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Approach for Calculating and Analyzing Carbon Emissions and Sinks of Villages: A Case Study in Northern China

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Abstract: Despite a gradual decline in rural population due to urbanization, as of 2022, approximately 35% of China's total population still resides in villages. Over a span of 40 years, carbon emissions from villages have significantly surged, with a sevenfold increase from energy consumption and a 46% rise from agriculture. Consequentially, the development of low-carbon villages is imperative. A comprehensive understanding of the primary sources of carbon emissions in villages is crucial for implementing practical and effective strategies towards low-carbon development. However, limited research has been conducted on quantifying carbon emissions and sinks for Chinese villages. This study aims to address this gap by proposing a methodology for assessing carbon emissions in villages, including the emissions of CO_2, CH_4 and N_2O. Inspired by the IPCC standard methodology for greenhouse gas emissions at national levels and provincial greenhouse gas inventory guidelines customized for China's context incorporating localized characteristics, this approach has been applied to seven villages in Northern China based on field investigations. Employing a range of methods including field surveys, questionnaires, statistical records and big-data platforms, we collected the carbon emission activity levels of the seven villages using the most up-to-date carbon emission factors. Subsequently, the collected data and facts are quantitatively processed to generate results that are compared among the seven villages. These findings are also compared with those from other studies. The analysis indicates that the primary industries in these villages significantly influence the total carbon emissions. Moreover, the study reveals that energy consumption in buildings, agriculture, transportation and waste disposal are the most influential emission sources. These findings provide valuable insights into the carbon emission landscape of villages and can serve as a guide for implementing strategies and policies aimed at promoting low-carbon development in the rural areas of Northern China.

Keywords: carbon emission calculation; low-carbon villages; case study; Northern China

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1. Introduction

Carbon emissions in Chinese villages have significantly increased in the past decades. However, there is still a lack of methods for calculating these carbon emissions. This paper developed an operational approach for calculating carbon emissions from CO_2, CH_4 and N_2O in villages, employing a bottom-up approach based on field investigations. This approach was subsequently applied to seven villages located in Northern China. In addition to quantifying carbon emissions, we conducted a thorough comparison and analysis on carbon emissions and sinks among the seven villages. The findings illuminate the diverse carbon emission scenarios across various village types, offering valuable insights to facilitate proper village planning and inspire well-informed recommendations for formulating effective strategies to promote low-carbon development in villages. To provide a comprehensive research context, a concise literature review is conducted as follows.

1.1. Carbon Emissions of Chinese Villages

Being one of the nations with the highest global carbon emissions, China has implemented a wide range of measures to mitigate its carbon footprint. Despite a gradual decline in the nation's rural population due to the ongoing process of urbanization, as of 2022, approximately 491 million individuals still inhabit villages, accounting for roughly 35% of the total population [1]. Characterized by their abundant natural ecological resources and rich carbon storage capacities, villages are consistently presumed to play a crucial role in environment preservation and ecosystems maintenance. However, the increase in economic activity and improvement in living standards in these regions have led to a rapid escalation in energy consumption and subsequent significant growth in carbon emissions. The carbon emissions in villages resulting from energy consumption for daily activities and production have undergone a substantial increase, escalating approximately sevenfold from 30 million tons in 1979 to 237 million tons in 2018 [2]. Meanwhile, the energy consumption in agriculture continues to rise with the increasing crop production and widespread implementation of agricultural mechanization, witnessing a growth of 46% from 665 million tons in 1980 to 970 million tons in 2020 [3]. Fortunately, rural areas boast abundant sustainable energy sources such as solar power, wind power and biomass resources that are crucial for reducing overall carbon emissions. Therefore, developing low-carbon villages can effectively contribute to the reduction of the nation's overall carbon footprint.

1.2. Limited Researches on Carbon Emission and Sink Calculation of Chinese Villages

Currently, the predominant focus of research on Chinese villages lies in exploring the implementation of renewable energy [4–6], while low-carbon development strategies are primarily directed towards sector-specific carbon emission calculations such as those pertaining to residential buildings [7,8] and agriculture [9–11]. However, it is crucial to acquire a comprehensive understanding of carbon emission patterns at the village level through proper calculations, coupled with the identification of pertinent sectors that exert significant impact and offer potential for improvement. This knowledge is essential for devising tailored and efficient measures to mitigate emissions, thereby facilitating sustainable low-carbon strategies at the village scale.

Existing studies on carbon emission calculations in China primarily focus on national [12,13], provincial [14] and city [15,16] scales, with limited research dedicated to the village scale. Unlike nations or cities, villages often lack comprehensive statistical data on carbon emission activities, posing challenges when applying calculation methods utilized at the national and city scales. Consequently, there remains a dearth of studies investigating the quantification of carbon emissions at the village level. For instance, Ref. [17] developed a methodology for villages where tourism serves as the main industry. This research classified carbon emission sources into three categories: tourism-related, agricultural and community-based. The method was applied to two villages in Anhui province located in the Yangtze River Delta region of China. Similarly, Refs. [18,19] developed a method for calculating carbon emissions in rural areas and applied it to eight villages within the same region. However, this approach lacks comprehensive quantification of agricultural emissions, particularly those arising from livestock production which constitutes the predominant industry in most Chinese villages. Moreover, there is a need to update the emission factors utilized in these studies. Similar studies by have investigated villages in the same region [20–22]; however, these methods were presented in a simplistic manner, confined to fuel consumption, electricity usage and transportation as sources of carbon emissions.

In conclusion, despite the existence of several studies focusing on the calculation of carbon emissions and sinks in Chinese villages, they have primarily concentrated on the

Yangtze River Delta region, neglecting a comprehensive investigation into agricultural carbon emissions. Considering that villages in different regions possess distinctive characteristics, it is crucial to examine their carbon emissions and sinks separately to obtain a holistic understanding of the actual situations. Therefore, there is a need to develop a comprehensive approach applicable across various regions for assessing village-level carbon emissions. This approach has been applied to seven villages in Northern China as a case study.

1.3. Studies on Small Spatial Scale in Other Countries

Although limited studies were conducted at the village scale in China, several investigations on similar spatial scales have been carried out in other countries. For example, Ref. [22] examined carbon emissions in the urban neighborhood of Barrio Tiro de Linea in Seville, Spain, proposing efficient decarbonization strategies. Comparable research was also undertaken in the Dubrovnik district of Gruž, Dubrovnik [23], as well as in a typical European city neighborhood comprising 10,000 households and 23,000 residents [24]. Furthermore, apart from urban areas, a similar methodology was applied to the campus of Delft University of Technology in the Netherlands to assist administrators in devising tailored and efficient decarbonization plans [25]. These studies collectively demonstrate the effectiveness of assessing carbon emissions at small spatial scales and facilitating the implementation of customized decarbonization measures.

1.4. Regional Difference in Carbon Emissions of Chinese Villages

The carbon emissions of villages in China exhibit regional variations, particularly with regards to agriculture-related emissions which vary among different regions due to diversified agricultural production methods, predominant crops and livestock types. The study of [26] calculated the agricultural carbon emissions based on data collected from 2009 to 2019, revealing distinct spatial differences among the eastern, western and central regions. Similar regional disparities were also observed in [3], which analyzed relevant data spanning from 1980 to 2020. Furthermore, regional discrepancies resulting from energy consumption for daily life in villages significantly contribute to these variations. Research conducted by [27] indicates that the geographical locations of Chinese villages greatly influence energy consumption patterns and subsequently lead to regional disparities in corresponding carbon emissions. This finding is further supported by the results from [28], which examined life-related carbon emission data in Chinese villages from 2001 to 2013. Additionally, the transportation sector within China also exhibits evident regional disparities in terms of carbon emissions, as demonstrated in [29]. Therefore, conducting region-specific calculations for carbon emissions is essential for obtaining a comprehensive understanding of village-level emission profiles.

2. Material and Method

This study presents a novel approach for quantifying and assessing carbon emissions and sinks at village level, incorporating both previous studies and field investigations. The proposed approach is applied to examine seven representative villages situated in Northern China as a case study.

2.1. Assessment Boundary of Carbon Emissions for Villages

The proposed approach primarily draws upon the guidelines outlined in the Guidelines for National Greenhouse Gas Inventory of the Intergovernmental Panel on Climate Change (IPCC) [30] and the Guideline for Provincial Greenhouse Gas Inventory (GPGGI) [31], both issued by China's National Development and Reform Commission. While referring to both resources, the GPGGI serves as the principal guide for this study. Collaboratively compiled by nationally recognized research institutes and universities under the organization of the Climate Change Department of the National Development and Reform Commission of China in 2011, the GPGGI aims to enhance scientific rigor, standardization and feasibility of provincial greenhouse gas inventory compilation. Within the frameworks of the IPCC, tailored adaptions based on specific conditions observed in China have been implemented in the GPGGI.

The assessment boundary in this study is defined by the geographic limits of an administrative village. In China, an administrative village is an administrative division in rural areas, comprising one or more natural villages or a portion thereof, along with the surrounding collectively owned lands. The establishment of administrative villages aligns with the Organic Law of the Villagers' Committee of the People's Republic of China. In contrast, natural villages refer to settlements formed by families, households, clans or other social factors over an extended period in a naturally conductive environment.

2.2. Selection and Classification of Carbon Emission Sources and Sinks

The selection and classification of carbon sources are conducted based on a review of previous studies as well as field investigations into villages. As presented in Table 1, the classification of carbon emissions and sinks is introduced as follows.

Table 1. Classification of carbon emissions and sinks.

	Sectors	Sub-Sectors	Category
Carbon emissions	Buildings	Residential buildings	Electricity (incl. electrical bicycles) Natural gas LPG Coal Fuelwood-CH4 Fuelwood-N2O Tap water #
		Commercial and public buildings	Electricity consumption of service center Other energy use (natural gas, LPG, coal, fuelwood, tap water, etc.)
		Solid waste *	Landfill * Incineration
		Sewage	Domestic sewage with treatment
	Transportation	Road transportation	Road transport (Gasoline)
		Others	-
	Industry	Industrial production *	Plastic products industry * Chemical products industry *
	Agriculture	Agricultural machinery #	Agricultural machinery—Diesel # Electric irrigation #
		Livestock *	Intestinal fermentation * Fecal management *
		Crops *	Fertilizer use-direct emission Fertilizer use-settlement * Fertilizer use-leaching * Return straw-Maize * Return straw-Wheat * Pesticide use-Maize * Pesticide use-Wheat * Agricultural film use # Ploughing #
Carbon sinks	Forestry and other land use	Forest *	Arbor forests * Bamboo groves, economic and shrub forests *

*: Categories differ from [18]; #: categories differ from GPGGI.

2.2.1. Sectors and Sub-Sectors

In this study, carbon sources and sinks are categorized into three components (life, production and ecology) in accordance with the national strategy of rural revitalization in China. The life component encompasses the building sector (carbon emissions from energy consumption, water usage and waste disposal) and the transportation sector. The production component includes the agriculture sector and the industry sector. The ecology component consists of the forestry sector and other land-use activity sectors serving as carbon sinks. Unlike [18], this study integrates livestock into the agriculture sector to acknowledge its significance as a key agricultural industry.

High carbon-emission factories are excluded from the Industry Sector in this study for two reasons. Firstly, these factories typically belong to large corporations but are not owned by village residents, and they usually implement their own initiatives and strategies for carbon emission mitigation with separated measurements. Secondly, these factories contribute substantially to the overall emissions of villages, as evidenced in the study of [18]. Therefore, incorporating their emissions would distort the accurate depiction of the emission scenarios in villages themselves. For example, the emissions from the cement production factory in Miaoqian, one of the villages under investigation, have been excluded from consideration in this study.

2.2.2. Categories

Under the sub-sector of residential buildings within the building sector presented in Table 1, carbon emissions from tap water usage are included as a category, which differs from the regulations outlined in GPGGI [31]. Regarding solid waste disposal, the previous study of [18] only considered the carbon emissions resulting from incineration. However, landfilling accounts for 73% of solid waste disposal in villages of Northern China, as stated in [32]. Therefore, this study includes landfill as a category in the sub-sector of solid waste.

In the agriculture sector, agricultural machinery is classified as a sub-sector, while the use of agricultural film and ploughing are included as separate categories. These classifications differ from the regulations set by GPGGI [31]. Unlike [18], which only considered direct emissions from fertilizer application, this study also incorporates the indirect emissions arising from settlement and leaching due to fertilizer application. The study of [18] classified straw returning as carbon sinks, while [33] shows that carbon emissions exceed carbon sinks associated with straw returning. Therefore, this study categorizes straw returning as carbon emissions within the sub-sector of crops. Moreover, unlike [18], which applied a uniform carbon emission factor to assess pesticide usage across different crops, this study separately calculates carbon emissions for each crop type, considering the specific pesticides used. Additionally, in line with the findings of [34], our study also incorporates CH_4 and N_2O from agriculture alongside CO_2 emissions.

Regarding the calculation of carbon sinks, Ref. [18] broadly classified land use into woodland and grassland. However, forests are further categorized as "arbor forests" and "bamboo groves, economic and shrub forests" in this study, based on distinct methods for calculating carbon sinks as referenced in [31]. In arbor forests, carbon sinks primarily result from the annual growth of trees, whereas in bamboo groves, economic forests and shrub forests, changes in forest area predominantly contribute to carbon sinks dynamics, occasionally resulting in negative values due to the reduction in forest areas.

2.3. Categorizing Emissions by Scope

According to the categorization methodology proposed by [35], this study encompasses three scopes: Scope 1 refers to carbon emissions from sources within the village boundary, which account for the majority of emissions; Scope 2 includes carbon emissions resulting from grid-supplied electricity and heating within the village boundary, encompassing electricity usage for residential buildings, factories, product manufacturing, irrigation and natural gas usage for heating purposes; Scope 3 comprises all other carbon emissions occurring outside the village boundary due to activities taking place within it, including out-of-boundary solid waste disposal, sewage treatment and transportation.

2.4. Calculation Method for Carbon Emissions and Sinks

2.4.1. Calculation Method for Carbon Emissions

The calculation method utilized in this study follows a specific sequence. Firstly, it utilizes the methodology outlined in the GPGGI. Secondly, it applies the carbon emission factor method as per IPCC guidelines, which involves multiplying the activity level of carbon emission sources by their corresponding carbon emission factors. In cases where specific carbon emissions are not covered by GPGGI (such as those arising from tap water, agricultural machinery, agriculture films and ploughing), the carbon emission factor method is then applied.

In addition to CO_2, this study also includes the emissions of two other primary greenhouse gases: CH_4 and N_2O. The N_2O emissions primarily result from fertilizer use, straw returning, fecal management and fuelwood usage, while CH_4 emissions mainly arise from intestinal fermentation, fecal management, fuelwood usage and sewage treatment. Since this study focuses on quantifying total greenhouse gas emissions without distinguishing among the three types individually, they are collectively referred to as carbon emissions in this paper. These emissions are measured in a standardized unit known as carbon dioxide equivalents (t CO_2-e), which represents the quantity of each of the three greenhouse gases multiplied by their respective 100-year Global Warming Potential (GWP_{100}): CO_2 GWP_{100} = 1, CH_4 GWP_{100} = 29.8, N_2O GWP_{100} = 273 [36].

2.4.2. Calculation Method for Carbon Sinks

Considering that ecosystems emit CO_2 through respiration, the calculation of carbon sinks involves reducing carbon emissions from forestry and other land use activities. This study takes into account the carbon emissions from arbor forest. As stipulated in GPGGI [31], the carbon sinks of arbor forest are calculated using the following formula:

$$Carbon\ sinks = (carbon\ stock\ change - consumed\ carbon\ stock) \times 44 \div 12;$$

Carbon stock change (t) is calculated with the following formula:

$$\Delta C_{arbor\ stock} = V_{arbor} \times GR \times \overline{SVD} \times \overline{BEF} \times 0.5;$$

Consumed carbon stock (t) is calculated with the following formula:

$$\Delta C_{cost} = V_{arbor} \times CR \times \overline{SVD} \times \overline{BEF} \times 0.5;$$

V_{arbor}: total storage volume (m^3); GR: annual growth rate of storage volume (%); CR: annual consumption rate of storage volume (%); $\overline{SVD}$: basic wood density (t/m^3); $\overline{BEF}$: biomass conversion coefficient.

Regarding the carbon sinks of bamboo groves, economic and shrub forests, the following formula is used, as stipulated in GPGGI [31]:

$$\Delta C_{bes\ stock} = \Delta A_{bes} \times B_{bes} \times 0.5$$

ΔA_{bes}: annual area change (hm^2); B_{bes}: average biomass per area (t/hm^2).

2.5. Collection Methods for Carbon Activity Levels

The data collection methods employed in this study for determining carbon activity levels are presented below. Table 2 provides the corresponding methods for each emission source.

(1) Field investigation: Initial field investigations are conducted to gain a comprehensive understanding of the target villages, including assessments of land types, industry classification, and the socioeconomic dynamics of local residents.

(2) Questionnaires: Conducting surveys among local residents serves as a crucial approach for collecting data on diverse emission sources. Interviews with the village

committees facilitate the gathering of information on population, industry and land use. Questionnaires administered to local villagers are indispensable in obtaining data regarding daily energy consumption, water usage, and other material applications for buildings and agriculture. Moreover, questionnaires specifically targeted at large-scale livestock breeders collect data associated with livestock-related emissions.

(3) Statistical data: Statistical data is utilized for emissions that are not directly obtainable from questionnaires, including the volume of water usage for irrigation, the usage level of agricultural films, the amount of domestic sewage and the weight of solid waste (Table 2).

(4) Big-data platform: With the advancement of information technology and statistical methods, China has developed various intelligent management platforms based on big-data technologies. In this study, the NFSSMP [37] is utilized to access land use information in detail for villages. The NFSSMP, a platform developed by the National Forestry and Grassland Administration and National Park Administration, offers a GIS-based national forest resources archive information database. This study employs the NFSSMP to obtain the geographic boundaries of villages, forest areas, tree species, diameter at breast height, stock volume per hectare (in 0.1 m^3/ha) and forest stock volume (in 0.1 m^3), which are utilized to calculate carbon sinks.

Table 2. Activity level data and collection sources.

Activity	Unit	Activity Level Data and Collection Sources
Energy		
Electricity	kWh	Questionnaire with villagers
Natural gas	m^3	Questionnaire with villagers
LPG	kg	Questionnaire with villagers
Coal	kg	Questionnaire with villagers
Firewood	kg	Questionnaire with villagers
Gasoline	kg	Questionnaire with villagers
Water		
Volume of tap water	L/person	100 L/d·person, statistical data [38]
Waste		
Weight of solid waste	kg/person	0.775 kg/d·person, statistical data [39]
Weight of sewage	L/person	100 L/d·person, statistical data [38]
Industrial production		
Plastic product output values	CNY	Interview with the factory owner
Chemical product output values	CNY	Interview with the factory owner
Agricultural machinery		
Diesel consumption of farm machinery	Kg	Questionnaire with villagers
Electricity usage for irrigation	kWh/mu *	Calculated with the following formula: Electricity use for irrigation: $E_a = W_a \div C_w \div C_e$ W_a, water use amount per area in Henan: Maize: 91 m^3/mu [40]; Wheat: 161 m^3/mu [41]; C_w, water utilization coefficient: 0.8; C_e, electricity conversion coefficient for irrigation: 3.196 m^3/kWh [42].
Livestock		
Intestinal fermentation—livestock number	-	Questionnaire with owners
Fecal management—livestock number	-	Questionnaire with owners
Crops		
Ploughing—cultivated land area	km^2	Interview with village committee
Pesticide—crop cultivation	kg	Questionnaire with villagers
Agricultural film—cultivation land area	mu	Henan: 1.35 kg/mu, Shandong: 2.76 kg/mu, statistical data [43]
Fertilizer	kg	Questionnaire with villagers
Straw return	kg	Questionnaire with villagers

* Mu is unit for land area used in China. 1 mu equals ~666.7 m^2.

2.6. Collection of Carbon Emission Factors

To ensure enhanced accuracy in the calculation results, this study employs a hierarchical approach for the selection of carbon emission factors. Initially, factors extracted from the latest scientific publications are utilized, followed by regional factors provided by national authority departments. Finally, factors recommended by the GPGGI and IPCC are employed. The detailed carbon emission factors and their references are illustrated in Table 3. Among all the emission factors considered, three specific ones are calculated.

Table 3. Carbon emission factors and corresponding references.

Item	Emission Factor		Unit	Note
		Energy		
Electricity	Henan: 0.435 Shandong: 0.902		t CO_2e/MWh	Assessment based on Lizhe et al., 2020 [44]
Natural gas	1.98		kg CO_2e /m^3	Assessment based on GPGGI [31], with updated average low calorific values in [45]
LPG	3.11		kg CO_2e /kg	
Coal	1.98		kg CO_2e /kg	
Firewood	CH_4: 0.068 N_2O: 0.024		kg CO_2e /kg	
Gasoline	2.93		kg CO_2e /kg	
		Water		
Tap water	0.225		kg CO_2e/m^3	F. Li et al., 2024 [46]
		Waste		
Solid waste	Landfill: 0.423 Incineration: 0.561		kg CO_2e/kg	Li and Jin, 2011 [47]
Sewage treatment	Henan: 0.1305 Shandong: 0.2706		kg CO_2/m^3	Assessment based on electricity consumption [48]
		Industrial production		
Plastic products	2020.7		kg CO_2/10,000 CNY	Yanqiu, 2012 [49]
Chemical products	2573.8		kg CO_2/10,000 CNY	Yanqiu, 2012 [49]
		Agricultural machinery		
Agricultural machinery-diesel	3.10		kg CO_2e/kg	Assessment based on GPGGI [31], with updated average low calorific values in [45]
Electric irrigation	Maize, Henan: 12.4 Wheat, Henan: 21.9		kg CO_2e/mu	Assessment based on the water quota in [40,41] and carbon emission factor of electricity in [44]
		Livestock-Intestinal fermentation		
Cow	2202.5		kg CO_2e/head	GPGGI [31]
Cattle	1322.5		kg CO_2e/head	GPGGI [31]
Buffalo	1762.5		kg CO_2e/head	GPGGI [31]
Sheep	205		kg CO_2e/head	GPGGI [31]
Goat	222.5		kg CO_2e/head	GPGGI [31]
Pig	25		kg CO_2e/head	GPGGI [31]
		Livestock-Fecal management (CH_4)		
	Shandong	Henan		
Cow	208.3	211.3	kg CO_2e/head	GPGGI [31]
Cattle	82.8	118.0	kg CO_2e/head	GPGGI [31]
Buffalo	138.8	206.0	kg CO_2e/head	GPGGI [31]
Sheep	6.5	8.5	kg CO_2e/head	GPGGI [31]
Goat	7.0	7.8	kg CO_2e/head	GPGGI [31]
Pig	127.0	146.3	kg CO_2e/head	GPGGI [31]
Poultry	0.5	0.5	kg CO_2e/head	GPGGI [31]
		Livestock-Fecal management (N_2O)		
	Shandong	Henan		
Cow	615.4	509.6	kg CO_2e/head	GPGGI [31]
Cattle	252.1	239.9	kg CO_2e/head	GPGGI [31]
Buffalo	260.8	256.3	kg CO_2e/head	GPGGI [31]
Sheep	33.7	31.6	kg CO_2e/head	GPGGI [31]
Goat	33.7	31.6	kg CO_2e/head	GPGGI [31]
Pig	52.2	46.8	kg CO_2e/head	GPGGI [31]
Poultry	2.1	2.1	kg CO_2e/head	GPGGI [31]

Table 3. *Cont.*

Item	Emission Factor	Unit	Note
Crops			
Ploughing	1150	kg CO_2e/km^2	Fenlin et al., 2007 [50]
Pesticide	Maize: 8.8 Wheat: 6.2	g CO_2e /kg	Guo, Fei, et al., 2016 [51]
Agricultural film	4.65	kg CO_2e/kg	Lee et al., 2021 [52]
Fertilizer	Settlement: 0.07 Leaching: 0.105	kg CO_2e /kg	Assessment based on GPGGI [31]
	Direct emission: 0.0057	kg N_2O/kg N_{input}	Assessment based on GPGGI [31]
Straw return	Maize: 0.11 Wheat: 0.01	kg CO_2e/kg	Assessment based on GPGGI [31]

2.6.1. Emission Factor for Energy Sources

The following formula, being adjusted based on GPGGI [31], is utilized to calculate the carbon emission factor of energy sources:

$$\textit{Carbon emission factor}\ (\mathrm{kg/kg}) = \textit{average heating value of the energy source}\ (\mathrm{kJ/kg}) \times \textit{carbon amount per unit of heating value}\ (\mathrm{t/tJ}) \times \textit{carbon oxidation rate} \times 44 \div 12 \div 1{,}000{,}000$$

The average heating value of each energy source is cited from [31], while the carbon amount per unit of heating value and carbon oxidation rate are sourced from the updated values of 2020 released in [45].

2.6.2. Emission Factor for Electric Irrigation

The carbon emission factor for electric irrigation commonly used in current studies is derived from the study of [53], which focuses on data from USA and India. However, it fails to account for the specific conditions in China. In China, the Ministry of Water Resources regulates the water volume for irrigation through a quota system.

This study utilizes regional irrigation water quotas delineated in [40,41] to determine the allocated water volume for individual villages. Subsequently, electricity consumption for irrigation is computed by correlating the allocated water volume with the corresponding electricity conversion coefficient (i.e., the water volume supplied per kilowatt-hour of electricity). Finally, based on this computed electricity consumption, a more precise estimation of the carbon emission factor for electric irrigation is determined to provide an accurate depiction of circumstances in China.

2.6.3. Emission Factor for Pesticides

The emission factor for pesticides utilized in recent studies in China is derived from experimental values obtained in the USA [54], which may not accurately reflect the specific circumstances in China. Therefore, our study adopts values from a previous investigation [51], which were calculated based on national questionnaires conducted in Chinese villages in 2012.

2.7. Carbon Emission Calculation for Seven Villages in Northern China

The carbon emission calculation methodology is implemented and applied to villages situated in Northern China, which is a prominent agricultural area. Three villages from Shandong and four villages from Henan provinces were selected, with their geographical locations depicted in Figure 1. Below, we provide essential details and collection methods for assessing carbon emissions.

Figure 1. Map of investigated villages. Base map: northern region of China encompasses Henan province, Shandong province, Hebei province, Beijing and Tianjin. Blue star: locations of three selected villages in Shandong: Zhangjiazhuang, Jiangjia and Qiganshi. Red star: locations of four selected villages in Henan: Miaoqian, Yidoushui, Shangliuzhuang and Zaiwan.

2.7.1. Selection of Investigated Villages in This Study

The selection of the seven villages was primarily considered based on the authors' accessibility for conducting field investigations. However, other factors were also considered. Based on the categorization of life-related carbon emissions [28], these villages fall within the high-to-middle range compared to other regions in China. Additionally, according to agricultural emission data analyzed in [3], the examined area in this paper ranks at a high level due to its elevated economic status, greater reliance on commercial energy resources and increased presence of agricultural residuals. These villages predominantly cultivate maize and wheat as their main crops. Apart from their common characteristics, the seven villages host a diverse range of industries which enable us to examine the impact of different industrial sectors on village-level emissions.

2.7.2. Information of the Investigated Villages

The seven villages exhibit variations in their primary industries, terrains, population and land areas. Their industries encompass grain production, livestock breeding, tourism, fruit cultivation, fishery and plastic/chemical materials production. The terrains span from plains to mountains and coastal regions. Table 4 presents the essential information for the seven villages, including population, number of households, land area, average income, terrain type and primary industry.

Table 4. Basic information of investigated villages.

	Population	Number of Households	Land Area (mu)	Forest Area (mu)	Average Income (CNY/Year·Capita)	Terrain	Primary Industry
Miaoqian, Henan	467	110	6333	103	8000	Plain	Crop cultivation
Yidoushui, Henan	226	68	6867	1418	10,000	Mountain	Environment-based tourism, crop cultivation

Table 4. *Cont.*

	Population	Number of Households	Land Area (mu)	Forest Area (mu)	Average Income (CNY/Year·Capita)	Terrain	Primary Industry
Shangliuzhuang, Henan	1590	384	5067	8	7500	Plain	Pig and cattle breeding, Crop cultivation, plastic and chemical material production
Zaiwan, Henan	820	202	6067	310	25,000	Near mountain	Culture-based tourism, Crop cultivation
Zhangjiazhuang, Shandong	810	380	1620	37	21,000	Plain	Pig breeding, Crop cultivation
Jiangjia, Shandong	400	254	927	158	19,000	Plain	Fruit cultivation, Crop cultivation
Qiganshi, Shandong	1140	443	1020	9	20,000	Near sea	Fishery, Crop cultivation

2.7.3. Data Collection for Carbon Activity Levels

An investigation was conducted in August 2023 across seven villages to collect data for carbon emission calculations. The methods outlined in Section 2.5 were employed to determine activity levels of carbon emission sources, and Table 2 presents the specific method used for each source within the seven villages. Interviews were conducted with village committees, livestock breeders and factory owners, along with 30 questionnaires administered to locals in each village. Despite the limited sample size of the survey, it is worth noting that Chinese villages typically operate small-scale agricultural economies where individual households are granted land-use rights [55], fostering a relatively egalitarian society where the households within the same village share similar lifestyles.

2.7.4. Uncertainty Analysis

The primary source of uncertainty lies in the carbon activity levels and carbon emission factors. Direct collection of local data on specific carbon activities was not feasible, such as the amount of solid waste and sewage, consumption of agriculture films and volume of water used for irrigation; therefore, statistical data were utilized instead. This introduces a certain degree of uncertainty when quantifying carbon emissions. Although this study has incorporated the most up-to-date carbon emission factors available, some factors were obtained from a decade ago, including the ploughing factor updated in 2007, industrial products factor updated in 2012 and solid waste factor updated in 2011. To reduce the uncertainty associated with calculating carbon emissions in the study, it is recommended to introduce more recent and localized carbon emission factors.

3. Results

The total carbon emissions and sinks are recorded in Table 5, while the per capita carbon emissions for the seven villages have been computed and presented in Appendix A.

Table 5. Carbon emissions and sinks of selected villages.

	Carbon Emission (kg)	Per Capita Carbon Emissions (t/Person)	Carbon Sinks (kg)	Per Capita Carbon Sinks (t/Person)
Miaoqian, Henan	650,533	1.39	−21,971	−0.05
Yidoushui, Henan	283,987	1.26	3,323,513	14.71
Shangliuzhuang, Henan	9,136,561	5.75	41,586	0.03
Zaiwan, Henan	2,304,625	2.81	180,555	0.22
Zhangjiazhuang, Shandong	2,259,074	2.79	24,808	0.03
Jiangjia, Shandong	760,617	1.90	221,521	0.55
Qiganshi, Shandong	10,439,904	9.16	3940	0.00

3.1. Result of Carbon Sinks

Comparing the per capita carbon sinks of each village (Table 5) with the national average per capita carbon sinks in 2020 (0.6 t CO_2e/person) [56], most villages exhibit lower levels than the national average, with the exception of Yidoushui. Among the seven villages, Yidoushui stands out with highest per capita carbon sinks at 14.71 t CO_2e/person, followed by Jiangjia and Zaiwan at 0.55 t CO_2e/person and 0.22 t CO_2e/person, respectively. The per capita carbon sinks of villages are strongly correlated with the per capita forest area, which is particularly abundant in these three villages, as indicated in Table 4. Yidoushui's carbon sinks significantly outweigh its carbon emissions due to its extensive mountainous forest coverage, while conversely, the carbon emissions in other villages exceed their carbon sinks by a significant margin. Notably, Miaoqian exhibits negative value of carbon sinks, attributed to a decline in forest area compared to the previous year.

3.2. Result of Carbon Emissions

This study compares the per capita carbon emissions of the seven villages (Table 5) with their corresponding provincial average data. According to the data provided by [57], the average per capita carbon emissions in Shandong province was 10.27 t CO_2e/person in 2021, while it was 5.11 t CO_2e/person in Henan province. It is evident that the per capita carbon emissions in most villages are lower than the provincial averages, with the exception of Qiganshi and Shangliuzhuang.

Figure 2 illustrates the per capita carbon emissions of the seven villages. It is worth noting that Qiganshi exhibits high carbon emissions attributed to agricultural machinery, particularly diesel consumption in fishing boats. Similarly, Shangliuzhuang's carbon emissions from its industrial activities, particularly in plastic and chemical materials production, surpass other carbon sources. Hence, the high carbon emissions in Qiganshi and Shangliuzhuang mostly result from emissions related to their primary industries, namely fishery and industry respectively. Therefore, further analysis is needed to understand the relationship between per capita carbon emissions and the primary industry of each village.

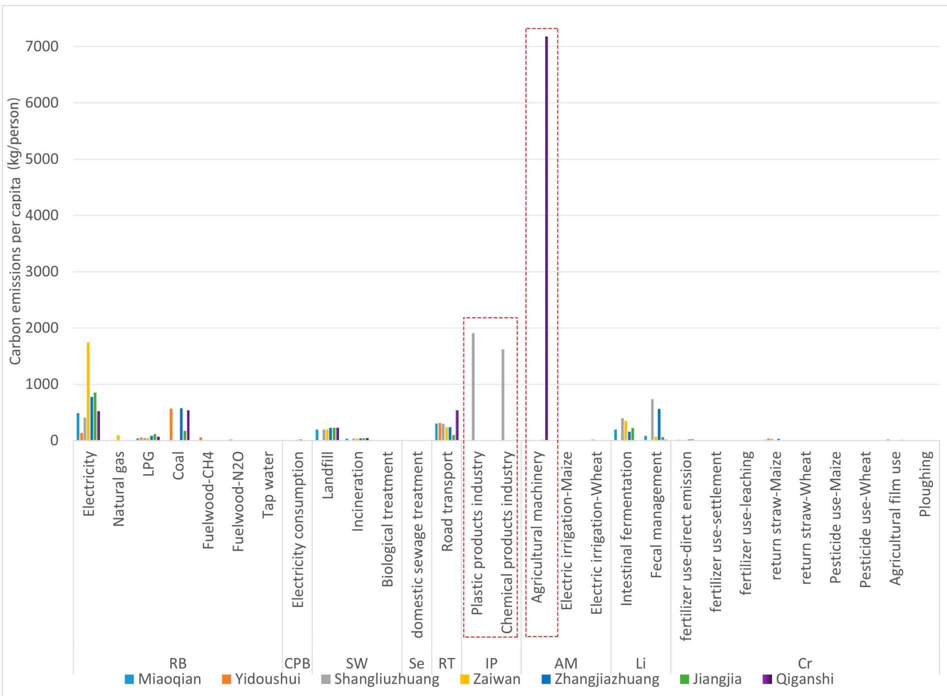

Figure 2. Per capita carbon emissions of selected villages. Note: RB: residential buildings; CPB: commercial and public buildings; SW: solid waste; Se: sewage; RT: road transportation; IP: industrial production; AM: agricultural machinery; Li: livestock; Cr: crops. The red dotted boxes: high carbon emissions in Qiganshi and Shangliuzhuang.

Among the seven villages, Miaoqian solely relies on crop cultivation as its primary industry. In comparison to Miaoqiao, the remaining six villages are categorized into three levels based on their per capita carbon emissions, as follows:

(1) Qiganshi and Shangliuzhuang exhibit per capita carbon emissions ranging from 5 to 9 t/person, with fishery and industrial production as their primary industries. These industries are recognized for their high carbon emissions compared to other sources.
(2) Zaiwan and Zhangjiazhuang exhibit per capita carbon emissions of approximately 3 t/person, with tourism and livestock breeding as their primary industries.
(3) Yidoushui and Jiangjia exhibit per capita carbon emissions below 2 t/person, with tourism and fruit cultivation as their primary industries. The two industries demonstrate relatively low levels of carbon emissions.

Although tourism is the primary industry for both Zaiwan and Yidoushui, their per capita carbon emissions differ significantly. Yidoushui, located in a mountainous area, attracts tourists who prioritize natural sightseeing experiences with shorter stays and simple accommodations, thus resulting in lower carbon emissions compared to Zaiwan. Therefore, the per capita carbon emissions in these villages are highly influenced by their primary industries. Villages in Northern China tend to harbor high-carbon emission industries like fishery, industrial production and livestock breeding.

3.3. Comparison with the Results of Other Studies

The results of this study are compared with those from other studies, with a particular emphasis on the emissions from different rural regions of China as well as emissions from comparable areas at similar spatial scales in various countries.

3.3.1. Comparison with the Results in Other Chinese Villages

Among the several studies cited in Section 1.2, the study of [18] presented a detailed calculation method and findings on carbon emissions from eight villages located in Yangtze River Delta region. Consequently, a comparative analysis is conducted between the results of [18] and those of this study to identify disparities in regions.

Carbon emissions: Despite the carbon emissions from livestock being excluded in [18], the average per capita carbon emissions at 3.13 t CO_2e/person in our study already possesses significantly lower value than that of the Yangtze River Delta region at 6.45 t CO_2e/person. This discrepancy can be attributed to two factors. Firstly, the per capita income of the villages in this study (18,066 CNY/yea·person) is considerably lower than that of the Yangtze River Delta region (13,813 CNY/year·person). Secondly, the industries prevalent in our study differ from those examined in [18], which exhibits relatively higher levels of carbon emissions.

Carbon sinks: Yidoushui is excluded from this comparison due to its significantly extensive mountainous forest coverage, which distinguishes it from the other six villages. The average carbon sinks of the remaining villages (0.13 t CO_2e/person) in the study are considerably lower than that of the Yangtze River Delta region (0.47 t CO_2e/person). Despite a lower average per capita land area in the Yangtze region (0.003 km^2/person) compared to the northern regions (0.006 km^2/person), the forest coverage in the villages within the Yangtze region surpasses that of their counterparts in the latter.

Conclusion: The carbon emissions of the investigated villages in the northern regions are lower than those in the Yangtze River Delta region, primarily attributed to their relatively lower per capita income. The carbon sinks of the investigated villages in the northern regions generally exhibit a lesser magnitude compared to those in the Yangtze River Delta region due to their relatively lower forest coverage.

3.3.2. Comparison with Carbon Emissions of Europe at Similar Spatial Scale

The study of [58] estimated the carbon emissions for the Belgian town of Roeselare without considering carbon sinks, resulting in per capita carbon emissions of 2.88 t CO_2e/person. Similarly, Ref. [24] calculated the carbon emissions of a typical European city neighborhood, yielding per capita carbon emissions of 3.01 t CO_2e/person. These two cases share a comparable spatial scale with Chinese villages. Among the seven villages investigated in this paper, only Shangliuzhuang and Qiganshi exhibit higher per capita carbon emissions compared to Roeselare and the European neighborhood due to significant contributions from industries such as plastic and chemical production in Shangliuzhuang and fishery in Qiganshi. Conversely, the remaining five villages demonstrate lower per capita carbon emissions than those of the two referenced cases.

3.4. Comparison among Different Carbon Emission Sectors

The comparison in carbon emission sectors and subsectors across the seven villages is outlined in Table 6. Among the carbon emission sectors, the sequence of emission sources from high to low is as follows: diesel consumption in fishing boats, manufacturing of plastic/chemical products, energy consumption in buildings, agriculture, transportation and waste disposal.

Table 6. Proportion distribution of different carbon emission categories.

	Miaoqian	**Yidoushui**	**Shangliuzhuang**	**Zaiwan**	**Zhangjiazhuang**	**Jiangjia**	**Qiganshi**
				Sectors			
Energy and water use in buildings	39%	67%	8%	68%	52%	61%	13%
Waste disposal	16%	0%	4%	8%	10%	14%	3%
Transportation	22%	25%	5%	8%	9%	5%	6%
Industry	0%	0%	61%	0%	0%	0%	0%
Agriculture	23%	8%	21%	16%	29%	20%	79%
				Subsectors			
Residential buildings	39%	67%	8%	67%	52%	61%	12%
Commercial and public buildings	0%	0%	0%	1%	1%	0%	0%
Solid waste	16%	0%	4%	8%	10%	14%	3%
Sewage	0%	0%	0%	0%	0%	0%	0%
Road transportation	22%	25%	5%	8%	9%	5%	6%
Industry	0%	0%	61%	0%	0%	0%	0%
Agricultural machinery	0%	0%	1%	0%	0%	1%	78%
Livestock	20%	0%	20%	15%	26%	15%	0%
Crops	3%	7%	1%	1%	3%	4%	0%

3.4.1. Diesel Consumption in Fishing Boats and Manufacturing

In Shangliuzhuang, diesel consumption in fishing boats and plastic/chemical production are the primary contributors of carbon emissions, accounting for approximately 61% and 78% of total carbon emissions, respectively. Therefore, developing low-carbon villages requires a transformation in these two industries. However, such industries are uncommon in the investigated villages. After excluding emissions from the two industries, the relative importance of other emission sources is presented as follows.

3.4.2. Energy and Water Usage in Buildings

As demonstrated in Table 6, the carbon emissions from energy and water usage in buildings account for approximately 30–70% of the total carbon emissions in most villages, except for Shangliuzhuang and Qiganshi. Among all energy sources, electricity and coal usage exhibit the highest emission level as they serve as the primary energy sources. Variations in energy usage emissions among villages stem from different energy source structures and lifestyles. For instance, the carbon emissions from electricity usage in Zaiwan significantly exceed those in other villages due to its reliance on electricity for heat pumps that provide a high level of comfort for tourists, resulting in increased electricity consumption. In contrast, Yidoushui exhibits considerably higher carbon emissions from coal usage than from electricity due to households relying on coal for heating while possessing fewer electrical appliances compared to other villages.

3.4.3. Agriculture

As depicted in Table 6, agriculture accounts for approximately 20% of total carbon emissions in most villages. These emissions primarily originate from livestock breeding and crop cultivation, with minimal contribution from agricultural machinery. As shown in Appendix A, the carbon emissions from livestock breeding far surpass those from crop cultivation in Shangliuzhuang and Zhangjiazhuang, where a substantial number of livestock are raised. Shangliuzhuang hosts 6000 pigs, 200 cattle and 200 sheep, while Zhangjiazhuang raises 2300 pigs. As presented in Appendix A, emissions from straw returning constitute half of the total carbon emissions for crops, being the most significant source in crop cultivation.

3.4.4. Transportation

The proportions of carbon emissions from transportation in most villages range from 5% to 25% of the total carbon emissions, as demonstrated in Table 6. Despite this wide range, the per capita carbon emissions are similar across all of the villages (Table 6). This portion of carbon emissions primarily arises from the gasoline consumption for private cars. Jiangjia stands out with the lowest per capita carbon emission due to its prevalent use of motorcycles for transportation rather than the reliance on private cars, as observed in other villages.

3.4.5. Waste Disposal

According to Table 6, roughly 10% of carbon emissions originate from waste disposal, encompassing solid waste and domestic sewage treatment. Notably, the emissions from sewage treatment are lower in comparison to solid waste disposal, with only Yidoushui and Zaiwan currently possessing sewage treatment facilities among all the investigated villages. In most villages, around 70% of solid waste is managed through landfilling, resulting in a significant level of carbon emissions. However, Yidoushui lacks centralized solid waste processing facilities and resorts to open-air disposal. Although this approach yields zero carbon emissions, it raises concerns regarding local environmental pollution.

4. Discussion

4.1. Findings of Study

The carbon emissions and sinks of the seven villages are compared in this study. Concerning carbon sinks, the per capita carbon sinks in most villages fall below the national average, with the exception of Yidoushui. The per capita carbon sinks in villages are highly relevant with their respective forest areas. Surprisingly, the carbon emissions of most villages exceed their sink levels. Hence, it is crucial to maintain stable forest growth and implement strict deforestation control to foster the development of low-carbon villages.

With the exception of two villages hosting industries with exceptionally high carbon emissions, the per capita carbon emissions in the remaining villages are below the average level of their respective provinces. Notably, primary industries significantly impact carbon emissions. When comparing the villages where crop cultivation serves as the primary industry with others, per capita carbon emissions can be categorized into three levels from highest to lowest. The first level includes villages engaged in fishery and industrial production, the second level comprises villages involved in livestock breeding and catering to high-comfort-need and longer-stay tourism, and the third level encompasses villages which focus on fruit cultivation and catering to low-comfort-need and shorter-stay tourism. These findings highlight the importance of implementing low-carbon industries for developing sustainable rural communities.

Furthermore, a comparative and analytical assessment is conducted on different sectors of carbon emission sources. Excluding the significantly high carbon emissions from fishery and industrial production, the primary sectors that exert influence on carbon emissions in villages, ranked in descending order, include energy consumption in buildings, agriculture, transportation and waste disposal:

(1) Carbon emissions from energy consumption in buildings account for approximately 30–70% of the total emissions, which are influenced by local energy structures and lifestyles.
(2) Agriculture accounts for around 20% of total carbon emissions, primarily coming from livestock breeding and crop cultivation.
(3) Transportation-related emissions range from 5% to 25%, mainly attributed to private car usage.
(4) Waste disposal contributes roughly 10% to the overall emissions.

4.2. Implications

4.2.1. Theoretical Implications

Carbon emission calculation method for small spatial scale: This study presents a comprehensive methodology for quantifying carbon emissions in Chinese villages, employing a localized approach with detailed methods to collect activity levels using updated emission factors. Moreover, this approach can be extrapolated to other spaces with similar spatial scale such as townships and districts. The findings of this study address the existing research gap in quantifying carbon emission at this specific scale in China.

4.2.2. Practical Implications

Necessity for developing low-carbon villages: Among the seven villages, only one village demonstrates its carbon sinks exceeding carbon emissions, while the majority of villages exhibit significant carbon emissions in comparison to their respective carbon sinks. Notably, certain villages display even higher levels of carbon emissions than those observed in the Yangtze River Delta region and the European town along with its neighborhood. These findings underscore the urgent need for policy makers to prioritize addressing carbon emissions in rural areas and emphasize the imperative of developing low-carbon villages.

Formulating quantitative strategies for low-carbon development based on findings: The comparison of carbon emissions across different sectors in villages facilitate a comprehensive understanding of the structural dynamics of carbon emissions. By utilizing calculated carbon emissions and sectoral composition, policymakers can formulate precise low-carbon development strategies that allocate efforts and investment proportionally to each sector's contribution to carbon emissions. Moreover, adopting a quantitative approach to plan low-carbon village development enhances policy coherence and consistency.

Developing low carbon industries: The comparison of the results obtained from this study with those derived from other regions both within China and abroad, as well as the intra-village comparison, collectively demonstrates a significant influence of industries located within villages on total carbon emissions. Therefore, the development of low-carbon villages necessitates the presence of low-carbon industries.

4.3. Limitations

Limited number of investigated villages: Only seven villages have been included in this study due to the constraints of the research period and limited accessibility for field investigation. However, a greater number of investigated villages would enhance the comprehensiveness in representing the selected region.

Statistical data of the region: Owing to the lack of adequate facilities for measuring and recording carbon emission data in these villages, the collection of certain carbon emission activity levels has become a challenge. To bridge this data gap, this study utilized regional statistical data, encompassing solid waste and sewage, agriculture film usage and water consumption for irrigation purposes. However, the statistical data of the region may not accurately reflect the actual situations of local villages.

4.4. Future Study

An increased number of villages in this region should be investigated and assessed. Based on the findings on carbon emissions, a correlation analysis should be performed between village-level carbon emissions and influential factors such as industry types, income levels, terrains, and energy structures. To facilitate an in-depth analysis of their impact on carbon emissions in villages, expanding the investigation scope to encompass a wider range of industries is advised. Furthermore, to acquire more localized and accurate data, it is recommended to deploy equipment within the villages for the purpose of measuring and recording carbon emission data.

5. Conclusions

This study presents an operational approach for calculating carbon emissions from CO_2, CH_4 and N_2O in villages of Northern China based on field investigations. The carbon emission sources in villages are classified into buildings, transportation, industry, agriculture, forestry and other land uses. Seven villages were investigated in this region to estimate their carbon emission activity levels using data collected from field surveys, questionnaires, statistical records and big-data platforms. Their carbon emissions were calculated across the seven villages. The proposed methodology specifically focuses on small spatial scales in rural areas and bridges the gap in research on carbon emission calculation at this scale in Chinese villages. It helps guide low-carbon planning and design at village levels while facilitating the implementation of low-carbon development strategies and policies. These findings offer valuable insights into actual situations regarding carbon emissions in rural areas of Northern China, providing a basis for future in-depth investigations and studies on rural low-carbon development.

6. Recommendations

Based on the carbon emission calculation of the seven villages and their comparative analysis, the following recommendations for low-carbon development of villages in Northern China are formulated:

(1) Carbon Sinks: Forests play a crucial role as the primary source of carbon sinks in villages. Policymakers should enforce stringent measures to prevent deforestation while promoting the expansion of forest areas.

(2) Promoting Low-Carbon Industries: The carbon emissions of villages are significantly influenced by their primary industries. To promote the development of low-carbon villages, it is imperative to foster low-carbon industries while simultaneously implementing initiatives aimed at augmenting villagers' income.

(3) Reducing Building Energy Consumption and Utilizing Renewable Energy: Carbon emissions from the building energy sector exhibit the highest level in most villages. Developing low-carbon villages should prioritize reducing the fossil energy consumption in buildings, particularly coal and fuelwood, while also promoting the adoption of renewable energy sources. However, the utilization of renewable energy remains limited among the surveyed villages, with less than one-third of buildings utilizing solar heaters or PV systems. Therefore, it is imperative to establish an effective system for harnessing renewable energy based on rural building characteristics.

(4) Developing Low-Carbon Livestock Farming and Enhancing Manure Management: Livestock breeding is a key industry in Northern China, characterized by relatively high carbon emissions. To mitigate this aspect of emissions, adjusting the nutritional composition of livestock feed can effectively reduce methane emissions from ruminant animals' digestive systems. Additionally, harnessing manure for household energy and organic fertilizer in agriculture presents an indispensable solution.

(5) Developing Low-Carbon Crop Cultivation: The reduction of carbon emissions from crop cultivation can be achieved through various strategies. It is imperative to control the burial depth and utilize straws for heating or electricity generation in order to mitigate carbon emissions from straw returning. Other decarbonization approaches

encompass the development of efficient techniques for nitrogen fertilizer application, promotion of agricultural film recycling, the adoption of biodegradable agricultural films and the reduction of pesticide usage.

(6) Encouraging Low-Carbon Transportation: The prevalence of private car usage in rural areas can be attributed to the inadequate of public transportation. To foster low-carbon development, it is imperative to bolster public transportation infrastructure for public transportation. Additionally, there should be a concerted effort to encourage the adoption of electrical vehicles and establish an extensive network of charging stations.

(7) Improving Waste Disposal Techniques and Enhancing Sewage Treatment: Conventional methods of solid waste disposal result in significant carbon emissions. It is recommended to advance low-carbon waste management techniques such as harnessing residual heat generated during waste processing for electricity generation. The carbon emissions from sewage treatments are not substantial, while only two villages have sewage treatment facilities. This deficiency significantly impacts the local residential environment, underscoring the necessity to enhance sewage treatment in villages.

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Appendix A

Table A1. Calculated per capita carbon emissions and sinks of investigated villages.

				Per Capita Carbon Emissions and Sinks (kg CO_2e/Person)						
				Miaoqian	**Yidoushui**	**Shangliuzhuang**	**Zaiwan**	**Zhangjiazhuang**	**Jiangjia**	**Qiganshi**
Carbon emissions	Buildings	Residential buildings	Electricity	487	140	408	1742	775	852	521
			Natural gas	0	0	0	93	0	0	0
			LPG	43	54	44	45	85	115	70
			Coal	0	567	0	0	573	174	540
			Fuelwood-CH_4	0	56	0	0	2	10	0
			Fuelwood-N_2O	0	20	0	0	1	4	0
			Tap water	8	8	8	8	8	8	8
		Commercial and public buildings	Electricity	1	2	10	17	19	1	9
		Solid waste	Landfill	196	0	196	196	228	228	228
			Incineration	33	0	33	33	39	39	39
		Sewage	sewage treatment	0	1	0	1	0	0	0
	Transportation	Road transportation	Road transport	301	311	296	233	238	99	538
	Industry	Industrial production	Plastic products industry	0	0	1906	0	0	0	0
			Chemical products industry	0	0	1619	0	0	0	0
	Agriculture	Agricultural machinery	Agricultural machinery—Diesel	3	2	3	2	6	15	7177
			Electric irrigation—Maize	0	0	10	0	0	0	0
			Electric irrigation—Wheat	0	0	18	0	0	0	0
		Livestock	Intestinal fermentation	195	0	400	353	161	222	2
			Fecal management	85	3	733	70	564	61	17
		Crops	fertilizer use-direct emission	7	16	8	3	21	26	3
			fertilizer use—settlement	1	3	1	1	4	5	1
			fertilizer use—leaching	2	4	2	1	5	7	1
			return straw—Maize	15	33	31	7	29	0	0
			return straw—Wheat	1	5	3	1	3	0	0
			Pesticide use—Maize	2	4	4	1	9	11	1
			Pesticide use—Wheat	1	5	3	1	6	8	1
			Agricultural film use	10	21	10	4	12	15	2
			Ploughing	1	1	1	0	1	2	0

Table A1. *Cont.*

				Per Capita Carbon Emissions and Sinks (kg CO_2e/Person)						
				Miaoqian	**Yidoushui**	**Shangliuzhuang**	**Zaiwan**	**Zhangjiazhuang**	**Jiangjia**	**Qiganshi**
Carbon sinks	Forest and land use	Forests	Arbor forests	74	14,394	26	143	31	554	3
			Bamboo groves, economic and shrub forests	−121	312	0	77	0	0	0
Total carbon emissions				1393	1257	5746	2811	2789	1902	9158
Total carbon sinks				−47	14,706	26	220	31	554	3
Net carbon emissions [1]				1440	−13,449	5720	2590	2758	1348	9154

[1] Net carbon emissions equal carbon emissions minus carbon sinks.

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