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Coal Supply Chains: A Whole-Process-Based Measurement of Carbon Emissions in a Mining City of China

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Abstract: The purpose of the study is to understand the carbon emissions in the coal supply chains of a mining city. The paper employed a conceptual methodology for the estimation of carbon emissions in the four processes of coal mining, selection and washing, transportation and consumption. The results show that the total carbon emission of the coal supply chain in Wu'an is up to 3.51×10^{10} kg and is mainly sourced from the coal mining and consumption, respectively accounting for 13.10% and 84.62%, which indicates that deep coal processing plays a more critical determinant in coal production and consumption. Among the pillar industries, the carbon emissions from the steel industry accounts for 85.41% of the total in the coal consumption process, which indicates that the structure of carbon emissions is dependent on the local industrial structure. Additionally, the carbon directly from CO_2 accounts for 89.46%. Our study is not only to be able to supply references for the formulation strategy of a low carbon city, but also to provide a new approach to urban development patterns with a new view for coal resource management.

Keywords: coal supply chain; carbon emission; whole process; mining city; China

1. Introduction

Over the recent decades, global carbon emissions have been experiencing a rapid increase owing to continued incredible economic growth and soaring carbon-intensive fossil-fuel consumption [1–3]. Such a significant increment of carbon emissions may induce climate change, sea level rise, and global temperature increases and shoreline erosion, which bring environmental impacts [4,5]. The IPCC (Intergovernmental Panel on Climate Change) affirms that greenhouse gases (GHG), in particular carbon emissions, from human activities has been the dominant reason for the observed global warming since the mid-20th century [6]. As one manifestation generated by industrialization, the loss of coal reserves has become one cause of man-made environmental liabilities [7], and its production concerns the mitigation of climate change [8]. Currently, coal provides about 30% of global primary energy needs, and remains a key primary energy resource globally [9,10], which consequently creates a big source of greenhouse gas emissions [11]. Environmentally, the country inventories of greenhouse gas emission sources and sinks are requested and commenced with the carbon emission of fossil fuels [12,13]. Crossing the national scale, like the US and Australia [14,15], to the local scale, like the Northwest of the UK [16], Beijing [17], etc., the calculation of carbon emissions generated by the consumption of fossil fuels has been treated as a key governmental task and is the concern of international scientific communities [18].

As a commodity, coal is experiencing the whole process from its production to consumption. The process in this cycle requires inputs and produces outputs, which include both materials and energy, and it transforms and dissipates energy in different ways [19]. To generate energy, the operation phase is extended to the mining and transportation of coal (upstream processes) as well as waste disposal and the recovery of land (downstream processes) [20]. However, at the same time, the various unfavorable environmental effects are simultaneously produced [21], including carbon emissions and their induced disasters [22]. Responding to the whole process of coal exploration and utilization, the carbon footprint is traced and measured by coal supply chains from mining, selection and washing, transportation, distribution and consumption [23,24], especially in the process of power generation [25,26]. Besides, the research into carbon emissions from energy consumption lists is gradually transited to the side view of product consumption [27–29], and the relevant method for carbon emissions is adopted to estimate the emission coefficient of each stage in the coal-extracted and -fired process [30,31]. Clearly, the carbon emissions associated with the coal industry completely follow the whole process from production to consumption [32].

The measure method, material balance method and discharge coefficient method are the three major adopted ways to estimate the carbon emissions from coal and other energy sources [33]. In general, there are two methods to calculate the coal bed methane emissions in the coal mining procedure: one is the IPCC guidelines for national greenhouse gas inventories, which combines the coal bed methane with the coal production [34], and the other is the measure method, including the gas concentration–depth relationship method, mine gas emission method and analogy method [35]. Accordingly, the model analysis method becomes the most effective method due to the complexity of research that carbon emission sources are related to all aspects of human production and living [36–39]. Provably, the framework of carbon emissions in coal power generation, which is composed of coal mining, coal transporting, coal combustion and waste disposal, has been modeled and examined [40].

As reported, it can be argued that the perspectives and objects of these researchers are mainly focused on a single aspect, such as coal-fired electricity or the steel industry chain rather than all industrial sectors which use coal as the main energy power [20,41–44]. Currently, many countries are involved in this research field, including China [45]. In the process of industrialization and urbanization in China, coal consumption accounts for 70% of energy consumption [46], and a characteristic significance exists in that it concentrates on the electricity, steel, cement and chemical industries. Moreover, in the foreseeable future, the coal will remain the dominating fuel and there is a great potential that its demand will be set to increase [47]. Therefore, understanding the carbon flows within the human–environment nexus will help to promote human well-being while protecting the earth's living systems [48]; besides, the carbon emissions in coal supply chains is of great importance for climate change mitigation and associated policy-making in developing countries. Based on these research gaps and possible contributions to urban sustainability, we choose Wu'an, a typical Chinese mining city, as a study case, and attempt to (1) establish the link of carbon emissions and coal supply chains; (2) measure and quantify the carbon emission in coal supply chains from coal mining, selection and washing, transportation, and consumption; and (3) create an understanding of land use changes in mitigating carbon emissions in the process of coal transportation. Our study, which regards the four main coal consumption sectors as a whole object in the coal consumption link, can improve the accuracy and rationality of the coal supply chain system.

2. Materials and Methods

2.1. General Situation of the Study Area

Wu'an, a mining city, belonging to the Hebei Province of China, lies at the eastern foot of the Taihang Mountains, and is located at 113°45′–114°22′ E, 36°28′–37°02′ N (Figure 1), which has a surface area of 1819 km^2. Wu'an is rich in mineral resources, such as coal, iron, cobalt, aluminum. The total coal reserve is up to 2.3×10^9 t, pig iron is as high as 1.61×10^7 t, crude steel is 1.66×10^7 t, and cement is 1.85 × 10^7 t. The rapid industrial development increases the demand for coal resources and results in environmental deterioration.

Figure 1. Location of Wu'an in the Hebei Province of China.

2.2. Data Sources

The data in this study is categorized into three types. The first type is statistical data, including the consumption of coal, cement, electric power, steel, fertilizer production in various industries for the estimation of carbon emissions and local meteorological data for the correction of carbon density. The second type is raster data, including multi-phase remote sensing images, which are used to extract land use types for estimating the underlying indirect carbon emissions from coal transportation. Another type is retrieved from the IPCC guideline for national GHG inventories, including carbon emission coefficients, low calorific values, carbon coefficients of fossil energy, etc. [34].

2.3. Research Methods

2.3.1. Trace of Coal Supply Chains

In a mining city, the whole process of coal production and utilization is actually tied to a supply chain, which in our study is composed of the complete activities, including coal mining, coal selection and washing, coal transportation and finally delivered users or enterprises to finish the final consumption of coal products according to the consumer requirements. The electricity, steel, cement and chemical industries were selected as the four main coal consumers in Wu'an according to a local industrial structure and field investigation. Accordingly, the illustration of carbon emission accounts and sources in the coal supply chains of Wu'an mainly follow the whole process from coal production to consumption (Figure 2). The estimate of CO_2, N_2O and CH_4 emissions is involved in the process. Thus, our study is to make it clear that where the greenhouse gases come from, what role the whole process of coal production and utilization plays and which process is the determinant for carbon emissions in a mining city.

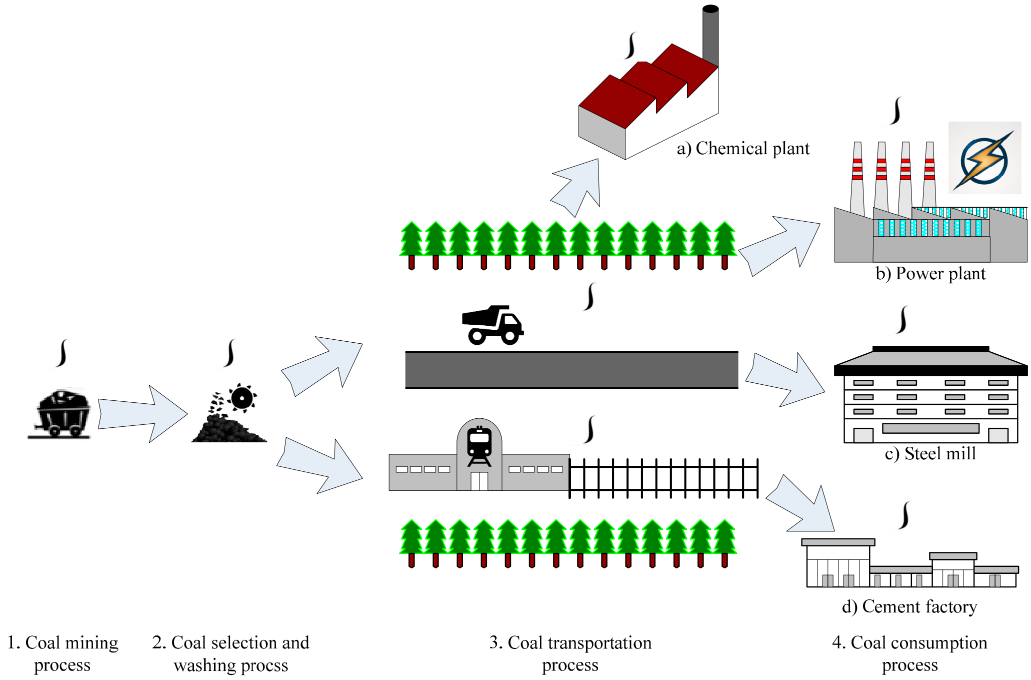


Figure 2. Coal supply chains in Wu'an.

The exploitation method, transportation path, and consumption type are the important sectors that affect carbon emissions in the complete coal supply chain. In the process of coal mining and selection and washing, the main carbon sources are from coal, electricity and energy consumption, and also include coalbed methane released in the mining process [45]. The carbon emissions in the coal transportation process mainly come from energy consumption and carbon sequestration by vegetation loss, as the construction of transport networks used by coal transportation has caused damage to the surrounding vegetation. In the coal consumption section, the carbon resources are mainly from fossil energy consumption, power consumption and chemical reaction to raw material production.

As shown in Figure 2, there are four main carbon-emitting processes in the coal supply chain of Wu'an: coal mining, coal selection and washing, coal transportation, and coal consumption. The carbon emissions in the coal supply chain are measured and summed by the carbon emissions of these four processes (Equation (1)).

$$E_{tc} = E_m + E_{sw} + E_t + E_c \tag{1}$$

where E_{tc} is the total carbon emissions in coal supply chains, E_m is the carbon emissions in the mining process, E_{sw} is the carbon emissions in the coal selection and washing process, E_t is the carbon emissions in the coal transportation process, and E_c is the carbon emissions in the coal consumption process.

2.3.2. Inventory of Carbon Emissions in Coal Supply Chains

Carbon Emissions in the Coal Mining Process

The carbon in the coal mining process is emitted from a coalbed carbon leak, energy consumption and motive power for machinery. The total carbon emissions in this process are calculated by Equation (2).

$$E_m = E_{cl} + E_{ec} + E_{ep} \tag{2}$$

where E_m is the total carbon emissions in mining process, E_{cl} is the coalbed carbon leak in this process, E_{ec} is the carbon emissions caused by energy consumption, E_{ep} is the carbon emissions caused by electricity consumption which provides motive power for running machinery.

(1) Coalbed carbon leaks in the coal mining process

According to the IPCC guideline for national greenhouse gas inventories [34], the coalbed methane emissions in the coal mining process is calculated by the Equation (3).

$$E_{cl} = P_c \times EF_j \times TF_j \times GWP_j \tag{3}$$

where E_{cl} is the energy consumed in the extraction of coal in the mining process, P_c is the amount of coal production, EF_j is the emission factor of greenhouse gas j (Table 1), TF_j is the transfer factor of greenhouse gas j under 20 °C and standard atmospheric pressure, GWP_j is the ratio of the greenhouse effect of a unit weight of greenhouse gas j emission (Table 2), named global warming potential of greenhouse gas j emission. The GWP value is used in the Kyoto Protocol of the United Nations Framework Convention on Climate Change as a metric for weighing the climatic effect of the emission of different GHGs.

Table 1. The factors influencing carbon emissions in coal production.

Mining Type	Mining Depth (m)	Emission Factors (m^3/t)
Underground coal mine	<200	10
	<400	18
	>400	25
Open strip mines	<25	0.3
	<50	1.2
	>50	2

Table 2. GWP values of greenhouse gases *.

GHG	GWP Default Values (g CO_2 Equivalent/g GHG)
CO_2	1
CH_4	23
N_2O	296

* The data was retrieved from the Third Assessment Report of the Intergovernmental Panel On climate Change [6].

(2) Carbon emissions caused by energy consumption

Underground mining is the main approach in Wu'an. The extraction of coal resources generally depends on energy consumption, including direct energy consumption such as the burning of fossil fuels for boilers [49] and the indirect electricity consumption for mining equipment [30]. They are estimated by Equations (4) and (5).

$$DE_{ec} = c_{ffi} \times NHV_i \times cc_i \times or_i \times r_c \tag{4}$$

where DE_{ec} is the direct carbon emission caused by energy consumption in the coal mining process, c_{ffi} is the amount of combusted fossil fuel i, NHV_i is the net heating value of combusted fossil fuel i, cc_i is the carbon content of combusted fossil fuel i, or_i is the oxidation ratio of fossil fuel i, r_c is the conversion ratio between CO_2 and C (44/12). This paper extracts the parameters from the "2006 IPCC Guidelines for National Greenhouse Gas Inventories" [34,50] (Table 3).

$$IE_{ec} = C_e \times P_c \times L_i \tag{5}$$

where IE_{ec} is the indirect carbon emission caused by energy consumption in coal mining process, C_e is the electricity consumption, P_c is the coal equivalent consumption for 1 kWh power, L_i is the emission coefficient of greenhouse gases. The emission coefficient of CO_2 is 840.1914 g CO_2/kWh, and that of N_2O is 0.053352 g CO_2/kWh [30].

Table 3. Net heating values and carbon contents of combusted fossil fuels.

Type	Lower Calorific Value (kJ/kg kJ/m^3)	Carbon Content (kg/GJ)
Raw coal	20,908	25.8
Coke	28,435	29.2
Washed coal	26,344	26.2
Crude oil	41,816	20
Gasoline	43,070	18.9
Kerosene	43,070	19.6
Diesel fuel	42,652	20.2
Natural gas	38,931	15.3

Carbon Emissions in the Coal Selection and Washing Process

Coal spontaneous combustion to a certain degree happens in the process of coal selection and washing [31], besides, electricity consumption also drives the equipment operations in that process, which both induce carbon emissions [43]. Similarly, the carbon is sourced from the two sources of direct and indirect emissions. The Equations (4) and (5) are similarly referenced for the calculation.

Carbon Emissions in the Coal Transportation Process

Mining and land use activities within the transport network are associated with energy consumption and carbon emissions. The sources are mainly from the combustion of fossil fuels for driving transport vehicles and the reduction of carbon sequestration capacity caused by vegetation loss along transportation lines, respectively regarded as direct and indirect carbon emissions.

(1) Direct carbon emissions in the coal transportation process

The calculation of direct carbon emissions is based on the coal transport modes and their corresponding consumption of fossil fuels for driving vehicles. The main means of coal transportation are railway and road in Wu'an and diesel fuels are combusted in the process of railway transport, while the road transport generally uses medium-duty trucks, which also provide the momentum by diesel fuels. The direct carbon emissions in coal transportation are calculated by Equation (6).

$$DE_{ct} = \sum_{i=1}^{n} P_c \times p_i \times l_i \times fc_i \times NHV_i \times cc_i \times or_i \tag{6}$$

where DE_{ct} is the direct carbon emission in the coal transportation process, P_c is the amount of coal production, p_i is the proportion of the transport capacity of mode i to the total, l_i is the average transport length of mode i, fc_i is the fuel consumption of mode i, NHV_i is the net heating value of diesel fuels consumed by mode i, cc_i is the carbon content of diesel fuels consumed by mode i, and or_i is the oxidation ratio of diesel fuels consumed by mode i.

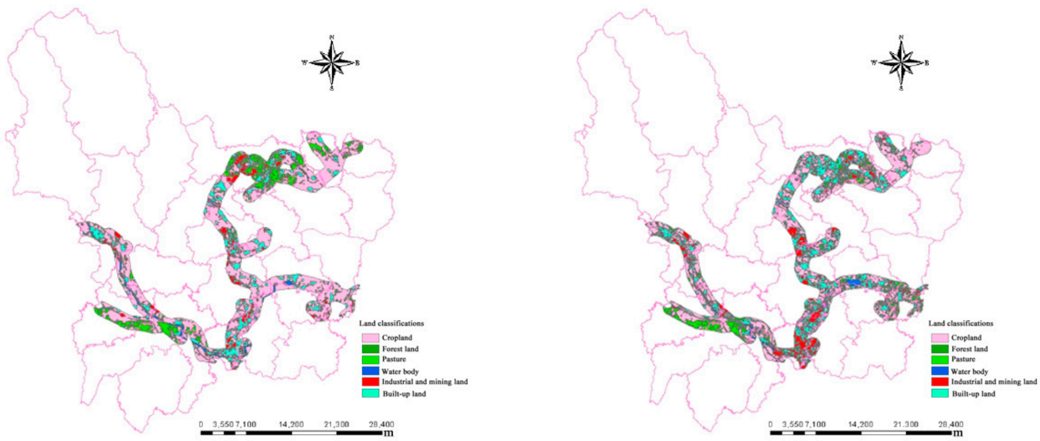
According to the local survey, the ratio of transport volumes by railway and road is 1:3. The transport lengths of railways and roads are 164.78 km and 386.22 km, respectively, which were extracted from the transport network maps. The NHV of diesel fuels is 42,652 kJ/kg (Table 3). The fuel consumption of a diesel locomotive is 24.6 kg/(10^4 t·km) [30]. In general, the fuel consumption of road transport trucks is around 500–700 kg/(10^4 t·km) [51], and the value in this study is 650 kg/(10^4 t·km) according to local transport and vehicle conditions. The carbon content of diesel fuels is 20.2 kg/GJ (Table 3). The oxidation ratio is assumed as 100% (default value).

(2) Indirect carbon emissions in the coal transportation process

The carbon emissions caused by ground vegetation destruction has a profound impact on carbon fluxes [52]. The carbon sequestration capacity of vegetation is lost owing to the land use conversion within coal transport networks [53]. Clearly, land use change is a massive source of carbon emissions and a significant contributor to carbon emissions [54–56]. In Wu'an, long-term coal transportation accelerates the conversion of vegetative cover to bare land, which results in reducing the original vegetation carbon sequestration capacity. Thus, the calculation of carbon sequestration reduction relies on the land transfer matrix, followed by the steps [57]: (1) classify land use types by remote sensing images; (2) extract the transport networks from land use maps; (3) treat railway and road as the center and select 1000 m as the buffer distance acting on the surrounding land types to obtain the land transfer matrix (Figures 3 and 4). The loss of carbon sequestration by land use change along coal transport lines is measured by Equation (7).

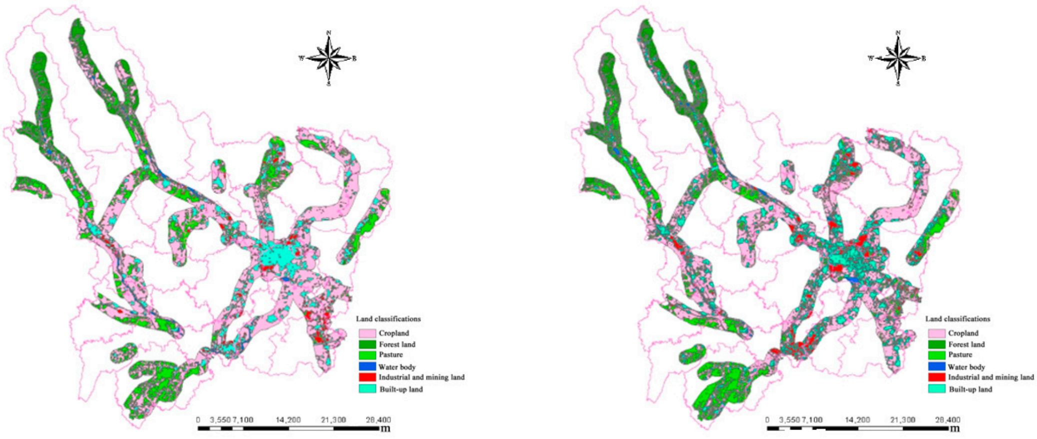
$$L_{cs} = \Delta A_{i-j} \times k = \left(A_i - A_j\right) \times k \quad (7)$$

L_{cs} is the loss of carbon sequestration in coal transportation process, ΔA_{i-j} is the total area of land use type i that is converted to all other land use types j, k is the carbon density of corresponding land type. For cropland subjected to a cycle of planting to harvest within one year, the substantial carbon accumulation by vegetative cover is ignored. Additionally, water bodies play an insignificant role in carbon sequestration, so this part is also ignored. Thus, the carbon densities of forest and pasture are substantially needed, which are determined by the local context (temperature, precipitation, light intensity, etc.) and reported literatures [58–60].



(**a**) 2010 (**b**) 2014

Figure 3. Land use within buffer zones along the railways of Wu'an in (**a**) 2010 and (**b**) 2014.



(**a**) 2010 (**b**) 2014

Figure 4. Land use within buffer zones along the roads of Wu'an in (**a**) 2010 and (**b**) 2014.

Carbon Emissions in the Coal Consumption Process

According to the Wu'an context, the electricity, steel, cement and chemical industries were selected as the coal consumption objects for further study. To avoid double counting, the carbon emissions caused by power consumption in these non-electricity industries will no longer be calculated separately, and the electricity industry is treated as a separate object. The calculation of carbon emissions in different industries are delineated as follows:

(1) Electricity industry

The electricity industry is currently the major driver of coal demand in China. The carbon emission is sourced from the two aspects of coal combustion for power generation and residue disposal. In our study, the estimate of carbon emissions similarly follows Equations (4) and (5).

(2) Steel industry

According to a variety of carbon sources in the steel industry, the carbon emissions come from the combustion of fossil fuels, chemical reactions in the production process, and electricity consumption for driving production. The estimate of the first carbon source is calculated by Equation (4), and raw coal, cleaned coal, coke, diesel fuel and gasoline are involved in the process. The estimate of the third carbon source is included in the calculation of the electricity industry, so this part is ignored. The estimate of the second carbon source is estimated by the reduction reaction for generating carbon dioxide. In general, 70% of consumed coal is used for coking, and 75% of coke is for combustion, and the rest (25%) is regarded as the reducing agent. The reduction reaction [43] and carbon emissions follow Equations (8) and (9)

$$C + Fe_xO_y = CO + Fe,\ CO + Fe_xO_y = Fe + CO_2 \tag{8}$$

$$E_{si} = M_{ra} \times EF \tag{9}$$

where E_{si} is the carbon emission by the reduction reaction in steel production process, M_{ra} is the mass of reducing agent (25% of coke consumption), and EF is the emission factor (here it is 3.1 [12]).

(3) Cement industry

The carbon emissions in the cement industry are sourced from the decomposition of limestone, the combustion of fossil fuels, and electricity consumption for driving production. The estimate of the first carbon source is calculated by Equation (10) [61], and the estimate of the second carbon source is estimated by Equation (4) (raw coal and diesel fuel involved), and the last source is estimated in the electricity industry.

$$E_{ci} = P_{cm} \times p_{ck} \times p_l \times r_c \quad (10)$$

E_{ci} is the carbon emission by the decomposition of limestone in cement industry, P_{cm} is the production of cement, p_{ck} is the proportion of clinker in limestone (here it is 61%), p_l is the proportion of lime in the clinker (here it is 68% [61]), and r_c is the conversion ratio between CO_2 and lime (44/56).

(4) Chemical industry

In our study, the carbon emissions in the chemical industry are sourced from the consumption of fertilizers and electricity consumption for driving production. Similarly, the estimate of electricity consumption is involved in the electricity industry, and the use of fertilizers generates carbon in the steps of production and transportation, expressed by Equation (11).

$$E_{chi} = C_f \times k_f \quad (11)$$

E_{chi} is the carbon emission caused by the consumption of fertilizers in the chemical industry, C_f is the consumption of fertilizers, and k_f is the summed coefficient of carbon emissions in the steps of production and transportation (here it is 857.54 g/kg [62]).

2.3.3. Analysis and Interpretation

To cater for the research objectives, we employed the comparative analysis method and the statistical analysis method to recognize the critical devotion(s) to carbon emissions in the coal supply chains. This study conducted three layers for comparative and statistical analyses of separate process types, industrial types and greenhouse gas types. The results are mainly characterized by the structure of carbon emissions in these layers, and the possible causes and effects are analyzed to link the coal supply chain.

3. Results and Analysis

3.1. Calculation of Carbon Emissions in Coal Supply Chains

3.1.1. Carbon Emissions in the Coal Mining Process

According to the carbon sources in coal mining, the carbon emissions were calculated from coalbed carbon leaks and energy consumption.

(1) By coalbed carbon leak

The coal mining process generally leaks CH_4 and CO_2. In 2014, the production of coal in Wu'an was 9.44 million tons, and the mining depth was more than 400 m. According to the Equation (3), the emissions of CH_4 and CO_2 are estimated as follows:

CH_4: $9.44 \times 10^6 \times 25 \times 0.67 = 1.58 \times 10^8$ kg CH_4 = $1.58 \times 10^8 \times 23$ kg CO_2 = 3.64×10^9 kg CO_2
CO_2: $9.44 \times 10^6 \times 25 \times 0.8 = 1.89 \times 10^8$ kg CO_2
Total: $3.64 \times 10^9 + 1.89 \times 10^8 = 3.83 \times 10^9$ kg CO_2

(2) By energy consumption

As analyzed above, the energy consumption in the coal mining process mainly comes from two sources: coal consumption for heating boilers in the mining area and electricity consumption for the mining equipment [45]. The two categories of carbon emissions are calculated by Equations (4) and (5).

- Coal consumption for heating boilers:

CO_2: $27.2 \times 9.44 \times 10^6 \times 20{,}908 \times 25.8 \times 10^{-6} \times 44/12 = 5.08 \times 10^8$ kg CO_2

- Electricity consumption for mining equipment:

  CO_2: 33.7 × 9.44 × 10^6 × 840.1914 × 10^{-3} = 2.67 × 10^8 kg CO_2

  N_2O: 33.7 × 9.44 × 10^6 × 0.053352 × 10^{-3} = 1.70 × 10^4 kg N_2O = 1.70 × 10^4 × 296 kg CO_2 = 5.03 × 10^6 kg CO_2

  Total: 2.67 × 10^8 + 5.03 × 10^6 = 2.72 × 10^8 kg CO_2
- Total:

  CO_2: 5.08 × 10^8 + 2.72 × 10^8 = 7.80 × 10^8 kg CO_2

(3) Total carbon emissions in the coal mining process

The total carbon emission in coal mining process is summed by the emissions caused by coalbed carbon leaks and energy consumption.

CO_2: 3.83 × 10^9 + 7.80 × 10^8 = 4.61 × 10^9 kg CO_2

3.1.2. Carbon Emissions in the Coal Selection and Washing Process

In coal selection and washing, the source of carbon emissions is from electricity consumption by equipment and spontaneous coal combustion. It is estimated that, at the present stage in China, the energy consumption per ton of raw coal for the selection and washing processes is approximately 3 kWh, and the spontaneous loss rate is approximately 1%. Therefore, the carbon emissions in this process include:

- By coal combustion:

  CO_2: 9.44 × 10^9 × 1% × 20,908 × 25.8 × 10^{-6} × 44/12 = 1.87 × 10^8 kg CO_2
- By electricity consumption:

  CO_2: 9.44 × 10^6 × 3 × 840.1914 × 10^{-3} = 2.38 × 10^7 kg CO_2

  N_2O: 9.44 × 10^6 × 3 × 0.053352 × 10^{-3} = 1.51 × 10^3 kg CO_2 = 1.51 × 10^3 × 296 kg CO_2 = 4.50 × 10^5 kg CO_2

  Total: 2.38 × 10^7 + 4.50 × 10^5 = 2.43 × 10^7 kg CO_2
- Total carbon emission in coal selection and washing process:

  CO_2: 1.87 × 10^8 + 2.43 × 10^7 = 2.11 × 10^8 kg CO_2

3.1.3. Carbon Emissions in Coal Transportation Process

(1) Direct carbon emissions in coal transportation

- By railway transport:

  CO_2: 944 × 25% × 24.6 × 164.78 × 42,652 × 20.2 × 10^{-6} × 44/12 = 3.02 × 10^6 kg CO_2
- By road transport:

  CO_2: 944 × 75% × 650 × 386.22 × 42,652 × 20.2 × 10^{-6} × 44/12 = 5.61 × 10^8 kg CO_2
- Total:

  CO_2: 3.02 × 10^6 + 5.61 × 10^8 = 5.64 × 10^8 kg CO_2

(2) Indirect carbon emissions in coal transportation

As mentioned above, the 1000 m buffer zones were made along transport lines, and the transfer matrix of land use within buffer zones was extracted through the geographic information system (GIS) (Table 4). It is clear that, before and after intensified mining activities, a lot of cropland, forest, pasture and water bodies are encroached on by industrial and mining land as well as associated built-up land.

Table 4. Railway/road buffer transfer matrix of land use.

Land Use Type	Built-Up Land (ha)	Industrial and Mining Land (ha)
Cropland	6.12/8.00	0.63/0.61
Forest	0/0.09	0/0
Pasture	2.26/3.32	1.09/0.91
Water body	0.54/0.99	0.06/0.12
Built-up land	20.16/37.77	3.19/3.03

According to the Equation (7), the carbon emissions by the reduction of vegetative cover are:

- By forest:

  CO_2: $0.09 \times 73.24 \times 10^3 \times 44/12 = 2.42 \times 10^4$ kg CO_2
- By pasture:

  CO_2: $(2.26 + 1.09 + 3.32 + 0.91) \times 6.20 \times 10^3 \times 44/12 = 1.72 \times 10^5$ kg CO_2
- Total:

  CO_2: $2.42 \times 10^4 + 1.72 \times 10^5 = 1.96 \times 10^5$ kg CO_2

(3) Total carbon emissions in the coal transportation process

The total carbon emissions in the coal transportation process are summed by direct and indirect carbon emissions.

CO_2: $5.64 \times 10^8 + 1.96 \times 10^5 = 5.64 \times 10^8$ kg CO_2

3.1.4. Carbon Emissions in the Coal Consumption Process

(1) Electricity industry

The electricity consumption of Wu'an in 2014 was $346{,}028 \times 10^4$ kWh. Therefore, the carbon emissions of the electricity industry are measured by:

CO_2: $346{,}028 \times 10^4 \times 840.1914 \times 10^{-3} = 2.91 \times 10^9$ kg CO_2

N_2O: $346{,}028 \times 10^4 \times 0.053352 \times 10^{-3} = 1.85 \times 10^5$ kg N_2O $= 1.85 \times 10^5 \times 296$ kg CO_2 $= 5.48 \times 10^7$ kg CO_2

Total: $2.91 \times 10^9 + 5.48 \times 10^7 = 2.96 \times 10^9$ kg CO_2

(2) Steel industry

- By the combustion of fossil fuels:

  a. Raw coal:

     CO_2: $41.70 \times 10^7 \times 20{,}908 \times 25.8 \times 10^{-6} \times 44/12 = 8.25 \times 10^8$ kg CO_2

  b. Cleaned coal:

     CO_2: $233.26 \times 10^7 \times 26{,}344 \times 26.209 \times 10^{-6} \times 44/12 = 5.90 \times 10^9$ kg CO_2

  c. Coke:

     CO_2: $610.19 \times 10^7 \times 28{,}435 \times 29.2 \times 10^{-6} \times 75\% \times 44/12 = 1.39 \times 10^{10}$ kg CO_2

  d. Diesel fuel:

     CO_2: $1.08 \times 10^7 \times 42{,}652 \times 20.2 \times 10^{-6} \times 44/12 = 3.41 \times 10^7$ kg CO_2

  e. Gasoline:

     CO_2: $0.00476 \times 10^7 \times 43{,}070 \times 18.9 \times 10^{-6} \times 44/12 = 1.42 \times 10^5$ kg CO_2

  Total: $8.25 \times 10^8 + 5.90 \times 10^9 + 1.39 \times 10^{10} + 3.41 \times 10^7 + 1.42 \times 10^5 = 2.07 \times 10^{10}$ kg CO_2

- By chemical reaction

  CO_2: 610.19 × 10^7 × 25% × 3.1 = 4.73 × 10^9 kg CO_2
- Total carbon emissions in the steel industry (electricity consumption not included)

  CO_2: 2.07 × 10^{10} + 4.73 × 10^9 = 2.54 × 10^{10} kg CO_2

(3) Cement industry

- By the combustion of fossil fuels

  a. Raw coal:

     CO_2: 17.04 × 10^7 × 20,908 × 25.8 × 10^{-6} × 44/12 = 3.37 × 10^8 kg CO_2

  b. Diesel fuel:

     CO_2: 0.0179 × 10^7 × 42,652 × 20.2 × 10^{-6} × 44/12 = 5.65 × 10^5 kg CO_2

     Total: 3.37 × 10^8 + 5.65 × 10^5 = 3.38 × 10^8 kg CO_2

- By the decomposition of limestone

  CO_2: 313.10 × 10^7 × 68% × 61% × 44/56 = 1.02 × 10^9 kg CO_2
- Total carbon emissions in the cement industry (electricity consumption not included)

  CO_2: 3.38 × 10^8 + 1.02 × 10^9 = 1.36 × 10^9 kg CO_2

(4) Chemical industry

The consumption of fertilizers in Wu'an in 2014 was 1.84 × 10^4 t. Therefore, the carbon emissions of the chemical industry are measured by:

CO_2: 1.84 × 10^7 × 836.08 × 10^{-3} = 1.54 × 10^7 kg CO_2

(5) Total carbon emissions in the coal consumption process

CO_2: 2.96 × 10^9 + 2.54 × 10^{10} + 1.36 × 10^9 + 1.54 × 10^7 = 2.97 × 10^{10} kg CO_2

3.2. Inventory of Carbon Emissions in Coal Supply Chains

According to the measurement model of carbon emissions in coal supply chains, the carbon emissions in different processes can be calculated and compared by using the normalized CO_2 equivalents, and thereby the total and subtotal carbon emissions are obtained (Table 5).

Table 5. Carbon emissions in the coal supply chains of Wu'an.

Process			GHG Type	GHG Emission (kg)	CO_2 Equivalent (kg)	Subtotal (kg)	Subtotal′ (kg)	Total (kg)
Mining	Coalbed carbon leak		CO_2 CH_4	1.89 × 10^8 1.58 × 10^8	1.89 × 10^8 3.64 × 10^9	3.83 × 10^9	4.61 × 10^9	3.51 × 10^{10}
	Energy consumption		CO_2 N_2O	7.75 × 10^8 1.70 × 10^4	7.75 × 10^8 5.03 × 10^6	7.80 × 10^8		
Selecting and washing	Coal combustion		CO_2	1.87 × 10^8	1.87 × 10^8	1.87 × 10^8	2.11 × 10^8	
	Electricity consumption		CO_2 N_2O	2.38 × 10^7 1.51 × 10^3	2.38 × 10^7 4.50 × 10^5	2.43 × 10^7		
Transportation	Direct emission		CO_2	5.64 × 10^8	5.64 × 10^8	5.64 × 10^8	5.64 × 10^8	
	Indirect emission		CO_2	1.96 × 10^5	1.96 × 10^5	1.96 × 10^5		
Consumption	Electricity industry		CO_2 N_2O	2.91 × 10^9 1.85 × 10^5	2.91 × 10^9 5.48 × 10^7	2.96 × 10^9	2.97 × 10^{10}	
	Steel industry	Combustion of fossil fuels Chemical reaction	CO_2 CO_2	2.07 × 10^{10} 4.73 × 10^9	2.07 × 10^{10} 4.73 × 10^9	2.54 × 10^{10}		
	Cement industry	Combustion of fossil fuels Decomposition of limestone	CO_2 CO_2	3.38 × 10^8 1.02 × 10^9	3.38 × 10^8 1.02 × 10^9	1.36 × 10^9		
	Chemical industry		CO_2	1.54 × 10^7	1.54 × 10^7	1.54 × 10^7		

3.3. Analysis and Interpretation

3.3.1. Analysis by Different Processes

Based on the streamlined assessment methodology above, it can be concluded that the total carbon emissions of the coal supply chains in Wu'an is up to 3.51×10^{10} kg. Clearly, the carbon emissions in the coal supply chains are mainly sourced from coal mining and consumption, respectively accounting for 13.10% and 84.62% of the total (Table 6). That is to say, the end consumption of coal resources is the greatest contributor to the carbon emissions of a mining city, which can be the entry point to mitigate the negative effects. Besides, it was found that deep coal processing accelerates the conversion and release of carbon contained in coal resources.

Table 6. Structure of carbon emissions in different processes.

Processes	Carbon Emission (10^{10} kg)	Proportion (%)
Mining	0.46	13.10
Selecting and washing	0.02	0.57
Transportation	0.06	1.71
Consumption	2.97	84.62
Total	3.51	100

3.3.2. Analysis by Different Industrial Types

Among the industries, the carbon emissions from the steel industry accounts for 85.41% of the total in the coal consumption process, which indicates that the local pillar industry plays a critical role in carbon emissions, see Table 7. Due to the support of the electricity industry for all production operations, coal-fired power also plays a critical role in carbon emissions, and it may even last in Wu'an for the long term. The structure of carbon emissions in different industries is characterized by industrial and economic structures. If the carbon emissions from the electricity consumption in non-consumption processes is categorized as the inventory of the "electricity industry", the total carbon emissions in this industry can reach 3.26×10^9 kg CO_2 (mining process—2.72×10^8 kg, selecting and washing process—2.43×10^7 kg and consumption process—2.96×10^9 kg) accounting for 10.85% (with an increase of about 1%). Even in that case, the steel industry is still the biggest source among the pillar industries in Wu'an, accounting for near 85%. Even so, the carbon emission generated by the steel industry is sourced by the combustion of fossil fuels in the production, rather than the steel itself. Clearly, the industrial structure in a mining city basically determines the structure of carbon emissions.

Table 7. Structure of carbon emissions in different industry types.

Industrial Types	Carbon Emission (10^{10} kg)	Proportion (%)
Electricity industry	0.296	9.95
Steel industry	2.540	85.41
Cement industry	0.136	4.57
Chemical industry	0.002	0.07
Total	2.974	100

3.3.3. Analysis by Different Greenhouse Gas Types

In Wu'an, the coal supply chain generally generates three main types of greenhouse gases, including CH_4, N_2O and CO_2. The carbon from CO_2 accounts for 89.46% of the total, and the equivalent CO_2 converted from CH_4 is also an important source for carbon emissions (Table 8). The majority of these emissions results from direct coal combustion. Clearly, the direct carbon emissions are sourced from carbon-related greenhouse gases.

Table 8. Structure of emitted greenhouse gases in the coal supply chains.

Greenhouse Gases	Equivalent Carbon Emission (10^{10} kg)	Proportion (%)
CO_2	3.14	89.46
N_2O	0.01	0.28
CH_4	0.36	10.26
Total	3.51	100

4. Conclusions and Discussion

4.1. Main Achievements

In China, the emergence and development of mining cities mainly depends on coal supply chains, which furnish the energy and economic momentum. Therefore, to achieve a low carbon economy in coal supply chains is the emphasis of sustainable development in mining cities. This study employed a conceptual methodology for the estimation of the whole process-based carbon emissions in a Chinese mining city. The coal supply chain was established from the four processes of coal mining, selection and washing, transportation and consumption. Furthermore, a more comprehensive coal consumption system was established, and the coal consumers in our study were extended to the steel, cement and chemical industries, rather than the simply calculation of coal-fired power plants. The research results show that the end consumption of coal resources is the greatest contributor to the carbon emission of Wu'an, and the local pillar industry plays a critical role.

Human requirements and activities determine land use [63,64], while land use is one of the impact factors of key underlying carbon emissions in coal transportation. Especially in our study, land use change and its impacts on carbon sequestration from coal transportation were considered in the measurement. The analysis of the impact of transport networks on carbon sequestration capacity is the difficulty of the research, but it is also the breakthrough and innovation which relies on the correct interpretation of remote sensing images. We attempted to employ the land use transfer matrix within transport network buffers through remote sensing (RS) and geographic information system (GIS) platforms. Energy consumption is considered an important step to support regional carbon emission mitigation policies. For the coal supply chain, the biggest carbon emissions contributor to a mining city, understanding the carbon flows in the supply chain becomes a precondition for the mitigation of greenhouse gas emissions and for providing systematic regulation and management by the government conveniently.

4.2. Limitations and Uncertainties

The research on the carbon emissions in the coal supply chain is mainly sourced from the whole coal-extracted and -fired process, which determines the carbon emission system of a mining city. As reported, city carbon emissions mainly can be divided into the four types of direct emissions, responsible emissions, indirect emissions and logistic emissions [65]. Based on the comparative analysis, it was found that the coal supply chain also has the same four types of carbon emissions. Direct emissions are represented as carbon emissions caused by local coal production and consumption. Indirect emissions are the consumption of other products that are introduced into the supply chain. At the same time, the coal production not only provides their own energy needs, but a part is delivered to the surrounding towns for energy support, which is regarded as responsible emissions. Moreover, there is also the logistics emission mainly reflected in the transit of coal freight services. Our study adopts a relatively independent objective perspective to study the carbon emissions of a coal supply chain that strips the responsible emissions and logistic emissions, and regards the direct emissions and indirect emissions as the study objects from the entire range independently. This is an innovation point of the article but also the limitation in a sense, a further study needs to pay close attention to the two types of carbon emissions.

After our field investigation in the coal-related industries, it was found that the power supply for most of the large- and medium-scale industries is mostly sourced from themselves (self-generating electricity). In order to know the entirety of carbon emissions in each process of coal supply chains, this paper basically followed the original way of power generation in these industries. Thus, the understanding of carbon emissions in the consumption process deserves further debate. However, the analysis in Section 3.3.2 indicates that the structure of carbon emissions in our study is dependent on the local industrial structure. In addition, as the data cannot be acquired, the coefficients in coal mining and processing were estimated according to the relevant literatures. This may result in a certain deviation in the calculation. Therefore, a further study needs to conduct investigations into the actual production process of urban industries and local factors of the study area to improve the accuracy and precision.

4.3. Implications for Environmental Management

With growing concerns over anthropogenic climate change, an appropriate understanding of the carbon emission characteristics of coal supply chains from an environmental perspective is required. Our study provided the results of carbon emissions in coal supply chains, from coal mining, selection and washing, transportation to consumption, analyzed the carbon resources of each section and sought reduction directions, which provides a basis for evaluating the clean production and consumption of coal resources in a mining city.

In addition, China is the largest coal producer and consumer in the world and also the biggest carbon emission country, caused by coal production and consumption. The coal field focused on production is not only the main energy manufacturing unit, but also the energy consumption unit. Coal production, processing and utilization generates a lot of GHGs that place a severe burden on the environment, and the coal utilization problems of low efficiency and serious environmental destruction become a great challenge for the coal industry and even the whole society. Environmentally, future mineral extraction should be targeted at mineral production efficiency, and the coal supply chain should be focused on unit GDP energy consumption and energy efficiency. Local government also has to pay attention to the ecological damage and restoration of mineral extractions [66]. The accurate calculation of carbon emissions in the each process of coal supply chains is an important indicator for understanding the effect of coal-fired industries on global warming. Therefore, our study is not only able to supply references for the formulation strategy of a low carbon city, but also to provide a new approach to urban development patterns with a new view for coal resource management.

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