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Review

Trends and features of embodied flows associated with international trade based on bibliometric analysis

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ABSTRACT

Trade plays an important role in redistributing resources and also brings significant environmental impacts to involved countries. This relatively complex research domain of international trade and environmental burden shifts is informed through study of embodied environmental flows of products. Research trends to identify features of international trade embodied flows between 1997 and 2016 are determined through a bibliometric study. Research contribution of countries, authors, institutions and journals are described. Co-citation and network analyses are completed. Results show that there has been significant research interest increase on this topic. Given the interdisciplinary and global nature of this topic, increases in countries, author, and institutional collaborations has occurred. USA, China, the Netherlands, the United Kingdom and Norway were the top 5 countries with high academic influence, and country as USA and institution as Chinese Academy of Sciences has the largest number of collaborations, respectively. Embodied flows such as carbon emission and water are popular ones associated with international trade in the given period, and the most popular methodological tool is Input/Output Analysis. In addition, hotspots which extracted from keywords are analyzed, additional avenues of research are also discussed in this study.

1. Introduction

Trade globalization has led to international economic integration that systemically links nations, and plays an important role in affecting sustainable economic development and ecological dynamics amongst nations (Jomo and Rudiger, 2009). Countries seek to determine if they are gaining or losing in international trade flows. The traditional economic discussion typically focuses levels of economic flows and imbalances. What has been given less focus in the literature and popular press are the impacts of trade on natural resources and the natural environment although these topics remain important and controversial (Jayadevappa and Chhatre, 2000; Moran et al., 2013).

Trade is sought out by nations to aid in their economic development. Countries seek out a share of the "trade pie". International trade flows are associated with comparative advantages or nations and regions. Comparative advantages occur for many reasons, some of which are natural resources availability and capabilities, such as water, land and carbon efficiency resources. The beneficial aspects of international trade and natural resources may be exemplified by global water resource balances. Countries and regions rich in water resources may be beneficial partners to those regions with water scarcity. For example, it has been found that international global water resources trade of agricultural products is 352 cubic gig meters per year (average over the period 1997–2001), greatly aiding water scarce areas (Chapagain et al., 2005). Another example is exports growth of carbon-intensive goods from Australia to China. This international trade relationship has helped in global carbon emissions reductions since Australian goods manufacturing carbon intensity is much less than China goods manufacturing carbon intensity (Tan et al., 2013).

International trade may result in resources and environmentally detrimental balances and trade shifts. This type of trade may allow one country to partially decouple its domestic economic and ecological systems while consuming goods from other national economic systems. Countries may seek to save their own environmental and resources capacity by shifting away from natural resources and pollutant-intensive activities in the manufacture of their goods (Machado et al., 2001). They can do this through importing high environmentally and resource burdensome products from other regions of the world. Under

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these circumstances, global issues such as “carbon leakage” and “ecologically unequal exchange” may occur across nations, resulting in greater overall environmental and natural resources degradation (Hoekstra and Mekonnen, 2012; Moran et al., 2013; Peters et al., 2011).

Inter-relational quantitative assessments incorporating socio-economic systems and the natural environment have gained attention with respect to global international trade. The major international trade assessment metrics and environmental indicators are called “embodied flows” (Bruckner et al., 2012; Giljum et al., 2011). Embodied flows quantify the natural resource or environmental quantities required directly or indirectly to make a product or provide a service. Embodied flows analysis helps identify and illustrate environmental burden shifts associated with raw materials extraction and processing, and product manufacture. Further analyses help to identify international trade balances. An important line of research focuses on “unequal ecological exchange” amongst nations.

To date, studies on trade-based embodied flows typically focus on either environmental or resources dimensions, based on different methods, such as Input-Output Analysis (IOA), Material Flow Analysis (MFA) and other relevant methods. These studies also aim to identify driving factors influencing embodied flows transfer, so that more appropriate policies can be raised to help address resources and environmental losses from trade (Caro et al., 2014; Davis et al., 2011; Tukker and Dietzenbacher, 2013; Steinberger et al., 2010; Wu et al., 2016; Guan et al., 2008).

However, due to the short period of this nascent field, publications related to embodied flows have not been comprehensively reviewed from either a quantitative or qualitative perspective. Although a number of reviews have been completed related to specific tools for embodied flows (Bruckner et al., 2015; Wiedmann, 2009; Wiedmann et al., 2007) or for specific types of embodied flows (embodied carbon, virtual water) (Liu et al., 2016; Zhang et al., 2017b); no research review has considered all the embodied flows, tools, and regions. A comprehensive integrative review provides insights into what topics have been covered and the reasons for these studies. It can also help identify research gaps and determine some consensus findings that policy makers can utilize.

In order to fill this gap in the literature and help to advance the field, this study applies bibliometric and complex network analysis for a systematic review of embodied flows associated with international trade. Systematic literature reviews are completed through an iterative process of defining appropriate search keywords, searching the literature and completing the analysis (Higgins and Green, 2009). Systematic reviews differ from traditional narrative reviews in that they employ a replicable, scientific and transparent process that minimizes the selection bias through exhaustive literature search (Vrabel, 2015).

The goals of this study include: (1) identifying trends and features of international trade embodied flows research for the period of 1997–2016; (2) summarizing contributions based on country, institutions, authors and journals and collaborative efforts to determine the perspectives and potential biases; (3) uncovering emergent research fields extracted from keywords through co-citation relationships; and (4) providing future directions for embodied flows and international trade research.

The remainder of this paper includes discussion of the methodology and data collection in Section 2. Section 3 pesents the main results. Section 4 provides a discussion and critical analysis of the results. Conclusions and future directions drawn from analysis are presented in the final section, Section 5.

2. Methods, data collection and treatment

2.1. Methods

Systematic bibliometric literature reviews follow a series of steps. Initially topically relevant keywords are needed for electronic database searches. Typical databases include the Web of Science or Scopus databases. Secondly some literature analysis tools (such as Bibexcel (Persson, 1986), in this study) are applied for identifying basic features of the selected papers. These data are then exported and processed for further analysis. The third step is the application of a network analysis tool. Network analysis provides insights into complex relationships amongst the publications and their various characteristics. In this regard, Gephi (Heymann, 2014) is used for network analysis and visualization of these networks. Various bibliometric statistics such as *h*-index, PageRank and cluster analysis could further help researchers identify the key roles of publications. The general flow chart for the systematic literature analysis used in this study is shown in Fig. 1. More details on these methodological steps and tools are now provided.

Fig. 1. The general flow chart for the systematic literature analysis.

Bibexcel is a bibliometric toolbox offering the user significant flexibility in data management and analysis. It is helpful in evaluating the research status and trends of various disciplines and topics. It is also helpful for identifying future research directions (Persson, 1986; Zheng et al., 2015). Bibexcel allows for modifying and adjusting data fields which can be imported from various electronic publication databases including Web of Science and Scopus. It can be integrated with other bibliometric and statistical software such as Pajek, Excel, SPSS, and Gephi (Fahimnia et al., 2015). Bibexcel extracts basic information from each publication, such as title, keywords, publication year, journal, authors’ information (names, countries and institutions), and citations. Additional information on Bibexcel operations and capabilities can be found in Šubelj et al. (2014a,b) and Persson (1986).

Network analysis helps evaluate various relationships among interacting units. Relations defined by linkages among units are a fundamental component. Network analysis evaluates observed attributes of social actors, such as race, ethnicity, size, and productivity of collective bodies such as cooperation or nation-states, as examples. It seeks to understand relationship patterns or structures amongst the units of

analysis (Wolfe, 1994). Network analysis is used in literature reviews by establishing nodes that may be represented by research papers, keywords, countries, institutions or authors. Arcs, which are relationships, such as collaborations and influences of these nodes, can also be evaluated. Gephi software is used to complete a network analysis and visualization of the networks. Gephi is an open-source platform for visualizing and manipulating large graphs (Heymann, 2014).

PageRank can help identify influential publications and researchers. PageRank was originally used to evaluate webpage connectivity. It was initially intended to help prioritize web pages when a keyword search is performed in a search engine (Boldi et al., 2009). PageRank for literature analysis can determine popularity of a given publication. The central idea of PageRank is to determine publication influence by the number of times a paper is cited by other highly cited papers. Higher PageRank scores mean greater publication influence (Yates and Dixon, 2015).

Cluster analysis helps to structure a network for analysis. Network nodes can be divided into several clusters or modules. Nodes within the same cluster typically contain similar features. These features provide grouped insights which can further detect latent or explicit general related topics or partnerships. For systematic literature analysis, cluster analysis is often used for co-citation analysis, papers which have similar topics, interrelations, and collaboration patterns (Everitt and Dunn, 2011).

2.2. Data collection and treatment

The Web of Science database is used to compile the literature data set. The Web of Science database provides comprehensive and standardized information searches of publications for academia. It represents the most influential and highest quality journals from a broad variety of disciplines. A two-level keyword assembly structure that aims to accommodate a broad range of search terms for capturing related publications was used in a search of publications between the years 1997–2016. Fig. 1 outlines the keyword search terms structure. Level 1 identifies the international trade related keywords; level 2 contains virtual and embodied flows related keywords.

The publication search was conducted in June 2017. Initial 1072 papers were identified and collected. The research results were stored in plain .txt format to include all the essential paper information including titles, keywords, abstracts, affiliations, authors, and references. Among these publications, according to categories within the Web of Science, articles account for 80.63%, followed by proceedings paper (15.14%), review papers (2.70%) and others. English (97.67%) is the most frequently used language, followed by Spanish (0.47%) and others. In this study, only articles in English (874) are selected due to its academic popularity. Further screening by the researchers after reading abstracts, titles and main texts was conducted to remove those articles which were found to be irrelevant. After screening the final study database is comprised of 419 research publications.

3. Results

3.1. General performance of selected publications

The per year total number of publications (TP), authors (TA), average numbers of references per paper (ARP) and published countries (TPC) from 1997 to 2016 are shown in Fig. 2. The results show that the values of TP and TA increased stably during the entire study period, while the values of TPPC and ARP first increased rapidly during 1997–2001, then significantly decreased during 2001–2004 and finally increased stably during 2004–2016.

As can be seen few publications on this topic were published before 2007, while the number increased rapidly from 2010 to 2016. Overall, during this time period, 889 unique researcher names were found to have studied embodied flows associated with international trade. The total unique author quantity increased from 4 in 1997–295 in 2016, a very significant increase in magnitude of researchers studying this topic. ARP increased between 1997 and 2016. The number of references in earlier papers may have been fewer since the research was nascent at that time. In later years given the increase in previous publications on this topic, the number of references per paper increased. It was also found that more countries involved in this topic over the years. The TPC increased from 1 in 1997–25 in 2016. This increase in the breadth of countries investigating this issue may relate to greater interests from the country research institutions as more countries developed economically and had increased environmental burdens due to international trade.

3.2. Country/region, author and institution influences

Countries/regions, authors and institutions perspectives can help provide insight into schools of thought due to demographic or personal features. For example, country/region level interest may derive from a country/region that is heavily dependent or influenced by international trade and its impact on the environment or resources. If a nation is under pressure to address environmental concerns, the embodied flows perspective may provide valuable insights on environmental influences in that nation. Scholar influence is important since it helps to define discipline relationships. For example, an international trade perspective may derive from economics and business scholars, while environmental embodiment concerns may derive from environmental policy scholars. Institutional perspectives may provide insights into influence of various institutions and their research groups as well as collaborative institutions. Schools of thought may be derived from the actual schools or institutions involved.

However, the quantity of publications may not be equivalent to the quality or influence of these publications. Another statistical indicator, the *h*-index, is used as a proxy for influence or quality of publication. The *h*-index is calculated by having an individual or group that has at least *h* papers cited by at least *h* times. It can be used to represent the academic influence of countries/regions, institutions and authors (Bornmann et al., 2011; Hirsch and Buelacasal, 2014). Fig. 3 summarizes this information. The dashed line in this figure refers to that x represents the total number of publications and y represents *h*-index where y = x. A large gap, for example, between total number of publications and *h*-index for a country, would indicate high output but minimal influence by that country. If a country, institution, or author is closer to the dashed line, then arguably they have greater academic influence. Academic cooperation among different countries/regions, institutions, authors are important. More opportunities and solutions could be found through cooperation, especially with the involvement of developing countries. Country/region, institutional and author level academic influences in this field are summarized as below.

3.2.1. Performance of countries/regions

A total of 44 countries have been represented in publications on embodied flows in international trade research from 1997 to 2016. Among these countries, China, USA, the United Kingdom, the Netherlands, Norway, Japan, Germany, Spain, Austria and Australia are the top ten most productive countries in that order; respectively they account for 29.8%, 26.3%, 13.8%, 10.5%, 7.9%, 7.9%, 7.6%, 7.4%, 6.7% and 5.7% of the total selected publications. In addition, from an *h*-index perspective, USA (32), China (31), the Netherlands (24), the United Kingdom (22) and Norway (20) are the top five countries in terms of influential publications. Some of these papers are cooperative across countries.

A co-occurrence analysis of the top 30 countries/regions is used for evaluating collaboration between countries. This number of countries/regions represents a natural break in total number of publications with two or more publications on this topic. The top 30 countries/regions range from 2 to 125 publications. Of these 30 countries/regions, the

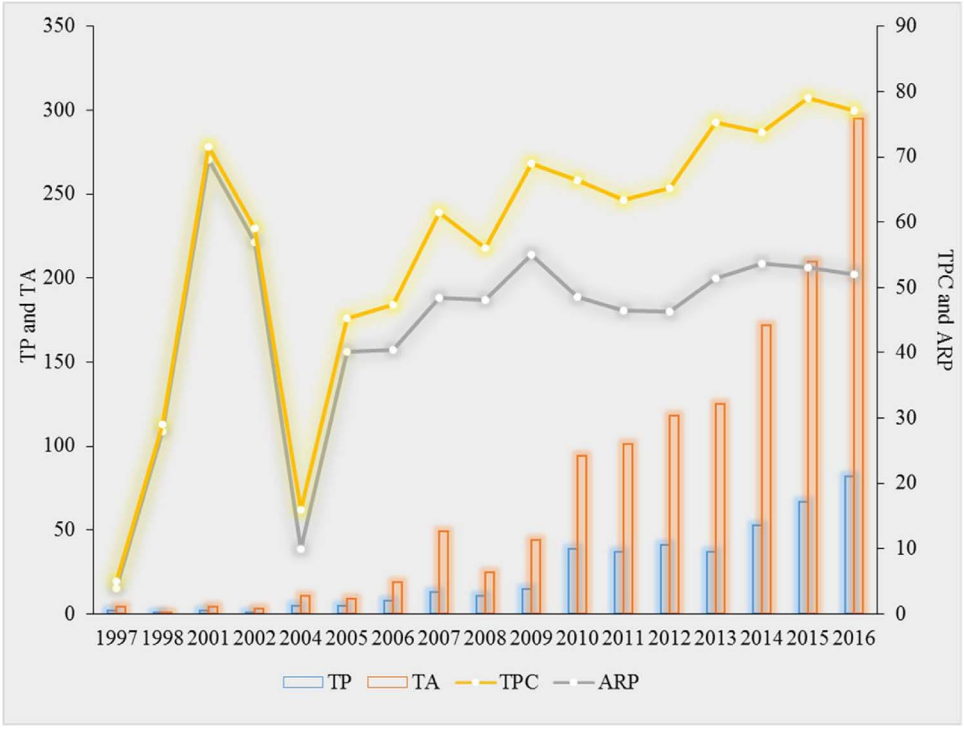

Fig. 2. General statistics of selected publications from 1997 to 2016.
Total number of publications/year (TP); Total authors/year (TA); Average references per paper (ARP); and Total published countries/per year (TPC)

USA, the Netherlands and China are the most collaborative. Each of these countries/regions has cooperated with 21, 19 and 17 of the other 29 countries/regions, respectively. The USA has the most collaborative publications with international partners for a total 123 papers with the other 29 countries/regions. This result shows a strong USA-centric focus of the research. This may not always be the case as the second largest collaboration and increasing set of collaborations is occurring with China and other nations; for example, the China-UK collaboration in this area is the third largest set of collaborative publications (see Fig. 3-CO).

3.2.2. *Performance of authors*

The total publications and *h*-index of the top 17 most productive scholars, who range from 8 to 18 publications, are shown in Fig. 3-AU. Among these scholars, 15 belong to the top 10 most productive countries. Chen GQ, Peters GP, Hoekstra AY, Chen ZM and Lenzen M are the most productive and influential scholars.

The most collaborative scholar is professor Guan DB which originally was from the University of Leeds, who is now working at the University of East Anglia in UK. His publications appear mostly with Liu Z (another fellow at the University of East Anglia), with an emphasis of work on emissions from China's international trade. Emissions by this collaboration include carbon emissions, $PM_{2.5}$ emissions and embodied

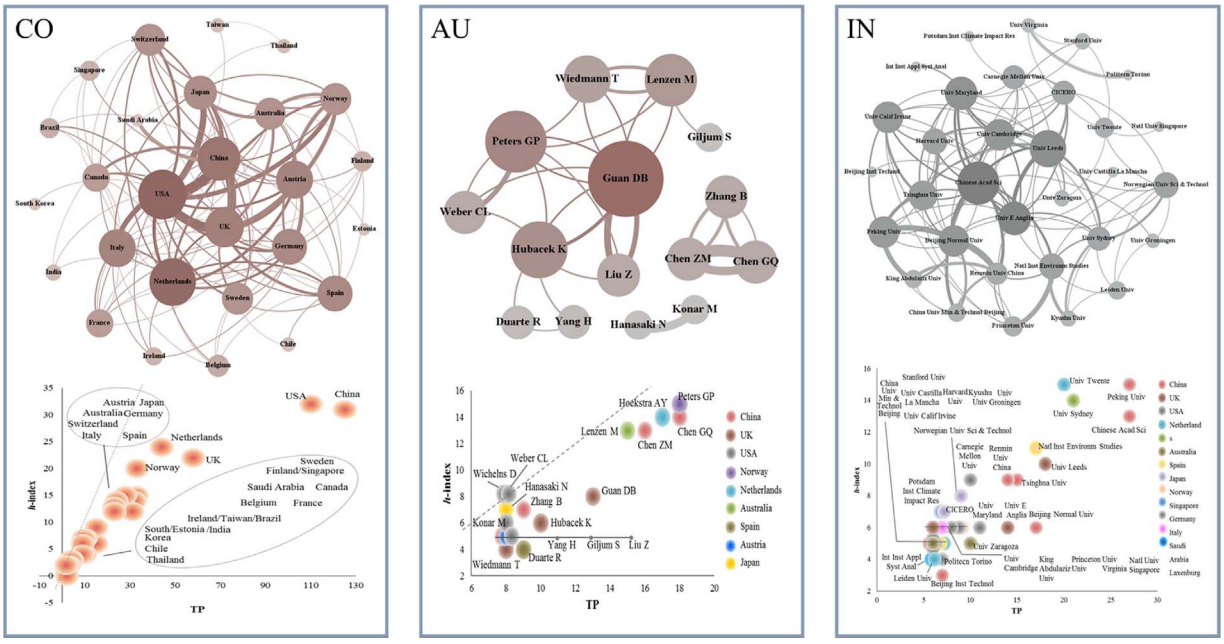

Fig. 3. Performance of countries (CO), authors (AU) and institutions (IN).

aerosols. Guan DB has also collaborated with Hubacek K on virtual water topics. A second scholar's cluster is centered by Peters GP from the Norwegian University of Science and Technology whose most co-authored publications appear with Weber CL, and Wiedmann T, with a focus on embodied carbon emissions in international trade.

3.2.3. Academic institution performance

In total 453 unique academic institutions had published on this topic from 1997 to 2016. Peking University (27 publications), the Chinese Academy of Sciences (27 publications), the University of Sydney (21 publications), the University of Twente (20 publications) and the University of Leeds (18 publications) are the top 5 productive institutions. These institutions also belong to some of the more productive countries.

The *h*-index results show that the Peking University, University of Twente, the University of Sydney, the Chinese Academy of Sciences, and the National Institute for Environmental Studies (Japan), are the top 5 academic institutions. The top 32 institutions are selected for collaborative analysis. The total publications from these institutions range from 6 to 27 publications. Of these 32 institutions, the Chinese Academy of Sciences, the University of Leeds, the University of East Anglia and the University of Maryland are the most collaborative. These institutions have collaborated with 18, 15, 13 and 13 of the other 31 institutions, respectively. The Chinese Academy of Sciences has the largest number of collaborations for a total 39, with its largest collaborative partner institution being Beijing Normal University with collaboration on 5 publications (see Fig. 3-IN).

3.3. Journals, citations and keywords analysis

This section evaluates the publication outlets, i.e. journals that have published the papers. This analysis provides an idea of the disciplines that are most interested and generative of this topic. Citations help to determine the level of connectedness of topics and papers. The citations and co-citations analysis help to identify core topics in the field. Keywords analysis can also help to identify core areas and topics and other paper features in the field. For example, keyword analysis allows for analysis of methods, relationships between topics, and research fields.

3.3.1. Journals analysis

The selected 419 papers appeared in 114 different journals. The top 15 journals are summarized in Table 1. The top 15 journals account for 60% of the publications in this dataset. This distribution shows great diversity in journals and disciplines. Among these journals, *Ecological Economics* is the most popular journal with a total of 52 publications, followed by *Energy Policy* (36 publications) and *Environmental Science & Technology* (24 publications).

These top 15 journals are directly linked with resources and the natural environment. *Ecological Economics* is concerned with extending and integrating the study and management of nature's household (ecology) and humankind's household (economics). Specific research areas mainly covered include: valuation of natural resources, sustainable agriculture and development, ecologically integrated technology, integrated ecologic-economic modelling at scales from local to regional to global. *Energy Policy* is an international journal addressing the policy implications of energy supply and use from economic, social, planning and environmental aspects. Topics of particular interests include energy and environmental regulation, energy supply security, the quality and efficiency of energy services. The objective of *Environmental Science & Technology* is to analyze the major advances, trends, and challenges in environmental science, technology, and policy for a diverse professional audience, and to promote interdisciplinary understanding in the environmental field. Given these journal descriptions, it is not surprising that this interdisciplinary topic appears in these journals.

Table 1
Top 15 journals from 1997 to 2016.

Journal	Amount	Percentage	Impact factor (based on 2017 year)
Ecological Economics	52	12.41%	2.965
Energy Policy	36	8.59%	4.14
Environmental Science & Technology	24	5.73%	6.198
Environmental Research Letters	20	4.77%	4.134
Journal of Industrial Ecology	20	4.77%	4.123
Journal of Cleaner Production	18	4.30%	5.715
Energy Economics	12	2.86%	2.862
Economic Systems Research	11	2.63%	5.306
Hydrology and Earth System Sciences	10	2.39%	4.437
Applied Energy	10	2.39%	7.182
Global Environmental Change	9	2.15%	6.327
Proceedings of The National Academy of Sciences of The United States of America	9	2.15%	9.661
Energy	8	1.91%	4.52
Climate Policy	7	1.67%	1.98
Water Resources Research	7	1.67%	4.397

3.3.2. Citation analysis

A total of 11,440 cited references appeared in the selected publications. The top 15 most cited references are shown in Table 2. In order to analyze the co-citations relationships, a co-citation network, with various clusters identified, is shown in Fig. 4. PageRank is also presented in Table 2, which is helpful for identifying the core papers within each cluster. The core paper topics help to further define the cluster features.

Fig. 4 shows 3 distinct clusters from the co-citation network. Cluster 1 includes 20 papers and is greatly influenced by the scholar Yan YF and his paper published in 2010 (with a PageRank of 0.1485). This cluster mainly focuses on climate change, carbon leakage, input-output analysis, structural decomposition analysis, and CO_2 emissions. The second cluster includes 16 papers and highlights multi-region input-output models, carbon footprints, producer responsibility, consumer responsibility, and ecological footprints. The lead publication in this cluster is Wiedmann T's paper published in 2010 (PageRank: 0.0575). The third cluster includes virtual water, water management, water policy, water use efficiency, globalization, and water footprints. Cluster 3 has 14 total publications with the most influential author and paper being Yang H and his paper published in 2006 (PageRank: 0.0477).

3.3.3. Keywords analysis

A total of 892 keywords with 1714 occurrences appeared from the 419 selected papers. From these keywords, 77.6% appeared only once. Only 2.4% of the keywords appeared more than 10 times each. Some keywords may have similar ultimate meanings, such as "input-output analysis" and "input-output"; these keywords are regarded as one keyword. After this integration a total of 802 keywords with 1169 occurrences are used for further analysis.

Keywords information in one publication may include objectives, methods, study areas, and purposes. Keywords are classified into these four areas. Fig. 5 illustrates the main topics which are extracted from keywords of the 419 selected publications.

The overall objectives are relevant to international trade. Topics within this general objective by scholars include global trade, agriculture trade, energy trade and food trade levels. Embodied flows typically focused on either environmental or resources dimensions. Environmental indicators typically include air emissions such as carbon, methane, sulfur dioxide, mercury, ozone, or particulate matter emissions (Caro et al., 2014; Davis et al., 2011; Deng et al., 2016; Li, 2016; Román et al., 2016; Zhang et al., 2017a). Embodied resources

Table 2
Top 15 most cited references from 1997 to 2016.

Year	Title	Country	Author	Journal	Citations	Page Rank
2007	On the conversion between local and global hectares in Ecological Footprint analysis	UK, Australia	Wiedmann and Lenzen	Ecological Economics	119	0.0498
2008	CO_2 embodied in international trade with implications for global climate policy	Norway	Peters and Hertwich	Environmental Science & Technology	117	0.0171
2011	Growth in emission transfers via international trade from 1990 to 2008	Norway, Germany, USA	Peters et al.	Proceedings of the National Academy of Sciences of the United States of America	88	0.0245
2010	Consumption-based accounting of CO_2 emissions	USA	Davis and Caldeira	Proceedings of the National Academy of Sciences of the United States of America	81	0.0076
2008	From production-based to consumption-based national emission inventories	Norway	Peters	Ecological Economics	77	0.0159
2008	The contribution of Chinese exports to climate change	USA, Norway, UK	Weber et al.	Energy Policy	71	0.0315
2009	Carbon footprint of nations: a global, trade-linked analysis	Norway	Hertwich and Peters	Environmental Science & Technology	70	0.0085
1970	Environmental repercussions and the economic structure: an Input-Output approach: a reply	USA	Leontief	Review of Economics & Statistics	65	0.0110
2001	Energy and carbon embodied in the international trade of Brazil: an input–output approach	Brazil and USA	Machado et al.	Ecological Economics	60	0.0126
2009	Input-Output Analysis	UK	Miller and Blair	Cambridge University Press	58	0.0132
2004	CO_2 multipliers in Multi-region Input-Output models	Australia and Denmark	Lenzen et al.	Economic Systems Research	57	0.0092
2007	Embodied environmental emissions in U.S. International Trade, 1997–2004	USA	Weber and Matthews	Environmental Science & Technology	57	0.0360
2005	Globalisation of water resources: international virtual water flows in relation to crop trade	Netherlands	Hoekstra and Hung	Global Environmental Change	56	0.0091
2001	CO_2 accounts for open economies: producer or consumer responsibility?	Denmark	Munksgaard and Pedersen	Energy Policy	52	0.0131
2007	China's growing CO_2 emissions-a race between increasing consumption and efficiency gains	USA, Norway, UK	Peters et al.	Environmental Science & Technology	46	0.0180

indicators include energy, virtual water, virtual land, materials, labor, biodiversity and aggressive resources (total amount of biosphere work used to generate products or services) (Bruckner et al., 2012; Cortésborda et al., 2015; Geng et al., 2017; Hoekstra and Mekonnen, 2012; Lenzen et al., 2012; Qiang et al., 2013; Xu et al., 2009). The five main embodied flow topics include embodied carbon emissions, embodied water, embodied land, embodied energy and embodied pollution.

Scholars tend to study these embodied flows from two perspectives, namely, consumption-based and production-based. Most recent studies focused on consumption-based perspectives, whereas previously production-based perspectives dominated. It has been argued that consumption-based measurements are more effective for allocating responsibility from an equity viewpoint. A consumption-based perspective has advantages of avoiding carbon leakage, increasing mitigation options, encouraging environmental comparative advantage, addressing competitiveness concerns, and inevitably speeding up technology diffusion. However, embodied carbon emissions research tended to focus on the production perspective rather than on the consumption perspective. Scholars in this research sought to identify aspects of carbon leakage and carbon intensity. Embodied water research also included two perspectives, namely, production (virtual water) and consumption (water footprints). Embodied water research typically utilized a blue water, directly from nature, and a green water, cleaned human grey water, with a dichotomy perspective. Embodied water research explored such diverse topics as water scarcity, water resources management, water policy, water-energy nexus and water allocation. With regard to land, embodied land, land footprints and virtual land topics included two main perspectives, namely net primary production and improvement of land use. In addition, embodied energy topics primarily included energy consumption, intensity, security, and recovery. Fossil fuels and biofuels were two popular topics within energy. Finally, embodied pollution had relatively fewer keyword occurrences. Pollution keywords, such as air pollutants, particulate matters, methane and sulfur dioxide, were the most popular pollution types. Besides the main five embodied topics, embodied technology, nitrogen, biodiversity, and labor also appeared amongst popular keywords.

In terms of research methods, input-output analysis (IO analysis) is the most popular method. IO analysis helps to identify interdependencies between different countries and economic sectors based on sectorial monetary transactions and physical data. This method can identify both direct and indirect production and consumption environmental burdens (Leontief, 1936). It has been used to evaluate a variety of flows in trade, including carbon emissions (Peters et al., 2011), pollutant emissions (Zhang et al., 2017a), virtual water (Guan and Hubacek, 2007), embodied materials (Bruckner et al., 2012), and virtual land (Ali et al., 2016). Multi-Regional Input-output (MRIO) analysis has received more attention than other types of IO analysis. MRIO analysis is more popular when scholars focus on footprint analyses. MRIO's major advantage is its ability tracing not only domestic supply chains, but supply chains on a global level. It takes into account varying resource intensities in different countries (Tukker and Dietzenbacher, 2013). Further IO methods and analyses information could be found in Tukker and Dietzenbacher (2013). Structural decomposition analysis, material flow analysis, ecological footprint analysis, complex networks, life cycle assessment, emergy accounting, uncertainty analysis, and cluster analysis are other major methods utilized in the literature. Each method has its advantages and limitations and is discussed in the relevant literatures (Hoekstra and Hung, 2005; Qiang et al., 2013; Steinberger et al., 2010; Kovanda and Weinzettel, 2013; Wiedmann and Lenzen, 2007; Geng et al., 2017).

Regions and locations are also investigated with 27 regions studied. China is the most frequently appearing keyword when it comes to locational or regional analysis; Europe is second. In addition, trade relationships between nations have been investigated. China-US trade and Japan-China trade dyadic relationships were the most popular.

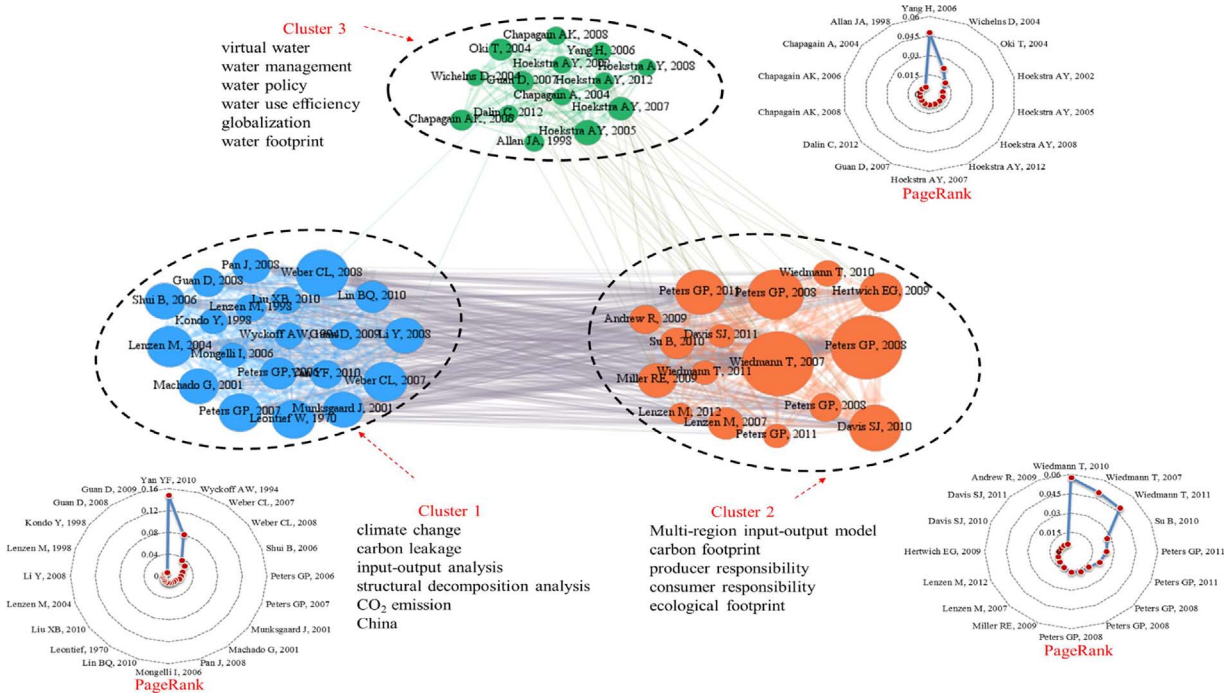

Fig. 4. The cluster structure of the authors' co-citation network.

These country relationship studies focused on trade and environment, as well as sustainable development. Scholars investigated trade policy alternatives for decreasing environmental and resources loss or impact in these regions. Scholars also recommended directions for improving resource efficiency and potential technological solutions, especially those that conserve resources and mitigate environmental burdens.

In order to improve trade in the long run, prescriptive and predictive studies in this field also exist. Researchers have sought to determine which factors contribute to various flows. These factors are used to prepare more appropriate policies to help address resources and environmental losses from trade. For instance, Wu et al. (2016) use decomposition analysis to investigate carbon emissions exchange from China-Japan trade and found that increasing trade volume induced the increase of embodied emissions, while technological improvement decreased such embodied emissions. Tuninetti et al. (2016) evaluated virtual water flows using a gravity-law model and found that population, geographical distances between countries, and agricultural efficiency (through fertilizers use) are major factors driving increases and decreases in virtual water trade. Dittrich et al. (2012) uncovered that resource amounts and population density are more relevant than per

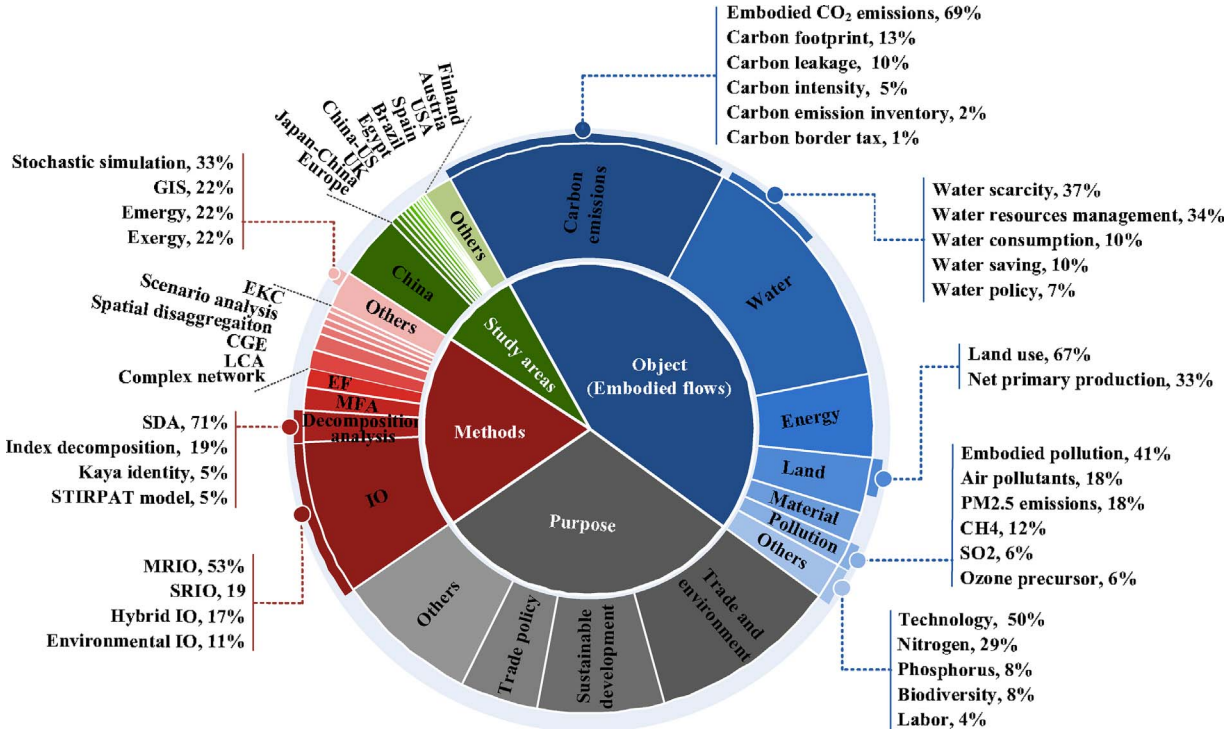

Fig. 5. Research topics from keywords.

capita income in determining the material physical trade balance based on regression analysis. Guan et al. (2008) combined structural decomposition analysis with input-output analysis to assess China's CO_2 emissions from 1980 to 2030 and predicted that production-related CO_2 emissions are expected to increase by 300 percent by 2030 and found that household consumption, capital investment and growth in exports are key factors driving this CO_2 emissions increase.

4. Discussions

The research on international trade has typically focused on economic development and international financial and goods flows. Globalization of commerce has caused even more emphasis on trade, causing greater concerns with environmental burdens and resource shifts. A major concern over the past couple decades has been the unbalanced resources and environmental burdens caused by international trade. The relationship between economy, resources and the environment has reached a critical point and for this reason the research in this field has started to gain more attentions.

Broadly, economic production and consumption use natural material and resource inputs. Environmental resources are currently highly undervalued as there are often little or no costs attached to their consumption. Given this undervaluation resources and environmental goods consumption is exacerbated. This situation has caused greater and more frequent global concerns related to resources depletion and environmental burdens (Bruckner et al., 2012).

The impact of economic development and international trade on the environment and its resources is clear. Alternatively the influence of resources and the environment on economic systems is also profound. For example climate change could change spatial distribution of economic patterns. Some countries will become better suited for agricultural production, while other countries' agricultural production will deteriorate. Thus, resource depletion and environmental shifts will influence one country's comparative advantage and disrupt international trade and economic patterns (Konar et al., 2013). Under such a circumstance, studies of embodied flows from international trade have increased, aiming to identify the relationships between economy, resources and the environment.

4.1. Typical countries

The analysis of the literature has resulted in a number of general findings. International trade embodied flows studies have primarily occurred within developed countries such as the USA, the Netherlands, the United Kingdom and Norway. These countries are at the high end of the national economic development, technological level and living quality scales. Given their situations, these nations tend to pay more attention on embodied flow research concerns, with a goal of improving environmental quality.

Developing and undeveloped countries are less represented in this research due to less economic development, environmental awareness, poor living quality, and data and economic resources availability. Within this general finding, China is one exception and has put more emphasis on this topic. China has become one of the fastest growing economies in the world. Currently, it may be at the early portions of the "environmental Kuznets curve" (Stern et al., 1996) and may soon reach the turning point causing it to further support study in this area. China's economic success has resulted in considerable improvements in people's quality of life. The country has realized that the economic achievements have required significant natural resources inputs, leading to serious environmental problems on both local and global scales (Shapiro, 2016). Global impact of China's environmental problems is evidenced since it has become the largest carbon emissions emitter in the world due to its coal-dominated energy structure and increasing exports (Peters et al., 2007). In addition, the co-occurrence analysis between countries indicates that cooperation between developed countries are frequent. Developing or underdeveloped countries had few cooperation with developed countries except China, implying that more cooperation should be encouraged between developed and developing countries so that environmental and resources issues can be addressed at the global level.

4.2. Typical clusters

The co-citation and keywords analyses provide insights into the major topics of focus in this area of research. The co-citation analysis shows that three clusters were created. Two of them focused primarily on embodied carbon in international trade, while the other cluster tended to be more focused on water resources.

Carbon emissions are clearly related with global climate change, one of the major topical areas of the first cluster. Research purports that understanding production and consumption of materials and goods that cause global climate change can be managed through international trade. Embodied carbon accounting will aid in mitigation opportunities by various nations, companies, and industrial supply chains. Cluster 1 seemed to focus on a standard specification and quantification of carbon flows amongst a variety of countries, aiming to understand and describe the general carbon embodiment and leakage situation. IO analysis was the most prevalent approach to understand carbon flows. Scholars also sought to determine what factors were driving the various carbon flows between countries. Interestingly, a large fraction of papers within this first cluster focused on China and its international trade partners. Given that China is the largest emitter of carbon emissions, it is not surprising that they are a focus of several studies.

Cluster 2 emphasized a more in-depth and nuanced set of studies. For example, further refinement of IO analysis to a MRIO occurred in this cluster. Also, in Cluster 2 a more consumption research perspective emerged and dominated. Many of this research, as emphasized in the earlier discussion of this section, aim to identify who should bear responsibility for the international trade influences on natural resources and the environment (especially in carbon emissions). The focus on footprint and responsibility analysis in these studies started the shift in analysis to specific industries and goods manufacture, a more detailed and disaggregated perspective. The research shows that the issue of whether the focus of studies is on production or consumption of international trade and embodied flows complicates the fundamental question of where the responsibility lies for resources depletion and environmental burden. A key finding from these studies is that developed countries benefit more from the resources and environment of developing and underdeveloped countries from a consumption perspective. Thus, these findings would imply that developed countries should take the lead on investing in technologies, practices, and policies to aid developing and underdeveloped countries. Conclusions of the consumption based studies indicate that the consuming countries should increase their investments and support for mitigating the impacts of international trade on resources and the environment, rather than those producing countries. This more nuanced approach sought to make progress on actions necessary to mitigate imbalances and poor embodied flows management, a more prescriptive stance rather than the descriptive perspective of Cluster 1.

Cluster 3 focused on embodied (or virtual) water flows in international trade. In this cluster, both descriptive and prescriptive literatures were evident. Essentially, this cluster was an integration of Clusters 1 and 2, but for water. Both a production and consumption perspective of water was included. Water use efficiency and water management policies and future practices were important. Water is a very significant issue in many countries and was not necessarily tied to a particular country, it is a truly global, but regionalized, concern that impacts countries in varying ways. This cluster was a resource based concern rather than an environmental concern.

4.3. Typical keywords

The keywords analysis helps to identify some of the limitations of the co-citation analysis in terms of coverage of topics. It also provides insight into underrepresented topical areas for further investigation. For example, energy, land, material, and other pollution embodiments are not well represented in the clusters. These research study areas may be more pronounced in the future, but may be at the whim of social pressures, policy makers, and funding agencies or other stakeholders.

Research methods and accounting tools may also need further development. At this time the IO Analysis tools seem to dominate methodologically. IO analysis may require data that are easily available for this type of analysis and thus is more popular. Also, given the economic nature of these studies, economics based tools dominate. As the field emerges, optimization, decision support tools, stochastic modelling, and other statistical analysis tools may become more prevalent. From an accounting perspective, emergent techniques like exergy and emergy analysis may be promising approaches for standardized environmental and resources accounting techniques. These research methodology tools and their applications could provide additional insights.

5. Conclusions and directions for future research

International trade plays a key role in global shifts of resources and environmental burdens between countries. Given the resources and environmental burdens embodied within goods exchange between countries, it is necessary for countries to identify trade patterns so that more appropriate policy planning and implementation can be completed.

In this study, a systematic and comprehensive review on embodied flows associated with international trade from both quantitative and qualitative perspectives is presented. The Web-of-Science database was used and only published peer reviewed journals appearing in this database were used. The main results show that annual publication quantity, the number of authors, average number of references per paper, and number of studying this issue all show increasing trends during the period 1997–2016.

Out of a total of 44 countries/regions, the USA, China, the Netherlands, the United Kingdom and Norway were the top 5 countries. The results show that most of the research was completed by developed nations, with China being the only exception. Chinese universities were also some of the most productive and collaborative. Hundreds of authors from these countries have studied this issue with most coming from ecological or environmental economics research backgrounds.

Three research clusters were determined through a co-citation analysis. Two clusters mainly focused on climate change, carbon leakage, input-output analysis, structural decomposition analysis, CO_2 emission, and carbon footprints. The third cluster focused more on water resources embodiment and trade.

From the analysis of the published research for the past two decades, some insights and future research directions about international trade embodied flows have been identified. For example, research in a number of environmental burdens and resources use still require further investigations. Also, emergent methodologies can be further investigated. These issues were identified previously in our discussion. Additional research, from the various directions have also been identified. Four of these major outstanding research concerns are now summarized.

(1) Improving data availability. From present research can be noted that developed countries have access to significant data resources. Developing and undeveloped countries are lacking in available data and information. Given the seriousness of environmental and resource problems in developing countries developing more reliable and accurate databases, and accounting tools, is needed. Not only are new databases required but maintenance of the trade and embodied data is also important. For example, updating national IO databases each five years and even longer for resources and environmental databases, makes it difficult for researchers and policy makers to monitor the dynamic shifts and patterns. Although supranational governmental agencies can help in this effort, researchers who develop and maintain databases should cooperate in their efforts to maintain updated information and sharing of this information.
(2) \Improving methods standards. Given that these studies will play an important role in potentially setting policy, having scientific and replicable methods to investigate the many dimensions of this research is necessary. Understanding and limiting the disadvantages of different methods and standardizing results are important. For example, integrating different methods taking advantage of each's complementary characteristics could improve understanding of the field. Research on this area is needed, as are how to approach these methodologies and understanding when they are appropriate and when not appropriate.
(3) Exploring more useful indicators. The resources and environmental features and dimensions can be quite diverse. Also resources and environmental burden features and needs within various countries or regions tend to differ. Exploring the development and selection of indicators reflect the idiosyncrasies of various regions, while maintaining consistency with sustainable development goals in these areas, is needed. In this way more knowledge can be gained using new indicators, in addition more specific location problems could be solved.
(4) Defining sustainability limits and analyzing trade-offs. The identification of sustainability limits for each of the resource use categories is a key issue for further investigation when researching new indicators. These targets need to be defined on a scientific basis. Issues such as the maximum amount of biomass extraction from a given area of crop lands and forests, or the maximum uptake of fresh water, given the limited capacity for water renewal are examples. Only when boundaries for embodied flow categories are known, can trade-offs between different options be properly evaluated. Having indicators that can standardize different types of resources plus knowing sustainability limits for each of the categories, can further support trade-offs analysis. For example, higher production of biofuels would likely decrease the abiotic resource indicator (less fossil fuels) and, depending on the type of biofuels, also the related GHG emissions. Alternatively, this would translate into increased demand for land area and water. The set of indicators and related limits can illustrate whether an improvement in one category leads to an unsustainable situation in another category, or may be a co-benefit.

This study provides helpful information for researchers and policy makers who seek to further broadly understand embodied flows associated with international trade. Overall, this is an emergent and necessary study area that needs to broaden its scope to more comprehensively address the world's resource and environmental burden limits. The complexity of this field will only increase as more research is completed. This paper tries to clarify this complexity to make sense of the field. Understanding how the field has evolved and where gaps and opportunities exist, is important to further scientific and policy understanding.

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