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Trade in the telecoupling framework: Evidence from the metals industry

ABSTRACT. As a conceptual framework for understanding contemporary sustainability challenges, telecoupling emphasises the importance of socio-economic and environmental interactions over long distances. These long-distance interactions can occur through multiple human activities. Here we focus on international trade, a major channel of telecoupling flows, and in particular on the international trade of metals. We use the data of physical products and embedded greenhouse gas (GHG) emissions trade in the World Input-Output Database (WIOD) to quantitatively examine how countries contribute to both economic and environmental flows through trade of metals, but also how that contribution varies depending on their position in the global value chain (GVC) of contemporary international trade. This analysis is built on previously developed techniques for decomposing gross exports of products which we apply to examine embedded GHG emissions. We make comparisons between countries' contributions to flows of economic value versus embedded GHG emissions, but also examine contributions beyond total volumes of trade and bilateral trade. Specifically, we quantify the economic and environmental 'spillover' effects that occur in contemporary international trade due to the GVC in which flows of intermediate goods form components in other subsequently traded goods. We interpret differences between countries' contributions to the flows of economic value versus embedded GHG emissions as being related to the intensity and efficiency of resource use during production. In turn, differences in contributions to direct trade flows versus spillover flows are related to their positions in the GVC. Subsequently, we discuss other elements of the telecoupling framework in trade – agents, causes and effects. Quantitatively incorporating these telecoupling framework elements alongside spillover flows will enable investigation of dynamics and relationships that traditional trade theories, data and models do not currently account for well.

Key Words: global value chain; international trade; metal industry; telecoupling framework; world input-output database

INTRODUCTION

The conceptual framework of telecoupling (Liu et al. 2013, 2015) highlights the importance of socio-economic and environmental interactions over large distances for understanding contemporary sustainability challenges. The framework integrates five elements: coupled human and natural systems (CHANS), flows, agents, causes and effects. Local interactions within CHANS are mediated by agents making decisions, with socio-economic and environmental causes and effects. Furthermore, in the telecoupling framework, CHANS are the origin and destination of long-distance interactions, connected by material and information flows, and can be distinguished between those that are sending systems, those that are receiving systems and those that are recipients of 'spillover' flows from the interaction of other systems. As highlighted previously (e.g. Liu et al., 2013), long-distance telecoupling interactions can occur through multiple human activities such as international trade, foreign direct investments, transregional projects by governments, migration by refugees and travel by tourism, and through natural processes like the hydrologic cycle, atmospheric circulation, seed dispersal and annual animal migrations. Here, we focus on international trade, a major channel of telecoupling flows but which also often couples human systems with natural systems.

Trade in general is a typical case of flows in telecoupling because both the production activities in an exporting country and the consumption activities in an importing country have

socio-economic and environmental effects. Through international trade, one country's demand can be another country's motivation to provide a product, thereby changing the use of natural resources or environmental assets (broadly defined as "the naturally occurring living and non-living components of the Earth, together constituting the biophysical environment, which may provide benefits to humanity", according to the Central Framework 2012 of United Nations' System of Environmental-Economic Accounting) in the other country. For example, Brazilian farmers have been shown to convert forests into land for farming soybeans in order to meet international demand for the product, mainly driven by China (Fearnside et al. 2013). In addition to land conversion issues, international trade also contributes to ecologically unequal exchange. Many studies reveal that developing nations export natural resources intensive commodities to developed nations, thereby allowing wealthy economies to avoid operating ecologically impactful industries at home (e.g. Davis and Caldeira 2010, Moran et al. 2013, Prell and Sun 2015).

Traditional studies of trade have focused on direct human benefits from goods and services. Neoclassical economic theories treat environmental problems as epiphenomena and tend to reserve judgement about them (Karp 2011). Not surprisingly, none of the mainstream trade theories (i.e. the classical trade theories developed in the 18th and 19th century to the 'new' new trade theory developed in recent two decades) considers the environmental consequences of trade. From the telecoupling perspective these trade theories do not enable comprehensive consideration of CHANS. Since the environmental impacts of economic activities have become of increasing concern, since the 1960s the environmental aspects of trade have come to receive more attention (Cropper & Oates, 1992, Frankel, 2009). One of the first important systematic analyses of the relationship between trade and the environment was published in the early 1990s (Grossman and Krueger 1991), laying the basis for other widely studied theories such environmental Kuznets curve hypothesis (Grossman and Krueger 1991, Shafik and Bandyopadhyay 1992) and pollution haven hypothesis (Tobey 1990, Mani and Wheeler 1998).

More recently, the unequal exchange of natural resources through trade has been examined using the input-output approach (Moran et al. 2013, Prell et al. 2014, Prell and Sun 2015, Prell and Feng 2016). This approach enables accounting of emissions associated with consumption, including both 'intermediate consumption' and 'final consumption' (as defined in GVC literature such as Timmer et al. 2015) of goods and services (Peters and Hertwich 2008, Peters 2008, Programme et al. 2009). It has been found that a substantial portion of global carbon emissions is traded internationally, primarily as exports from developing countries to consumers in developed countries (Davis and Caldeira 2010, Davis et al. 2011, Steinberger et al. 2012, Prell et al. 2017). In this paper we build on the input-output approach and incorporate it into the telecoupling framework, showing how it is useful for examining economic and environmental consequences of global trade.

Our primary aim in this paper is to contribute to improvements in the quantification and analysis of key concepts in the telecoupling framework, focusing in particular on flows between CHANS. We do this by examining the international trade of metals to show how recently developed data sources and accounting methods enable examination of economic and environmental impacts, both of which must be considered in the telecoupling framework. Furthermore, in contemporary international trade, goods are often composed of component parts that have been previously imported from other countries. Consequently, the flow of embedded environmental assets around the world cannot be captured by considering bilateral trade between two countries alone, and must include consideration of (multiple) third parties. In the telecoupling framework these third-party flows are known as 'spillover' flows, but

to-date have received limited attention. Spillover flows occur in contemporary international trade because of its dependence on a GVC in which flows of intermediate goods form components in other subsequently traded goods. Using contemporary data sources and accounting methods for trade in the global metals industry we make one of the first quantitative analyses of spillover flows in a telecoupled system. We initially provide a brief overview of our conceptualisation of contemporary international trade using telecoupling framework concepts, before presenting methods and results of our quantitative analyses. We then discuss these results and how they relate to our conceptual model and other components of telecoupled trade (i.e. agents, causes and effects).

TRADE VIEWED THROUGH THE TELECOUPLING FRAMEWORK

Our conceptual model of international trade viewed through the telecoupling framework focuses on flows between CHANS (Fig. 1). The key flows in trade are those of products, money and embedded environmental assets, the latter of which are most important when considering physical good (as opposed to information products or services). Viewing international trade through the telecoupling framework, the sending system is the country exporting products and the receiving system is the country importing products. Products flow from the exporting country into the importing country through some form of transportation or communication. As a return, money flows in the opposite direction from the importing country to the exporting country. Through trade, an importing country substitutes these resources that they would otherwise need to consume from their own resources (Norder et al. 2017). Thus, along with the flow of physical products and money, the environmental assets consumed in production travel from the exporting country to the importing country and can be thought of as being substituted from the importing country's resources.

The representation and consideration of spillovers within the telecoupling framework enables explicit consideration of relationships of flows of embedded environmental assets between systems. In particular, spillover systems in international trade are the countries affected by the interaction between exporting and importing countries, often the production or consumption of the traded products through a third country. For example, the production of automobiles in Germany for export to USA uses component parts imported from Poland which were produced using steel provided by China (Diehl 2001, Meng et al. 2015). The trade between Germany and USA, therefore, induces the production (and consumption) of environmental assets in third party countries of Poland and China (Fig 2.).

Thus, in contemporary telecoupled international trade, coupled human-natural systems (i.e. countries in this study) often produce goods for export using imported intermediate products from other systems, which further use intermediate inputs from an 'upstream' sector through imports from other systems (and so on upstream for previous imports). We refer to such interactions between flows as 'upstream spillover effects' as they are caused by the production in the sending system (e.g. exporting country) spilling over to the upstream sectors in the spillover system (e.g. third countries). Alternatively, spillover effects can also occur through consumption of the downstream sectors in the spillover system. In the automobile example above, the consumption of automobiles in USA contributes to Germany's import of component parts from Poland, who further imports steels from China (see Fig. 2). From this perspective, we see the interactions between flows as 'downstream spillover effects'.

In addition, these spillovers may vary through time due to competition for imports or exports with other supply or demand countries. As these interactions are usually implicit or subtle,

and thus are difficult to measure, we focus here on upstream and downstream spillover flows. Using a case study of the international trade in the metals industry, we define these spillover effects further below and show how they can be quantified for better understanding of flows in telecoupled systems.

DATA AND METHODS

Data

This study uses multi-regional input-output (MRIO) tables to quantify the net flows and spillover flows of products and embedded GHG emissions (i.e. the emissions attributed to the production of the products being consumed; see Li et al. 2007, Weber and Matthews 2007, Peters et al. 2011). The MRIO approach considers a full range of inputs located across different countries in bringing a product from its conception to the final consumer (Gibbon et al. 2008, Baldwin and Lopez-Gonzalez 2015). It thus provides a sector-by-sector track of the value and environmental assets added by each country in the production chain of goods that are consumed worldwide. Specifically, we use the World Input-Output Database (WIOD, <http://www.wiod.org>), a database containing trade flows for 35 sectors of an economy in 41 global regions (40 major countries with the remainder wrapped up as “Rest of the World”). There are other MRIO databases to consider, but they each have some disadvantages compared to WIOD: EORA (<http://www.worldmrio.com>) has a lower sector-resolution, with only a 26-sector harmonized classification; EXIOBASE (<http://www.exiobase.eu>) is less timely, with the latest update at 2007; and OECD-ICIO database misses many emissions sources for its CO₂ emission factors (Wiebe and Yamano 2016). A limitation of the WIOD is that it does not include as many countries as other databases. However, since the major trading countries in the world are included (mainly developing world countries are missing), this limitation does not substantially affect our analyses.

WIOD socio-economic accounts provide data on value added (i.e. net flow of products and money), whereas the environmental accounts refer to atmospheric emissions (for all greenhouse gases, plus selected others) and water use. The data for both socio-economic and environmental accounts are currently available up to the year 2009. We use the 2009 data to quantify the flows and spillovers in the world trade of the sector ‘basic metals and fabricated metal products, except machinery and equipment’ (code 27t28 in WIOD, hereafter ‘metals’). The metals sector is chosen because it is a typical sector with high emissions and with a large proportion of the emissions traded internationally. Specifically, the production in this sector generates 7% of the world’s CO₂ emissions (second greatest among all 35 sectors worldwide) and over 40% of the production is exported, which leads to 11% of the world’s trade of embedded CO₂ emissions (also second largest; according to WIOD). In this study, we present how to quantify the flows and spillovers in the telecoupling framework by focusing on a single year. Dynamic analysis can be conducted by applying our method to other years.

Methods

We use the method proposed by Johnson and Noguera (2012) to quantify the flows of value added and embedded environmental assets between sending and receiving systems, and the method proposed by Wang et al. (2013) to quantify these flows between sending systems and spillover systems (i.e. spillover flows). Johnson and Noguera (2012) provide the measure of value added exports (VAX), the value added produced in the source country and absorbed in the destination country. The measure thus represents the net flow of valued added from exporting to importing countries. By applying this measure to gas emissions data –

technologically, replacing the value added coefficient vector by direct emission intensity vector in the decomposition formulas as e.g. Meng et al. 2015 does) previously— we also computed the flows of embedded GHG emissions.

The quantification of spillover flows is more challenging as it requires a more detailed decomposition of gross exports so that value added or embedded environmental assets sourced from non-direct trading partners (i.e. third parties) can be identified. Wang et al. (2013) provide a procedure decomposing bilateral sector-level gross trade flows into various value added and double-counted components. Refer to Appendix 1 for a graphic display of the decomposition results (Fig. A1.1) and a detailed explanation of which components constitute the upstream and downstream spillovers.

Performing the Wang et al. (2013) method directly produces the upstream and downstream spillover flows of value added. We then applied it to the emissions data, as we did with the Johnson and Noguera (2012) method, to calculate the upstream and downstream spillover flows of embedded GHG emissions. A summary of the steps analysing the WIOD data is presented in Appendix 2.

In addition, some indication of countries' relative position in the GVC is necessary to understand differences in their potential to induce spillovers. This can be given by 'upstreamness', a measure of the distance to final demand in terms of the production stages a particular product goes through (Antràs and Chor 2013). A country that produces intermediate inputs within the GVC has a greater upstreamness than a country producing a final product, and the more production stages that the intermediate inputs need to go through to reach final consumers, the greater the upstreamness. In the above example (Fig. 2), China has greater upstreamness than USA (3.66 versus 3.13). We calculate each country's value of upstreamness using the method that Antràs et al. (2012) present. Finally, to understand countries' contributions to GHG emissions, a measure of emissions intensity is required. We calculate this GHG emissions intensity per region as the volume of emissions in production per unit gross output, as has been done previously (e.g. Meng et al. 2015).

RESULTS

Flow of products

For the 40 countries (plus combined Rest of the World; RoW) analysed here, we find that 19 countries have positive net VAX and 21 (including RoW) are net importers (Table 1). The results show that the sources of VAX are concentrated in a handful of countries and the primary import destination is the USA. The largest five net exporters (Japan, Germany, China, Italy and South Korea), for instance, are the source of over 80% of net export flows. Conversely, the USA receives nearly a quarter of metals from the world market, five times the second largest receiver, India.

By decomposing each country's gross export to its sources (the exporting country, the importing country and third parties) and the form it is exported (final products and intermediate inputs), we are able to plot the flows of value added between the 41 countries (Fig. 3). Japan, the largest net exporter, provides metal goods (in either final or intermediate state) primarily to the USA, China, South Korea and European countries. South Korea has similar customers to Japan. Another major Asian net exporter, China, sends the majority of its products to the USA, and receives products from Japan and South Korea. Our decomposition also shows that intra-EU trade is active as most EU members both receive value added from

and send value added to other EU members. Two major European net exporters, Germany and Italy, also have a substantial outflow to the USA.

Flow of embedded GHG emissions

Analysis of flows of GHG emissions embedded in metals trade (for 38 countries and RoW, but excluding Romania and Luxembourg for which data are unavailable), shows that 48% of total emissions are embedded in products exported by China, followed by Russia (28.9%) and South Korea (9.5%; Table 1). East Asia countries (i.e. China, Japan and South Korea) has a dominant role in exporting embedded GHG emissions around the world, accounting for two-thirds of the total. Most European countries, however, are net receivers. The major European net exporters of value added goods, such as Germany, Italy and Sweden, are also large net receivers of embedded GHG emissions. The few net senders of embedded GHG emissions in Europe, such Czech Republic, Slovakia and Austria export small volumes relative to the three major exporters. Not surprisingly as the largest net importer of products, the USA is also the largest net receiver of GHG, with one-third of the world's embedded emissions flowing into it.

When flows of embedded GHG emissions are decomposed into specific sender and receiver systems (Fig. 4), we find that China provides about half of the embedded GHG emissions of USA imports and a substantial portion of European imports. China is also a net exporter to Japan, which is the reverse of the situation for products (see Table 1). Another striking net exporter of embedded GHG emissions is Russia, related to its extremely high GHG emission intensity (7.21 kCO₂/\$, the highest among large economies) and very high upstreamness (U=3.55, the third highest among large economies, following South Korea and China). In contrast, the USA is a primary destination of flows from many countries around the world (importing 87.14 Mt from 29 countries).

Spillover flows

Germany generates the greatest upstream spillovers, valued at \$17.30 billion over all third parties (dark red bars in Fig. 5), which is understandable considering it is the largest gross exporter of metals (Table 1). China and South Korea, however, generates more upstream spillover than Japan, the second largest gross exporter. This indicates that China and South Korea's production of value added goods for export uses a large amount of products produced elsewhere, and thus their metal industries are more reliant on imports from other countries than Japan. Similarly, the USA, the fourth largest exporter, generates less upstream spillover than the countries that export less (Belgium, Italy and Canada) as it uses relatively less products imported from other countries.

Germany also induces the largest volume of third parties' imports for final consumption and intermediate input (i.e. downstream spillovers; light red bars in Fig. 5). In other words, many other countries' consumption and further production of metals rely on the imports from Germany. Following Germany are Japan and China, the same as ranked in the list of gross exports. The USA, however, is ranked lower than in the list of gross exports, indicating a relative smaller proportion of the value of its exports is consumed in the third parties. The upstream spillovers of embedded GHG emissions (dark red bars in Fig. 6) show a similar pattern to those of VAX (dark red bars in Fig. 5). For the downstream spillovers of embedded GHG emissions (light red bars in Fig. 6), it is striking that China and Russia are far ahead of other countries.

DISCUSSION

Flows

Our results show that in 2009 over 200 million tons of carbon emissions were transferred through the trade of metals all over the world (Table 1), primarily from the developed countries to the developing countries that the database contains (Fig. 3). There are two major flows of metals worldwide: those between East Asia countries to North America (mainly the USA, and also Canada and Mexico) and those between European countries, wherein Germany and Italy are major net exporters and the UK and France are major net importers (Fig. 3). The flows of embedded GHG emissions, however, generally originate in East Asia countries and Russia, whereas both America and Europe are net importers (Table 1). The USA is the largest net importer of products and the largest net receiver of embedded carbon emissions.

The imbalanced flows of emissions between developed countries and developing countries provides new evidence of ecologically unequal exchange (Rice 2007, Moran et al. 2013). A well-documented reason for this is the pollution haven hypothesis. That is, developed countries externalise their pollution-intensive manufacturing to developing countries and retain the cleaner manufacturing processes at home (Hornborg and Jorgensen 2010, Prell et al. 2014). This transfer is economically motivated as developing countries often execute less stringent environmental regulations, and conversely, developed countries have stricter environmental regulations. It is therefore more expensive for companies to meet environmental standards in developed countries (Levinson and Taylor 2008, Millimet and Roy 2011). The environmental Kuznets curve hypothesizes a relationship between economic growth and environmental degradation that could contribute to the imbalanced emission flows. This hypothesis implies that degradation and pollution increase in the early stages of economic growth and the trend reverses when the economy reaches a certain level (Dinda 2004, Prell et al. 2014).

Analysing differences in VAX compared to embedded GHG emissions allows insights about the types of industries that use metals within telecoupled trade. For example, as highlighted above China is a net importer from Japan for VAX but a net exporter to Japan of GHG (compare Fig. 3 and Fig. 4); that is, China holds deficits in both the economic and environmental accounts in the trade with Japan. This is a common phenomenon in the trade between countries with more and less developed economies (e.g. between Poland/Hungary/Turkey and Germany/Italy, Russia and Japan/Germany, and Brazil/India and Italy). A major contribution to this phenomenon is that the less developed economy is generally located more upstream in the value chain, and thus more specialised in producing carbon intensive but low value added products in the global division of labour. For instance, China generally exports intermediate products that require more energy to produce and have lower prices (due to low value added) than Japan. Japan then uses its more advanced technologies to add value to the products with small energy use and then re-exports them to China at much higher prices. The disparity of emissions between the two countries is strengthened by the fact that the emission intensity of metal industries in the less developed economy is higher. This phenomenon is rooted in the institutional situation that more developed countries generally apply stricter environmental regulations and is an important contributor to carbon leakage worldwide (e.g. Babiker 2005).

Spillovers

Countries' different contributions to spillover effects can be better understood by considering their upstreamness in the GVC, and not simply their total trade volumes. For example, we observe differences between USA, Italy and Canada in terms of their relative ranking in total export of products compared to spillovers; despite the USA having larger total exports (Export in Table 1), the two smaller exporters have greater upstream spillovers of value added (Fig. 5). This is the case largely because the USA's upstreamness of metals (3.13) is greater than Italy (2.89) and Canada (2.97); in other words, Italy and Canada are located further downstream in the GVC and so the products they export generally rely more on intermediate inputs from upstream countries than is the case for the USA. We also notice that Belgium has a slightly higher upstreamness (3.21) than the USA, but still generates more upstream spillovers than the USA (Figs 5 and 6). This result is shaped by the fact that Belgium has an extremely high proportion of upstream spillovers to gross export (24%, the third highest among all countries) compared to the USA (0.08%, the fourth lowest).

The dominance of China and Russia in downstream spillovers (Fig. 6) can be explained in part by their high GHG emission intensities (Table 1). Russia and China have GHGi of 2.05 and 0.48, respectively which are large compared to Germany with 0.19, USA with 0.21, Japan with 0.21 and South Korea with 0.32. The major contribution to Russia's extremely high emissions intensity is the use of old production facilities and more energy intensive technologies overall. For instance, more than 20% of its production uses open hearth furnace, a technology not used today in other large steel producers in the world (McKinsey&Company 2009). China's iron and steel industry is undergoing a low-carbon transition accompanied by remarkable technological progress, but its share of production using electric arc furnaces, which has lower CO₂ emissions intensity than production using blast furnaces/basic oxygen furnaces, is still below 10%, compared to 30% in Germany, 61% in the USA, 22% in Japan and 42% in South Korea, in 2010 (BIR Ferrous Report 2015, Hasanbeigi et al. 2016).

Agents, causes and effects

Our quantitative analyses using MRIO approach have focused on flows, but future studies should consider how other aspects of the telecoupling framework are represented in trade, including agents, causes and effects (Liu et al. 2013). Agents in trade are the people or decision-making entities that facilitate or regulate the production, transaction and consumption of the traded products. They specifically include producers and consumers, public or private investors, export and import agencies, and the financial investors. Governments are a final and important agent in international trade, making and enforcing trade agreements and policies influencing domestic production and consumption. In the case of metal products trade, the key agents are metal companies who frequently act as both producers and traders and can influence both the causes and effects of trade. Because of the dual-role these companies can take, future studies that examine how their decision-making shapes the pattern of metals trade might exploit the flexibility that agent-based approaches to modelling can offer (e.g. Farmer and Foley 2009).

Causes and effects are another key component in the telecoupling framework. International trade theories traditionally commit themselves to accounting for the economic causes of trade (both export and import) and evaluation of its effects. These classical theories leave a large gap in accounting for environmental aspects of trade. However as mentioned earlier, more recent trade theories (such as the pollution haven hypothesis and environmental Kuznets curve hypothesis) now provide consideration of environmental causes and effects of trade. Complementarily use if these theories with environmental theories such the theory of ecological unequal exchange (Rice 2007), while also capitalising on new global data sets,

will help contribute to a more comprehensive understanding of the socio-economic and environmental causes of world trade as viewed through the lens of the telecoupling framework.

CONCLUSION

The telecoupling framework offers a means to examine complex relationships between coupled human-natural systems over large distances to better understand the possibilities for global sustainability. Our aim here was to contribute to improvements in the quantification of flows between CHANS and particularly for spillover effects, using global trade as an example. The results of the application of our methods show how the impacts of trade can be understood in new ways when analysing a MRIO dataset (i.e. WIOD) using the telecoupling framework. In particular, the use of telecoupling framework has allowed us to investigate how countries contribute to both economic and environmental flows, but also how their contribution varies due to bilateral trade compared to spillover flows due to their position in the GVC. We thus gain an extensive view of both economic versus environmental impacts and direct versus indirect impacts that a country generates and receives. By making comparisons between countries' contributions to different flows (e.g. Figs. 5 and 6), we are able to understand contributions beyond the volumes of trade (Table 1) and bilateral trade (Figs. 3 and 4). Specifically, here we have interpreted differences between countries' contributions to the flows of products versus embedded GHG emissions as being related to their emission intensities. In turn, differences in contributions to direct flows versus spillover flows is related to their positions in the GVC (i.e. upstreamness). Our analysis used the World Input-Output Database which provides useful worldwide dataset for the examination of spillovers, but only at a broad sectoral level and for national economies. Continued improvements in data sources will be needed to build on initial quantification like ours to establish environmental effects and impacts of spillovers at finer industrial aggregations and at sub-national levels. More comprehensive use of the telecoupling framework would incorporate representation of decision-making to understand influences of agents on trade flows and spillovers, and this will require yet further innovation in data and models.

LITERATURE CITED

- Antràs, P., and D. Chor. 2013. Organizing the Global Value Chain. *Econometrica* 81(6):2127–2204.
- Antràs, P., D. Chor, T. Fally, and R. Hillberry. 2012. Measuring the upstreamness of production and trade flows. *American Economic Review* 102(3):412–416.
- Baldwin, R., and J. Lopez-Gonzalez. 2015. Supply-chain Trade: A Portrait of Global Patterns and Several Testable Hypotheses. *World Economy* 38(11):1682–1721.
- BIR Ferrous Report. 2015. *World Steel Recycling in Figures 2010 – 2014*.
- Cropper, M. L., and W. E. Oates. 1992. Environmental Economics: A Survey. *Journal of Economic Literature* 30(2):675–740.
- Davis, S. J., and K. Caldeira. 2010. Consumption-based accounting of CO₂ emissions. *Proceedings of the National Academy of Sciences of the United States of America* 107(12):5687–92.
- Davis, S. J., G. P. Peters, and K. Caldeira. 2011. The supply chain of CO₂ emissions. *Proceedings of the National Academy of Sciences of the United States of America* 108(45):18554–9.

- Diehl, M. 2001. *International Trade in Intermediate Inputs: The Case of the Automobile Industry*.
- Dinda, S. 2004. Environmental Kuznets Curve Hypothesis: A Survey. *Ecological Economics* 49(4):431–455.
- Farmer, J. D., and D. Foley. 2009. The economy needs agent-based modelling. *Nature* 460(7256):685–686.
- Fearnside, P. M., A. M. R. Figueiredo, and S. C. M. Bonjour. 2013. Amazonian forest loss and the long reach of China's influence. *Environment, Development and Sustainability* 15(2):325–338.
- Frankel, J. 2009. *Environmental Effects of International Trade*.
- Gibbon, P., J. Bair, and S. Ponte. 2008. Governing global value chains: an introduction. *Economy and Society* 37(3):315–338.
- Grossman, G. M., and A. B. Krueger. 1991. Environmental Impacts of a North American Free Trade Agreement. *National Bureau of Economic Research Working Paper Series No.* 3914(3914):1–57.
- Hasanbeigi, A., M. Arens, J. C. R. Cardenas, L. Price, and R. Triolo. 2016. Comparison of carbon dioxide emissions intensity of steel production in China, Germany, Mexico, and the United States. *Resources, Conservation and Recycling* 113:127–139.
- Hornborg, A., and A. K. Jorgensen. 2010. *International trade and environmental justice: Toward a global political ecology*. Nova Science Publishers.
- Johnson, R. C., and G. Noguera. 2012. Accounting for intermediates: Production sharing and trade in value added. *Journal of International Economics* 86(2):224–236.
- Jorgenson, a. K., and B. Clark. 2009. Ecologically Unequal Exchange in Comparative Perspective: A Brief Introduction. *International Journal of Comparative Sociology* 50(3–4):211–214.
- Karp, L. 2011. The Environment and Trade. *Annual Review of Resource Economics* 3(1):397–417.
- Levinson, A., and M. S. Taylor. 2008. UNMASKING THE POLLUTION HAVEN EFFECT. *International Economic Review* 49(1):223–254.
- Li, H., Z. Pei Dong, H. Chunyu, and G. Wang. 2007. Evaluating the effects of embodied energy in international trade on ecological footprint in China. *Ecological Economics* 62(1):136–148.
- Liu, J., V. Hull, M. Batistella, R. deFries, T. Dietz, F. Fu, T. W. Hertel, R. Cesar Izaurralde, E. F. Lambin, S. Li, L. A. Martinelli, W. J. McConnell, E. F. Moran, R. Naylor, Z. Ouyang, K. R. Polenske, A. Reenberg, G. de M. Rocha, C. S. Simmons, P. H. Verburg, P. M. Vitousek, F. Zhang, and C. Zhu. 2013. Framing sustainability in a telecoupled world. *Ecology and Society* 18(2).
- Liu, J., H. Mooney, V. Hull, S. J. Davis, J. Gaskell, T. Hertel, J. Lubchenco, K. C. Seto, P. Gleick, C. Kremen, and S. Li. 2015. Systems integration for global sustainability. *Science* 347(6225):1258832.
- Mani, M., and D. Wheeler. 1998. In Search of Pollution Havens? Dirty Industry in the World Economy, 1960 to 1995. *The Journal of Environment & Development* 7(3):215–247.
- McKinsey&Company. 2009. *Pathway to an Energy and Carbon Efficient Russia*.

- Meng, B., G. P. Peters, and Z. Wang. 2015. *Tracing Greenhouse Gas Emissions in Global Value Chains*.
- Millimet, D. L., and J. Roy. 2011. Three New Empirical Tests of the Pollution Haven Hypothesis When Environmental Regulation is Endogenous. *Journal of Applied Econometrics* 31(4):652–677.
- Moran, D. D., M. Lenzen, K. Kanemoto, and A. Geschke. 2013. Does Ecologically Unequal Exchange Occur? *Ecological Economics* 89:177–186.
- Norder, S. J., A. C. Seijmonsbergen, S. D. D. V. Rughooputh, E. E. van Loon, V. Tatayah, A. T. Kamminga, and K. F. Rijdsdijk. 2017. Assessing temporal couplings in social-ecological island systems: historical deforestation and soil loss on Mauritius (Indian Ocean). *Ecology and Society* 22(1):art29.
- Peters, G. P. 2008. From production-based to consumption-based national emission inventories. *Ecological Economics* 65(1):13–23.
- Peters, G. P., and E. G. Hertwich. 2008. Post-Kyoto greenhouse gas inventories: production versus consumption. *Climatic Change* 86(1–2):51–66.
- Peters, G. P., J. C. Minx, C. L. Weber, and O. Edenhofer. 2011. Growth in emission transfers via international trade from 1990 to 2008. *Proceedings of the National Academy of Sciences of the United States of America* 108(1):8903–8908.
- Prell, C., and K. Feng. 2016. The evolution of global trade and impacts on countries' carbon trade imbalances. *Social Networks* 46:87–100.
- Prell, C., K. Feng, L. Sun, M. Geores, and K. Hubacek. 2014. The Economic Gains and Environmental Losses of US Consumption: A World-Systems and Input-Output Approach. *Social Forces* 93(1):405–428.
- Prell, C., and L. Sun. 2015. Unequal carbon exchanges: understanding pollution embodied in global trade. *Environmental Sociology* 1(4):256–267.
- Prell, C., L. Sun, K. Feng, J. He, and K. Hubacek. 2017. Uncovering the spatially distant feedback loops of global trade: A network and input-output approach. *Science of the Total Environment* 586:401–408.
- Programme, I. E., I. Climate, E. Research-oslo, E. G. Hertwich, and G. P. Peters. 2009. Carbon Footprint of Nations : A Global , Trade-Linked Analysis. *Environmental science & technology* 43(16):6414–6420.
- Rice, J. 2007. Ecological Unequal Exchange: Consumption, Equity, and Unsustainable Structural Relationships within the Global Economy. *International Journal of Comparative Sociology* 48(1):43–72.
- Shafik, N., and S. Bandyopadhyay. 1992. *Economic growth and environmental quality : time series and cross-country evidence*.
- Steinberger, J. K., J. Timmons Roberts, G. P. Peters, and G. Baiocchi. 2012. Pathways of human development and carbon emissions embodied in trade. *Nature Climate Change* 2(2):81–85.
- Timmer, M. P., E. Dietzenbacher, B. Los, R. Stehrer, and G. J. de Vries. 2015. An Illustrated User Guide to the World Input-Output Database: The Case of Global Automotive Production. *Review of International Economics* 23(3):575–605.
- Tobey, J. A. 1990. The Effects of Domestic Environmental Policies on Patterns of World Trade: An Empirical Test. *Kyklos* 43(2):191–209.

Wang, Z., S.-J. Wei, and K. Zhu. 2013. Quantifying International Production Sharing At the Bilateral and Sector Levels. *NBER Working Papers* 19667:1–127.

Weber, C. L., and H. S. Matthews. 2007. Embodied environmental emissions in U.S. international trade, 1997-2004. *Environmental Science and Technology* 41(14):4875–4881.

Wiebe, K. S., and N. Yamano. 2016. *Estimating CO2 Emissions Embodied in Final Demand and Trade Using the OECD ICIO 2015: Methodology and Results*. Page *OECD Science, Technology and Industry Working Papers No. 2016/05*.