Resources Policy 64 (2019) 101506

Contents lists available at ScienceDirect

Resources Policy

journal homepage: http://www.elsevier.com/locate/resourpol

Temporal and spatial evolution of global iron ore supply-demand and trade structure

Yunting Song, Wang Nuo*, Anqi Yu

School of Transportation Engineering, Dalian Maritime University, Dalian, 116026, China

ARTICLE INFO

Keywords:
Iron ore
Supply-demand
Transport
Distribution
Field theory

ABSTRACT

Driven by economic demand, the world's iron ore production has been on the rise since the 1970s. The total production has increased 1.77 times, with an average annual growth rate of 2.24%, indicating that iron ore production has become a large-scale industry. The total output of iron ore in international trade has increased 4.35 times, with an average annual growth rate of 3.72%, iron ore has become one of the main seaborne cargo. The above supply-demand structure suggests that the world's steel industries are mainly supported by sea-transportation across the northern and southern hemispheres, and the continued supply from specific countries. There is almost no alternatives. Such a fragile industrial chain is obviously not conducive to the security of the world economy, and it also buries potential risks for the development of related industries. This analysis reveals that it has become an important task for relevant countries to formulate new economic policies to deal with the unbalanced supply-demand and trade structure of iron ore resources in the world.

1. Introduction

Iron ore is the basic raw material in the steel industry. As an important strategic resource, the production and consumption of iron ore has an important impact on the world economy. Different countries have different iron endowments, and iron ore demand is also quite different around the world. Thus, the global supply-demand structure for iron ore has great geographical differences. Under the background of global economic integration, the spatial scale and scale effect of iron ore flowing around the world are undergoing a series of significant changes. Therefore, it is of great value to study the temporal and spatial evolution of the global iron ore supply-demand structure.

With regard to iron ore supply and demand, scholars have analysed iron ore's development strategies (Wu et al., 2016), the influencing factors of iron ore's demand in major countries (Yin and Chen, 2013) and the world (Kozawa and Tsukihashi, 2009, 2010); Using optimization algorithm (Ma et al., 2013), supply-driven model (Mohr et al., 2015), material flow method (Pauliuk et al., 2012) and method considering stock hypothesis (Hatayama et al., 2010) to forecast iron ore's supply and demand in major countries and the world. On iron ore trade, some scholars have analysed the trans-Atlantic (Inwood and Keay, 2015), Asia-Pacific (Wilson, 2012), Asian (Hurst, 2015) and Chinese (Yue et al., 2016) iron ore markets in detail from different perspectives, revealed the competitive intensity among iron ore importing countries (Li et al., 2018; Hao et al., 2018).

Geographically, the flow of iron ore is the physical movement among the areas of production and consumption. By visualizing the flow of iron ore as the motion of particle, and considering the motive of flow as the function of some force, the field theory can be applied to reveal the generation reasons and operation mechanism of iron ore flow. There are many studies on natural resources from the perspective of supply, demand and flow (Fesharaki, 1996; Klein, 2009; Wang et al., 2014; Zhang et al., 2012), among which the field theory has a wide range of applications, such as spatial structure analysis of coal flows (Song and Wang, 2019a) and oil flows (Zhao and Wang, 2010, 2011), spatial characteristics of population migration (Ding et al., 2005).

Through the analysis of the above literatures, it is found that although there are some studies on the supply-demand or trade of iron ore, they generally focus on the influence factors of iron ore market and the prediction of iron ore production and consumption. However, no study has been devoted to exploring the long-term evolution of global iron ore's supply-demand and trade structure. Accordingly, this paper takes 1971–2017 as the research period, introduces the field theory to study the generation and operation mechanism of iron ore, and uses the concept of weight entropy to analyse the stability of the trade structure of major trading countries. The main contributions of this paper are as

* Corresponding author.
E-mail addresses: songyunting@dlmu.edu.cn (Y. Song), wangnuodl@126.com (N. Wang), yuanqidlmu@163.com (A. Yu).

https://doi.org/10.1016/j.resourpol.2019.101506
Received 27 November 2017; Received in revised form 17 June 2019; Accepted 19 September 2019
Available online 24 September 2019
0301-4207/

follows: ① presenting the evolution of the production and consumption structure of the world iron ore for 47 years; ② revealing the characteristics of iron ore trade structure by using the method of weight entropy; ③ analysing the evolution characteristics of flow field distributions and the flow traces by using field theory; and ④ putting forward policy suggestions on ensuring the stable supply and transportation safety of iron ore worldwide, and promoting the sustained and healthy development of iron ore industry.

The remainder of this paper is organized as follows: Section 2 is the methodology and data sources used in this paper. Section 3 presents the production and consumption structure of the global iron ore market. Section 4 presents the spatial structure of the iron ore flow around the world. Section 5 analyses the characteristics of the flow field. The conclusions and discussions are summarized in Section 6.

2. Methodology and data sources

2.1. Methodology

From the basic concept of field theory, the gradient force between the high- and low-potential centres is the motivating force of iron ore flow (Zhao et al., 2007). Positive potential values refer to the volume of iron ore outflow, which describes the possibility of iron ore output and forms a high potential array in economic space; negative potential values refer to the volume of iron ore inflow, which describes the possibility of iron ore input and forms a low potential array in the economic space. The output region is the "source" of the iron ore flow, and the input region is the "destination" of the iron ore flow. The trail between the "source" and the "destination" is the "flow trace". In all of the regions considered for iron ore movement, the source, the destination and the flow trace all correspond to definite quantities.

① Classification of the flow balance types in each region.

The flow balance type determines whether a region i mainly takes in iron ore, mainly sends out iron ore, or plays a conductive role. The paper defines the ratio between iron ore production and consumption of region i as a self-sufficiency rate to classify the flow balance type (Zhao et al., 2007). The self-sufficiency rate is expressed as follows:

$$r_i^t = \frac{p_i^t}{c_i^t} \times 100\% \tag{1}$$

where r_i^t is the self-sufficiency rate of region i in year t, p_i^t is the iron ore production of region i in year t, and c_i^t is the iron ore consumption of region i in year t.

When $r_i^t \leq 50\%$, region i is defined as an ingathering region; when $50\% < r_i^t \leq 100\%$, region i is defined as self-sufficient region; and when $r_i^t > 100\%$, region i is defined as a payout region.

② Classification of liquidity types in each region.

Compared with the balance type, the liquidity types determine how iron ore will flow in a certain region. This paper defines the ratio between the iron ore input and output in region i as the liquidity ratio (Zhao et al., 2007). The liquidity ratio is expressed as follows:

$$R_i^t = \frac{O_{p_i^t}}{I_{p_i^t}} \tag{2}$$

where R_i^t is the liquidity ratio of region i in year t, $O_{p_i^t}$ is the iron ore output of region i in year t, and $I_{p_i^t}$ is the iron ore input of region i in year t.

In this paper, $R_i^t < 1$ indicates that the input is greater than the output, and the smaller the value of R_i^t is, the more likely the flow pattern of region i tends to flow in. $R_i^t > 1$ indicates that the output is greater than the input, and the greater the value of R_i^t is, the more likely the flow pattern of region i tends to flow out. The input centre is where the iron ore inflow is much larger than the outflow, and the output centre is where the outflow is much larger than the inflow.

③ Trade structure security and standard weight entropy.

In the social sciences, entropy is used to describe the disorder degree of a system. The less the entropy of the system is, the more orderly the system is and the more inhomogeneous the spatial structure is. Conversely, if the system is more unorderly, then the spatial structure is more homogeneous. Thus, the study uses weight entropy to characterise the trade homogeneity of the trade structure of country i (Cheng et al., 2013).

Specifically, J_i^{out} denotes the homogeneity of the output structure, and the expression is as follows:

$$J_i^{out} = -\sum_{j=1}^{N} \varphi_{ij} \ln\varphi_{ij} \tag{3}$$

In equation (3), ϕ_{ij} is the importance of the weight, means the importance of w_{ij} to the total output volume of output country i, the expression is as follows:

$$\varphi_{ij} = w_{ij} \Big/ \sum_{j=1}^{N} w_{ij} \tag{4}$$

Additionally, J_i^{in} denotes the homogeneity of the input structure, and the expression is as follows:

$$J_i^{in} = -\sum_{j=1}^{N} \varphi_{ji} \ln\varphi_{ji} \tag{5}$$

In equation (5), ϕ_{ji} denotes the importance of the weight, means the importance of w_{ji} to the total input volume of input country i, the expression is as follows:

$$\varphi_{ji} = w_{ji} \Big/ \sum_{j=1}^{N} w_{ji} \tag{6}$$

Based on the concept, the entropy describes the degree of homogeneity of the system. When the system is completely homogeneous, $\varphi_{ij} = 1/K_i^{out}$ (or $\varphi_{ji} = 1/K_i^{in}$), weight entropy is maximised, i.e. $J_i^{max} = \ln K_i$. When the trade structure is concentrated in one country, the space structure is the most inhomogeneous, i.e. $K_i = 1$, $\varphi_{ij} = 1$ (or $\varphi_{ji} = 1$), and weight entropy is minimised, i.e. $J_i^{min} = 0$. To eliminate the influence of the trade volume on the comparison of weight entropy, the weight entropy of spatial structure is normalised to obtain the standard weight entropy J_i^s. The expression is as follows:

$$J_i^s = (J_i - J_i^{min}) \big/ (J_i^{max} - J_i^{min}) \tag{7}$$

2.2. Data sources

The data used for the production, input and output were summarized from the "Steel statistical yearbook" (1981–2016), which was issued by the World Steel Association. Data regarding the iron ore trade comes from the United Nations Database on Commodities and Trade.

3. Iron ore production and consumption structure

3.1. The production structure

The reserves of iron ore in the world are relatively rich. Although mining activities have increased year by year, the reserves of iron ore are still increasing due to continuous improvements in exploration technology. The production of iron ore in the world shows an increasing trend in general, and has increased 1.77 times between 1971 and 2017 (Fig. 1 and Fig. 2). The following results can be determined from the graph.

(1) The production of iron ore in Asia has increased and reached its highest historical value in 2007. From 1971 to 2007, production increased from 102.99 million t to 660.43 million t, with an average annual growth rate of 5.30%. In that time period, Asia's proportion of the world total production has increased from 13.20% to 38.72%, and the average proportion is 23.18%. After 2007, which was marked by a decline in iron ore production in China, the total production of iron ore in Asia also declined and decreased to 400.32 million t by 2017, with an average annual decline rate of 4.88%.
(2) The production of iron ore in Oceania has continued to grow, and has increased 13 times between 1971 and 2017. The proportion of the world total production rose from 8.03% to 41.08%. Australia is the main source of iron ore in Oceania, accounting for 99.07%–99.61% of the Oceania's total production.
(3) The production of iron ore in South America increased from 79.14 million t in 1971 to 465.59 million t in 2017. Brazil has become a major producer, growing from 38.00 million t to 435.53 million t, increasing 10.46 times. In 2001, South American iron ore production was the highest of all continents, and its proportion of the world's total production reached 26.06%. After 2001, the proportion decreased abruptly, accounting for only 21.56% in 2017. The reason is that the increase in world iron ore production is far greater than the increase in South America.
(4) Iron ore production in Europe decreased and then increased. From 1971 to 1998, production dropped from 348.21 million t to 153.17 million t, showing a decline of 56.03%. Then, production fluctuated and increased from 156.61 million t to 207.21 million t, with an average annual growth rate of 1.60%, increased slowly. The Soviet Union (the Soviet Union and Russia, after the breakup of the Soviet Union, are listed as European countries, the same below) was a large producer of iron ore before the disintegration, with an average annual production of 235.63 million t from 1971 to 1991, which accounts for 26.34% of the world total production. After the collapse of the Soviet Union, iron ore production in Russia and Ukraine ranked in the top two in Europe.
(5) Production in North America has remained at approximately 100 million t in recent years, but the world share shows a decreasing trend. The proportion declined from 16.67% to 5.27%, showing a total decrease of 68.39%.
(6) From 1971 to 2017, the average annual iron ore production in Africa was 59.87 million t. South Africa has the largest share among the African countries, with an average annual production of 34.02 million t, accounting for more than half of all production in Africa.

Overall, the most significant changes in the world iron ore production structure have occurred in the most recent 15 years. The production rankings at the country level have reversed, and Europe has been replaced by Oceania as the world iron ore production centre. The production volume in Oceania and South America accounted for more than 60% of the world total production. At the country level, the production of iron ore in the Soviet Union ranked first in the world between 1971 and 1991, during which its highest production values reached to 250.90 million t a year. After the collapse of the Soviet Union, China and Brazil successively became the largest producers of iron ore in the world. In 2008, iron ore production in Australia began to exceed that in Brazil, achieving a ranking of first in the world, followed by Brazil. Iron ore production in China reached an all-time high of 401.90 million t in 2007. Iron ore production in the United States has declined, and its world share has fallen by 8.32%. The proportion of the world total production in Russia, Ukraine and South Africa is relatively small and has been declining because their growth rates are far lower than those of Australia, Brazil and other countries.

3.2. The consumption structure

The consumption of iron ore in the world lacks direct statistical data, but 99% of iron ore is used to produce crude steel (Chen and Xu, 2007), so the consumption of iron ore in each region can be calculated using the production of crude steel (Fig. 3 and Fig. 4).

As shown in Fig. 3, the world iron ore consumption increased 178.81 million t between 1971 and 2000, with an average annual growth rate of 0.69%. After 2000, global iron ore consumption increased rapidly, rising from 930.37 million t to 2.05 billion t in 2017. According to regional level, the growth of iron ore consumption in Asia had the greatest impact on the world market. In the 30 years between 1971 and 2000, Asian consumption only increased 272.54 million t, with an average annual growth rate of 3.16%. But in the past 17 years of this century, it has increased 1.15 billion t. By contrast, the consumption of iron ore in South America has been low (100 million t), and Brazil is the largest consumer among the South American countries. Most of the developed countries in Europe and North America experienced an adjustment in industrial structure and the implementation of strict environmental protection policies that resulted in a decrease of iron ore demand. The

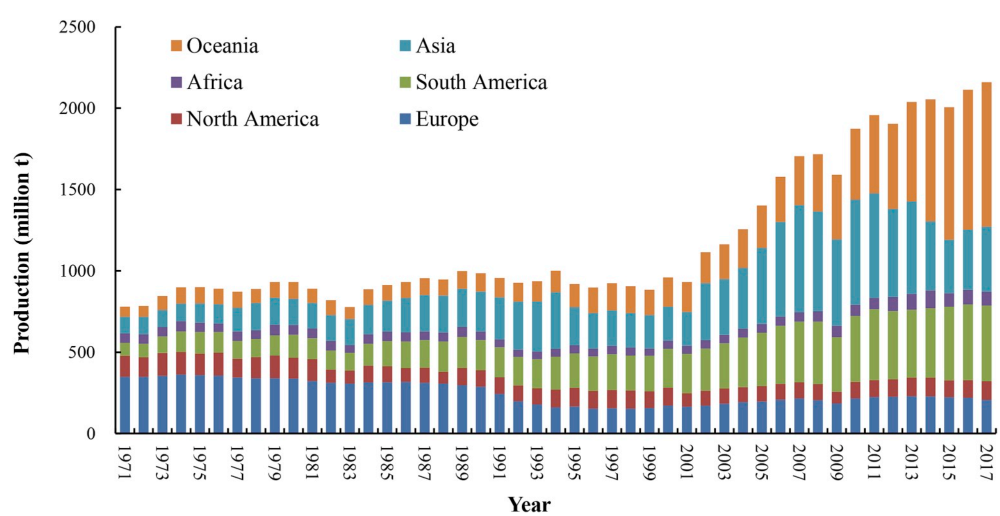


Fig. 1. Production of iron ore in each continent.

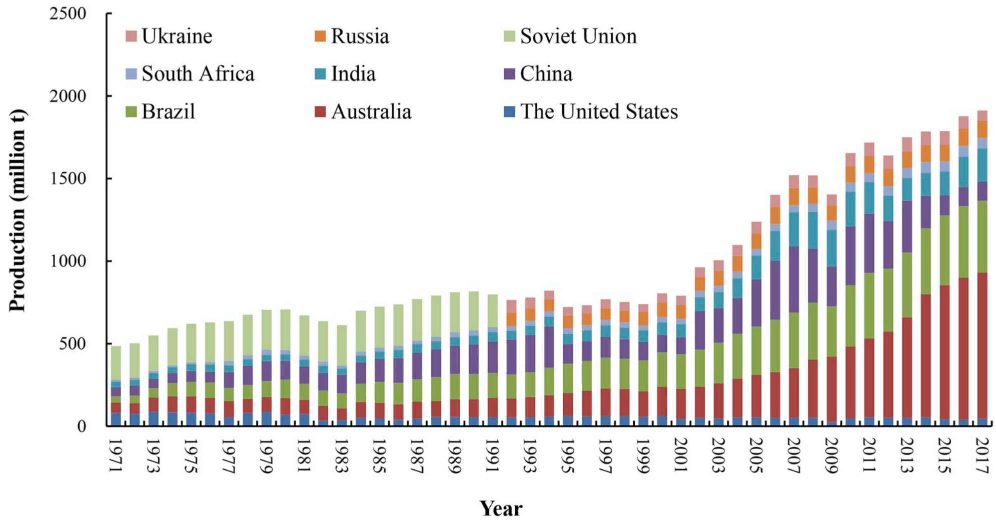


Fig. 2. Production of iron ore in major countries.

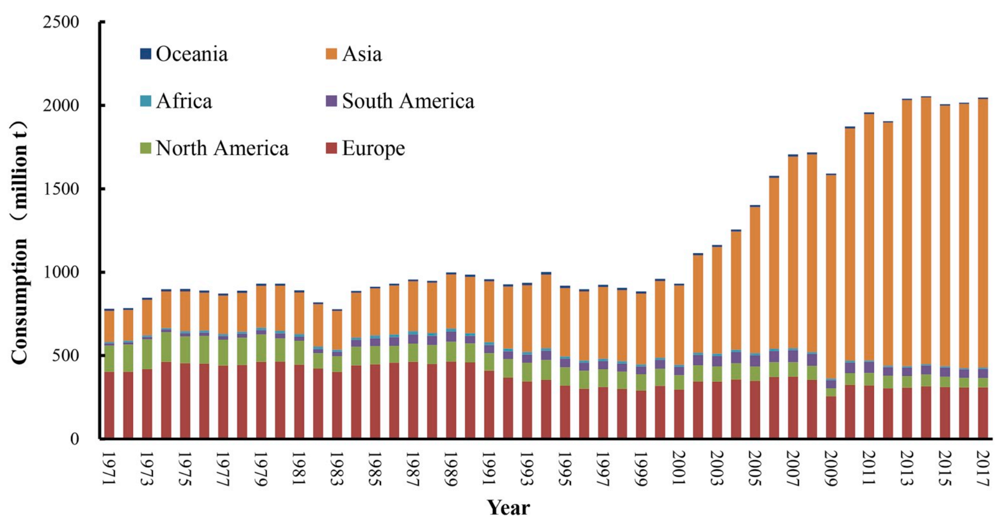


Fig. 3. Consumption of iron ore in each continent.

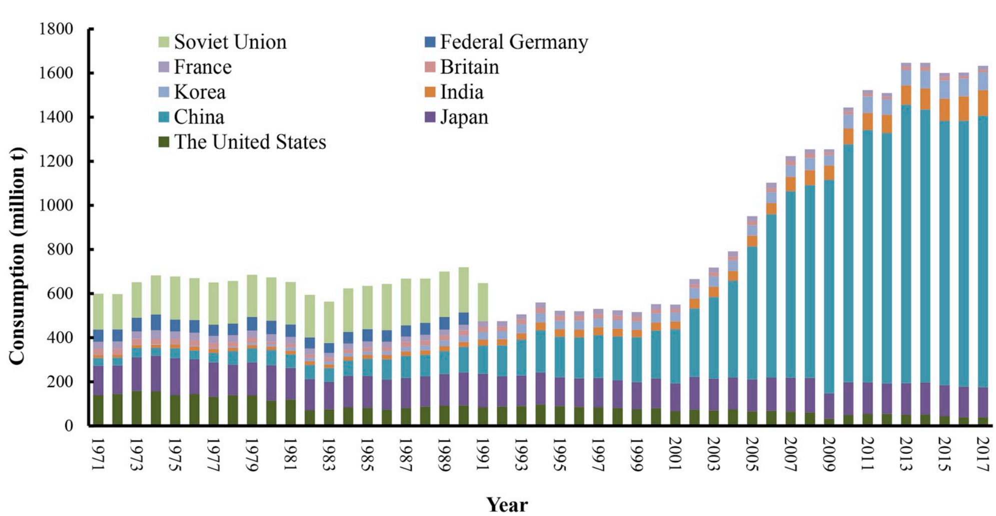


Fig. 4. Consumption of iron ore in major countries.

demand in Europe and North America decreased from 402.45 to 158.22 million t to 308.89 and 57.12 million t, respectively. The steel industry shrank and almost disappeared in these areas. Iron ore consumption in Oceania and Africa fluctuated approximately 100 million t, which is considered to be negligible in magnitude.

Base on the analysis, between 1971 and 1991, Europe was the iron ore consumption centre of the world, whose average annual consumption accounted for 49.31% of the world total. Of the European countries, the Soviet Union, the Federal Republic of Germany (combined with democratic Germany as Germany in 1990), the United Kingdom and France are major iron ore-consuming countries. The next largest consumer continent is Asia, with an average annual consumption of 28.97% of the world total. In Asian countries, the major consuming countries are Japan and China. Since 1991, the average annual consumption of iron ore in Asia has reached 898.09 million t, accounting for 64.38% of the world total. In contrast, the consumption in Europe has dropped to 328.37 million t, accounting for 23.54% of the world total, which is far less than Asia.

In general, world iron ore consumption is mainly driven by Asia and Europe. In recent years, with the decline in European and the rapid growth in Asian, the difference between the two continents is increasing. Asia has gradually become the new "engine" of world iron ore consumption growth.

3.3. The balance types

Based on formula (1), the self-sufficiency rate of European is in the range of 50%–100% from 1971 to 2017, which makes it a self-sufficient region in general. However, different countries in Europe have different balance types. For example, the United Kingdom is a net ingathering country. France was a net payout country at first, and then changed to a net ingathering country. Sweden is a net payout country. North America transformed from a self-sufficient type to a net payout type, and among the North American countries, Canada is a net payout country and the United States is basically a self-sufficient country. South America, Africa and Oceania are all net payout types. In those continents, Australia, Brazil and South Africa are all net payout type countries. The self-sufficiency rate of Asia has been declining, as it changed from a self-sufficiency type to a net ingathering type. In Asian countries, China has become the largest iron ore ingathering country because of its limited domestic iron ore production. Japan and South Korea are short of resources, so they have always been net ingathering countries. India is a net payout country (Table 1 and Table 2).

4. The spatial structure of iron ore flow

4.1. The output structure

World iron ore output basically showed an increasing trend between 1971 and 2017. From 1971 to 2000, world iron ore output increased from 306.20 million t to 499.03 million t, with an average annual growth rate of 1.7%. From 2001 to 2017, there was a surge in output from 493.28 million t to 1.64 billion t, with an average annual growth rate of 7.80% (Fig. 5).

From the regional level, Europe, South America and Oceania were the top three continents in total iron ore output from 1971 to 1973, with an average annual outputs of 91.70, 71.30 and 60.85 million t, respectively. This accounted for 28.18%, 21.91% and 18.7% of world total output, respectively. From 1974 to 2007, South America have risen to the largest iron ore producer, followed by Oceania, and gradually widening the gap with the third-place continent. The average annual outputs of the two continents are 145.65 and 124.63 million t, respectively, accounting for 32% and 27.38% of the world total output. In 2008, iron ore output in Oceania began to exceed South America, making it the world's largest exporter of iron ore. From 2008 to 2017, the average annual output in Oceania was 602.83 million t, which was far higher than 357.18 million t of South America. Oceania accounts for 46.60% of the world total output, whereas South America accounts for only 27.61%. At the country level, the iron ore output in Australia, Brazil, South Africa and other countries showed a substantial increase between 1971 and 2017. By 2017, the proportion of the world total output for the three countries reached 53.23%, 23.39% and 4.05%, respectively. In contrast, iron ore output and the corresponding proportion for France, Sweden, India and other countries all declined to different degrees (Table 3 and Table 4).

Iron ore output were increased in all continents. Due to differences in resource endowments, economic development and trade policy, the growth of each continent is different, Oceania and South America increased faster. In terms of the proportion of the world total output, the iron ore output sources are increasingly concentrated in Oceania and South America.

4.2. The input structure

Due to differences in resources reserves, some regions and countries must rely on the input of iron ore to meet the needs of development, which is presented as the increase of iron ore input. In the 30 years

Table 1
Trends in iron ore flows in each continent (million tons).

Continent		Year				
		1971/1980	1981/1990	1991/2000	2001/2010	2011/2017
Europe	Production	348.21/337.41	322.29/287.52	244.64/171.70	164.77/215.84	223.95/207.21
	Consumption	402.54/463.06	445.35/459.55	409.48/318.44	296.01/324.25	321.04/308.89
	Balance type	Self-sufficient	Self-sufficient	Self-sufficient	Self-sufficient	Self-sufficient
North America	Production	130.10/127.63	135.91/101.36	100.97/110.35	82.49/101.40	104.61/113.84
	Consumption	158.22/140.83	143.68/113.10	105.12/102.63	86.85/71.05	74.77/57.12
	Balance type	Self-sufficient	Self-sufficient	Self-sufficient turned to payout	Self-sufficient turned to payout	Payout
South America	Production	79.14/142.44	127.92/185.61	185.04/239.03	242.42/405.96	435.64/465.59
	Consumption	13.68/28.20	23.51/45.73	48.02/52.66	49.01/62.56	66.57/54.63
	Balance type	Payout	Payout	Payout	Payout	Payout
Africa	Production	57.43/58.71	60.67/52.97	47.27/49.21	49.79/69.06	69.98/85.66
	Consumption	9.56/18.09	17.99/16.96	18.56/14.19	12.88/12.18	9.87/8.93
	Balance type	Payout	Payout	Payout	Payout	Payout
Asia	Production	102.99/162.83	155.76/245.53	259.94/210.04	208.13/646.38	643.77/400.32
	Consumption	186.13/268.37	248.09/336.64	364.24/458.67	474.98/1391.73	1474.88/1608.66
	Balance type	Self-sufficient	Self-sufficient	Self-sufficient turned to ingathering	Ingathering	Ingathering
Oceania	Production					
	Consumption	11.46/12.78	12.07/12.46	11.83/12.74	10.56/12.09	10.51/7.70
	Balance type	Payout	Payout	Payout	Payout	Payout

(*Data source*: Steel Statistical Yearbook).

Table 2
Trends in iron ore flows in major countries (million tons).

Country		Year				
		1971/1980	1981/1990	1991/2000	2001/2010	2011/2017
The United States	Production	82.12/70.73	75.19/55.46	55.52/63.09	45.78/49.90	54.70/47.64
	Consumption	139.05/114.21	119.49/92.58	83.80/79.72	66.75/48.63	53.61/38.83
	Balance type	Self-sufficient	Self-sufficient	Self-sufficient	Self-sufficient turned to payout	Payout turned to self-sufficient
Brazil	Production	38.00/113.02	97.85/152.30	150.66/208.83	210.00/372.00	397.00/435.53
	Consumption	8.61/23.24	19.32/39.41	43.10/46.16	43.42/56.08	59.09/49.28
	Balance type	Payout	Payout	Payout	Payout	Payout
South Africa	Production	10.40/25.74	25.30/30.29	28.96/33.71	34.76/55.00	52.90/62.26
	Consumption	8.18/13.22	13.19/11.66	13.23/10.48	9.23/9.84	8.16/7.54
	Balance type	Payout	Payout	Payout	Payout	Payout
China	Production	55.00/112.58	104.59/179.34	190.56/105.26	102.00/357.00	358.90/115.50
	Consumption	34.89/69.66	61.17/116.26	128.49/218.14	246.59/1079.02	1144.63/1232.22
	Balance type	Payout	Payout	Payout turned to ingathering	Ingathering	Ingathering
India	Production	34.31/40.68	41.62/53.70	56.88/74.95	79.21/209.00	191.80/201.82
	Consumption	12.82/15.59	16.96/22.37	26.92/35.50	34.68/71.67	77.36/115.82
	Balance type	Payout	Payout	Payout	Payout	Payout
Japan	Production	1.42/0	0/0	0/0	0/0	0/0
	Consumption	133.58/159.46	143.31/149.54	151.91/134.99	124.98/149.07	143.70/135.80
	Balance type	Ingathering	Ingathering	Ingathering	Ingathering	Ingathering
Australia	Production	62.06/99.16	84.66/109.17	117.13/176.30	181.14/432.78	477.33/883.36
	Consumption	11.46/12.78	12.07/11.42	10.70/11.74	9.54/10.88	9.34/6.52
	Balance type	Payout	Payout	Payout	Payout	Payout

(*Data source*: Steel Statistical Yearbook).

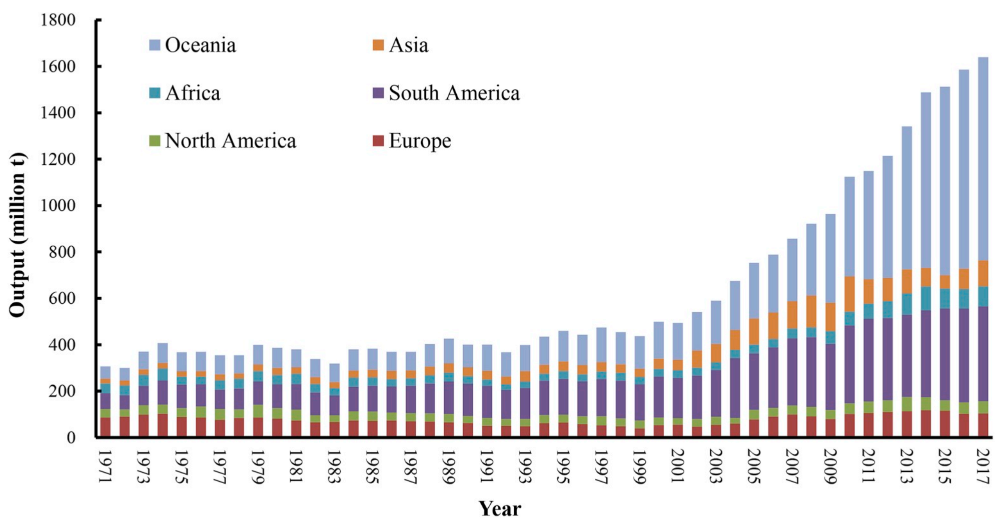


Fig. 5. Output of iron ore in each continent.

preceding 2000, the average annual growth rate of world iron ore input was 1.68%. In the subsequent 17 years, the average annual growth rate was 7.36%, increased 3.38 times (Fig. 6). On the whole, the world's iron ore output is slightly higher than the input, which may be due to statistical errors and different data sources, but does not affect the analysis results of the article.

As shown in Fig. 6, the growth of world iron ore input is mainly driven by Europe and Asia. However, as time goes by, the leading position has reversed. Asia has more inputs than Europe now, and the gap between the two continents is widening. Before 1991, the average annual input of Europe was 180.94 million t, accounting for 49.65% of the world total. The following continent was Asia, with an average annual input of 147.60 million t, accounting for 40.5% of the world total. Since 1991, the iron ore input in Asia has surged, reaching 1.37 billion t in 2017 and showing a 1.26 billion t increases compared to 1991, increased 6.36 times. In 2017, the world share of Asia was up to 87.14%, whereas that of Europe fell to 10.71%, which was no longer comparable to that of Asia.

As shown in Table 4, the country that displays most obvious increase in iron ore input is China. In 1971, China's input was 0 million t, whereas in 2017, it was as high as 1.08 billion t, accounting for 65.59% of the world total. Although the inputs of Japan, Holland and France increased, their proportions of the world total declined. For example, in 2017, Japan's input increased 11.73 million t compared to 1971, but the corresponding proportion dropped 28.68%.

Further analysis revealed that, in 1971, the world's main iron ore input regions were Europe and Japan. The total input of the two regions was up to 273.58 million t, accounting for 83.28% of the world total. In 2017, iron ore inputs in China, Japan and South Korea reached 1075.40, 126.53 and 72.43 million t, respectively, ranking the top three input nations in the world. The total inputs for the three countries accounted for 77.73% of the world total. The results indicated that iron ore inputs are becoming more and more concentrated in Asia.

4.3. *The liquidity structure*

The liquidity types for each region and country were calculated using formula (2). The liquidity ratios in Europe and Asia are less than 1,

Table 3
Iron ore output (million t), input (million t) and flow ratio in each continent.

Continent		Year				
		1971/1980	1981/1990	1991/2000	2001/2010	2011/2017
Europe	Output	86.29/81.70	73.37/62.77	50.73/53.73	55.35/101.44	105.03/104.31
	Input	157.78/195.58	130.87/187.37	173.99/188.30	169.15/172.34	165.91/169.06
	Liquidity ratio	0.54/0.42	0.56/0.34	0.29/0.29	0.33/0.59	0.63/0.62
North America	Output	36.65/44.77	47.09/30.55	33.73/32.74	28.10/46.25	50.39/51.90
	Input	41.93/31.33	34.57/22.70	18.76/25.31	18.84/15.97	14.11/16.91
	Liquidity ratio	0.88/1.45	1.34/1.35	1.79/1.32	1.47/2.88	3.57/3.07
South America	Output	69.17/102.50	110.21/139.18	138.16/176.92	173.02/335.43	356.90/408.72
	Input	0.76/1.89	2.28/4.18	3.40/7.80	8.12/10.91	11.62/8.77
	Liquidity ratio	69/51	55/34.75	46/22.13	21.63/30.45	30.71/46.6
Africa	Output	41.06/40.50	44.53/32.39	27.52/32.47	33.61/59.08	64.95/86.49
	Input	0/0	0/2.07	2.78/5.70	4.98/6.95	4.92/7.92
	Liquidity ratio	–	–	9.33/5.33	6.8/8.43	13.20/10.92
Asia	Output	20.38/30.46	27.73/38.29	37.74/44.28	45.64/153.23	105.19/112.43
	Input	114.90/159.01	142.66/183.63	197.98/281.83	303.82/860.12	938.83/1374.98
	Liquidity ratio	0.17/0.19	0.2/0.21	0.19/0.16	0.15/0.18	0.11/0.08
Oceania	Output	52.66/86.72	77.32/97.17	112.70/158.90	157.57/428.20	465.86/875.68
	Input	0/0	0/1.10	2.95/1.86	1.80/5.50	4.99/0.34
	Liquidity ratio	–	–	37.67/79.5	79.00/71.33	93.2/2575.53

(*Data source*: Steel Statistical Yearbook).

Table 4
Iron ore output (million t), input (million t) and flow ratio in major countries.

Country		Year				
		1971/1980	1981/1990	1991/2000	2001/2010	2011/2017
America	Output	3.09/5.78	5.64/3.51	4.05/6.15	5.61/9.95	11.07/10.61
	Input	40.55/25.46	28.78/18.08	13.34/15.68	10.65/6.42	5.27/6.37
	Liquidity ratio	0.07/0.24	0.21/0.22	0.31/0.38	0.55/1.67	2.10/1.67
Brazil	Output	31.00/78.96	85.80/114.30	114.68/160.11	155.74/310.93	330.83/383.54
	Input	0/0	0/0	0/0	0/0	0/0
	Liquidity ratio	–	–	–	–	–
South Africa	Output	3.30/13.14	13.71/17.03	15.83/21.40	23.52/47.97	53.34/66.43
	Input	0/0	0/0	0/0	0/0	0/0
	Liquidity ratio	–	–	–	–	–
India	Output	20.38/26.19	23.93/31.59	31.54/34.92	36.61/95.93	39.16/28.06
	Input	0/0	0/0	0/0.51	0.30/0.45	1.32/5.36
	Liquidity ratio	–	–	–	–	39/5.23
China	Output	0/0	0/0	0/0	0/0	0/0
	Input	0/75.24	33.36/14.19	19.04/69.97	92.39/618.92	686.747/1075.40
	Liquidity ratio	0/0	0/0	0/0	0/0	0/0
Japan	Output	0/0	0/0	0/0	0/0	0/0
	Input	114.80/133.72	123.36/125.29	127.19/131.73	126.30/134.34	128.49/126.53
	Liquidity ratio	0/0	0/0	0/0	0/0	0/0
Korea	Output	0/0	0/0	0/0	0/0	0/0
	Input	0/8.68	11.20/22.71	28.56/38.98	45.88/56.29	64.86/72.43
	Liquidity ratio	0/0	0/0	0/0	0/0	0/0
Australia	Output	52.66/83.50	74.5/96.16	111.46/157.33	157.08/427.39	465.63/872.75
	Input	0/0	0/1.10	2.95/1.86	1.80/5.50	4.99/0.34
	Liquidity ratio	–	–	37/78.5	78.5/71.17	93.2/2559.39

(*Data source*: Steel Statistical Yearbook).

indicating that iron ore tends to flow in. Asia has a much smaller liquidity ratio, indicating that the input of iron ore resources in Asia are much larger than output. The major countries in Asia, such as China, Japan and South Korea, which have a liquidity ratio of nearly 0, are net importers of iron ore. Sweden is a net exporter of iron ore, and France changed from output type to input type. The liquidity ratio of North America increased from 0.88 to 3.07, indicating that North America has changed from an input type to an output type. In addition to the above continents, liquidity ratios for the remaining regions are greater than 1, indicating that they are all output types (Tables 3 and 4).

4.4. Homogeneity of trade structure

The study uses the standard weight entropy to measure the homogeneity of the trade structure of major countries and to measure the safety condition of different countries in iron ore trade (Table 5, Table 6). Based on the results of formulae (3)–(7), the homogeneity of the spatial structure of different countries exhibits significant differences.

With respect to the output structure, the United States exhibited the lowest standard weight entropy, and this implied that its output structure is the weakest. From the data in 2017, it can be seen that although there are 18 countries trade in iron ore with the United States, 81.27% of the total iron ore export to Canada, 13.81% to Japan, and only less than 1% to the remaining 16 countries, the flow of iron ore is too concentrated. Sweden has the highest standard weight entropy and the strongest spatial homogeneity. In 2017, Germany is Sweden's largest importer, but only accounts for 26.09% of Sweden's export share, and 90% of the other Sweden's iron ore evenly flowed to 9 countries. In addition, it is clear that India's weight entropy has dropped dramatically in 2010, from 0.53 in 2000 to 0.11 in 2010. The reason is that China, Japan, South Korea and some other Asian countries accounted for nearly

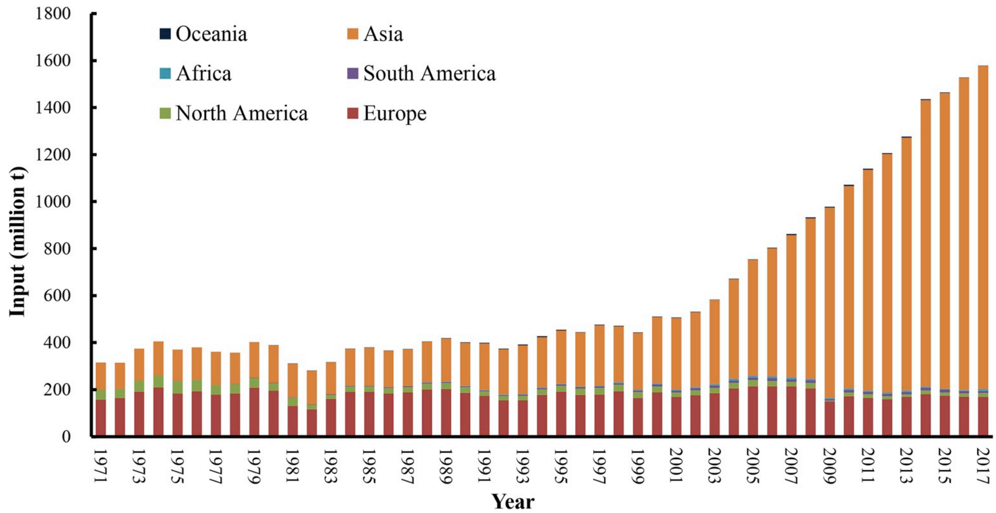


Fig. 6. Input of iron ore in each continent.

Table 5
Changes in the standard weight entropy in the main output countries.

Country	1990	2000	2010	2017
Sweden	–	0.67	0.63	0.63
Brazil	0.73	0.80	0.58	0.54
France	–	0.60	0.65	0.53
South Africa	–	0.58	0.38	0.41
India	0.44	0.53	0.11	0.22
Australia	0.54	0.54	0.41	0.26
The United States	–	0.01	0.28	0.23

Table 6
Changes in the standard weight entropy in the main input countries.

Country	1990	2000	2010	2017
The United States	–	0.44	0.42	0.49
Japan	0.55	0.50	0.36	0.46
Netherlands	–	0.57	0.40	0.36
China	–	0.48	0.48	0.35
South Korea	0.54	0.56	0.38	0.34
France	–	0.48	0.42	0.34
Canada	0.46	0.05	0.01	0.10

85% of India's total exports in 2000, while by 2010, 93.47% of India's iron ore exported to China. Australia's weight entropy also dropped significantly, from 0.41 in 2010 to 0.26 in 2017. In 2010, China accounted for 67.86% of Australia's exports, followed by Japan and South Korea, which accounted for 18.96% and 9.70% respectively. But by 2017, China's share of Australia's exports rose to 83.23%, while Japan and South Korea's share fell to 8.02% and 5.96%, the flow of iron ore were more centralized.

With respect to the input structure, the standard weight entropy of Canada is much smaller than that of other countries, and the homogeneity of spatial structure is very weak. The main reason is that Canada imports iron ore mainly from the United States. For example, in 1990, 90.17% of the Canada's iron ore came from the United States and 9.83% from Brazil, while by 2010, the iron ore from the United States had risen to 99.40%. The standard weight entropy of the United States is the highest, and the main reason is that Brazil and Canada are both the main importers of the United States. In addition, Argentina, Chile and other countries also supply about 10% of the import share. In Asian countries, China, Japan and South Korea are the main importers of iron ore, but from the calculation results in 2017, it can be seen that the weight entropy of Japan was 0.46, higher than 0.35 of China and 0.34 of South Korea. Looking for reasons from trade structure, the iron ore of these three countries mainly came from Australia, but Australia accounted for 54.88% of Japan's total iron ore imports, 62.21% of China's total imports and 70.45% of South Korea's total imports, respectively. As a result, Japan's market is more disorderly and its trade structure is relatively stable.

5. The characteristics of iron ore flow

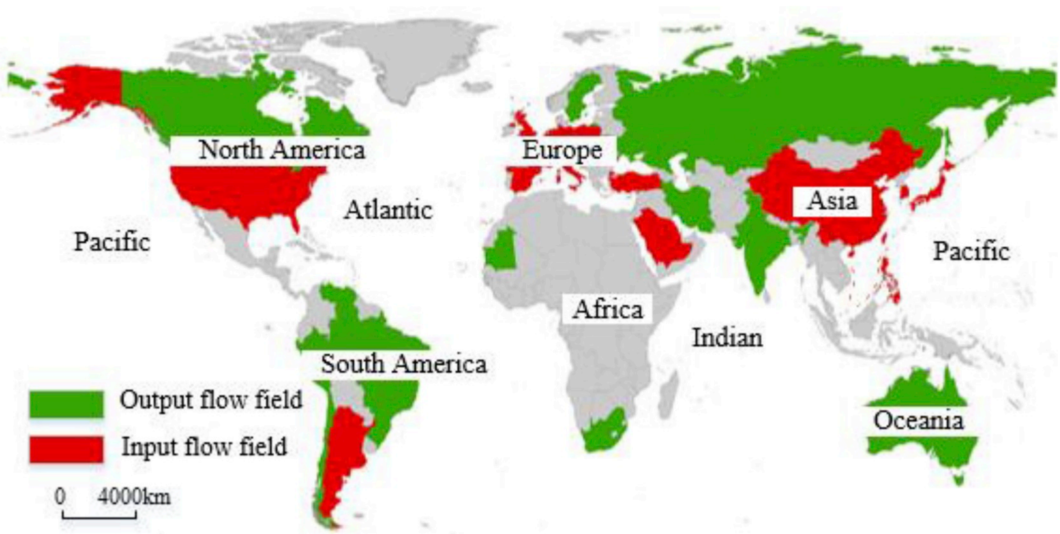
5.1. The motivation of iron ore flow

From the basic concept of field theory, the gradient force between the high- and low-potential centres is the motivating force of iron ore flow. In 1991, the consumption centre and input centre of iron ore is changed from Europe to Asia. So, using 1991 as a boundary, the output and input centre before 1991 and after 1991 were divided according to the output and input volume over the years (Fig. 7).

As shown in Fig. 7, before 1991, Australia, Brazil, Canada, Sweden, India, Liberia and the Soviet Union, which had larger outputs, were the high-potential centres of iron ore resources. Japan, the Federal Republic of Germany, the United Kingdom and the United States, which had larger input volumes, were the low-potential centres of iron ore resources. After 1991, the iron ore output and input structure changed. The high-potential statuses of Australia and Brazil were further strengthened. The potential status of India, Canada, Russia and Ukraine (after the disintegration of the Soviet Union) declined, but they remained high-potential centres. China, South Korea and Japan formed the most prominent low-potential centres in the world. Germany, France, Britain and Italy in Western Europe also formed low-potential regions. In general, the potential structures of iron ore are higher in Southern Hemisphere and lower in the Northern Hemisphere.

The gradient force between the high- and low-potential centres generates the motivating force of iron ore flow. In practice, the closer an area is from an iron ore input region, the more likely it is to achieve iron ore flow. With increasing distance between the output centre and the input centre, the difficulty of iron ore flow increases, and the flow rate will be attenuated. For example, the iron ore input into China mainly comes from Australia, Brazil and South Africa, etc. Although Brazil and South Africa also have high-potential, the two countries only accounted for 21.33% and 4.20% of the China's total input (Table 7). The main reason is the geographical location. Australia is relatively close to China (only 3600 nautical miles), whereas the distance between Brazil and China is up to 11000 nautical miles. The geographical positions are crossed from the western hemisphere to the eastern hemisphere, so the

(a) 1971-1991



(b) 1992-2017

Fig. 7. World changes in iron ore demand and supply potential.

Table 7
Main sources of iron ore imports in China.

Year	Australia		Brazil		South Africa		Others	
	Output /billion tons	Proportion /%	Output /billion tons	Proportion /%	Output /billion tons	Proportion /%	Output /billion tons	Proportion /%
2011	0.32	46.97	0.16	23.94	0.04	5.69	0.16	23.39
2012	0.38	51.32	0.17	23.10	0.04	5.49	0.15	20.08
2013	0.46	55.20	0.17	20.34	0.04	5.34	0.16	19.12
2014	0.60	65.14	0.18	19.61	0.04	4.28	0.10	10.97
2015	0.66	69.17	0.19	19.53	0.02	2.53	0.08	8.77
2016	0.64	62.49	0.21	20.95	0.04	4.38	0.12	12.18
2017	0.67	62.21	0.23	21.33	0.05	4.20	0.13	12.26

(*Data source*: UN Comtrade Database).

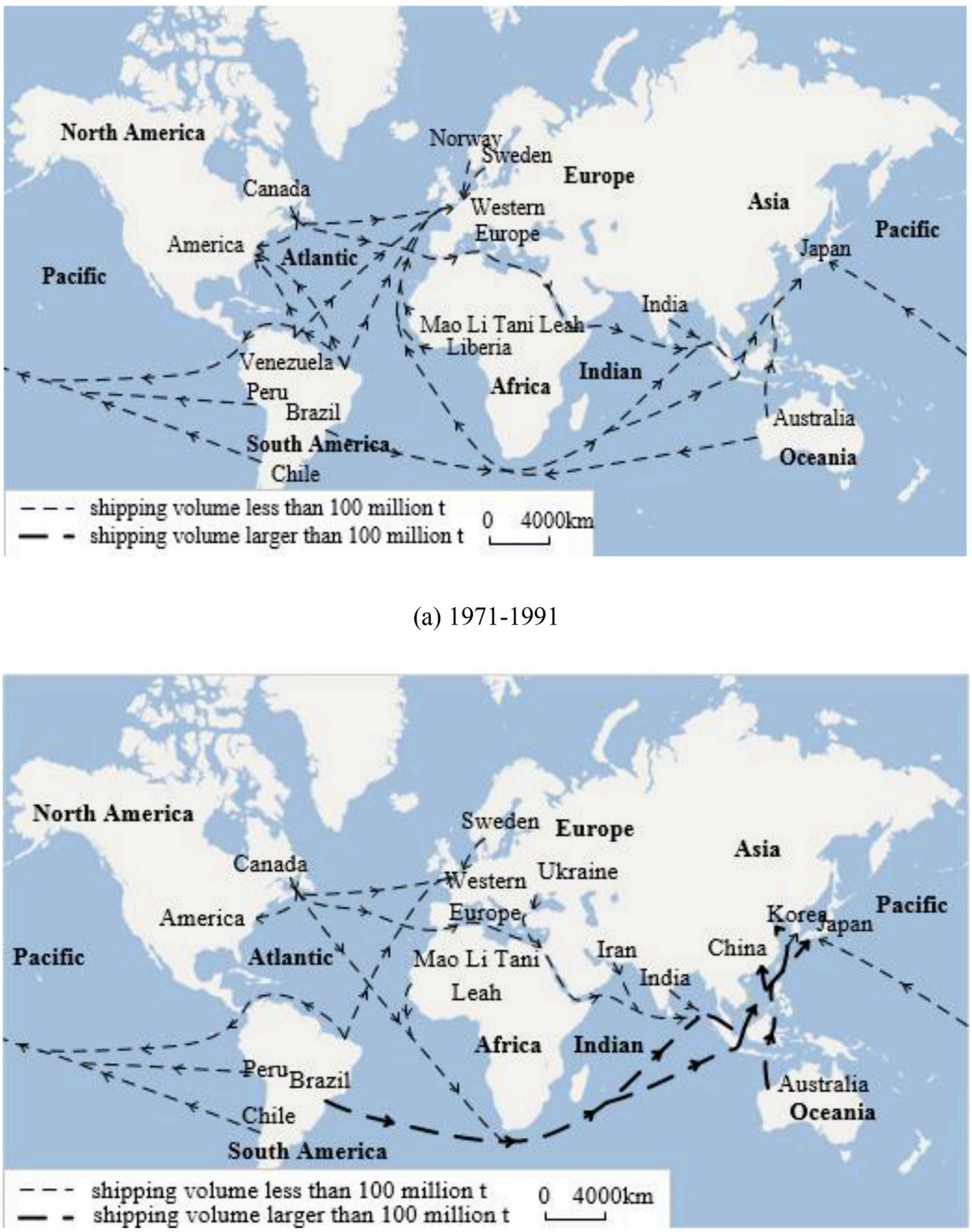
economic and time costs of transportation are very large.

Trade policy also has a significant impact on the iron ore flow volume. For example, the iron ore output of India increased from 20.38 million t to 101.40 million t between 1971 and 2008, making India a leading power in iron ore output at that time. However, since 2011, due to the prohibition of mining in some parts of India and increases in export taxes, the output of iron ore in India fell sharply. By 2017, the output dropped to 28.06 million t.

In addition to geographic distance and trade policy, market factors, transnational monopoly of enterprises and geopolitics also influence the flow of iron ore. From a market perspective, insufficient demand and excess supply are the main reasons for the increasingly sharp contradictions of the imbalance between production and consumption. First, China has the largest iron ore input proportion and has shown a decline in its demand in recent years because the steel enterprises in China have suffered extensive losses and have experienced serious overcapacity. Second, the iron ore producers have used a strategy that "cuts prices to boost production" to compete for additional market shares. For example, the Rio Tinto Group, the world's largest iron ore production enterprise, produced 349 million t in 2017, with high rates of production further exacerbated by the excess supply.

5.2. The distribution of iron ore flow field

Base on the above analysis and the flow field concept, iron ore flow regions can be divided into 6 flow fields: North America, South America, Europe, Africa, Asia and Oceania. North America is an output flow field. The iron ore flows from Canada to the countries of East Asia, mainly including China, Japan and South Korea, as well as some Western European countries. South America is an output flow field, which includes Brazil, Venezuela, Chile and Peru, and the iron ore mainly flows to China, Japan and Western Europe. Europe is an input flow field, including the Federal Republic of Germany (and the reunited Germany), Britain, Holland, France and Italy and other countries that attract the



(a) 1971-1991

(b) 1992-2017

Fig. 8. Major iron ore shipping routes in the world.

iron ore from other outflow fields, and the input iron ore mainly comes from Brazil and Canada. Africa is an output flow field, with iron ore mainly flowing from Mao Li Tani Leah, Liberia and South Africa. Oceania is the largest output flow field in the world, where the iron ore mainly flows from Australia. Asia is the world's largest input flow field, which includes China, Japan, Korea and Taiwan of China.

5.3. The flow traces of iron ore flow field

The trace of global iron ore flow is a flow network composed of iron ore transport channels (Wu et al., 2019). The iron ore flow from output regions to input regions is mainly through sea transportation, and the volume that is moved through railway transportation and combined sea-rail transportation is very low. Areas of iron ore production and consumption are extremely unequal in the world, so that the volume that is transported by sea is very large, and this is huge commercial potential (Wang and Wang, 2019a; Wang and Wang, 2019b; Song and Wang, 2019b). The main shipping routes for iron ore are along the east coast of North America-Far East route, the east coast of North America-Western Europe route, South America -East Asia route, east coast of South America-Western Europe route, west coast of Australia-East Asia route, West Africa-East Asia route and South Asia-East Asia route. Between 1992 and 2017, with the evolution of the world iron ore supply and demand structure, some shipping routes had a significant decline in shipping volume, such as the east coast of South America-east coast of North America route, the Australia-Western Europe route, and the West Africa-Western Europe route. At the same time, the destinations of the shipping routes in East Asian countries have changed from Japan to China, Japan and South Korea (Fig. 8).

6. Conclusions and discussions

This paper studied the evolution of the supply-demand and trade structure of the global iron ore resources from 1971 to 2017, revealed the operation mechanisms of iron ore flow, presented flow regions and flow traces, and analysed the security of the trade structure of major iron ore trading countries. The main conclusions are as follows.

(1) From a production perspective, the average annual growth rate of iron ore production was 2.24% from 1971 to 2017, increasing slowly in the first 30 years and then increasing sharply in the subsequent 17 years. The production in Oceania and South America increased significantly. Australia is the biggest producer, followed by Brazil. From a consumption perspective, global iron ore consumption has increased 1.27 billion t. Before 1992, Europe was the world's iron ore consumption centre, the major iron ore consuming countries are the Soviet Union, the Federal Republic of Germany, France, the United Kingdom and Italy, etc. After 1992, the consumption centre changed to Asia, and the main consumer was China. In 2017, iron ore consumption in China was up to 1.23 billion t, accounting for 60.23% of world total consumption, which was far higher than other countries.

(2) From 1971 to 2017, the average annual growth rate of the world's iron ore output was 3.72%, fluctuating but increasing between 1971 and 2000 and then increasing sharply between 2001 and 2017. Oceania and South America were the main iron ore output continents. In 2008, iron ore output in Oceania exceeded that in South America, making Oceania the world's largest exporter of iron ore. The gap between Oceania and South America gradually widened after 2008. In general, the iron ore output of all continents increased. In the international trade, a region or a country exports a product not only because of its comparative advantage in labour productivity but also its resource character advantage. Australia, Brazil and other export countries have rich iron endowment conditions and higher iron ore grade, which is an obvious advantage for producing a natural resource. In 2017, the total outputs in Australia and Brazil were 1.26 billion t, accounting for 76.63% of the world total. From the input perspective, global iron ore input increased to 1.19 billion t from 1971 to 2017. In recent years, the largest input continent is Asia, in which the main input countries are China, Japan and South Korea. The world shares of the three countries are 68.15%, 8.02% and 4.59%, respectively.

(3) From field theory, the potential difference in economic geography and the gradient force between the high- and low-potential centres are the motivating forces of iron ore flow. In general, the potential structures of the iron ore are higher in Southern Hemisphere and are lower in the Northern Hemisphere. Iron ore flow regions include 6 flow fields. The output flow fields are North America, South America, Oceania and Africa. The input flow fields are Europe and Asia. There are large volumes of iron ore flowing between the flow fields, mainly through sea transportation mode.

(4) In the past 47 years, the iron ore production centre shifted from Europe to Oceania and the consumption centre shifted from Europe to Asia. China is an important country in the evolution history. At first, China was a self-sufficient country, and then becoming the world's largest input country, accounting for more than half of the world's total input. That structure indicates that the steel industries in the world have been mainly supported by sea transportation across the Northern and Southern Hemispheres, facilitating the continued supply of iron ore in certain countries. Additionally, there is almost no alternative supply structure for the global steel industries at present. Such a fragile industrial supply chain brings an unsafety factor to the world economy and brings potential risks to the development of related industries. It has become an important task for relevant countries, especially China, to formulate a new economic policy to reverse the unbalanced structure pattern of supply-demand and the flow of iron ore resources in the world.

Based on the above analysis, in order to guarantee the stable supply and safety transportation of iron ore worldwide, and promote the sustainable and healthy development of iron ore industry, the following suggestions are put forward in this paper:

(1) Although there are nearly hundreds of countries participating in iron ore trade globally, only a few countries really control the iron ore trade network. Among them, Australia, Brazil and other countries occupy a very important position in the international iron ore trade, so it is easy to form trade monopoly. Therefore, for countries with high dependence on iron ore imports, attention should be paid to avoiding only trade with individual countries, which will lead to low standard weight entropy and reduce the trade security.

(2) In order to improve the security of iron ore international trade, reserve mechanism should be established and perfected as soon as possible for countries highly dependent on iron ore imports, so that iron ore reserve can meet the needs of production in a period of time when the trade environment is unfavourable; Iron ore and steel futures markets need to be improved, and financial instruments and related derivatives should be used to build platforms to avoid price risks; It is reasonable to increase investment in overseas resources to participate iron ore development in exporting countries through joint or sole proprietorship, so as to stabilize supply sources; Technological innovation should be encouraged to improve the utilization efficiency of iron ore, reduce waste of resources, and increase the recovery and utilization of waste iron and steel.

(3) Iron ore trade mainly depends on maritime transport for geographical reasons, therefore relevant countries should actively strengthen the construction of their own transport fleets,

make targeted investment in specific types of ships, rationally arrange maritime transport capacity to improve the reliability of transport; at the same time, the construction of iron ore ports should also be strengthened to improve port handling capacity and overall transport level. In addition, long-term and stable strategic cooperation with international shipping companies should be actively established to prevent transport risks.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.resourpol.2019.101506.

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