Science of the Total Environment 658 (2019) 659–668

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Evolution of multiple global virtual material flows

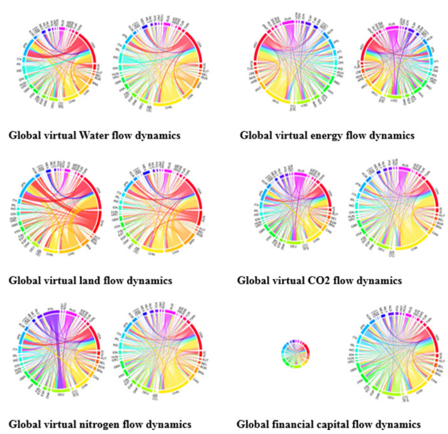
Zhenci Xu [a], Sophia N. Chau [a], Franco Ruzzenenti [b,c], Thomas Connor [a], Yingjie Li [a], Ying Tang [d,a], Dapeng Li [e], Mimi Gong [a], Jianguo Liu [a,*]

[a] *Center for Systems Integration and Sustainability, Michigan State University, East Lansing 48823, USA*
[b] *Center for Energy and Environmental Sciences, University of Groningen, 9747 AG Groningen, the Netherlands*
[c] *International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria*
[d] *Department of Geography, Environment, and Spatial Sciences, Michigan State University, East Lansing 48823, USA*
[e] *Department of Geography, South Dakota State University, Brookings, SD 57007, USA*

HIGHLIGHTS

- This study presents the first comprehensive assessment of evolution of six kinds of global networks.
- The volumes of all water, energy, CO_2, nitrogen and financial capital flows increased over time while land flow decreased.
- The top five trade countries accounted for a surprisingly large proportion (47% to 80%) of total trade volumes.
- Different kinds of virtual material flows tended to enhance each other through synergistic effects.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 12 November 2018
Received in revised form 11 December 2018
Accepted 11 December 2018
Available online 12 December 2018

Editor: Deyi Hou

Keywords:
Global networks
Water
Energy
CO_2
Energy
Nitrogen

ABSTRACT

The world is connected through multiple flows of material, but a comprehensive assessment of their temporal dynamics and interactions is rare. To address this knowledge gap, we assessed the evolution and interactions of global flows of virtual water, energy, land, CO_2, nitrogen as well as financial capital embodied in international trade from 1995 to 2008. We found that the volumes of all these flows, except for land flow, increased over time. Financial capital flows increased most (188.9%), followed by flows of CO_2 (59.3%), energy (58.1%), water (50.7%) and nitrogen (10.5%), while land transfer decreased by 8.8%. Volumes of virtual material flows among distant countries were much higher than those among adjacent countries. The top five countries accounted for a surprisingly large proportion (47% to 80%) of total flow volumes. Different kinds of virtual material flows tended to enhance each other through synergistic effects, and CO_2 and nitrogen flows tended to have stronger positive synergetic impacts on the other virtual material flows. Our results suggest that it is important to pay particular attention to such fast-growing material flows, promote cooperation between distant countries, and target countries with the largest flows to achieve global sustainable development goals.

* Corresponding author.
E-mail address: liuji@msu.edu (J. Liu).

https://doi.org/10.1016/j.scitotenv.2018.12.169

1. Introduction

The world has become increasingly connected (Lambin and Meyfroidt, 2011; Liu et al., 2015). The proliferation of material flows (e.g., international food trade, and energy trade across borders) is increasingly connecting adjacent and distant places into integrated systems (Liu, 2017). Such material flows may continue to proliferate and intensify with global population growth, lifestyle changes, growing resource consumption, and the uneven distribution of resources (Liu et al., 2015).

Virtual resources consumed in commodity production have attracted global attention since their transfer affects environmental systems in trading areas (Liu et al., 2015; Wiedmann and Lenzen, 2018). For instance, importing food allows China to gain virtual land from other countries, enabling China to meet its food demand while maintaining the areal extent of its domestic agricultural land for food production (Qiang et al., 2013). Water, energy and land are critical resources for environmental conservation and socioeconomic development (Xu et al., 2017), and the world faces great threats from their shortage and uneven distribution (Lambin and Meyfroidt, 2011; International Energy Agency, 2015; Mekonnen and Hoekstra, 2016). Four billion people suffer from severe water scarcity (Mekonnen and Hoekstra, 2016); more than one billion people lack electricity (International Energy Agency, 2015); and a growing world population may need an additional 2.7–4.9 M ha of cropland per year to ensure food security. This cropland shortage threatens forests that provide biodiversity and vital ecosystem services (e.g., oxygen production and carbon sequestration) (Lambin and Meyfroidt, 2011). However, international trade also displaces environmental burdens such as CO_2 and nitrogen emissions via natural capital transfers. For example, importing food has allowed China to become a global leader in carbon sequestration since its CO_2 emissions from deforestation are displaced to distant, exporting countries such as Brazil (Torres et al., 2017). CO_2 plays a major role in global warming, and nitrogen emissions pose various threats to environmental and human health such as biodiversity loss, stratospheric ozone depletion and chronic respiratory and heart disease (Kampa and Castanas, 2008; Erisman et al., 2013). Both CO_2 and nitrogen pollution have increased over the past decades (Peters et al., 2011; Crippa et al., 2016). Furthermore, large increases in virtual resource flows have increased financial capital flows between countries (Forbes and Warnock, 2012).

Water, energy, land, CO_2, nitrogen, and financial capital are highly interconnected (Conway et al., 2015; Maris et al., 2015; Rulli et al., 2016). For example, water is used to produce energy (e.g., hydropower production), and in turn, energy is required to produce and distribute water (e.g., desalination, water diversion). All of these processes generate CO_2 and nitrogen emissions. Land can be used to store water and grow crops for bioenergy, a process that also produces nitrogen emissions. National and local economies affect, and are also affected by, these highly interconnected processes.

Despite a growing body of research on spatial pattern and impacts of distant virtual material flows (e.g., water, CO_2, and energy embodied in traded goods) (Konar et al., 2011; Dalin et al., 2012; Liu et al., 2013; Ji et al., 2014; Zhang et al., 2016; Zhong et al., 2016; Wiedmann and Lenzen, 2018), there is little research focused on the evolution and interactions of multiple material flow networks. Moreover, no study has assessed multiple major networks of natural capital, financial capital and environmental burdens simultaneously over time. Also, the evolution of land, CO_2 and nitrogen flow networks has rarely been studied. While several studies have analyzed the typology of the global virtual water trade network and energy trade network separately (Peters et al., 2011; Dalin et al., 2012), a comparison of trade interactions between distant and adjacent countries is lacking. Furthermore, the evolution of trade volumes of top trading countries in such transfer networks has not been examined (Dalin et al., 2012; Zhong et al., 2016). Such an assessment is urgently required (Liu et al., 2013) because ignoring these cross-border interactions leads to an incomplete understanding of the mechanisms behind global environmental and socioeconomic changes, thereby hindering global sustainability efforts. Comparing interactions between distant countries and adjacent countries can reveal potential key partners in international cooperation. The comparison can also help reveal socioeconomic and environmental impacts from trade between distant and adjacent countries, particularly since distant trade often consumes more energy for transport and therefore emits more CO_2. Also, assessing multiple kinds of material flows simultaneously can generate cross-sectoral knowledge to inform more effective policies, overcoming the shortcomings of most policies which focus on a single sector and neglect interrelationships (e.g., synergies, trade-offs) among different kinds of material flows (Liu et al., 2015; Liu, 2017).

To fill these knowledge gaps, we simultaneously assessed the evolution and interactions of six global flows of virtual water, energy, land, CO_2, and nitrogen as well as financial capital embodied in international trade from 1995 to 2008 (when the most recent data are available). In the following text, for the sake of simplicity, we also considered financial capital flow as a type of virtual material flow since financial capital flow refers to the capital value embedded in international trade. Therefore, there were six virtual material flows in this analysis. Guided by the integrated framework of intercoupling (environmental and socioeconomic interactions between adjacent and distant places (Liu, 2017)), we addressed several related questions. First, how did the total volume of these global virtual material flows change over time? Second, was the transfer volume of virtual material flows greater between distant countries than between adjacent countries over time? Third, what was the temporal pattern in intensity and dominance of top trade countries (measured by the ratio between the trade volume of top trade countries and the total trade volume of all countries analyzed)? Fourth, how did multiple global virtual material flow networks interact with each other (e.g., synergies, trade-offs)? Using data from the World Input-Output Database (WIOD) (Timmer et al., 2015), we performed multiregional input-output analyses and network analysis to address these questions. Finally, we discussed the implications of these findings for global sustainability.

2. Materials and methods

Our analysis covered 35 sectors across environmental, economic and social dimensions such as "agriculture, hunting, forestry and fishing" and "mining and quarrying", in all countries with available data, giving our study a broader scope than other studies focusing only on a single or few sectors (Dalin et al., 2012; Zhong et al., 2016).

2.1. Data

We obtained multi-regional input-output tables for all sectors' material inputs and outputs (water, energy, land, CO_2, nitrogen, and financial capital output for all 35 sectors) from the World Input-Output Database (WIOD) (Timmer et al., 2015). WIOD is one of the most developed global databases. It shows the trade flows between countries, has homogeneous sectors for all countries, and allows direct comparison between sectors (e.g., agriculture, hunting, forestry and fishing, mining and quarrying, education etc.) in different countries. It also provides a reasonable coverage of countries (40 countries accounting for 97% of world's GDP; see Supplementary Table S1 for country names) and temporal range (1995–2011) (Kander et al., 2015). Data for environmental impacts (water, energy, land consumption, CO_2, and nitrogen) were available through 2008, while data for financial flows were available through 2011. To keep all the datasets consistent, 2008 was the last year of data included our analyses.

2.2. Construction of global material flow networks

Global material flow networks are composed of nodes (each representing a country) and links (each representing a material flow such as virtual land between trading countries) between pairs of nodes. The weight of a link indicates the volume (e.g., hectares of virtual land) of a flow from one country to another, and the weight of a node indicates the total flow volume that is imported or exported by a given country. Two kinds of directed weighted networks exist, each representing one of two potential flow directions. Import-directed networks are those in which links represent imports, and export-directed networks are those in which links represent exports. Either kind of network represents the total global material flows for a given network because each flow is associated with both an import country and an export country. Thus, a certain flow is represented in both kinds of networks.

For each kind of material flow, we constructed a global network by applying multi-regional input-output analysis, a method commonly used to determine interdependencies between countries by tracking monetary flows. Assuming there are m countries and each country has n sectors, we can calculate the monetary output of sector i in country R by:

$$x_i^R = \sum_{S=1}^{m}\sum_{j=1}^{n} x_{ij}^{RS} + \sum_{S=1}^{m} y_i^{RS} \quad (1)$$

where the x_{ij}^{RS} represents capital flow from sector i of country R to sector j of country S, and y_i^{RS} indicates country S's final demand provided by sector i in country R.

The direct input coefficient a_{ij}^{RS} is calculated by:

$$a_{ij}^{RS} = x_{ij}^{RS} / x_j^S \quad (2)$$

where a_{ij}^{RS} indicates the amount of monetary flow from sector i of country R that results in one monetary output in sector j in country S.

Letting $X = [x_i^R]$, $A = [a_{ij}^{RS}]$ and $Y = [y_i^{RS}]$, we obtained the following matrix based on Eqs. (1) and (2):

$$X = A \cdot X + Y \quad (3)$$

In the following consumption driven equation, $(I - A)^{-1}$ is the Leontief inverse matrix indicating both direct and indirect monetary flows from other countries to meet one unit of final monetary demand:

$$\begin{aligned} X &= B \cdot Y \\ B &= (I - A)^{-1} \end{aligned} \quad (4)$$

To calculate the virtual material flow embodied in international trade, we applied the direct material consumption coefficient. The direct material consumption coefficient of sector i in country R can be expressed as Eq. (5):

$$e_i^R = \frac{w_i^R}{x_i^R} \quad (5)$$

where w_i^R represents total material consumption in sector i of country R, therefore e_i^R represents the amount of material consumed to increase one monetary unit of output in sector i in country R.

Letting $E = [e_i^R]$, we obtained the following material transfer matrix (Feng et al., 2013):

$$\text{Material} = E \cdot B \cdot Y \quad (6)$$

2.3. Network analysis

We analyzed the temporal change of trade flow volumes of all kinds of material flow networks by tracking the sum of the volumes of each material flow network over time. We compared flow volumes between distant countries (not sharing a border) and adjacent countries (sharing a border) over time. On average, each of the 40 countries was linked with 35 distant and 4 adjacent countries.

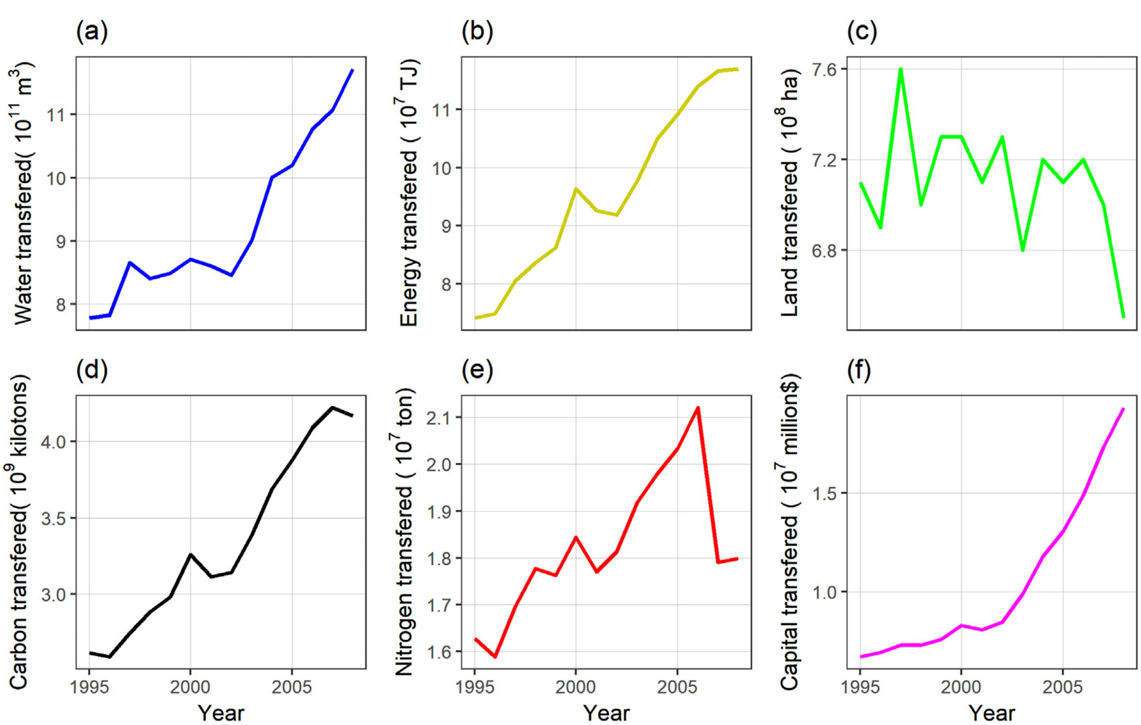


Fig. 1. Temporal changes in total transfer volume of global (a) virtual water, (b) virtual energy, (c) virtual land, (d) virtual CO_2, (e) virtual nitrogen, and (f) financial capital.

In both the export-directed and import-directed networks, we assessed each country's node strength (total volume of a country's trade links) and designated the top five countries (top five highest node strengths) as "trade hubs". We then tracked the node strength of these hubs over time in both export-directed and import-directed networks. For example, country *a*'s node strength in an export-directed network is $O_a = \sum_b P_{ab}$, where P_{ab} represents the virtual material flows exported from country *a* to country *b*. The ratio between the combined strength of the world's five trade hubs in a given network and the total global network's volume quantifies the dominance of these hubs.

We used the "multiplexity" and "multireciprocity" index developed by Gemmetto et al. (2016) to explore two kinds of synergies between two or more global material flow networks: multiplexed synergies and multireciprocated synergies (Ruzzenenti et al., 2015; Gemmetto et al., 2016). The first kind of synergy occurs when a link (trade flow) between two nodes (countries) in one network is paralleled by a link that flows in the same direction between the same two nodes in another network (Ruzzenenti et al., 2015; Gemmetto et al., 2016). The second kind occurs when the link between two nodes in a network flows in the opposite direction between the two nodes in another network. We created a null model to clear the spurious effects of chance in the correlation analysis (Gemmetto et al., 2016). Z-score tests were used to determine the significance of synergistic effects between global networks (Ruzzenenti et al., 2015; Gemmetto et al., 2016).

3. Results

Global virtual versions of water, energy, CO_2, nitrogen and financial capital transfers intensified from 1995 to 2008, while virtual land transfers decreased during that time (Fig. 1). The virtual transfer of financial capital increased the most (188.9%), followed by CO_2 (59.3%), energy (58.1%), water (50.7%) and nitrogen (10.5%). Virtual land transfer declined by 8.8%.

In each kind of virtual material network, distant countries had higher total trade volumes with each other than adjacent countries (Fig. 2). The total flow volumes between distant countries were much more than those between adjacent countries. Over time, all flows between distant countries, except for virtual land, also increased more than those between adjacent countries (Fig. 2). However, the average flow volume between each pair of adjacent countries was larger than that between each pair of distant countries (Fig. 3).

All material flow networks were highly connected, and the US and China were in the top five trading countries of each network (Fig. 4). Both the US and China had trade relations with all other countries, but China became more influential over time (Fig. 4). In 1995, the US was the top trading country in all six material flow networks. In 2008, however, China replaced the US as the top trading country of virtual CO_2 and nitrogen transfer. China's virtual trade volumes in all six global networks increased over time, although the US continued to dominate the virtual water, energy, land and financial capital networks.

The top five countries that dominated global networks accounted for 47% to 80% of the total volume in various material flows over time (Fig. 5). In both import-directed networks (in which flow links represent imports) and export-directed networks (in which flow links represent exports), the sum of virtual material flows of the top five countries increased over time (Fig. 5). Their dominance increased in all export-directed networks except for virtual land network, and decreased in all import-directed networks. In 1995, the top five countries' dominance in virtual energy, CO_2, nitrogen and financial capital in export-directed networks was weaker than that in their corresponding import-directed networks. Interestingly, their dominance in all export-directed networks surpassed their dominance in their corresponding imported-directed networks over time (Fig. 5h and j). The US and

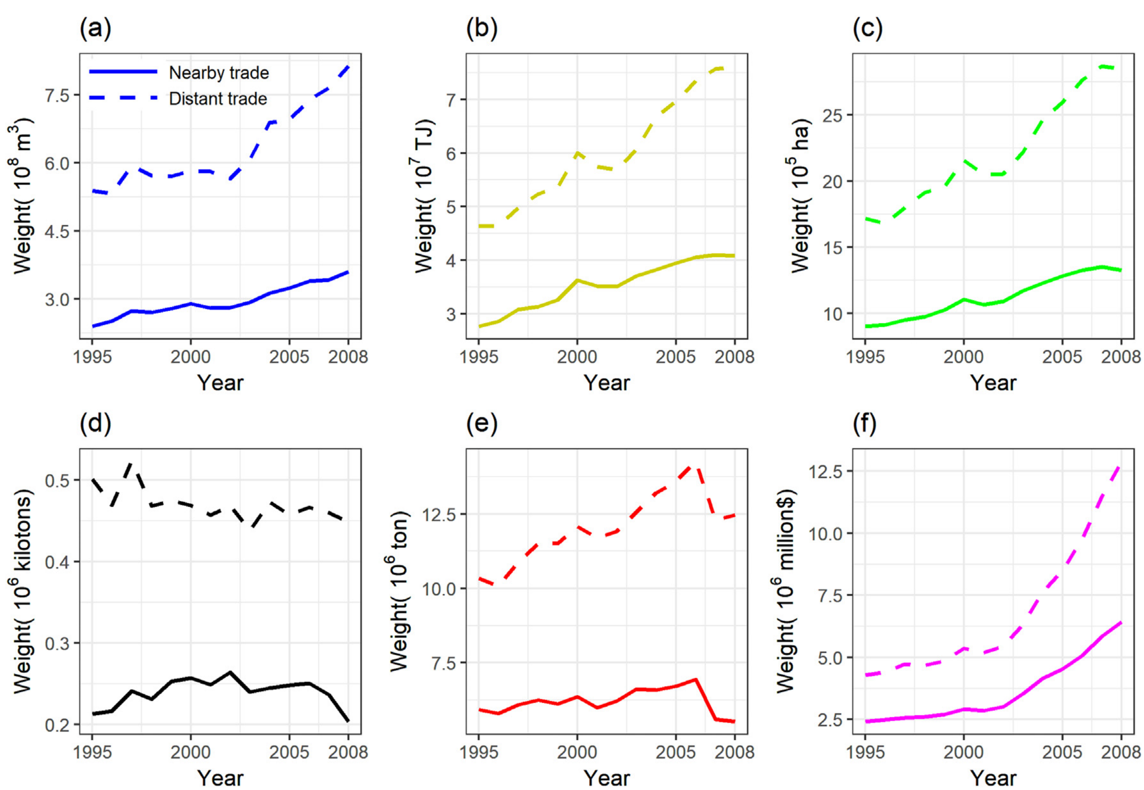


Fig. 2. Volume of virtual material transfer between distant countries and adjacent countries over time. (a) Virtual water. (b) Virtual energy. (c) Virtual land. (d) Virtual CO_2. (e) Virtual nitrogen. (f) Financial capital.

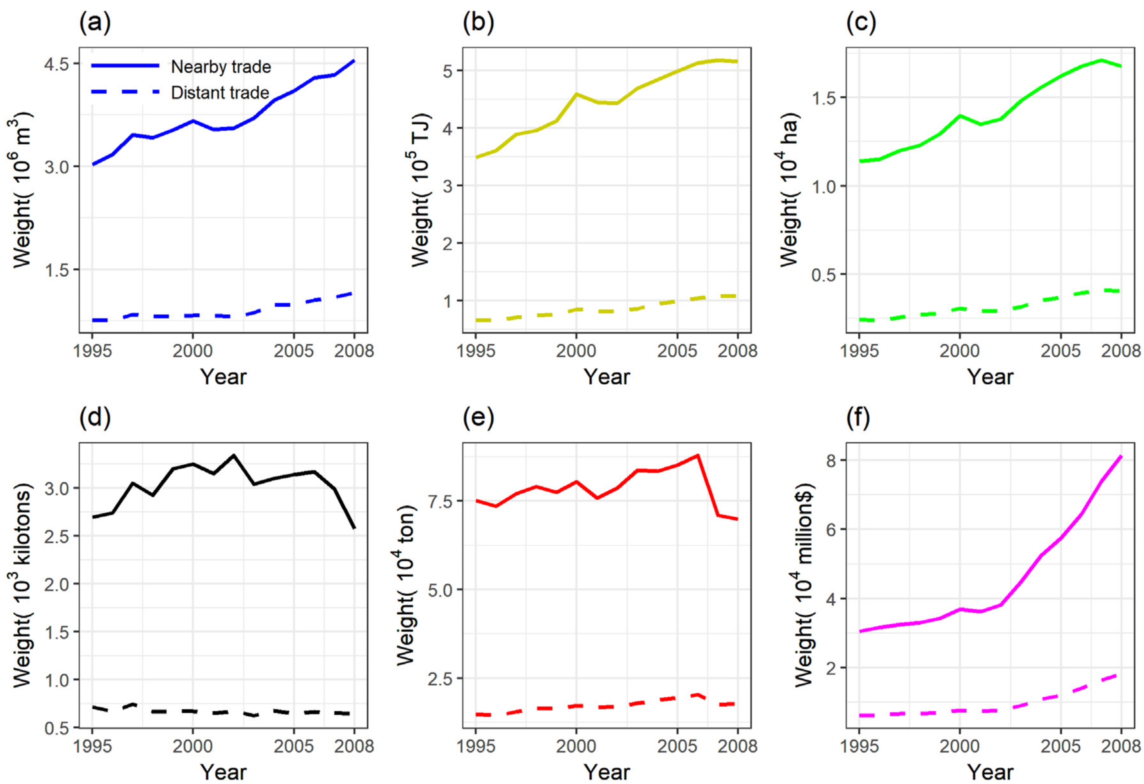


Fig. 3. Average volume of virtual material transfer between per pair of distant countries or per pair of adjacent countries over time. (a) Virtual water. (b) Virtual energy. (c) Virtual land. (d) Virtual CO_2. (e) Virtual nitrogen. (f) Financial capital.

China were the top trading countries in all networks, accounting for a large percentage of total trade volumes (Fig. 4).

Different kinds of material flows tended to enhance each other through synergistic effects (Fig. 6), and the synergistic effects between different material flows in the opposite direction have generally strengthened over time. The synergistic effects also varied among different pairs of material flows. Virtual CO_2 and nitrogen flows tended to have stronger, positive synergistic impacts on the other material flows. The synergistic effect between CO_2 and energy flows was the strongest and intensified with time.

4. Discussion

Flow volumes of all virtual materials embodied in international trade, except for virtual land, intensified over time. Distant countries had larger total flow volumes than adjacent countries, partially because there were more distant countries than adjacent countries. But adjacent countries had greater average transfer volumes per country due to the ease of trading over shorter distances. Improvements in land use efficiency, such as agricultural intensification, are likely partially responsible for the decline in virtual land flow (Rudel et al., 2009; FAO, 2016). Thus, despite rapid growth in international agricultural trade, the virtual land embodied in trade commodities has not increased accordingly. The virtual energy network had very strong synergistic effects with the virtual CO_2 network because countries tended to import virtual energy with a higher CO_2 content (e.g., developed countries tended to displace manufacturing industries with high energy consumption and low energy efficiency and large CO_2 emissions to developing countries (Cherniwchan et al., 2017)).

The world's population is expected to reach nine billion by 2050 (Evans, 2009), bringing with it an exponential rise in global demand for natural resources and accompanied environmental burden. In response, global material flows will likely continue to intensify and play increasingly important roles in shaping environmental and socioeconomic conditions at multiple scales. For example, large increases in the international trade of soybeans have lowered soy prices in China and caused farmers in northeast China to shift the types of crops they plant (Sun et al., 2017; Sun et al., 2018). This, in turn, affects water use and gross primary productivity (Viña et al., 2017). Enhancing environmental sustainability and human wellbeing therefore requires a multi-scale perspective that encompasses global cross-border interactions (Liu et al., 2013).

Global trade hubs such as the US and China dominate global networks. Environmental and socioeconomic shifts in these hubs result in consequences worldwide. For example, the 2008 financial crisis that originated in the US resonated across the globe; exceptionally rapid economic development in China led to increased importation of forest products, which led to deforestation in the Asia-Pacific region and many other regions (Zhang, 2007; Liu, 2014) as those countries harvested large forest areas to meet China's demands for forest products. To manage global flows of virtual materials, policymakers must consider forces from these hubs which can exert strong power over global trade dynamics. Safeguarding the environment through sustainable resource use will require a better understanding of the existing mechanisms and structures of international trade networks to target top trading countries.

More governance aiming at virtual material trade should be developed to enforce trade regulations (Lenzen et al., 2012; Zhao et al., 2015). Though some institutions and agreements like the World Trade Organization and the Kyoto Protocol are able to promote the multilateral trade governance, there has been little focus on virtual material trade. Additional institutions should be established to promote multilateral and bilateral trade governance aimed at virtual material trade across national borders (Frankel, 2009). Consumption-based virtual material consumption/emissions should be measured so that the responsibility of consumption can be partly allocated to consumers

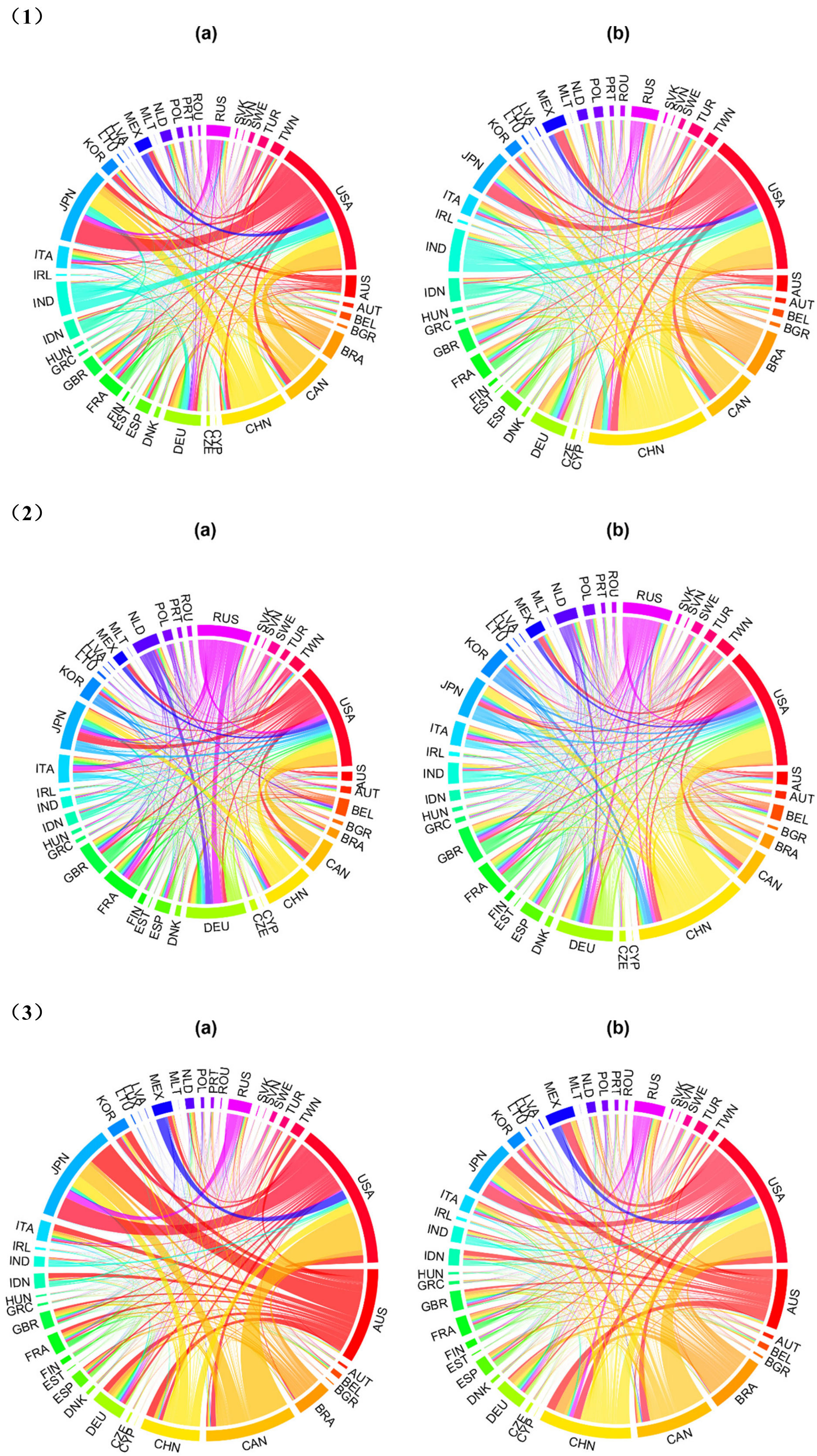


Fig. 4. Transfer of virtual (1) water, (2) energy, (3) land, (4) CO_2, (5) nitrogen, and (6) financial capital between individual countries (a: in 1995; b: in 2008). The arc length of an outer circle indicates the sum of exports and imports in each country (see Supplementary Table S1 for the acronyms of country names). Ribbon colors suggest the country of export.

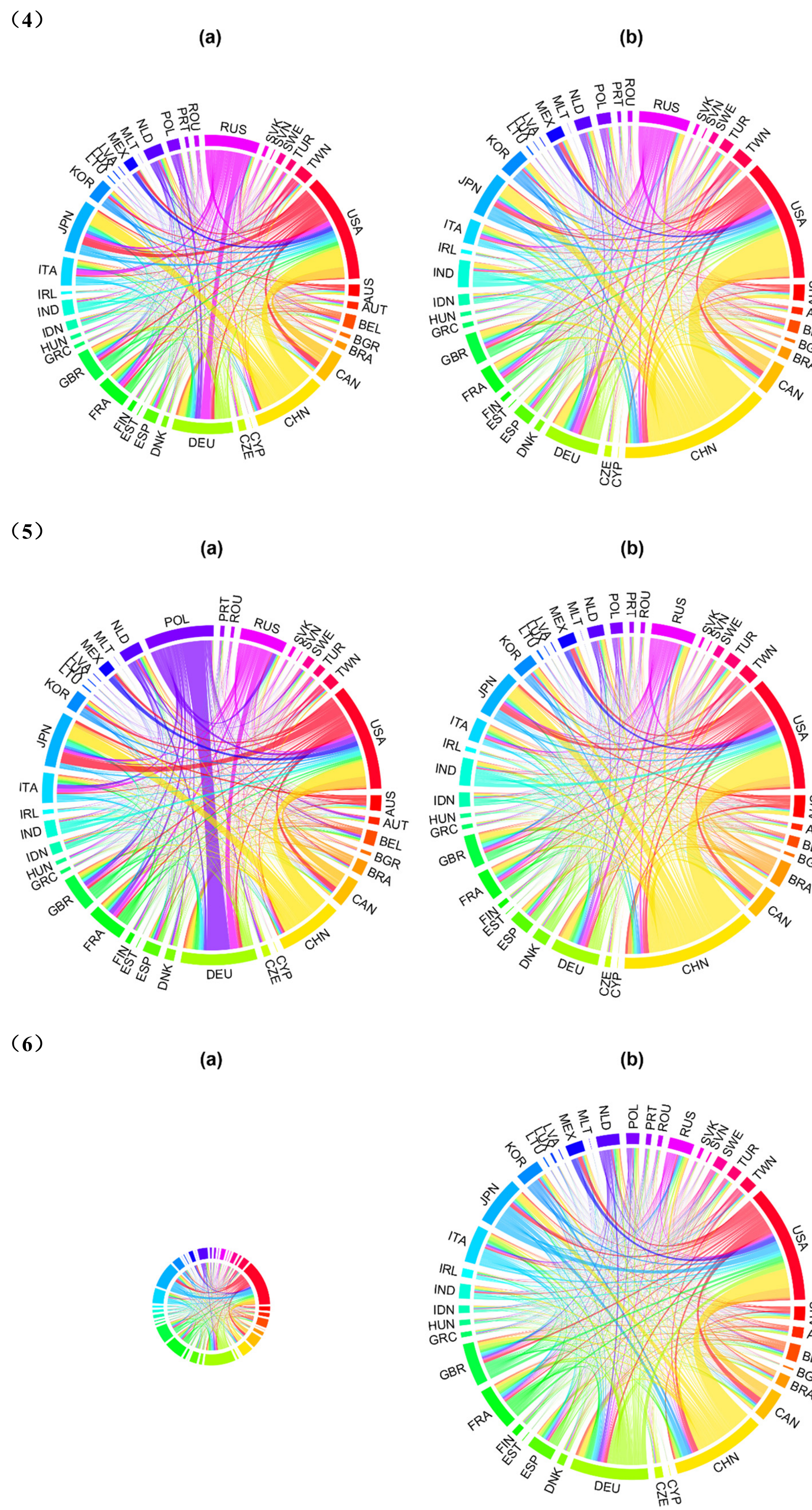


Fig. 4 (*continued*).

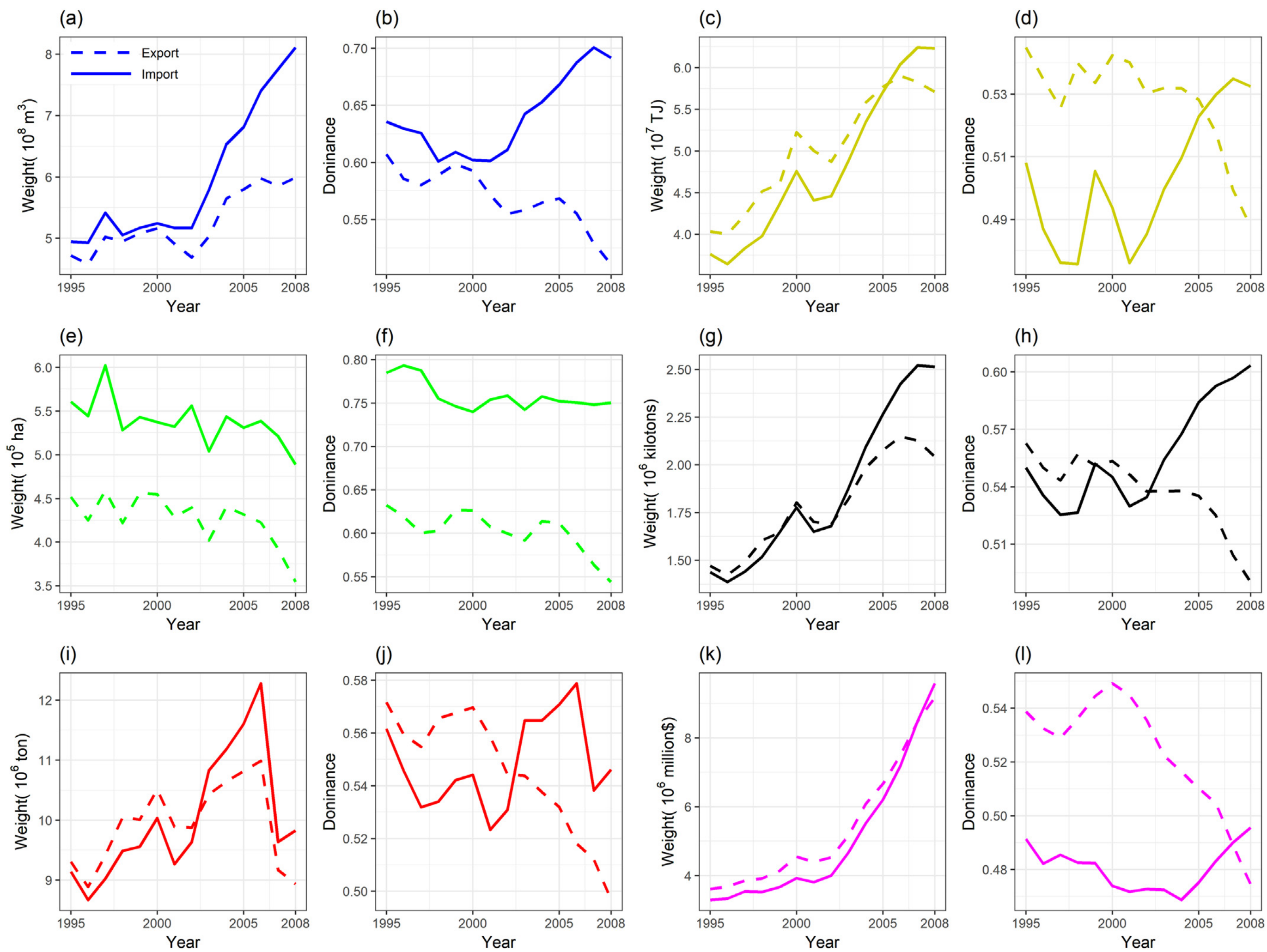


Fig. 5. The weight and dominance (measured by the ratio between the trade volume of top trade countries and the global total trade volume) of virtual material flows in the top five countries. (a–b) Water. (c–d) Energy. (e–f) Land. (g–h) CO_2. (i–j) Nitrogen. (k–l) Financial capital. The solid line indicates import and the dashed line refers to export.

(Frankel, 2009; Peters, 2010). More consumption-based policies such as this should be built to manage virtual material trade.

By examining the temporal pattern of multiple virtual material flow networks simultaneously, the environmental and socioeconomic interdependencies between countries, driven by trade, can be better clarified. Research and policy-making should not be limited to a single sector like water or energy or CO_2, but consider synergies and trade-offs between two or more sectors (Liu et al., 2015; Wicaksono et al., 2017; Miglietta et al., 2018). While nexus approaches (e.g., food, energy, and water nexus) have gained increasing attention to understand the interactions among sectors, they mainly focus on sectors in a specific place such as within a country (Liu et al., 2018). To gain a comprehensive understanding of interactions among sectors and identify previously overlooked environmental and socioeconomic harms and benefits, more studies that assess these sectors among different countries simultaneously are needed. Such integration would enhance our understanding of complex system dynamics and chart a path towards achieving human well-being and global sustainability (Liu et al., 2015; Lamastra et al., 2017).

5. Conclusions

Here we present the first comprehensive assessment of the evolution and interactions of six kinds of global environmental and socioeconomic interaction networks – global trade of three virtual sources of natural capital (water, energy, land), two virtual environmental burdens (CO_2 and nitrogen emissions), and financial capital (money). All global networks increased over time, with the exception of virtual land transfer. Financial capital transfer increased much more sharply (188.9%) than other material networks. Distant countries generated greater volumes of material flow than adjacent countries. Surprisingly, the top five trade countries in each material network accounted for a considerable proportion (47% to 80%) of the total transfer volume. Different networks tend to enhance each other. We suggest policy-makers consider the influence of powerful material flow networks between trading countries for achieving the United Nations Sustainable Development Goals (Liu, 2018).

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.12.169.

Acknowledgements

We acknowledge insightful editorial comments from Sue Nichols.

Funding

We are grateful for financial support from the National Science Foundation, Michigan State University, Michigan AgBioResearch, and China Scholarship Council.

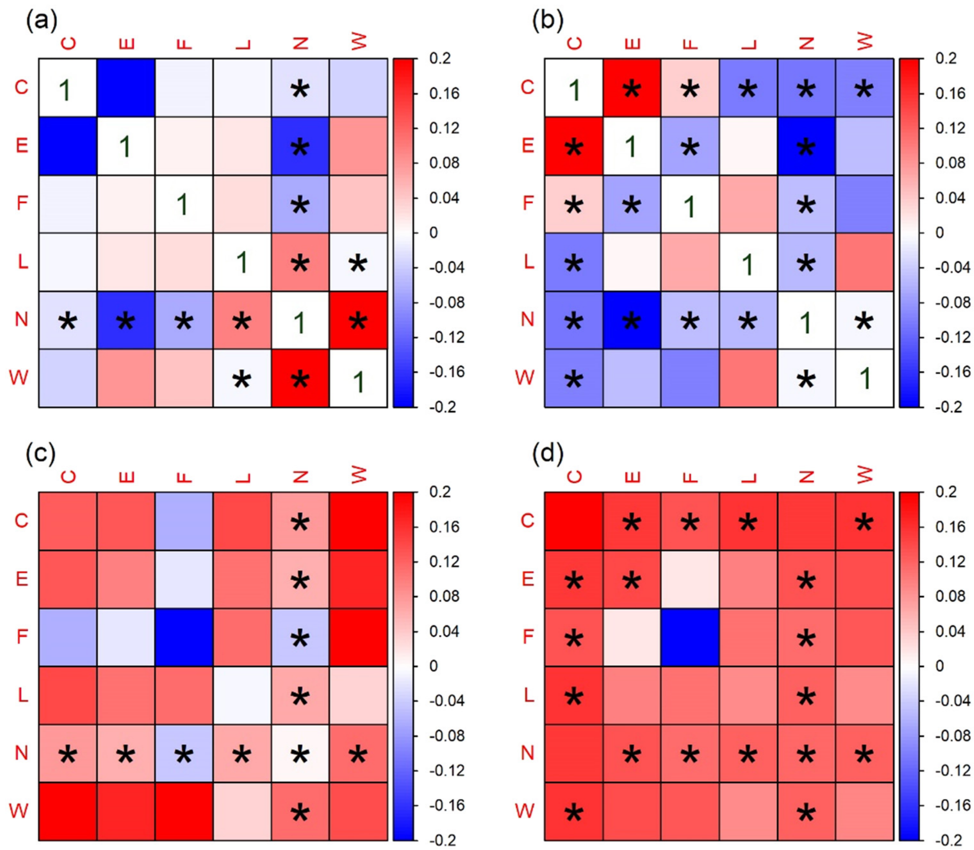


Fig. 6. Interrelationships among different kinds of virtual material flows. Note: C-CO_2, E-energy, F-financial capital, L-land, N-nitrogen pollution, W-water. (a) and (b) indicate synergistic effects for trade flows with the same direction in 1995 and 2008 while (c) and (d) indicate synergistic effects for trade flows with the opposite direction in 1995 and 2008, respectively. Synergistic effect means flows with the same direction or flows with the opposite direction enhance each other. * refers to analyses with statistically significant Z-scores. We have cleared the spurious effects of chance in the correlation analysis.

Author contributions

Z.X. and J.L. designed the research; Z.X. contributed data; S.C., J.L., T.C., Y.L., D.L. and Y.T., provided comments on the manuscript; Z.X. and F.R. analyzed the data and wrote the manuscript. All authors reviewed the manuscript.

Competing interests

The authors declare that they have no competing interests.

Data and materials availability

All data related to the paper which are publicly available online are at http://www.wiod.org/. Additional data related to this paper may be requested from the authors.

References

Cherniwchan, J., Copeland, B.R., Taylor, M.S., 2017. Trade and the environment: new methods, measurements, and results. Ann. Rev. Econ. 9, 59–85.
Conway, D., Van Garderen, E.A., Deryng, D., Dorling, S., Krueger, T., Landman, W., Lankford, B., Lebek, K., Osborn, T., Ringler, C., 2015. Climate and southern Africa's water–energy–food nexus. Nat. Clim. Chang. 5, 837.
Crippa, M., Janssens-Maenhout, G., Dentener, F., Guizzardi, D., Sindelarova, K., Muntean, M., Van Dingenen, R., Granier, C., 2016. Forty years of improvements in European air quality: regional policy-industry interactions with global impacts. Atmos. Chem. Phys. 16, 3825–3841.
Dalin, C., Konar, M., Hanasaki, N., Rinaldo, A., Rodriguez-Iturbe, I., 2012. Evolution of the global virtual water trade network. Proc. Natl. Acad. Sci. 109, 5989–5994.
Erisman, J.W., Galloway, J.N., Seitzinger, S., Bleeker, A., Dise, N.B., Petrescu, A.R., Leach, A.M., de Vries, W., 2013. Consequences of human modification of the global nitrogen cycle. Philos. Trans. R. Soc. B 368, 20130116.
Evans, A., 2009. The Feeding of the Nine Billion: Global Food Security for the 21st Century. Chatham Historical Society Incorporated.
FAO, 2016. FAOSTAT.
Feng, K., Davis, S.J., Sun, L., Li, X., Guan, D., Liu, W., Liu, Z., Hubacek, K., 2013. Outsourcing CO_2 within China. Proc. Natl. Acad. Sci. 110, 11654–11659.
Forbes, K.J., Warnock, F.E., 2012. Capital flow waves: surges, stops, flight, and retrenchment. J. Int. Econ. 88, 235–251.
Frankel, J.A., 2009. Environmental Effects of International Trade.
Gemmetto, V., Squartini, T., Picciolo, F., Ruzzenenti, F., Garlaschelli, D., 2016. Multiplexity and multireciprocity in directed multiplexes. Phys. Rev. E 94, 042316.
International Energy Agency, 2015. World Energy Outlook 2015. IEA, Vienna.
Ji, Q., Zhang, H.-Y., Fan, Y., 2014. Identification of global oil trade patterns: an empirical research based on complex network theory. Energy Convers. Manag. 85, 856–865.
Kampa, M., Castanas, E., 2008. Human health effects of air pollution. Environ. Pollut. 151, 362–367.
Kander, A., Jiborn, M., Moran, D.D., Wiedmann, T.O., 2015. National greenhouse-gas accounting for effective climate policy on international trade. Nat. Clim. Chang. 5, 431–435.
Konar, M., Dalin, C., Suweis, S., Hanasaki, N., Rinaldo, A., Rodriguez-Iturbe, I., 2011. Water for food: the global virtual water trade network. Water Resour. Res. 47.
Lamastra, L., Miglietta, P.P., Toma, P., De Leo, F., Massari, S., 2017. Virtual water trade of agri-food products: evidence from Italian-Chinese relations. Sci. Total Environ. 599, 474–482.
Lambin, E.F., Meyfroidt, P., 2011. Global land use change, economic globalization, and the looming land scarcity. Proc. Natl. Acad. Sci. 108, 3465–3472.
Lenzen, M., Moran, D., Kanemoto, K., Foran, B., Lobefaro, L., Geschke, A., 2012. International trade drives biodiversity threats in developing nations. Nature 486, 109–112.
Liu, J., 2014. Forest sustainability in China and implications for a telecoupled world. Asia Pac. Policy Stud. 1, 230–250.
Liu, J., 2017. Integration across a metacoupled world. Ecol. Soc. 22 (4).
Liu, J., 2018. An integrated framework for achieving Sustainable Development Goals around the world. Ecol. Econ. Soc. 1, 11–17.

Liu, J., Hull, V., Batistella, M., Defries, R., Dietz, T., Fu, F., Hertel, T.W., Izaurralde, R.C., Lambin, E.F., Li, S., Martinelli, L.A., McConnell, W.J., Moran, E.F., Naylor, R., Ouyang, Z., Polenske, K.R., Anette, R., Rocha, G.d.M., Simmons, C.S., Verburg, P.H., Vitousek, P.M., Zhang, F., Zhu, C., 2013. Framing sustainability in a telecoupled world. Ecol. Soc. 18.

Liu, J., Mooney, H., Hull, V., Davis, S.J., Gaskell, J., Hertel, T., Lubchenco, J., Seto, K.C., Gleick, P., Kremen, C., Li, S., 2015. Systems integration for global sustainability. Science 347, 1258832.

Liu, J., Hull, V., Godfray, H.C.J., Tilman, D., Gleick, P., Hoff, H., Pahl-Wostl, C., Xu, Z., Chung, M.G., Sun, J., 2018. Nexus approaches to global sustainable development. Nat. Sustain. 1, 466.

Maris, S., Teira-Esmatges, M., Arbonés, A., Rufat, J., 2015. Effect of irrigation, nitrogen application, and a nitrification inhibitor on nitrous oxide, carbon dioxide and methane emissions from an olive (*Olea europaea* L.) orchard. Sci. Total Environ. 538, 966–978.

Mekonnen, M.M., Hoekstra, A.Y., 2016. Four billion people facing severe water scarcity. Sci. Adv. 2, e1500323.

Miglietta, P.P., Morrone, D., De Leo, F., 2018. The water footprint assessment of electricity production: an overview of the economic-water-energy Nexus in Italy. Sustainability 10, 228.

Peters, G.P., 2010. Policy Update: Managing Carbon Leakage. Taylor & Francis.

Peters, G.P., Minx, J.C., Weber, C.L., Edenhofer, O., 2011. Growth in emission transfers via international trade from 1990 to 2008. Proc. Natl. Acad. Sci. 108, 8903–8908.

Qiang, W., Liu, A., Cheng, S., Kastner, T., Xie, G., 2013. Agricultural trade and virtual land use: the case of China's crop trade. Land Use Policy 33, 141–150.

Rudel, T.K., Schneider, L., Uriarte, M., Turner, B.L., DeFries, R., Lawrence, D., Geoghegan, J., Hecht, S., Ickowitz, A., Lambin, E.F., 2009. Agricultural intensification and changes in cultivated areas, 1970–2005. Proc. Natl. Acad. Sci. 106, 20675–20680.

Rulli, M.C., Bellomi, D., Cazzoli, A., De Carolis, G., D'Odorico, P., 2016. The water-land-food nexus of first-generation biofuels. Sci. Rep. 6.

Ruzzenenti, F., Joseph, A., Ticci, E., Vozzella, P., Gabbi, G., 2015. Interactions between financial and environmental networks in OECD countries. PLoS One 10, e0136767.

Sun, J., Tong, Y.-x., Liu, J., 2017. Telecoupled land-use changes in distant countries. J. Integr. Agric. 16, 368–376.

Sun, J., Mooney, H., Wu, W., Tang, H., Tong, Y., Xu, Z., Huang, B., Cheng, Y., Yang, X., Wei, D., 2018. Importing food damages domestic environment: evidence from global soybean trade. Proc. Natl. Acad. Sci. 115, 5415–5419.

Timmer, M.P., Dietzenbacher, E., Los, B., Stehrer, R., Vries, G.J., 2015. An illustrated user guide to the world input–output database: the case of global automotive production. Rev. Int. Econ. 23, 575–605.

Torres, S.M., Moran, E.F., Silva, R.F.B.d., 2017. Property rights and the soybean revolution: shaping how China and Brazil are telecoupled. Sustainability 9, 954.

Viña, A., Silva, R., Yang, H., Liu, J., 2017. Effects of the international soybean trade on the dynamics of gross primary productivity in soybean-producing regions in China and Brazil. AGU Fall Meeting Abstracts.

Wicaksono, A., Jeong, G., Kang, D., 2017. Water, energy, and food nexus: review of global implementation and simulation model development. Water Policy 19 (3), 440–462 (wp2017214).

Wiedmann, T., Lenzen, M., 2018. Environmental and social footprints of international trade. Nat. Geosci. 11, 314–321.

Xu, Z., Tang, Y., Connor, T., Li, D., Li, Y., Liu, J., 2017. Climate variability and trends at a national scale. Sci. Rep. 7, 3258.

Zhang, J., 2007. Who will meet China's import demand for forest products? World Dev. 35, 2150–2160.

Zhang, J., Zhao, N., Liu, X., Liu, Y., 2016. Global virtual-land flow and saving through international cereal trade. J. Geogr. Sci. 26, 619–639.

Zhao, X., Liu, J., Liu, Q., Tillotson, M.R., Guan, D., Hubacek, K., 2015. Physical and virtual water transfers for regional water stress alleviation in China. Proc. Natl. Acad. Sci. 112, 1031–1035.

Zhong, W., An, H., Fang, W., Gao, X., Dong, D., 2016. Features and evolution of international fossil fuel trade network based on value of energy. Appl. Energy 165, 868–877.