decreases from 0.0258 to 0.0189 when clustering into four clusters to five clusters, and then the decreasing trend tends to be gentle and close to 0. According to the elbow criterion of hierarchical clustering, clustering into five clusters has the best effect. The clustering results are shown in Figure S1d.

All the farms, water areas and woodlands, were classified into the cluster where the farmland is located within 2 km of them. Since the distribution of agricultural elements in Cluster 5 is similar to that in Cluster 3, and they are geographically close, Cluster 5 was merged into Cluster 3 for convenience. The number of farmlands, farms, special terrain grids and fecal production in each cluster were statistically analyzed.

Combining the clustering results with Figure S1c, it can be found that there are many water areas and woodlands in both Clusters 3 and 4. In the process of optimizing the manure distribution plan, we set the obstacle coefficient to reflect the role of the terrain.

To reduce the complexity of optimization, the Voronoi diagram algorithm was used to partition all the clusters. Figure S1e shows the results of the division of Cluster 3. We selected the two regions of Figure S1f,g. The regions were analyzed as cases of farm-intensive type and water-intensive type.

Figure 1 shows the descriptive statistics of various agricultural elements in Xinzhou District. Figure 1a,b show the statistics of the farmland, farm and terrain in each cluster. The statistical results and preliminary observation results after clustering are similar, and there are many special terrains in Cluster 3 and Cluster 4. In Cluster 1, there are a few special terrains, and more livestock farms than in the other clusters. Figure 1c,d are box graphs of the manure production and the discharge rate of the farms.

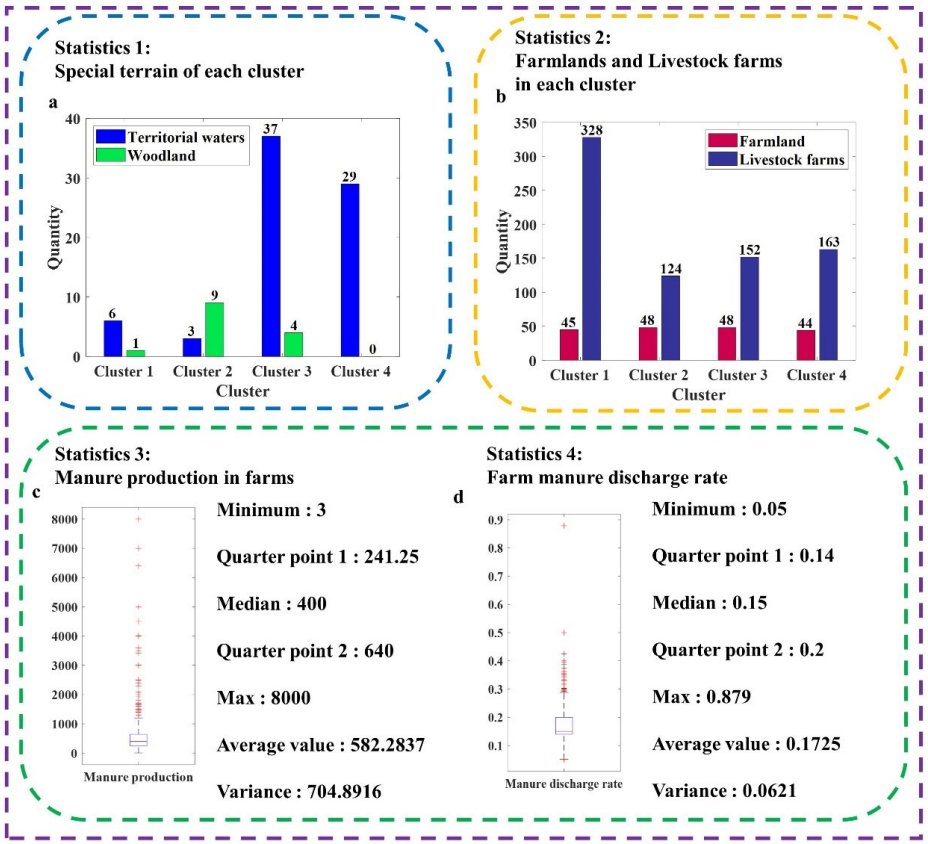


Figure 1. The location of farmland, farms, special terrain quantities and farm manure production, and manure utilization statistics in Xinzhou District. (**a**) is the statistics of the special terrain in each cluster; (**b**) is the statistics of the farmland, livestock farm in each cluster; (**c**) is the box graphs of the manure production in farms; and (**d**) is the box graphs of the manure discharge rate of the farms.

Fifty percent of the farms had an annual manure production of more than 400 tons, and 25% of the farms had an annual manure production of more than 640 tons (Figure 1c). Fifty percent of the farms had a discharge rate of more than 15%, and 25% of the farms had a discharge rate of more than 20% (Figure 1d).

4.2. Analysis of Regional Manure Distribution Scheme

Table 2 shows the parameters required to determine the benefit function of the optimization model [47] and convert the fecal pollution carrying capacity of each farmland.

Table 2. The parameters of determining benefit function and changing the bearing capacity of farmland manure.

Parameters	Values (Unit)
Nitrogen content of chemical fertilizer	46%
Nitrogen content of nitrogen fertilizer	0.83%
Manure transport price	16 (Yuan/t·km)
Fertilizer unit price	1723 (Yuan/t)
Rice yield per mu	700 (kg)
Required nitrogen content of 100 kg rice	2.2 (kg)
Nitrogen content of 1 kg pig manure	2.28 (mg)

By substituting the coefficients in Table 2 into Equation (2), the benefit function can be obtained as follows:

$$f = \omega_1 \sum_{j=1}^{n} (1732.31 \times \sum_{i=1}^{m} x_{ij} - 886.747 \times \sum_{i=1}^{m} d_{ij} x_{ij}) + \omega_2 \sum_{i=1}^{m} \sum_{j=1}^{n} x_{ij} \quad (6)$$

4.2.1. Farm-Intensive Type

There are three farmlands (the total area is 2045 ha) and eight livestock farms (the total manure yield is 3560 t) in the area of Figure S1f. Meanwhile, we also found that there are fewer water areas and woodlands in this region, which can be ignored. Thus, they are regarded as the farm-intensive type. To obtain more economic benefit from returning manure to the field, the economic coefficient and environmental coefficient were set as 0.005 and 0.995, respectively, and the optimal manure distribution scheme obtained by using the genetic algorithm is shown in Figure 2a.

Based on the survey data, the livestock manure utilization rate in this area in 2017 was only 81.5%. Considering the transportation economics of livestock manure, we assumed that livestock manure is transferred and used on average for farmland within 3 km of the livestock farm. Then, the total economic benefit is 1057.64 Yuan/ha (total 2,162,894 Yuan) (Table 3), which is calculated according to the expression of economic benefit in the benefit function. We also found that the longer routes, such as Farm 4 transport to Farmland 1 and Farm 8 transport to Farmland 3, had caused a certain loss of economic benefits when using the distribution scheme for livestock manure transportation.

According to the distribution scheme optimized by the genetic algorithm for transportation, compared with the average distribution of the transportation scheme, the utilization rate of regional manure can be increased by 12.2%, from 81.5% to 93.7% (Table 3), of which the manure of Farm 2 to Farm 8 is almost fully utilized and potential pollution is greatly reduced. The comprehensive growth of the economic benefits is increased by about 580.16 Yuan/ha (total 1,186,408 Yuan) (Table 3); the total benefit function is improved. In addition, the usage of livestock manure of all the farmlands is within their bearing capacity of crop land.

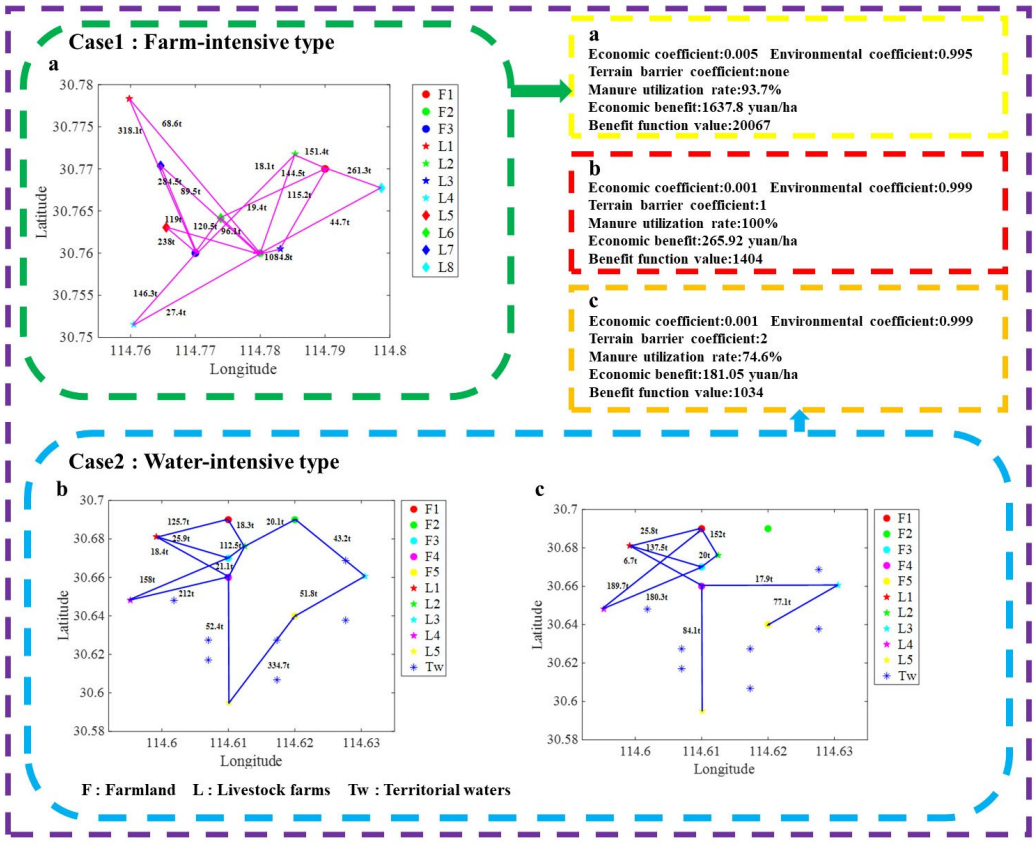


Figure 2. Regional manure distribution schemes. (**a**) is the optimization result of the manure distribution scheme in the farm-intensive area selected in this paper. (**b**,**c**) are the optimization results of the manure distribution scheme when the barrier coefficient is 1 and 2 in the water-intensive areas selected in this paper, respectively.

Table 3. Results of regional optimization.

Variables	Farm Intensive		Water Intensive		Water Intensive	
Period	**Before**	**After**	**Before**	**After**	**Before**	**After**
Obstruction coefficient	\		1		2	
Coefficient combinations (environmental coefficient—economic coefficient)	0.995–0.005		0.999–0.001		0.999–0.001	
Utilization amount (t)	2902	3337	1024	1194	1024	891
Utilization rate	81.5%	93.7%	85.8%	100%	85.8%	74.6%
Economic benefits (Yuan/ha)	1057.64	1637.8	75.81	265.92	49.05	181.05
Total benefits	14,627	20,067	1079	1404	929	1034

4.2.2. Water-Intensive Type (Obstruction Coefficient Is Equal to 1)

There are five farmlands with a total area of approximately 794 ha, five livestock farms with a total manure output of 1194*t* per year and seven water areas in the region of Figure S1g. First, the obstruction coefficient was set as 1, which means the transportation distance of manure from livestock farm to crop land in a straight line where the terrain does not hinder transportation. At the same time, the economic coefficient was set as 0.001, and the environmental coefficient was set as 0.999. The results obtained by using the algorithm are shown in Figure 2b.

In the absence of scientific guidance, the benefit of returning manure in this region is also not ideal. According to the production and usage data of manure from farms, the

manure utilization rate in this region is calculated to be 85.8%, and the economic benefit generated was 75.81 Yuan/ha (total 60,195 Yuan) (Table 3).

However, when the optimized distribution scheme was used for livestock manure transportation, the environmental benefit, economic benefit and total benefit for the region were improved. All the livestock manures in this region can be used for the crop land, and the economic benefit increases by 190.11 Yuan/ha (Total 150,950 Yuan), from 75.81 Yuan/ha to 265.92 Yuan/ha (Table 3). The main reason for the benefit improvement is that the impact of the terrain on the transport path is not considered in the manure transport path optimization scheme, and livestock manure is preferred to be transported to the farmland close to the farm.

4.2.3. Water-Intensive Type (Obstruction Coefficient Is Equal to 2)

Then, we also explored the change in the optimization results when the terrain hindered transportation by twice as much. The economic coefficient and environmental protection coefficient were kept unchanged in the same region in Figure S1g. The obstruction coefficient was set as 2 to reoptimize the scheme.

Under this obstruction coefficient, the benefit of the optimized distribution scheme is not ideal. The manure utilization rate was 74.6% (Table 3), which is lower than the scheme when the obstruction coefficient is 1. Although the manure utilization rate of manure was 11.2% lower than before, the economic benefits of the manure were improved from 49.05 Yuan/ha to 181.05 Yuan/ha.

Table 3 is a comparison of multiple indicators of the above three optimization results. We found that in the transportation scheme optimized by this model, the benefits of farm intensity and water intensity with an obstruction coefficient of 1 were greatly improved. However, when the hindrance coefficient was 2, the latter's improvement was very limited, and the utilization rate of the manure declined. The obstruction of terrain plays an important role in optimizing our manure distribution plan.

4.2.4. Influence of Terrain Obstacles on the Optimization Scheme of Manure Transportation

Since we had found that terrain obstruction has a certain impact on the benefits of returning manure to the field, we also analyzed the impact of the magnitude. Taking the water-intensive area in Section 4.2.3 as an example, four coefficient combinations were set up. Meanwhile, the ratio of the environmental coefficient to the economic coefficient was defined as the coefficient ratio. The greater the coefficient ratio is, the greater the preference for environmental protection benefits in the process of scheme optimization. Setting nine kinds of obstruction coefficients at intervals of 0.1, starting from 1 to 1.8, a genetic algorithm was used to optimize the distribution scheme (Figure 3a; Table S1). Table S1 shows the manure utilization rate and the regional economic benefits under all the distribution schemes.

Figure 3a shows the manure utilization rate with the terrain obstruction coefficient, under the four coefficient combinations, and the regression of manure utilization rate with the terrain obstruction coefficient. The regression results of the manure utilization rate and the economic benefits with the obstruction factors are shown in Table S2. In the four coefficient combinations, the manure utilization rate in the region has a downward trend with the rise of the obstruction coefficient, especially when the coefficient ratio is 0.999, and the increase of the obstruction coefficient has the most significant effect on the manure utilization rate (Figure 3a).

Figure 3c shows the economic benefit changing with the terrain obstruction coefficient under the four coefficient combinations, and the regression of the economic benefit on the terrain obstruction coefficient. In terms of economic benefits, except for the coefficient combination with the coefficient ratio of 0.999, the economic benefits of the other three coefficient combinations are stable or declining (Figure 3c).

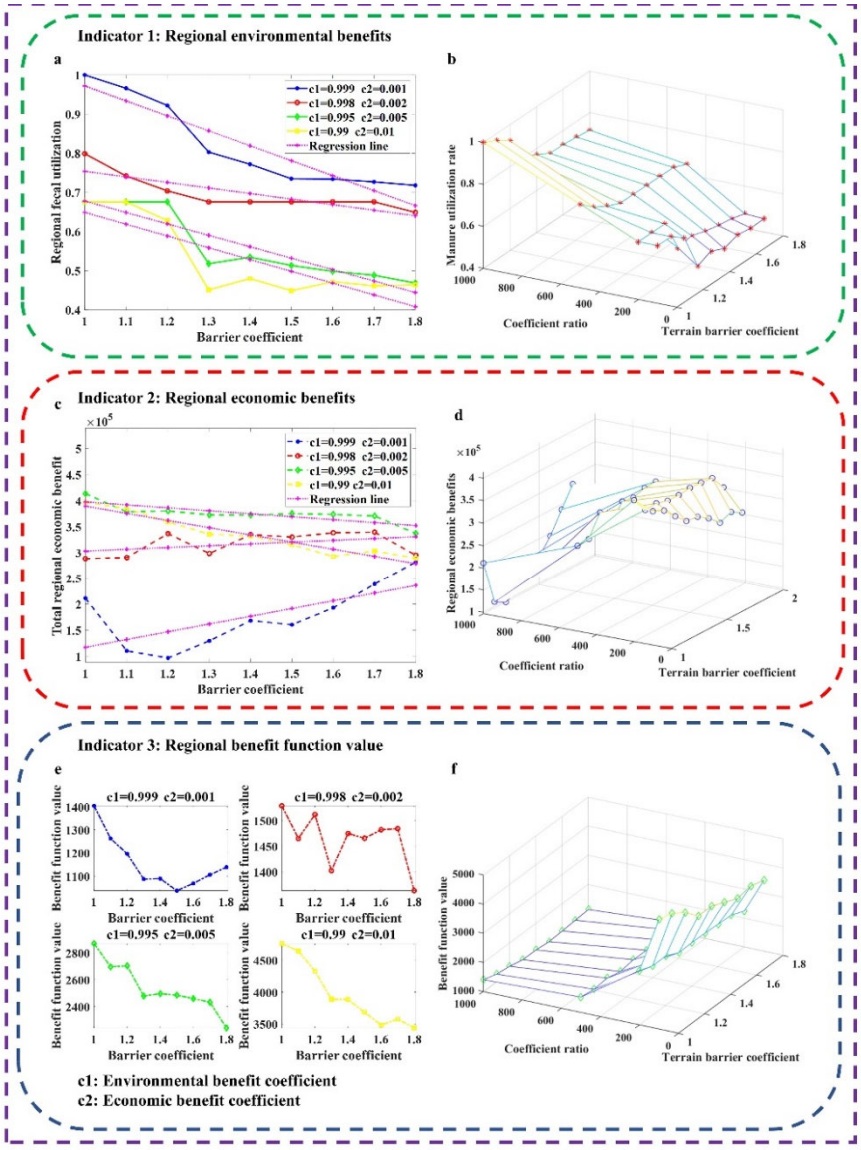


Figure 3. Analysis of benefit loss of terrain obstruction. (**a**) is the image of the relationship between regional manure utilization rate and barrier coefficient, and the image of the regression line. (**b**) is the three-dimensional graphs of the relationship between the regional manure utilization rate, barrier coefficient and coefficient ratio. (**c**) is the image of the relationship between regional economic benefit and barrier coefficient, and the image of the regression line. (**d**) is the three-dimensional graphs of the relationship between the regional economic benefit, barrier coefficient and coefficient ratio. (**e**) is an image of the relationship between the benefit function value and the barrier coefficient under the combination of four coefficients. (**f**) is the three-dimensional graphs of the relationship between the benefit function value, barrier coefficient and coefficient ratio.

Figure 3e shows the change in the total benefit function value. At the same time, in several of the coefficient combinations, except that of the tail of the optimization function value with the coefficient ratio of 0.999, which increases slightly, the others have a downward trend, which also shows that the increase of the obstruction coefficient weakens the overall benefit of the manure returning area (Figure 3e). Although the rise in the coefficient combination of 0.999–0.001 is because the coefficient ratio is too large and does not pay attention to the economic benefits, there is an economic benefit that will rise in a certain probability, resulting in the value of the optimization function rising (Figure 3e).

Figure 3b,d,f are the variation images of the manure utilization rate, the economic benefits and the benefit function value with the change of obstruction coefficient to coefficient ratio, respectively.

As shown in Table 4, according to the regression coefficient, the average increase of the regional manure discharge amount, and the rate and the decrease of the economic benefit, and the benefit function value obtained by each farmland can be determined when the obstruction coefficient increases by 0.1 under the four coefficient combinations.

Table 4. The results of average increase of regional manure discharge amount and rate and the decrease of economic benefit and benefit function value under the four coefficient combinations.

Groups	Group 1	Group 2	Group 3	Group 4
Economic coefficient	0.001	0.002	0.005	0.010
Environmental coefficient	0.999	0.998	0.995	0.990
Increased manure discharge rate	3.82%	1.42%	2.92%	3.01%
Increased manure discharge amount (t)	45.6	17.0	34.7	35.9
Decreased average economic benefit (Yuan)	−2976.5	−691.9	1134.6	2760.2

Combining the results of Table 4 and the regression analysis, it can be found that when the economic coefficient is too low and the environmental coefficient is too high, the economic benefits will be lost as the obstacles of the terrain increase. Conversely, in some cases, setting an economic coefficient that is too high will cause some farms to consider the economic benefits and not return manure to the field at all.

4.3. Global Optimal Solution Analysis

All regional distribution schemes in Xinzhou District are optimized. The economic and environmental coefficients were set as 0.005 and 0.995, respectively. Then, the economic benefits of each farmland and the manure discharge rate of each farm before and after optimization were calculated, as shown in Figure S2. Table 5 shows the relevant statistics of each subpoint and the highest value and average.

Table 5. Statistics indexes of global optimization results.

Index	Minimum	Lower Quantile	Upper Quantile	Maximum
Discharge rate before optimization	0.0500	0.1400	0.2000	0.8790
Discharge rate after optimization	0.0000	0.0001	0.0020	0.5000
Economic benefits before optimization	−17,003,654	6844	395,618	9,660,998
Economic benefits after optimization	−6,018,232	116,885	1,114,178	10,910,522
Index	**Standard Deviation**	**Coefficient of Variation**	**Skewness**	**Average**
Discharge rate before optimization	0.0621	0.3600	3.0286	0.1725
Discharge rate after optimization	0.1318	2.4019	2.4258	0.0549
Economic benefits before optimization	2,236,826	6.3071	−1.6516	354,654
Economic benefits after optimization	2,253,632	2.0083	2.1669	1,122,134

Observing the box diagram and the statistical results in Figure S2 and Table 5, it can be found that the discharge rate of manure before the optimization is more evenly distributed. The discharge rate of most farms is higher than 10%, and a few are higher than 80%. After optimization, the number of farms between 30–50% has increased, but the overall upper quartile is 0.2%, which means that three-quarters of the farms control the discharge rate within 0.2%. Regarding the economic benefits of each quantile compared with the optimization before the optimization, the average economic benefit of each farmland has increased by 767,480 Yuan, which is an ideal optimization result.

The grid with a longitude and latitude span of 0.05 (approximately 5 km) as the side length divides Xinzhou District into a 9 × 11 network, corresponding to the latitude and

longitude range of the network. After that, the amount of manure collected and used in all the farms in each grid and their discharge rates were calculated. Figure 4a,b are heat maps of the manure discharge rates in Xinzhou District before and after optimization, respectively. The rate shows a significant downward trend after optimizing the discharge of manure in the entire region. However, because some areas of farmland are small, to avoid phosphorus enrichment, the maximum amount of manure consumption of each piece of farmland has a certain limit, resulting in a very small number of areas in which the discharge rate increased. The utilization rate of manure before optimization was up to standard, and after optimization, the farmland received an extra 7.73% of the manure in the carrying capacity range.

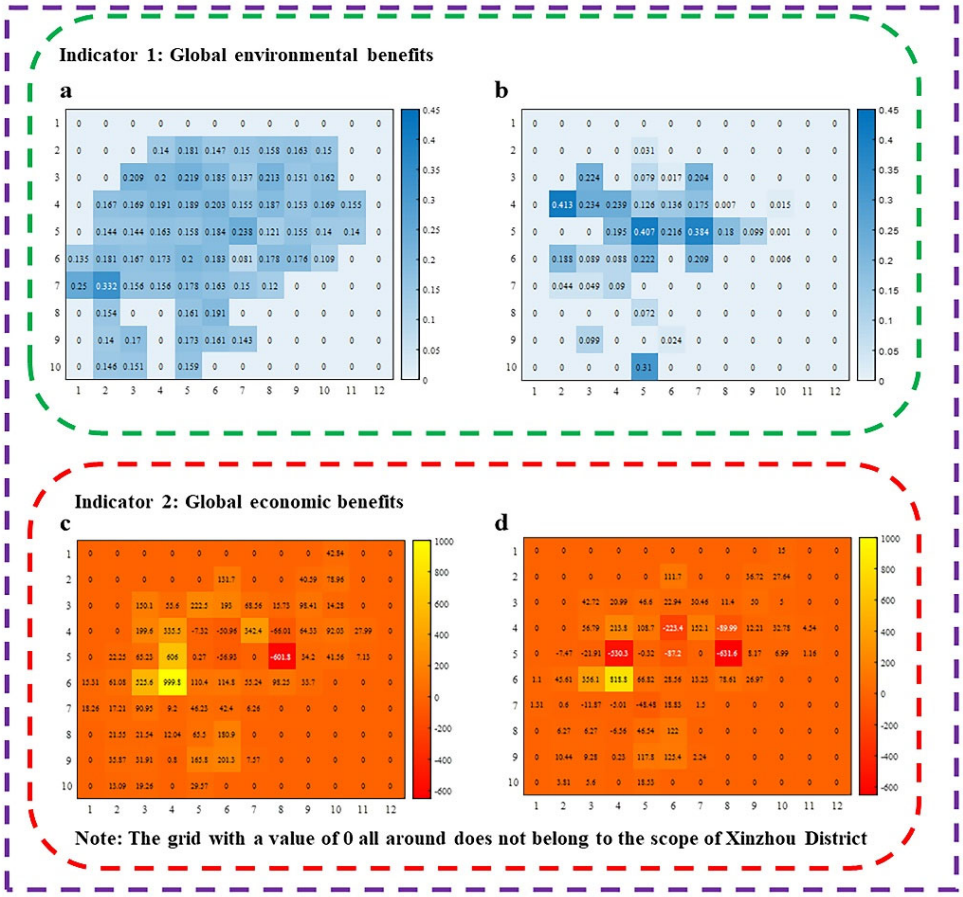


Figure 4. Heat map of manure discharge rate and economic benefits before and after optimization. (**a**) is the heatmap of the manure discharge rate in Xinzhou District before optimization. (**b**) is the heatmap of the manure discharge rate in Xinzhou District after optimization. (**c**) is the heatmap of the economic benefits of manure returning in Xinzhou District before optimization. (**d**) is the heatmap of the economic benefits of manure returning in Xinzhou District after optimization.

The heat maps of the average economic benefits of using manure instead of chemical fertilizer in all the farms in each grid area before and after optimization are shown in Figure 4c,d; the data in the grid mean the economic benefit value is X*10,000 Yuan. In most of the grid areas of Xinzhou District, the optimized average economic benefits of the farmland have been improved to a certain extent, as has the utilization rate of manure. Before optimization, if all the farms in Xinzhou District sent manure to those farms within 3 km of them on average, the average economic benefit to the farmland of returning manure to the field was 354,654 Yuan (703.8 Yuan/ha); after optimization, it was 1,122,134 Yuan (2226.75 Yuan/ha) (Table 5). Without policy guidance or manual inter-

vention, allowing farmers to transport manure spontaneously will result in an economic benefit of 128,929,901 Yuan (1522.95 Yuan/ha) less for all farmers per year.

5. Discussion

The development of animal husbandry and planting has played an important role in improving living standards in China. Meanwhile, it also leads to problems relating to the difficult usage of livestock waste and the excessive use of chemical fertilizers [29,50,51].

As the manure of livestock and poultry contains abundant nutrients such as nitrogen, phosphorus and potassium for the growth of crops [6], the usage of organic fertilizer made by animal manure can increase the humus formation [52] and the production of crops [53,54]. The replacement of chemical fertilizer by livestock manure in cropland can solve the problem of the difficult usage of livestock manure and the excessive use of chemical fertilizers [55]. The Chinese government has formulated a series of policies, such as the "zero growth of chemical fertilizer" plan, which pioneers replacing chemical fertilizer with organic fertilizer.

Due to the huge output of livestock manure in China, we must consider whether the application of manure will exceed the carrying capacity of the land. Zhang et al. [55] found that fertilizers needed for crop growth in China can be provided by livestock manure at a national scale, but the nitrogen of livestock and poultry manure in some provinces, such as Shandong, Liaoning and Sichuan, exceeded that needed for crop growth. In addition, the locations of livestock and poultry farms in China, were usually far away from the farmland. Some terrains, such as weir ponds, woodlands, swamps, construction land, and other landforms around the livestock farms and farmland, had increased the difficulty of the transportation of livestock manure, and decreased the utilization efficiency [56,57]. Moreover, compared with chemical fertilizer, livestock manure had a larger volume under the same nitrogen content, which further increased the difficulty of transportation and application [9]. Strom et al. [27] found that the transportation cost, land availability, crop and soil need, transport logistics, and farmers' reluctance also influence the usage of manure instead of inorganic fertilizer. The optimization of the redistribution of livestock manure would be very important.

In our research, we established a method for the efficient redistribution and transportation of manure to farmland, considering both utilization efficiency and environmental benefits. In addition, we used the data of Xinzhou District of Wuhan as a case study. According to the topographic characteristics around the farms in Xinzhou District, we divided the farms in this area into farm intensity, water intensity and other obstructions, which can be widely used in most of the combined planting and breeding areas in China. Our research showed that in the absence of government guidance, the utilization rate of livestock manure in a given area could reach only 82.91%, or even lower. After optimization of the manure utilization rate using the model we built, under the condition that the manure returned to the farmlands did not exceed the maximum carrying capacity, the manure utilization rate in Xinzhou District could be increased from 82.91% to 90.64%, which was a great improvement compared with before optimization. Although, the resource utilization rate of livestock waste had reached more than 76% by 2021 in China [8], further increasing of the utilization rate would be very difficult. Our optimization model could be used for increasing the utilization rate of livestock manure in China.

Special terrain indirectly affects the various benefits obtained by returning manure to the field, through the influence on the redistribution of manure in farms. By comparing Figure 2b with Figure 2c, it can be found that there is a water area between Farm 3 and Farm 2. When the obstruction coefficient increases from 1 to 2, Farm 3 abandons transporting manure to Farm 2, which is close but obstructed by the water area. At the same time, due to the high environmental protection coefficient set by the model, to avoid pollution caused by a large amount of residual manure, the farm should be chosen to transport the manure to Farmland 3, which is far from Farmland 2, which led to the

decrease of economic benefits. Similar reasons are shown in the scheme of transportation of livestock manure of Farm 5 to Farmland 5.

Under some specific terrain conditions, such as mountains and forests, which affect the transport path of manure, we can set the terrain obstruction coefficient through calculating the ratio of the actual transportation distance to the straight-line distance and quantifying the impacts of the terrain obstruction on the economic and environmental benefits. In that case, regression analysis should be used to calculate the loss value of economic and environmental benefits. When the obstacle coefficient increases by 0.1, the actual transportation distance will increase, becoming 10% longer than the straight-line distance. The government can build bridges, pipelines or other methods to reduce the loss of benefits by improving the transport efficiency.

It should be noted that there are also some limitations in this study. For example, while [47] analyzed the optimal transport distance of animal and poultry manure in Chongqing and concluded that 2 km is the most economical manure transport distance, it is assumed that the optimal transport distance of the farm is 3 km in this research. Actually, the most economical transport distance is not the same for each animal and poultry manure because their nutrient content is not the same. In practical applications, the most economical transport distance of each manure can be set according to the type of animal and poultry manure, freight and labor, etc.

6. Conclusions

Taking an example of Xinzhou District of Wuhan City in China, we present a transportation network optimization model for livestock manure under different terrains, considering economic and environmental benefits. The main work includes:

(1) Hierarchical clustering and regional division applying the Voronoi diagram were used to evaluate the density of breeding and the situation of special terrains in Xinzhou District. It can be divided into one farm-intensive region and three water-intensive or woodland-intensive regions.
(2) An optimization model of manure transportation considering economic and environmental benefits under terrain obstruction was established. With the global solution of our method, the utilization rate of manure is improved to 90.64%, which is far higher than the requirement of the General Office of the State Council.
(3) Under different optimization preferences, i.e., four benefit coefficient combinations, the impact ranges of topographic obstacles on the return benefit of manure were quantified. Through our model for optimization and evaluation, some suggestions are given for improving the benefit of the livestock and poultry breeding industries.

Although our proposed optimal model is verified with the application in Xinzhou District of Wuhan City, the method is also suitable for other areas in China, which can help to achieve China's goal of carbon neutrality by 2060. Moreover, it can be expanded to other countries, especially for different terrains in specific districts.

However, there are some shortcomings in this study. The proposed method assumes that the transportation route is a straight line, and the undulation of rural terrain is not considered. Moreover, the optimization result may produce a certain range of errors, so the optimization algorithm can be further improved in the future.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14137721/s1, Figure S1: Grid cropping, data point coordinate acquisition, zoning, and classification; Figure S2: Box chart of global optimization results in Xinzhou District; Table S1: Regional manure utilization rate and economic benefits under multiple coefficient combinations and obstruction coefficients; Table S2: Regression results of manure utilization rate, economic benefits with obstruction factors.

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