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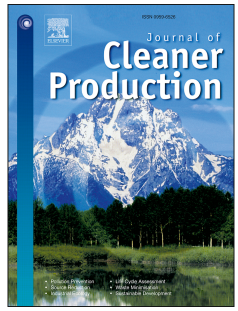

Analysis of the ecological relationships within the CO_2 transfer network created by global trade and its changes from 2001 to 2010

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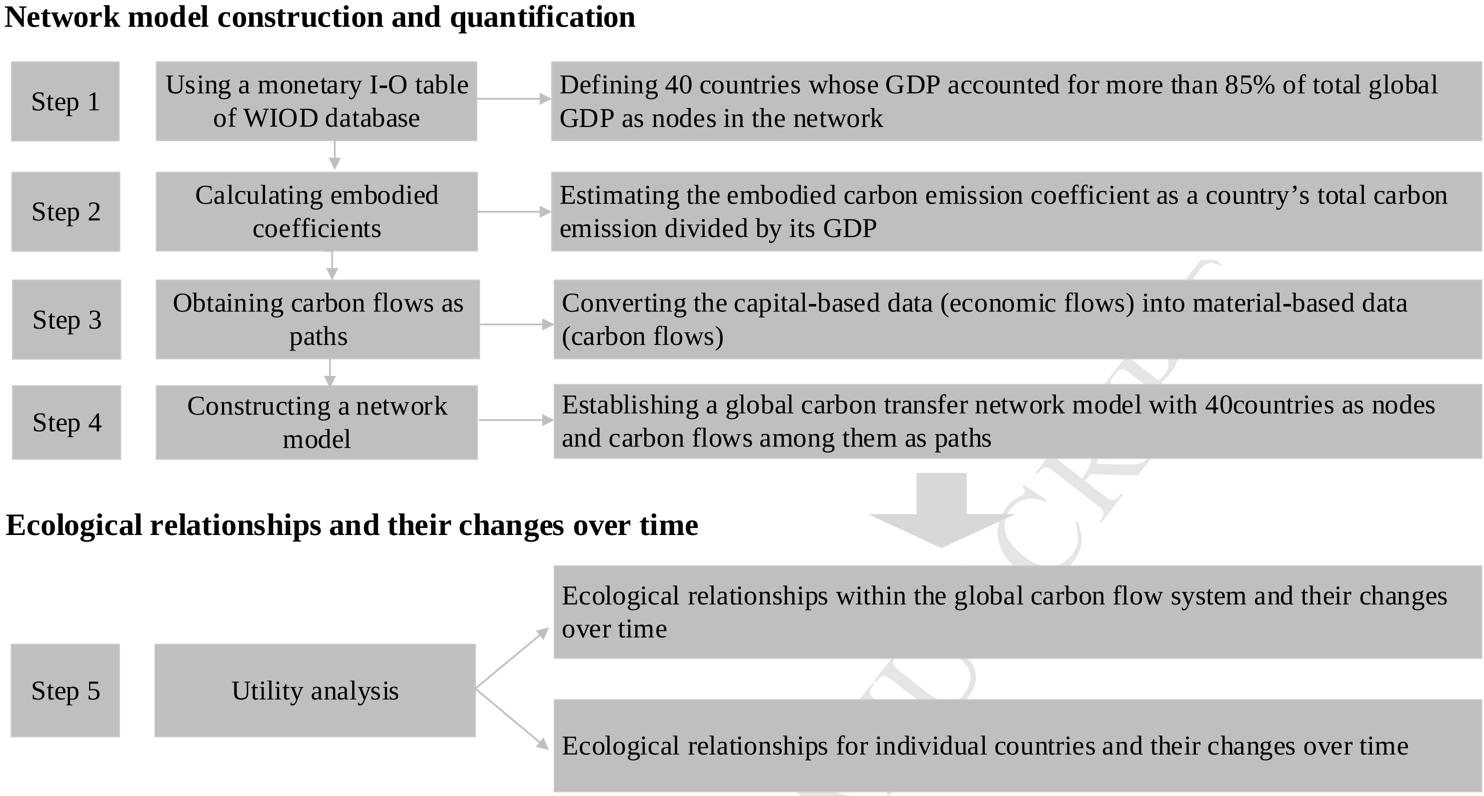
Network model construction and quantification
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Ecological relationships within the global carbon flow system and their changes over time
Ecological relationships for individual countries and their changes over time

Full title: Analysis of the ecological relationships within the CO_2 transfer network created by global trade and its changes from 2001 to 2010

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Abstract

With the increasing scale and scope of global trade, the magnitude of the CO_2 flows embodied in goods and services through international trade has aroused great concern among researchers and governments. In this study, we established a global network model of these CO_2 transfers from 2001 to 2010 using ecological network analysis and data from the World Input-Output Database for 40 selected countries whose GDP accounted for more than 85 % of the total global GDP. Based on the utility analysis, we determined the ecological relationships among the countries involved in the global trade network and their changes during the study period. The analysis revealed that competition and exploitation/control relationships dominated the global network, with each accounting for more than 40 % of the total relationships throughout the study period; mutualism accounted for the smallest proportion (less than 4 %). More than 80 % of the competition and 75 % of the exploitation/control relationships were within Europe or involved flows from Europe to North America or Asia. Finland, France, Japan, Greece, and Spain had the largest proportions of competition relationships. In Denmark, Luxembourg, Malta, and Switzerland, exploitation was dominant, whereas in Russia, Indonesia, and India, control was dominant. Our analysis identifies the key nodes of the many adverse ecological relationships within the global CO_2 network and those with more mutual relationships. Our work provides a scientific basis for developing more ecologically sustainable national and global CO_2 flows through trade.

Keywords: CO_2 transfer, ecological relationships, ecological network analysis, global trade, temporal variation

1. Introduction

In the 21st century, economic globalization and trade liberalization have continued to accelerate, leading to an increasing separation of production and consumption. The scale and scope of international trade are increasing with increasing economic dependencies every year. By 2007, global trade had increased to 32 times that in 1950, with global trade's share of the whole world's GDP increasing from 5.5 % in 1950 to 21 % in 2007 (Helpman, 2011). The growth of trade has inevitably had impacts on the environment. One such impact results from the environmental contaminants embodied in the flows of goods and services through global trade. The separation of production and consumption and the increase in global trade have led to the advent of CO_2 embodied in goods and services transferred from one country to another. Davis and Caldeira (2010) found that 23 % of global CO_2 emissions were traded internationally, primarily as exports from China and other emerging markets to consumers in developed countries. There are two different accounting principles, the Production-based Principle and Consumption-based Principle. Under the Consumption-based Principle, the emissions of manufacturing-export countries, such as China, have been reduced by up to 20 % in recent years (relative to the Production-based Principle) (Raupach et al., 2014). Zhao and Yan (2014) reported that 29 % of China's CO_2 emissions resulted from CO_2 consumption in other countries, versus 33 % in the eurozone and 17 % in North America. The existence of carbon embodied in goods and services creates an imbalance in the carbon reduction responsibility among countries. Some countries' reduction responsibilities should be undertaken by other countries; i.e., some countries should transfer part of their carbon reduction responsibility to other countries. It is important to analyze the relationships between different countries in the global CO_2 transfer system. This knowledge may support decision-making and the development of international conventions and protocols to clarify the carbon reduction responsibility of countries, determine the relationships between countries, and optimize the whole global CO_2 transfer system.

Estimates of CO_2 transfers via trade have been largely focused on the carbon embodied in final goods and services (i.e., embodied carbon). In 1974, the International Federation of Institutes for Advanced Studies defined embodied energy as the total energy that is consumed during a production process (IFIAS, 1974). Researchers derived the concept of "embodied carbon" based on these studies. Wyckoff and Roop (1994) first studied the carbon embodied in products imported by the 6 largest OECD members. Subsequent studies of the flows of embodied carbon in production, consumption, imports, and exports were carried out (Munksgaard and Pedersen, 2001; Peters and Hertwich, 2008). In addition, some researchers also considered the role of transports, such as cargo ships and airplanes, in overall emissions growth incurred in production shifts (Andersen et al., 2010). The methods used in these studies included input-output analysis (Ahmad and Wyckoff, 2003), life-cycle analysis (Wiebe et al., 2012), and economic input-output life-cycle assessment (Norman et al., 2007). Input-output analysis was the method most commonly used to estimate CO_2 transfers. Researchers first used the single-regional input-output approach (Ferng, 2003; Druckman et al., 2008) to estimate embodied carbon. Later, researchers realized they needed to incorporate the carbon emission coefficient differences in the various regions and began to utilize the multi-regional input-output approach (Peters and Hertwich, 2008; Davis and Caldeira, 2010). Input-output analysis has been used to study a single country (Weber et al., 2008), bilateral relationships (Shui and Harriss, 2006; Li and Hewitt, 2008), and multi-national studies at a regional scale (Peters and Hertwich, 2008; Chen and Chen, 2011) or at a global scale (Wiedmann et al., 2007; Wiedmann, 2009).

However, input-output analysis only provides qualitative conclusions about the relative fairness and unfairness of the relationships. It does not quantify the ecological relationships among countries, such as competition, exploitation/control, and mutualism. However, ecological network analysis can, since it is an effective method for analyzing a system's function and quantitatively studying the interactions among the components of the network (Allesina and Bondavalli, 2004; Jørgensen and Fath, 2006). It has roots in input-output analysis, which examines the flows of materials and energy through ecological systems (Fath and Patten, 1999). Ecological network analysis first focused on natural ecosystems (Heymans et al., 2002), then socio-economic systems, particularly on industrial systems (Bailey, 2004) and urban systems (Zhang et al., 2009; Liu et al., 2011b), including water (Zhang et al., 2010b), energy (Liu et al., 2011a; Li et al., 2012), and carbon (Chen and Chen, 2012) flows in cities. These studies opened the door for implementing network analysis in the study of socio-economic systems. Some scholars extended the research scale to global scale. Hertwich and Peters (2009) quantified greenhouse gas emissions associated with the final consumption of goods and services for 73 nations and 14 aggregate world regions. Steinberger et al (2012) focused on carbon embodied in global trade, exploring the benefits of carbon-exporting countries and carbon importing countries. Mishra (2015) continued to study trade's growing impact on greenhouse-gas emissions, especially the great impact of consumption of each country. Apart from quantifying carbon emission all over the world, a few scholars stared to study ecological relationships between countries, based on global carbon emission. Using ecological network analysis, Yang et al. (2012) divided the world into 13 regions and analyzed the virtual water trade among regions and levels of symbiosis throughout the system. Studies such as this one have revealed the potential of ecological network analysis to quantify the ecological relationships among countries in international trade.

We used ecological network analysis to define the ecological relationships between different countries in global trade, which provided important insights into the impacts of international trade. We established a global network model of CO_2 transfers based on the input-output data for 40 countries whose GDPs accounted for more than 85 % of the total global GDP. Using utility analysis (Patten, 1991; Fath and Patten, 1998), we quantified the ecological relationships among the regions and countries and analyzed their temporal and spatial distributions from 2001 to 2010. This analysis can provide scientific support for efforts to clarify the carbon reduction responsibility of countries, determine relationships between countries, and optimize the whole global CO_2 transfer system.

2. Methods and data

2.1 Network model construction and quantification

We used ecological network analysis to establish a network model of CO_2 transfers in global trade and analyzed the resulting relationships between countries. Using data from the World Input and Output Database (WIOD; www.wiod.org), we obtained data for 40 countries whose GDP accounted for more than 85 % of the total global GDP during the study period. We then defined these countries as nodes in the network and defined the flows of CO_2 between countries and regions as paths between the nodes, leading to the establishment of a network model of CO_2 transfers in global trade (Fig. 1). This is a bidirectional and weighted network. Paths in this network represent values of embodied CO_2 transfers in global trade. We assumed that the rest of the countries in the world were part of the external environment and that the total inputs to and outputs from the 40 selected countries represented the network's inputs and outputs. From the four study years, we can see that China is the largest CO_2 exporter, discharging more than 500 Mt CO_2, while the minimum value was less than 0.005 Mt. There are great differences in the CO_2 transfer flows among countries. Trade mainly occurs among the USA, China, Russia, India, Japan and some European countries, such as Germany, France, and the UK, distributed within Europe, between Asia and Europe and between Asia and North America.

We used WIOD data on the value flows between countries from 2001 to 2010, WIOD data on each country's CO2 emissions inventory from 2001 to 2009, and emissions data compiled by the International Energy Agency (IEA, www.iea.org) in 2010. We estimated the emissions intensity of the economy as a country's total CO_2 emission divided by its GDP and used this coefficient (see ε_i in equation (2)) to convert the value-based data (economic flows) into CO_2 emission data (CO_2 flows), which represented the flow along each path in the network.

Using the world input-output table and its previous year prices, we calculated the inflation rates as the ratio of the prices in a given year to the prices in 2000 to adjust the 2001, 2004, 2007, and 2010 economic data to constant 2000 values (which we used as the base year). Based on this, the comparable price of world input-output table was obtained to eliminate the effect of price factors. We then integrated the data to obtain macro-scale capital flows resulting from trade among the 40 countries (including 29 European countries, 1 Pacific Ocean country, 4 North and South American countries, and 6 Asian regions and countries). We used the following carbon flow formula:

$$f_{ij} = x_{ij} * \varepsilon_i \quad (1)$$

where

$$\varepsilon_i = \frac{m_i}{X_i} \quad (2)$$

$$X_i = \sum_{j=1}^{n} x_{ij} \quad (3)$$

where X_i represents the total capital flow from the other 39 countries to country *i*. x_{ij} represents the capital flow from country *j* to country *i*. m_i represents the CO_2 emissions of country *i*. ε_i represents the emissions intensity of the economy. We assumed that the internal flow within a component of the network (i.e., from *i* to *i*) is 0 because we focused on the flows between countries, not internal flows. We established a network model of CO_2 transfers in global trade based on the above approach. Fig. 1 is a conceptual model that simplifies the CO_2 transfer network created by global trade with only 10 nodes. In the actual model, the network is more complex, with 40 nodes and complicated paths.

Insert Figure 1

2.2 Ecological relationships and their changes over time

The global CO_2 transfer system behaves similarly to an organism, in that it has a certain organizational structure and functional relationships, and it can be analogized to an ecosystem. Therefore, the global CO_2 transfer network can be seen as an ecological network (Yang et al., 2012).

Its functional relationships can be quantified by using the utility analysis of ecological network analysis, which is similar to the 4 major ecological relationships of a natural ecosystem: competition, exploitation, control, and mutualism.

Utility analysis is an efficient way to describe the characteristics of the relationships within an ecological network and was first introduced by Patten (1991) to express the mutual benefits and costs for each relationship among the nodes of a network. In this method, an integral utility matrix that shows the relationships between all nodes in the network is constructed and used to analyze the consequences of the relationships.

In the network model, f_{ij} represents the flow from node *j* to node *i* (Table S1), and z_i and y_i represent the environmental inputs to and outputs from node *i*. The left side of the formula shown below is the input and the right side is the output. According to the material-balance principle (i.e., the conservation of mass), the inflow into the system equals the outflow from the system. The formula is as follows:

$$\sum f_{ij} + z_i + C = \sum f_{ji} + y_i \quad (4)$$

where *C* represents the change in carbon storage. If $C < 0$, it represents a net decrease in the carbon storage of component *i*, whereas $C > 0$ represents a net increase in carbon storage.

We defined T_i as the sum of the flows into country *i*, which includes cross-boundary inputs from the environment into country *i*:

$$T_i = \sum_{j=1}^{n} f_{ij} + z_i \quad (5)$$

where z_i is the cross-boundary inputs to country *i* from the rest of the countries in the world (Row) that are not included in the 40 selected countries.

We can then compute a dimensionless direct utility intensity matrix (**D**), in which matrix element d_{ij} represents the utility of an inter-country flow from country *j* to country *i*, which is expressed as:

$$d_{ij} = (f_{ij} - f_{ji}) / T_i \quad (6)$$

From matrix **D**, a dimensionless integral utility intensity matrix **U**=(u_{ij}) can be computed from the following power series (Fath and Patten, 1999):

$$\mathbf{U} = (u_{ij}) = \mathbf{D^0} + \mathbf{D^1} + \mathbf{D^2} + \mathbf{D^3} + \ldots + \mathbf{D^m} + \ldots = (\mathbf{I} - \mathbf{D})^{-1} \tag{7}$$

where the matrix $\mathbf{D^0}$ reflects the self-feedback of the flows within each country (it is not considered further in the present analysis because we were only concerned with the flows between countries), $\mathbf{D^1}$ reflects the direct flow utilities between any two countries in the network along a path of length 1, $\mathbf{D^2}$ represents the indirect flow utilities that pass along the pathways of length 2 (i.e., that pass through an intermediate country), and $\mathbf{D^m}$ ($m \geq 2$) reflects the indirect flow utilities along the paths of m steps. **I** is the identity matrix, u_{ij} represents the integral dimensionless utility value of d_{ij} (which is calculated using a Leontief inverse matrix (Fath and Patten, 1999)), and the matrix **U** is the integrated utility intensity among nodes, representing the integrated relationships between any pair of nodes (countries) in the network. It does not only consider the direct ecological relationship between the two nodes, but also considers the indirect relationships. Some relationships are very different in the direct utility matrix **D** and integrated utility matrix **U** because of the role of a third node. For example, according to the direct utility matrix **D,** node *i* exploits node *j*. However, it may be the case that node *j* exploits node *i* in turn, considering their relationships with intermediate nodes. Fig. 2 shows the direct and indirect paths (take a four-node network as an example):

Insert Figure 2

According to matrix **U** (Table S2), we can obtain a sign matrix **sgn(U)** in which each element is su_{ij} and the signs determine the characteristics of the relationship between the countries based on the flows between the pairs of the nodes that represent the countries (Fath et al., 2007). If (su_{ji}, su_{ij}) = (+, −), country *j* gets a net CO_2 emission share from country *i* through global trade*;* that is, country *j* exploits *i* (Fig. 3). Country *j* consumes goods and services produced in country *i* while not burdening the corresponding carbon reduction responsibility. That is, country *j* transfers part of its carbon reduction responsibility to *i*, and *i* undertakes excessive reduction responsibility. If (su_{ji}, su_{ij}) = (−, +), country *j* is exploited by country *i*; that is, country *j* controls *i*. Control and exploitation relationships are equivalent, and since only the directions differ, they are reciprocal relationships. This pair of relationships means that one country benefits from global trade while the other is damaged. We introduced a third country *p* to explain the competition relationship. If (su_{ji}, su_{ij}) = (−,−), countries *j* and *i* both obtain a net CO_2 emission share from country *p* through global trade. Countries *j* and *i* both exploit country *p*; that is, country *j* and *i* are in a competition relationship (Fig. 3). Countries *j* and *i* both transfer part of their reduction responsibilities to country *p* (p has a limited CO_2 emission share) and *p* accepts an excessive reduction responsibility. The "two-predators, one-prey" example mentioned above is a reflection of competition in the global CO2 transfer network and is similar to that found in natural ecosystems. Competition indicates that the two countries involved in bilateral trade are in similar positions in which they exploit the same country at the same time. If (su_{ji}, su_{ij}) = (+,+), countries *j* and *i* benefit from each other and obtain their CO_2 emission shares through the goods and service flows in global trade to achieve a win-win pattern, without transferring a reduction responsibility to the other (Zhang et al., 2010a,b). In this scenario, countries *j* and *i* are experiencing mutualism (Fig. 3). For example, if *j* exports resources to *i* and *j* exports a high carbon reduction technology to *i*, then *j* and *i* are in a mutual relationship. In the CO_2 transfer network of global trade, a mutual relationship means that both countries benefit from global trade.

Insert Figure 3

Using ecological network analysis, we studied 4 types of ecological relationships and their temporal and spatial distributions from the perspectives of the global CO_2 transfer system and individual countries. At the global level, we obtained the ecological relationships between every two compartments using the utility analysis. By counting the numbers of each kind of relationship, we obtained the proportions of the 4 relationships and their temporal and spatial distributions. At this level, we did not distinguish between exploitation and control relationships, and simply expressed this pair of relationships as an "exploitation/control" relationship. At the individual country level, we counted the ecological relationships of every country, identified the typical countries for each type of relationship, and studied their temporal and spatial distributions. At this level, we distinguished between exploitation and control relationships, so the total number of relationships considered here were twice those found at the global level.

3. Results

3.1 Ecological relationships within the global CO_2 flow system and their changes over time

There were 780 relationships among the selected 40 countries participating in global trade. Throughout the study period, the global CO_2 transfer network was dominated by competition and exploitation/control relationships, both accounting for more than 40 % of the total. Competition relationships accounted for approximately 52 % of the total in 2001 and 2004 then decreased to 44 % in 2007 and 2010; in contrast, exploitation/control relationships accounted for approximately 41 % of the total in 2001 and 2004 and subsequently increased to 51 % (Fig. 4). The mutual relationship was a minor component of the network, accounting for less than 4 %, and decreased to 1.9 % in 2007. Competition relationships decreased by 15.5 % from 2001 to 2010. During the same period, exploitation/control relationships increased substantially by 21.5 % from 2001 to 2010 and reached 52.6 % in 2010.

Insert Figure 4

These relationships also changed spatially to reflect the changing patterns of global trade (Table 1). In the international network, more than 80 % of the competition relationships and more than 75 % of the exploitation/control relationships were found within Europe, between Europe and North America, and between Europe and Asia throughout the study period. Trade within Europe accounted for approximately 50 % of all competition relationships in the network, amounting to at least 3 and 2 times the corresponding proportions for trade between Europe and North America and between

Europe and Asia. However, the European contribution to competition relationships decreased by 19.7 % from 2001 to 2010. The overall level of 50 % competition relationships for the entire network was maintained by a 73.4 % increase between Europe and North America from 2001 to 2010. Although the proportion of the competition relationships between Europe and Asia fluctuated, it remained near 20 %.

Insert Table 1

Europe accounted for the largest proportion of the exploitation/control relationships, at approximately 50 %, followed by relationships between Europe and Asia and between Europe and North America, at approximately 24 % and 8 % of the relationships, respectively. The proportion of exploitation/control relationships within Europe was over 4 times that between Europe and North America and twice that between Europe and Asia. Exploitation/control relationships within Europe increased by 25 % during the study period, while those between Europe and North America decreased by 5 %, which was too low to affect the overall trend in the exploitation/control relationships. Exploitation/control relationships between Europe and Asia remained relatively constant. Mutual relationships accounted for a small proportion of the 4 ecological relationships, and at first, only occurred in trade within Europe; subsequently, mutualism occurred in some trade between Europe and North America, between Europe and Asia, and between Europe and Australia (the Pacific Ocean region), accounting for nearly all of the mutual relationships in 2001 and 2004. Since 2007, trade between North America and Asia has contributed to approximately 10 % of the mutual relationships.

3.2 Ecological relationships for individual countries and their changes over time

Based on the average pairs of the ecological relationships during the study period, we obtained the typical countries for each relationship and their relationship proportions of the 4-year average value (Fig. 6). Competition relationships were the dominant type in the majority of countries throughout the study period. There were 24 competition dominant countries, including 11 countries whose competition relationships accounted for more than 50 % of the total throughout the study period, 9 countries in 3 study years, and 3 countries in 2 study years in which the proportion of competition was less than 50 %. For exploitation relationships, Denmark, Luxembourg, Malta, and Switzerland were exploitation-dominant countries in 2 study years. Russia, India, and Indonesia were control-dominant countries throughout the study years. No countries were mutual-dominant countries.

Insert Figure 5

Among these competition-dominant countries, Finland, France, Japan, Greece, and Spain had the largest proportions (more than 60 %) of the competition relationships (Fig. 6; Fig. S1). Italy, Lithuania, Romania, Slovakia, the United States, Latvia, and South Korea had the second largest proportions (more than 50 %) of competition relationships within their ecological relationships (Fig. 6). More than 80 % of the competition relationships mentioned above were distributed in Europe (Fig. S1). Exploitation relationships also had a prominent position in Finland, France, Spain, Greece, Italy, the United States, and Japan, accounting for 15 to 40 % of their ecological relationships (Fig. 6). More than 50 % of these exploitation relationships were in Europe, and approximately 25 % were in Asia. In addition, control relationships were less common than competition and exploitation relationships in these 7 countries. Lithuania, Latvia, Romania, Slovakia, and South Korea's exploitation and control relationships both accounted for approximately 20 % of their total (Fig. S1).

Insert Figure 6

Competition relationships accounted for more than 50 % in 3 of the 4 years in Austria, Germany, Hungary, Poland, Turkey, Brazil, Mexico, Canada, and the Netherlands (Fig. 6). The competition relationships of Austria, Germany, Hungary, Poland, and Turkey showed a decreasing trend, from more than 50 % of the total in 2001 to less than 50 % in 2010 (Fig. 5). As competition in Germany and Turkey decreased, exploitation increased by more than 40 % from 2001 to 2010. In 2010, exploitation accounted for more than 20 % in these two countries; more than 67 % of the countries that formed exploitation relationships with them were in Europe and less than 25 % were in Asia (Fig. S1). However, in Hungary and Poland, control relationships dominated the exploitation relationships, accounting for 15 to 50 % of each, and more than 60 % of countries controlled by Hungary and Poland were in Europe (Fig. S1). Mexico showed no clearly dominant relationship from 2001 to 2007, but its competition relationships increased by 50 % between 2007 and 2010, with 80 % of the countries competing with Mexico located in Europe and only 20 % were with the United States, South Korea, and Japan (Fig. S1). Mexico's proportion of exploitation relationships was higher than control, with exploitation accounting for approximately 30 % of the total (approximately 1.5 times greater than control relationships). Approximately 50 % of the countries that formed an exploitation relationship with Mexico were in Europe, and the rest were mainly in Asia. Mexico’s control relationships accounted for approximately 20 % of the total, with all of the countries that formed control relationships with this country located in Asia. Among the countries whose dominant relationship type was competition, only the Netherlands had more control relationships than exploitation. Its control relationships accounted for approximately 30 % since 2007. Control was twice as common as exploitation in the Netherlands, and more than 90 % of countries that formed a control relationship with the Netherlands were in Europe, whereas most countries that formed an exploitation relationship with the Netherlands were in Asia (Fig. S1).

In China, competition relationships dominated in 2001 and 2004, accounting for approximately 50 % of the total relationships (Fig. 5). Countries that competed with China were located mainly in Europe but included India and Indonesia in Asia (Fig. S1). However, after 2007, control relationships increased to 67 %, becoming the dominant relationship type, and 70 % of these countries were located in Europe, versus 20 % in North and South America and 10 % in Asia (most in South Korea and Japan). The Czech Republic, Estonia, and Slovenia were dominated by competition relationships in 2001 and 2004, and 70 % of the countries that formed competition relationships with these countries were in Europe, 10 % were in South and North America, and 20 % were in Asia. However, control relationships became dominant in 2007, increasing by 100 % for the Czech Republic and Slovenia and by 27 % for Estonia. All countries that formed control relationships with these countries were in Europe. In contrast, control relationships dominated Bulgaria in 2001 and 2004. However, competition relationships became dominant in 2007.

Denmark, Luxembourg, Malta, and Switzerland were dominated by exploitation relationships throughout the study period (Fig. S1). Exploitation relationships accounted for more than 30 %, and countries that formed exploitation relationships with these 4 countries were mainly in Europe, but also included Taiwan, Indonesia, India, and China. Denmark's exploitation relationships accounted for approximately 35 % of the total in 2001, 2004, and 2007, but in 2010, they accounted for more than 50 % of the total, representing a 54 % increase from 2001 to 2010. Approximately 67 % of the countries exploited by Denmark were in Europe, versus approximately 11 % in North and South America and 22 % in Asia (Fig. S1). As exploitation relationships increased in Denmark, control relationships decreased by 67 % from 2001 to 2010, and more than 75 % of the countries controlled by Denmark were in Europe. Similar to the trend found in Denmark, Luxembourg’s exploitation relationships have been increasing steadily, accounting for 30.7 % of the total at the beginning of the study and 43.6 % in 2010. More than 76 % of the countries controlled by Luxembourg were in Europe, and approximately 15 % were in Asia. Most of the countries that formed a control relationship with Luxembourg were in Europe. Malta’s exploitation relationships increased sharply at the beginning of the study period, started to decrease in 2004, and finally stabilized at 34 % in 2010 (which was still higher than the proportion of approximately 30 % in 2001). More than 75 % of the countries that formed exploitation relationships with Malta were in Europe, and approximately 15 % were in Asia. As exploitation relationships decreased, control increased by 25 %, changing from 28 % in 2001 to 35 % in 2010. Approximately 65 % of the countries that formed control relationships with Malta were in Europe, versus 14 % in North and South America, and 14 % in Asia.

Switzerland's exploitation relationships accounted for more than 40 % of the total in all years except 2004. Approximately 65 % of the countries that formed an exploitation relationship with Switzerland were in Europe and 15 % of the countries that formed this kind of relationship with Switzerland were in Asia. There were few control relationships other than those found in 2001.

Russia, Indonesia, and India were dominated by control relationships throughout the study period (Fig. S1). For Russia, control relationships accounted for more than 60 %, and most countries forming control relationships with Russia were in Europe. However, some control relationships were with Taiwan, South Korea, and Japan. Russia's exploitation and competition relationships both accounted for less than 5 % of the total. Russia maintained a stable competition relationship with Bulgaria and stable exploitation relationships with Australia and Mexico. Similarly, control relationships accounted for 54 % of Indonesia's ecological relationships; more than 60 % of the countries that formed a control relationship with Indonesia were in Europe, with the remainder in the Americas (North and South) and some Asian countries. Indonesia's exploitation relationships accounted for approximately 25 % of the total, and all the countries that formed an exploitation relationship with Indonesia were located in Europe. Competition relationships accounted for less than 18 % of the total. Countries competing with Indonesia were mainly in Europe. India's relationships were also dominated by control relationships, which accounted for approximately 56 % of the total, and 60 % of the countries that formed a control relationship with India were located in Europe, versus 40 % in North America and South America. Exploitation relationships accounted for only 10 % of the total. Most of the countries that formed an exploitation relationship with India were in Europe, but these relationships also existed with China and Indonesia.

Mutual relationships accounted for a small proportion of the total, generally less than 15 %. Compared with other countries, there were more mutual relationships in Luxembourg, Russia, Australia, Canada, Taiwan, and Indonesia, with the proportion ranging from 4 to 18 % of the total. More than 80 % of the countries that formed mutual relationships with these countries were India and European countries.

4. Discussion

Ecological network analysis is an effective method to analyze the functional relationships of an ecosystem. From the current studies of natural ecosystems, we can see that mutual relationships are common in natural systems (Fath and Patten, 1998; 1999). However, the proportions of ecological relationships in socioeconomic systems differ greatly from those in natural ecosystems, and the most important difference is the decrease in mutual relationships (Fath and Patten, 1998; Patten, 1991). As the scale of research has increased, the mutual relationships between components have decreased. For example, when studying regional virtual water flows, Mao and Yang (2012) indicated that mutualism accounted for 20 % of the total relationships in the Baiyangdian Basin. However, some researchers noted that there were lower proportions of mutual relationships in the city. In Beijing, 19 % of the relationships were mutual in an urban metabolic system (Li et al., 2012) and 14 % were mutual in an urban energy metabolic system (Zhang et al., 2010), indicating that there are insufficient mutual relationships in cities. At the country level, researchers showed that the proportions of mutualism at this scale were lower to a large degree. For example, Zhang et al. (2012) suggested that mutual relationships accounted for 14.3 % of the total relationships in China's societal metabolic system in 2006. A similar conclusion was drawn in a study of the embodied energy flows among 30 Chinese provinces, in which mutual relationships accounted for 3.8 % of the total in 2007 (Zhang et al., 2015). In our study, mutualism in the global CO_2 transfer network is low, accounting for approximately 3 % of the total number of relationships. That is, compared with a stable and dominant proportion of mutual relationships in a natural system, socio-economic systems tend to have fewer mutual relationships.

Insert Table 2

Socio-economic systems are also different from natural ecosystems in that they are dominated by exploitation/control or competition relationships (Li et al., 2012; Xia et al., 2016).

Exploitation/control decreases and competition increases with the increasing research scale. Some researchers have focused on the regional scale. For example, Mao and Yang (2012) noted that the virtual water flows in the Baiyangdian Basin had 70 % exploitation/control and 10 % competition relationships. Later, Fang and Chen (2015) found a proportion of 67.7 % exploitation/control relationship in the Heihe River Basin. In studies of urban metabolism, researchers concluded there are few exploitation/control relationships and more competition relationships. Li et al. (2012) noted that approximately 62 % of the relationships were exploitation/control and 23.8 % were competition relationships, while Zhang et al. (2014) found that nearly 50 % of the relationships were exploitation/control and 30 % were competition relationships. This means that the exploitation/control characteristics of these sectors were weakened and replaced by competition in cities to a large degree. However, there are still some upstream and downstream relationships between the different sectors, so the proportions of exploitation/control relationships were still relatively high. On the country scale, Zhang et al. (2015) found a value of 48 % for China's 30 provinces' exploitation/control relationships in 2007. At this level, the upstream and downstream relationships between the different provinces and sectors were lower, and it was more difficult to coordinate the different provinces compared to the city. When considering the global CO_2 transfer system, our results showed that exploitation/control and competition relationships both accounted for approximately 50 % (ranging from 40 % to 60 %) of the total relationships in the CO_2 flows through the global trade network. Countries that participated in global trade had political and economic conflicts of interest with other countries, leading to more competition relationships, even when international treaties and trade agreements existed.

5. Conclusions

The ecological network method, based on the global CO_2 transfer network model in this study, was used to quantitatively study the proportions of the 4 ecological relationships and their temporal and spatial distributions, provide support for clarifying the carbon reduction responsibility of countries, and optimize the whole global CO_2 transfer system.

We identified 780 pairs of relationships among the 40 countries. The global CO_2 transfer network was dominated by competition and exploitation/control relationships, with both accounting for more than 40 % of the tot al. Mutual relationships accounted for less than 4 % of the total throughout the study period. More than 80 % of the competition and 75 % of the exploitation/control relationships were within Europe, between Europe and North America and between Europe and Asia (i.e., were dominated by developed countries). Competition relationships were the dominant types for Finland, France, Japan, Greece, and Spain. Denmark, Luxembourg, Malta, and Switzerland tended to exploit other countries, while Russia, Indonesia, and India were mostly exploited by other countries.

Because of the data sources and the standards we chose to select the key nodes of the network, we did not consider many countries in Asia, Africa, or South and North America when establishing the CO_2 transfer network created by global trade. We need to seek more data to complete this research in the future. This is the first limitation of our study. The second limitation is that our analysis focused more on the nature of the relationships within the network rather than on the actual benefits and costs for each country. In future research, it will be necessary to account for the magnitude of the flows rather than only their utility.

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List of Tables:

Table 1 Intercontinental distribution of the four types of ecological relationships in 2001, 2004, 2007, and 2010.

Proportion of total relationships (%)														
		Competition trend	2001			2004			2007			2010		
			Competition	Exploitation/ control	Mutualism	Competition	Exploitation/ control	Mutualism	Competition	Exploitation/ control	Mutualism	Competition	Exploitation/ control	Mutualism
Competition (>15%)	EU-EU	-	61.0	44.1	17.2	58.1	45.5	31.8	51.1	53.6	33.3	49.0	55.1	42.9
	EU-NA	+	9.4	11.2	34.5	11.2	9.7	31.8	16.8	6.1	13.3	16.3	6.6	14.3
	EU-AS	None	21.3	23.4	24.1	20.6	24.2	27.3	19.3	24.6	33.3	19.5	24.6	23.8
Competition (1%-15%)	EU-SA	None	3.9	3.8	0.0	5.1	2.1	0.0	4.8	2.9	0.0	5.2	2.7	0.0
	EU-OA	+	0.7	5.6	24.1	1.9	5.8	9.1	3.6	3.7	6.7	4.9	2.4	9.5
	NA-AS	None	1.2	3.8	0.0	0.9	4.2	0.0	1.4	2.7	13.3	1.4	2.7	9.5
	AS-AS	None	1.0	3.3	0.0	0.9	3.3	0.0	0.8	2.9	0.0	1.2	2.7	0.0
Competition (<1%)	OA-SA	+	0.0	0.3	0.0	0.0	0.3	0.0	0.3	0.0	0.0	0.3	0.0	0.0
	OA-AS	+	0.0	1.8	0.0	0.0	1.8	0.0	0.0	1.5	0.0	0.6	1.0	0.0
	OA-NA	None	0.7	0.6	0.0	0.5	0.9	0.0	0.8	0.2	0.0	0.9	0.2	0.0
	SA-NA	None	0.2	0.3	0.0	0.0	0.3	0.0	0.6	0.0	0.0	0.6	0.2	0.0
	SA-AS	None	0.2	1.5	0.0	0.5	1.2	0.0	0.3	1.2	0.0	0.3	1.2	0.0
	NA-NA	None	0.2	0.6	0.0	0.2	0.6	0.0	0.3	0.5	0.0	0.0	0.7	0.0

Notes: Intercontinental relationships are divided into three categories based on the proportion of competition relationships. In this table, represents a decreasing trend for competition relationship, + represents an increasing trend, and “none” represents no significant trend (i.e., fluctuation). Trade types: EU-EU, Europe-Europe; EU-NA, Europe-North America; EU-AS, Europe-Asia; EU-SA, Europe-South America; EU-OA, Europe-Pacific Ocean; NA-AS, North America-Asia; AS-AS, Asia-Asia; OA-SA, Pacific Ocean-South America; OA-AS, Pacific Ocean-Asia; OA-NA, Pacific Ocean-North America; SA-NA, South America-North America; SA-AS, South America-Asia; NA-NA, North America-North America.

Table 2 Comparative analysis of results in different studies

	Literatures	Exploitation/control	Competition	Mutualism
Small region level	Mao and Yang (2012)	70%	10%	20%
	Fang and Chen (2015)	Above 67.7%	——	——
City level	Zhang et al (2010)	49%	37%	14%
	Li et al. (2012)	62%	23.8%	19%
	Zhang et al (2014)	50%	30%	13%-16%
Country level	Zhang et al (2012)	——	——	14.3%
	Zhang et al. (2015)	48%	——	——
Global scale	Our study	40%-53%	45%-55%	Around 3%

List of Figures:

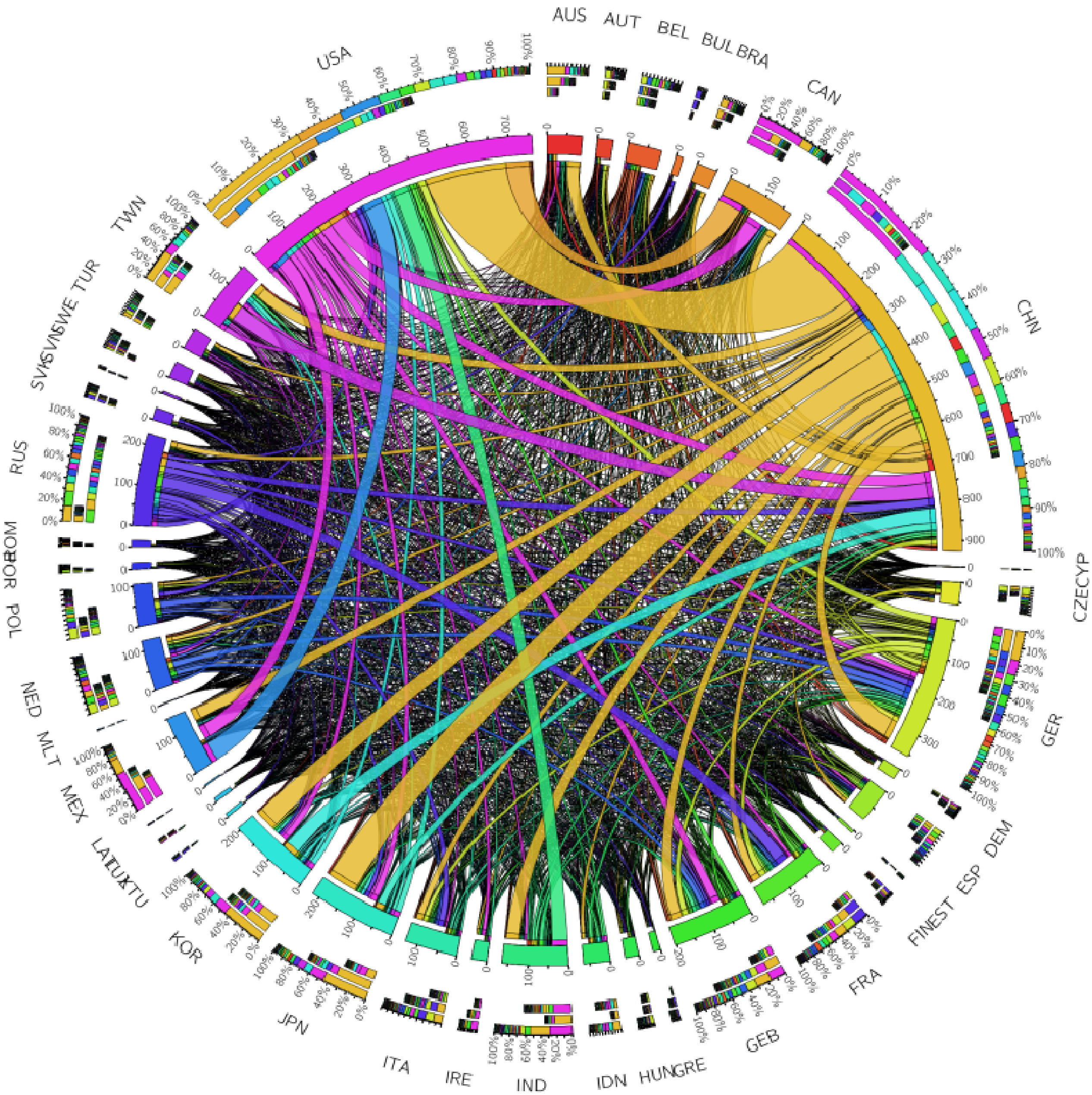

Fig. 1 Network model of global carbon flows through international trade.

Note: Fig.1 shows global carbon flows (inputs and outputs) among 40 countries whose GDP accounted for more than 85 % of the total global GDP during the study period. The width of the line represents the amount of carbon flows. As can be seen from the chart, countries in the world are engaged in frequent trade activities, which tend to imply huge embodied carbon transfer and is worthy of great attention.

40 countries: AUT: Austria; BEL: Belgium; BUL: Bulgaria; CYP: Cyprus; CZE: Czech Republic; GER: Germany; DEM: Denmark; ESP: Spain; EST: Estonia; FIN: Finland; FRA: France; the United Kingdom; GRE: Greece; HUN: Hungary; IRE: Ireland; ITA: Italy; LTU: Lithuania; LUX: Luxembourg; LAT: Latvia; MLT: Malta; NED: the Netherlands; POL: Poland; POR: Portugal; ROM: Romania; RUS: Russia; SVK: Slovakia; SLV: Slovenia; SWE: Switzerland; TUR: Turkey; AUS: Australia; BRA: Brazil; USA: the United States; MEX: Mexico; CAN: Canada; TWN: Taiwan; KOR: South Korea; JPN: Japan; IDN: Indonesia; IND: India; CHN: China.

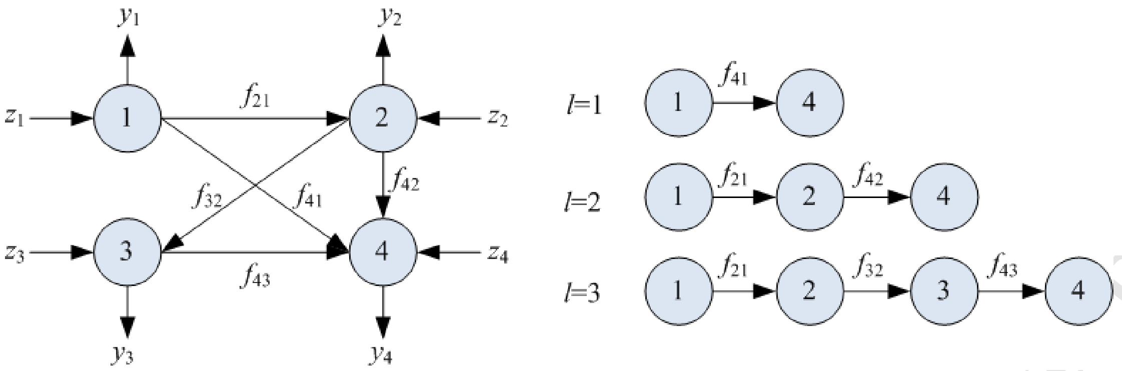

Fig. 2 Direct and indirect paths in the global CO_2 transfer network.

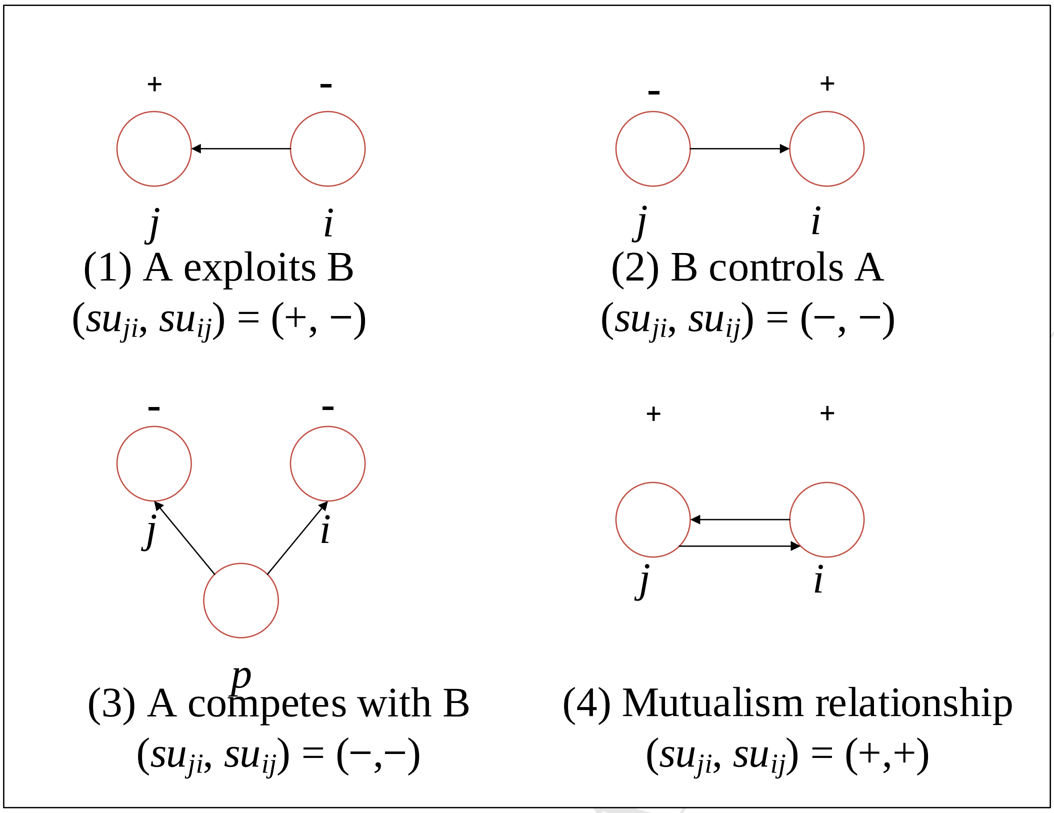

Fig. 3 Four types of ecological relationships in global carbon transfer network.

Note: su_{ij} is an element of matrix sgn(U) which represents the sign (positive or negative) of u_{ij} in matrix **U.**

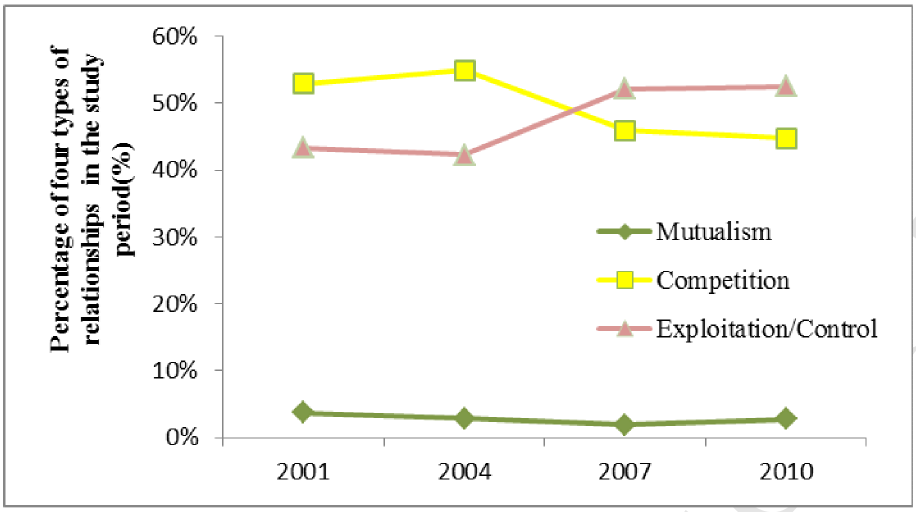

Fig. 4 Changes in the proportions of the four types of ecological relationships among countries from 2001 to 2010.

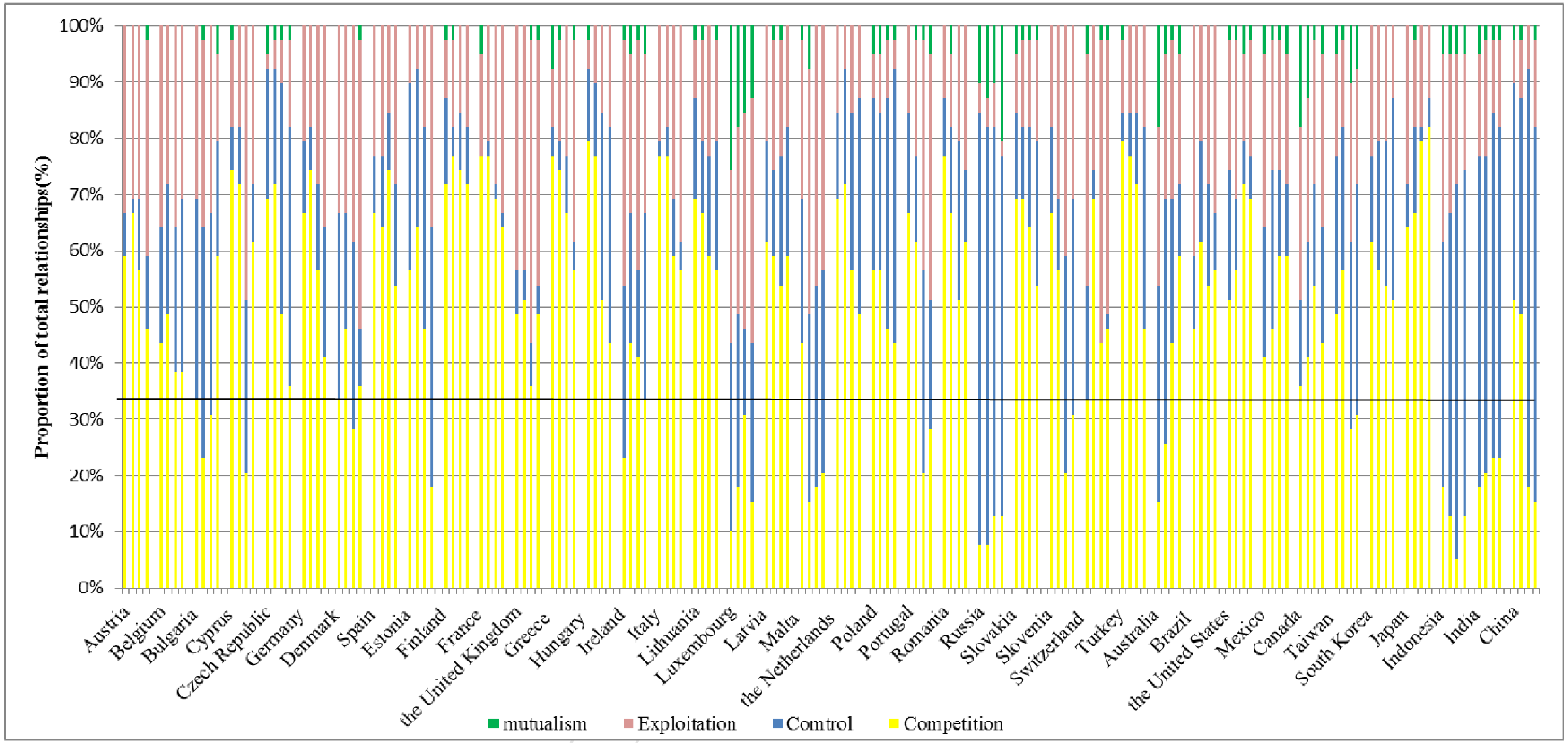

Fig. 5 Proportions of the four types of ecological relationships with other countries for each country during the study period. The (four bars for each country represent (from left to right) the four study years: 2001, 2004, 2007, and 2010

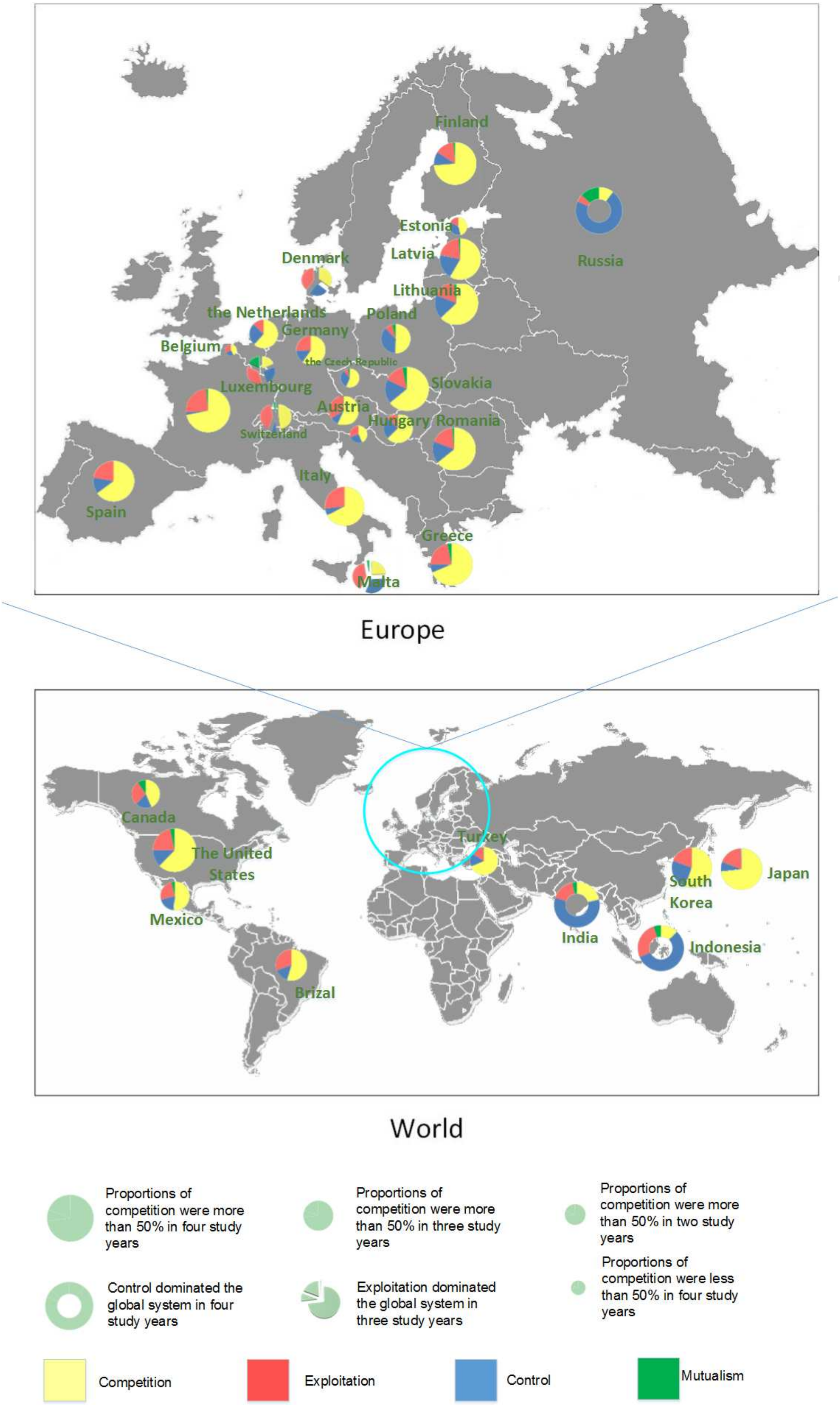

Fig. 6 Dominant countries of the four types of ecological relationships using the average value of the study years

Highlights

- We established a network model of the carbon flows that occur in global trade.
- We analyzed changes in the system's ecological relationships from 2001 to 2010.
- We analyzed changes in each country's ecological relationships from 2001 to 2010.
- Global carbon network was dominated by competition and exploitation/control.
- Finland, France, Japan Greece and Spain were most competition dominant countries.