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Synthesis

Transboundary flows in the metacoupled Anthropocene: typology, methods, and governance for global sustainability

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ABSTRACT. The world has become increasingly metacoupled through flows of materials, energy, people, capital, and information within and across systems. Transboundary flows, connecting adjacent and distant systems, are deemed the most critical indicators for measuring the intensity of interactions among coupled human-natural systems. To advance metacoupling flow research and governance, we make the first attempt to develop a typology of transboundary flows using six flow attributes (i.e., type, magnitude, direction, distance, time, and mode). Furthermore, we synthesize a portfolio of quantitative and practical methods for characterizing transboundary flows. To effectively govern transboundary flows for global sustainability and resilience, we highlight the need to recognize the shared risks and goals embedded in the interlinkages, use system thinking, and enhance multilateral cooperation.

Key Words: *ecosystem service flows; environmental footprints; international trade; social footprints; socio-environmental interactions; Sustainable Development Goals (SDGs); telecoupling; transboundary rivers*

INTRODUCTION

Everything is connected to everything else (Barabási 2014), and even things far away from each other become increasingly interconnected in the globalized Anthropocene (Kapsar et al. 2019, Carlson et al. 2020). Since the advent of the “Great Acceleration” in the mid-20th century (Steffen et al. 2015), there has been a significant surge in the exchange of goods, as well as the flows of materials, resources, energy, capital, and information within and between systems. These heightened interactions have resulted in complex and far-reaching socioeconomic and environmental impacts spanning local to global scales, and impacted the progress toward achieving the United Nations Sustainable Development Goals (SDGs; Liu 2018).

To address those cross-scale challenges and achieve sustainable development (i.e., “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” Brundtland 1987), a number of sustainability theories and frameworks have been put forward (Turner et al. 2003, Folke 2006, Liu et al. 2007, 2015a, Ostrom 2009, Liu 2017, Clark and Harley 2020, Chen et al. 2022). Among these, the metacoupling framework is a newly developed and more integrated conceptual construct that comprehensively links not only socioeconomic-environmental interactions within a place, between adjacent places, but also between distant places (Liu 2017). The framework consists of five core components: systems (e.g., country, state, and region), flows (e.g., movements of information and goods), agents (entities that facilitate flows such as traders and policy makers), causes (reasons behind the flows), and effects (consequences of the flows). Systems are further classified as sending, receiving, and spillover systems (Liu 2017). Sending and receiving systems are entities that send and receive flows of material, energy, products, humans, capital, and information. Spillover systems are entities that affect, or are affected by, interactions between sending and receiving systems. The framework has been widely used across different places, e.g., Arctic, tropical, and Antarctic regions (da Silva et al. 2021, Vergara et al. 2021, Kapsar et al. 2022a); rural and urban areas (Herzberger et al. 2019, Carlson et al. 2022); sectors, e.g., conservation and tourism (Zhao et al. 2018, 2020); and issues such as those related to planetary boundaries, e.g., pollution, biodiversity, biogeochemical flows, climate change, freshwater use, land use (Rockström et al. 2009). Recent studies have elaborated the key concepts and methodologies for characterizing agents (Dou et al. 2019, 2020), feedback (Hull et al. 2015), and systems (Liu et al. 2018a) in the metacoupling framework. These studies, therefore, provided an in-depth understanding of the framework. Flows, as the most critical component that connects adjacent and distant systems, have frequently been used to describe the strength of connectivity among systems, as well as the extent of impacts that one system imposed on the other (Liu et al. 2013, Eakin et al. 2017, Xu et al. 2020a). Yet, a comprehensive synthesis about the attributes of flows is still lacking.

Flows have drawn increasing attention in recent decades partly because of the growing transboundary activities (e.g., international trade) and the associated prominent transboundary impacts (Liu 2020, Xu et al. 2020a). Understanding and quantifying these transboundary flows are therefore critical to implement the metacoupling framework, as well as to inform other disciplines to address the world’s pressing socio-environmental challenges for sustainability (Dou et al. 2018, Yang et al. 2018, Xu et al. 2020b, Li 2021). Because of the diversity of transboundary flows across the metacoupled world, a clear typology is needed to better understand the complexity of system interactions. Schröter et al. (2018) provided a typology for ecosystem service (ES) flows, and Koellner et al. (2019) further provided guidance for assessing four types of ES flows. Their work laid a foundation for subsequent applications in investigating interregional flows of multiple ecosystem services (Hou et al. 2020, Kleemann et al. 2020, Klapper and Schröter 2021, Wang et

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al. 2021, 2022). In addition to ES flows, there are other types of flows, such as information flows (de Lange et al. 2019), flows of goods and products in trade (Wood et al. 2018, Liu 2020), biophysical flows (e.g., movement of water, sediments, and pollutants), movement of people (Müller et al. 2016, Chung et al. 2018, Horton et al. 2021) and organisms (Liu et al. 2017, Wyckhuys et al. 2018). Noteworthily, virtual flows (e.g., virtual water and virtual land that are embedded in trade products) have increasingly been used to examine the often ignored environmental and social impacts across borders (Wiedmann and Lenzen 2018, Xu et al. 2020a). These diverse flows were often investigated in separate fields to approach sustainability, but have not been comprehensively synthesized. Different types of flows may interact with each other in complex ways (e.g., amplification, offsetting) and generate unexpected outcomes (Liu et al. 2015a). Identifying multiple transboundary flows and understanding how they interact to shape sustainable development is a new and important frontier in sustainability research. A synthesis of typologies for a range of transboundary flows across disciplines would be beneficial in addressing complex human-environmental challenges through holistic and interdisciplinary efforts.

With more researchers from different disciplines interested in applying the metacoupling framework to address real-world sustainability issues but encountering methodology challenges, there is also a great need to provide methodological guidance for assessing transboundary flows. Closing the gap between researchers interested in the metacoupling framework and the variety of transboundary flows in the literature can have the potential to provide a generalized, quantitative understanding of different types of flows across the metacoupled planet. Armed with the knowledge of various transboundary flows, scientists could provide stakeholders with more quantitative and spatially explicit socio-environmental flow information for facilitating flow-based governance and for achieving a range of sustainability goals. To advance the efforts for metacoupling flow research and governance, we aim to: (1) develop a typology of transboundary flows with illustrative examples; (2) highlight methods for investigating the flows; and (3) discuss the usefulness of flow-based governance.

TYPOLOGY OF TRANSBOUNDARY FLOWS

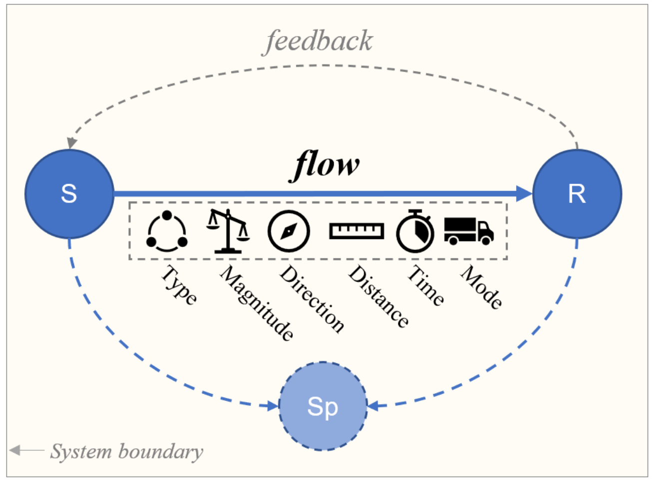
To characterize and quantify the various transboundary flows, we synthesize existing knowledge and develop a typology using six flow attributes (i.e., type, magnitude, direction, distance, time, and mode; Fig. 1). The typology development was based on our knowledge and a systematic review, guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) standards (Page et al. 2021). For the review, we collected relevant articles from the Web of Science by using the tailored search terms "(#1 OR #2 OR #3)."

#1: TS = (metacoupl* OR telecoupl* OR meta-coupl* OR tele-coupl*) NOT (*coupler OR meta-meta)

#2: TS = (sustainab*) NEAR/10 ("ecosystem service*") NEAR/2 flow$

#3: TS = (sustainab*) NEAR/10 (transboundary OR trans-boundary OR transborder OR trans-border OR transnational OR trans-national OR international OR interregional OR inter-regional) NEAR/2 (flow$ OR migrat* OR movement* OR trade) NOT (tradeoff* OR trade-off*)

Fig. 1. Key attributes for characterizing transboundary flows: system boundaries, magnitude, directions, distance, time, and mode of flows. S – sending system, R – receiving systems, Sp – spillover system.



In total, we compiled 730 related articles, all of which were imported to and analyzed in Covidence, a web-based tool that streamlines the process of title/abstract screening, full-text screening, and data extraction (see details in Appendix 1). After title/abstract screening and full-text screening, 289 papers were included for data extraction and analysis (see Fig. S1 and a full list of papers in Appendix 1). Although we focus on transboundary flows, the typology is also applicable to flows within a system.

Defining system boundaries is critical to untangle the complexity of various connections among different systems. Depending on questions of interest, system boundaries can be defined by political/administrative units (e.g., countries, states, counties, cities), socioeconomic and cultural units (e.g., conservation donor group, indigenous area), management units (e.g., protected areas), or geographical and ecological units (e.g., hydrological units, ecoregions; Liu et al. 2019, Qin et al. 2022). To limit the scope of this study, we focus on transboundary flows among coupled human and natural systems. Therefore, system boundaries between individuals (e.g., human entities or environmental elements) are not included in this study.

Flow type

Based on the nature of flows, we divide them into three broad categories (Table 1).

(1) Physical flows refer to the movement or transfer of physical goods, materials, natural resources (e.g., water), substances (e.g., PM2.5 pollutants), animals, and people, as well as disease transmission from one place to another (Table 1). Most of these material and organism flows overlap with provisioning ecosystem service flows (e.g., food, materials, fresh water, and energy; Díaz et al. 2018, Schröter et al. 2018). Trade-related physical flows are well covered in the metacoupling literature (Manning et al. 2023) and were examined in 34% of the evaluated studies, followed by human flows (8%; including tourism, human migration, and human trafficking; Fig. 2). Human flows can be used to investigate

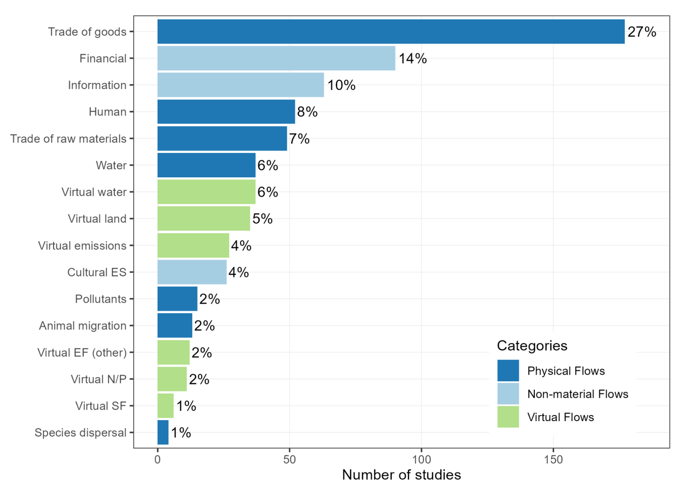
Table 1. Types of transboundary flows and the quantification methods. † Embodied nutrients are different from virtual nutrients (‡). The former represents the matters or elements (e.g., protein, energy, zinc, calcium, iron, vitamin B12, folate, vitamin A, nitrogen, and phosphorus) that are physically contained in the trade products, whereas the latter represents the matters used in the production process but are not physically contained in the final products.

Categories	Sub-category	Commonly studied flow examples	Methods
Physical flows	Trade-related flows	Trade of raw materials (e.g., wood, minerals, waste) Trade of goods (e.g., foods, energy, wildlife, weapons) Movement of embodied physical nutrients† (physical content)	• Statistical data-based approach • Data mining & crowdsourcing approaches • Modeling approaches (e.g., gravity model) • Remote sensing (e.g., detection of container ships and cargo trucks)
	Biophysical flows	Water flows Pollutants dissemination through the air (e.g., GHG emissions, PM2.5) or waterway (e.g., nitrogen leaching)	• Statistical data-based approach • Process-based hydrological models • Air current models • Remote sensing (e.g., use GRACE satellites to track water movement)
		Disease transmission (e.g., waterborne diseases, airborne diseases like COVID-19)	• Big data approach (e.g., human mobility trajectory from mobile phone and social media) • Modeling
	Active movement of humans and animals	Human flows - Tourism - Human migration (e.g., refugees, skilled professionals) - Human trafficking Animal migration Species dispersal (e.g., species invasion)	• National visitor statistics • Big data approach (e.g., human mobility trajectory from mobile phone and social media) • Nighttime light remote sensing data for estimating human migration • Traditional field observation • Stationary camera traps • Citizen science • Modern animal tracking technologies • Modeling (e.g., species distribution models)
Non-material flows	/	Flows of social services (e.g., international investments in conflict prevention and peacekeeping)	• Statistical data-based approach
		Financial flows (e.g., foreign direct investment, foreign aid, remittances, payment for ecosystem services)	• Statistical data-based approach • Data mining & crowdsourcing approaches
		Information (e.g., knowledge, technology, trade agreements)	• Statistical data-based approach • Public surveys • Big data approach (e.g., geotagged text, photos, and videos)
Virtual flows	/	Environmental footprints (e.g., virtual water/energy/land/emissions/phosphorus/nitrogen, biodiversity embedded in production‡) Social footprints (e.g., social risks embodied in production)	• Life cycle assessment • Input-output analysis

a variety of metacoupling effects. Apart from human flows related to tourism, migration of humans in traditionally intellectual careers can be used to study the extent to which brain-drain (substantial emigration or migration of valuable specialists, such as doctors, healthcare professionals, scientists, engineers, or financial professionals) can harm a country's economy and sustainable development (Brücker et al. 2013). Studies on water-related flows account for 6% of the evaluated studies, followed by pollutants (2%), animal migration (2%), and species dispersal (1%). Among water-related flow studies, > 90% focused on transboundary surface water, while only a small portion of the studies investigated transboundary groundwater or aquifers (Müller et al. 2017, Luetkemeier et al. 2021, Mullen et al. 2022). Future studies need to include groundwater as a crucial element in transboundary watershed governance. Additionally, it is essential to conduct a more extensive investigation into the "causes" (such as excessive pumping in one system) and "effects" (such as drawdown in the other system and common-pool overdraft) of groundwater flow across systems, particularly in internationally shared river basins (Mullen et al. 2022).

(2) Non-material flows refer to the transfer of intangible resources or services between systems. These flows usually include the exchange of information (10%) and financial flows (e.g., foreign direct investment, foreign aid, and remittances; 14%). Information flows can be in the form of technology transfer, knowledge transfer, and other news or messages that could be spread through media channels or social ties, while financial flows can occur through various channels such as banks, stock markets, or digital platforms. Flows of cultural ecosystem services (e.g., recreational and spiritual use of nature) also belong to non-material

Fig. 2. Flow types examined in the literature. ES – ecosystem services, EF – environmental footprints, SF – social footprints, N/P – nitrogen/phosphorus.



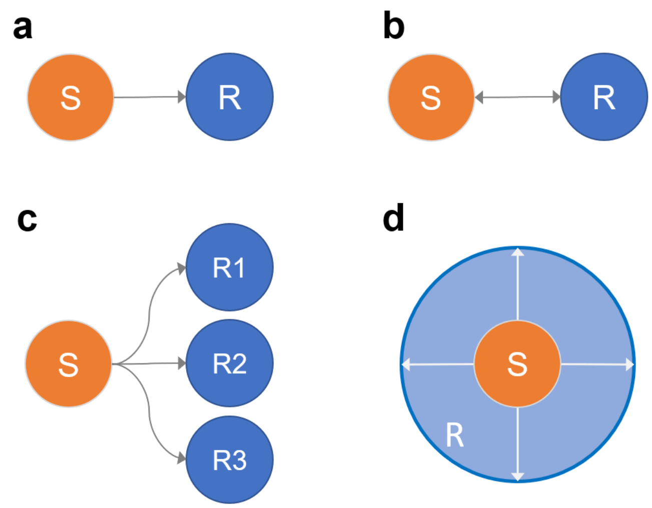
flows. Information flows and financial flows have emerged to generate unexpected large socio-environmental impacts (Eakin et al. 2014, Liu et al. 2022a, Qin et al. 2022). For example, the Belt and Road Initiative pledged to invest US$1 trillion in 138 countries to boost infrastructure and economic development but led to the loss of natural land (Li et al. 2021).

(3) Virtual flows are also intangible but specifically refer to the embedded resources and socio-environmental risks (or footprints) "hidden" in products (Galli et al. 2012). Virtual flows, such as virtual water and energy, do not have a physical existence but are a conceptual tool used to measure the hidden socio-environmental impacts associated with the trade of goods and services. For example, virtual water is the water "hidden" in the products, services, and processes people buy and use every day. Virtual water often goes unseen by the end-users of a product or service, but that water has been consumed throughout the value chain, which makes the creation of that product or service possible (Allan 1998, Hoekstra and Hung 2005). Virtual nitrogen is any nitrogen that was used in the food production process but is not physically contained in the final products (Galloway et al. 2007, Leach et al. 2012). Similarly, virtual flows also cover embedded energy, GHG emissions, and phosphorus. In addition to the resource and environmental aspects, social footprints (e.g., vulnerable employment, child labor, and health risks) embedded in trade have drawn growing attention, but have not been well examined (only covered in 1% of the evaluated studies) because of data challenges (Simas et al. 2014, Alsamawi et al. 2017a, Xiao et al. 2017, Chung et al. 2021). Virtual flow is an important concept to unveil the indirect (or externalized) drivers of local resource problems and pave the way for analyzing what can be done elsewhere rather than locally to improve the sustainability and equity of resource use (Hoekstra 2017).

Flow magnitude
The magnitude of flows is the amount of flows and can be measured by weight (e.g., in kg), volume (e.g., in m^3), value (e.g., in US dollars), and number count. Because sustainability is, in part, affected by the size of humanity's footprint relative to the planet's carrying capacity (Hoekstra and Wiedmann 2014), flow magnitude is usually the key indicator to estimating the potential impacts on sending systems, receiving systems, or spillover systems with consideration of each system's resource endowment. Over 80% (n = 229) of studies evaluated flow magnitude among systems. The magnitude of transboundary flows has increased dramatically in recent decades (Munroe et al. 2019). For example, international tourists leaped 20-fold (from 69 million in 1960 to 1.4 billion in 2018; Herre et al. 2023), and international food exports surged 45-fold during the same period (Liu 2020).

Flow directions
Flows can be unidirectional, bidirectional, multidirectional, or omnidirectional (Fig. 3). For unidirectional, bidirectional, and multidirectional flows, it is relatively intuitive to track the exact direction because the flows usually follow certain pathways that proceed directly between sending and receiving systems, or indirectly between the two by passing through or leaking into the spillover systems (Liu et al. 2018a; Fig. 1). The direction of a specific flow determines which system is the sending system and which is the receiving system. For instance, when it comes to food flows, if country A exports food to country B, then country A is considered as the sending system; when examining money flows (i.e., when country B pays country A for food products), country A is considered the receiving system in terms of financial transactions. Conventionally, outward flows are also termed "outflows", and incoming flows are termed "inflows." Among the analyzed studies, approximately 83% (n = 238) provided information on flow directions. However, sometimes, it can be challenging to track the exact flow directions of omnidirectional diffusions, such as greenhouse gases and air pollutants. One way to determine the directions is based on atmospheric currents at broad spatial scales (Schröter et al. 2018). Another way is to identify the source of emissions and treat the surrounding regions as receiving systems without directional bias (Fisher et al. 2009).

Fig. 3. Possible flow directions. (a) unidirectional, e.g., river flows; (b) bidirectional, e.g., bilateral trade or investment; (c) multidirectional, e.g., overseas development finance from one country to multiple countries (China's Belt and Road Initiative); (d) omnidirectional: the flows diffuse to the surrounding regions, e.g., carbon emissions.



Flow distance
Distances between systems can be geographical, political, institutional, social, or cultural (Boisso and Ferrantino 1997, Tadesse and White 2010, Eakin et al. 2014, Liu 2017, Liu et al. 2018a, Tromboni et al. 2021). Geographic distance is the most used measurement (95.6%, n = 283) in the evaluated literature and is determined by variables such as Euclidean space distance, or dummy variables such as whether or not two systems share common borders (e.g., land border or water border), and whether or not two systems have transportation or communication links (Takayama 2013). Geographic distance is useful to determine whether a flow such as trade flow is a telecoupling or pericoupling process (Xu et al. 2020a). Because of geographic distance is usually linked with transportation, it has also been used to estimate environmental costs embedded in product transport. For example, the concepts of "food miles" and "footprint distance" have been used to measure the impact of food transport on the environment (Coley et al. 2009, Li et al. 2022).

Other distance measurements, such as cultural distance (0.7%) and administrative distance (3.0%), have been used for trade analysis and modeling and could be useful for future metacoupling studies beyond international trade. Cultural distance refers to differences in norms, beliefs, and values between countries (Hofstede 2001). Increasing cultural distance between nations is expected to have a negative effect on trade flows between them because it complicates trade and leads to increased transaction costs (Söderström 2008). Key attributes creating cultural distance include different languages, different ethnicities, lack of connective ethnic or social networks (e.g., colony/colonizer), different religions, and different social norms. Administrative distance can be measured by the absence of colonial ties, the absence of shared monetary or political association, political hostility, and institutional weakness.

Flow time

The temporal dimension of flows describes the timing (e.g., when the flow starts), duration (i.e., from start to end), frequency, and change rate of a targeted flow. Knowing the temporal dynamics of flows can also help understand time lags in the metacoupled human-natural systems (Liu et al. 2007). For example, in a telecoupled system, the sending and receiving systems are usually far away from each other. Therefore, there are usually time lags between changes in the sending system and effects in the receiving system. For instance, the impact (e.g., coastal eutrophication and "dead zones") of excess fertilizer applied to agricultural land in the U.S. Midwest cannot be immediately observed at the Mississippi River estuary (Van Meter et al. 2018, Li et al. 2023). Temporal scales of interregional flows vary and largely rely on certain types of flows. For instance, trade-related flows are usually recorded at the annual level, with some at the quarter or month level (USDA ERS 2022). Physical water flow monitoring can be at the daily or even minute level (e.g., the USGS real-time streamflow data).

Flow Mode

Flow mode distinguishes different ways of movement, including several types: (1) trade-related flows depend on man-made carriers (e.g., boats, vehicles, airplanes, pipelines, and cable); 50.5% of the evaluated studies examined this flow mode; (2) biophysical flow through ecological processes (12.3%), for example, water and sediment flows follow certain hydrological pathways. In some cases, water flow might also follow man-made channels after human intervention. For example, China implemented the South-to-North Water Transfer Project to divert freshwater from water-abundant southern China to northern China to mitigate water shortages (Zhao et al. 2015, Xu et al. 2020b); (3) movement of people and animals (15.1%) for certain purposes (e.g., tourism via airplanes, and animal migration through flying or walking; Chen et al. 2012, Hulina et al. 2017); (4) flows of information and knowledge through man-made communication channels (7.7%; Schröter et al. 2018, Schirpke et al. 2019). Other flow modes, such as financial/capital flows through banking or debt, transfer ownership or the right to use of land, account for 14.1% of the evaluated studies.

Flow mode is important for characterizing flows and the interactions among systems. Particularly, the reliability of man-made transportation largely depends on transport infrastructure networks and intergovernmental networks (Liu et al. 2013). Disruption of these networks, e.g., port disruptions, can have a large impact on international trade flows (Verschuur et al. 2023).

Interactions among flow attributes

Although we elaborate on each of the six flow attributes above individually, they are necessarily interrelated in predicting metacoupling consequences. Flow magnitude alone is not the single factor in determining the potential impacts. Taking the pandemic as an example, small flows (i.e., magnitude attribute) of disease transmission with high frequency (i.e., frequency dimension of the time attribute) played a critical role in the beginning stage (i.e., timing dimension of the time attribute) among nearby systems (i.e., distance and direction attributes). Later, the disease expanded to distal systems (i.e., distance, direction, and duration attributes) via international flights (i.e., flow mode attribute), and large flows (i.e., magnitude attribute) became the dominant factor. The importance of each attribute and interactions among the attributes varies in different contexts, and can change over time and across spaces (or systems). For instance, during the pandemic, disease transmission greatly increased while trade flows were reduced substantially. Therefore, a collection of flow attributes presented here can be helpful for more inclusively examining complex interactions among coupled human-natural systems over different distances.

METHODS FOR QUANTIFYING FLOWS

Approaching and characterizing flows are key to describing the reciprocal interactions among systems and estimating the potential impacts. According to the nature of flows and our systematic review, we summarized the commonly used methods for approaching flows by flow type (Table 1). Because of the distinct methods used in practice, in this section, we further divided the physical flow category into three sub-categories based on flow mode (i.e., trade-related flows, biophysical flows, and active movement of humans and animals). The methods presented here are far from complete, but the objective is to provide readers with a starting point to initiate their metacoupling projects. Additionally, we discussed the barriers and highlighted the emergence of new data (e.g., remote sensing) and approaches for flow quantification. For instance, recent developments in big data provided a rich data source for mining and tracing human movements, information flows, and illicit trade (Di Minin et al. 2019). We hope that these new approaches can stimulate wider transfer learnings and implementation in quantifying other similar types of flows.

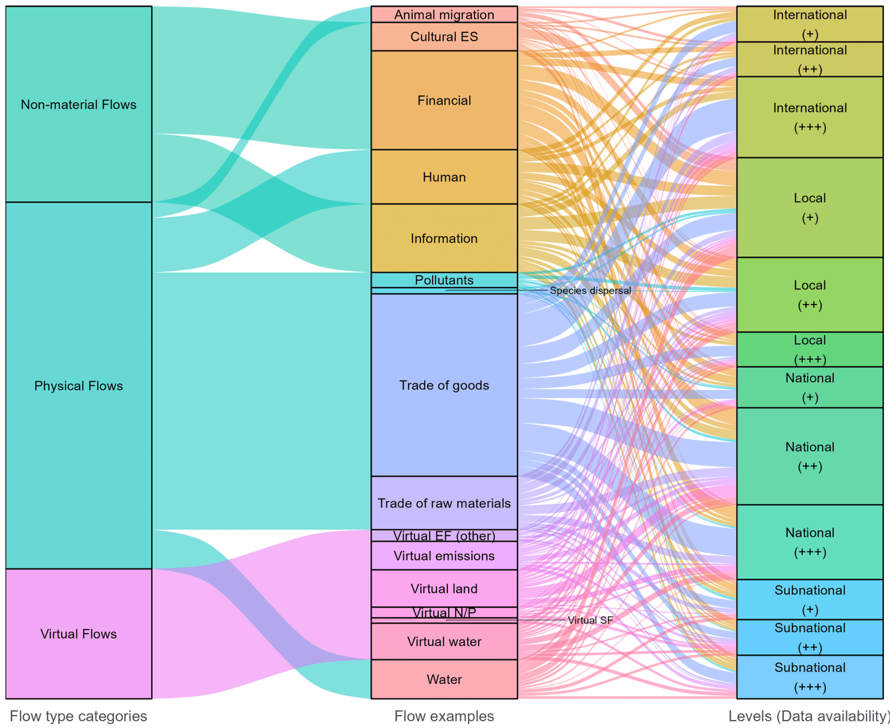
Physical flows

Trade-related flows

The number of studies related to trade flows is more than double that of any other type of flow (Fig. 2). We, therefore, summarized the three primary methods (i.e., statistical data-based approach, data mining/crowdsourcing approach, and modeling approach) for quantifying trade flows and provided elaboration on each of them below.

(1) Statistical data are widely available at the national level but are relatively limited at the subnational level (Fig. 4). National-level bilateral trade data can be acquired from either the Food and Agriculture Organization Corporate Statistical Database or the United Nations Commodity Trade Statistics Database (UN Comtrade). The former focuses on agricultural products, while the latter includes broader materials and product coverage. At the

Fig. 4. Flow types and corresponding data availability for quantification across organizational levels. The data availability based on our systematic review provides a broad and general pattern across regions, though some regions may have variations. The width of the horizontal flows represents the number of studies considered in the systematic review. "+++" – high data availability, "++" – moderate data availability, "+" – low data availability. ES – ecosystem services, EF – environmental footprints, SF – social footprints, N/P – nitrogen/phosphorus.



subnational level, the U.S. Economic Research Service provides state-level agricultural trade estimated from farm production value and farm cash receipts for exported products (USDA ERS 2022). In addition to the conventional traded products, illicit trade can have more unexpected impacts on sustainability but is more difficult to trace the flows (Magliocca et al. 2021). The Stockholm International Peace Research Institute Arms Transfers Database is among the few that compiled information on the trade of weapons. Illegal wildlife trade information is becoming more accessible thanks to research initiatives, such as TRAFFIC (https://www.traffic.org/), CITES (the shorter name for the Convention on International Trade in Endangered Species of Wild Fauna and Flora; Koellner et al. 2019), and the Oxford Martin Programme on Wildlife Trade (https://www.illegalwildlifetrade.net/). At the local level, statistical trade data are less available in some regions but are accessible in other regions. For example, panda loans can be obtained from the Giant Panda registry managed by the China Conservation and Research Center for the Giant Panda (Liu et al. 2015a).

(2) Data mining and crowdsourcing approaches are emerging in recent years, showing great potential to fill the data gap at the subnational level and even the local organizational level (e.g., company level). For instance, the Land Matrix Initiative takes a decentralized data collection strategy by establishing a broad international network in different regions to obtain information on large-scale land acquisitions. They synthesize and cross-check data from multiple sources (such as research papers, policy reports, official government records, company websites, annual reports, media reports, and field-based research projects) to produce data products on the global flow of transnational land acquisitions (Land Matrix 2022). The rich information at very fine spatial and temporal scales has facilitated food-water-energy-land-related telecoupling studies across scales (Liu et al. 2014, Liao et al. 2016, Chiarelli et al. 2022). Similarly, the Trase Finance initiative takes a unique supply chain mapping approach to map in unprecedented detail subnational trade flows by combining self-disclosed data from companies with customs, shipping, tax, logistics, and other data (Godar et al. 2015). The approach is unique because it links consumer countries and traders with the patterns of ownership and investment in trading companies, as well as places of production down to the lowest level of government administrative unit (e.g., individual farms or production areas). This spatially explicit information can help trace multiple environmental impacts (e.g., deforestation, biodiversity loss) of supply chains in great detail (Schim van der Loeff et al. 2018, Green et al. 2019, dos Reis et al. 2020, zu Ermgassen et al. 2020, 2022). However, these two example data initiatives are largely focused on land deals and agricultural commodity supply chains, and the spatial coverage is still relatively low. Future research could build on these novel and creative approaches and further expand data initiatives to address data gaps in mapping flows of other types of goods and services.

(3) Modeling and simulation approaches are especially useful when statistical data or public data are insufficient. The gravity model is widely used for analyzing bilateral trade flows of various commodities at both national and subnational levels (Liu et al. 2015b, Kabir et al. 2017). The gravity model is based on Newtonian physics, and trade volume between two areas is modeled as an increasing function of their sizes (often using GDP) and a decreasing function of the distance between the two (Anderson 1979, Kepaptsoglou et al. 2010). Though geographic distance is the most commonly used distance variable, revised versions of gravity models have also considered other impedance factors such as transportation costs, tariffs, quality of infrastructure, and common language (Kepaptsoglou et al. 2010). In addition to the gravity model, input-output (IO) analysis and generalized equilibrium models have been exploited for simulating trade flows. Constructing interregional IO tables usually takes large financial and labor efforts, and running computable generalized equilibrium models requires a considerable number of parameters (Boero et al. 2018). For application purposes, users usually resort to existing IO tables and datasets released by professional institutions and teams. For instance, the Food and Agriculture Biomass Input-Output tables provide a comprehensive flow of agricultural, food, and forestry products among 191 countries (Bruckner et al. 2019). The Chinagro model, a geographically detailed general equilibrium model, depicts the interregional trade of agricultural products among eight regions in China (Fischer et al. 2007, Dalin et al. 2014).

In addition to the aforementioned models focusing on national and subnational levels, freight flow models can be used to map trade flows at more spatially explicit levels (e.g., county and pixel level) (Lin et al. 2019, Kinnunen et al. 2020, Karakoc et al. 2022). For example, the U.S. Bureau of Transportation Statistics and Federal Highway Administration integrate data from a variety of sources (e.g., Commodity Flow Survey) to create a freight movement database, Freight Analysis Framework, among states and major metropolitan areas by all modes of transportation (Hwang et al. 2021). Lin et al. (2019) and Karakoc et al. (2022) further downscaled this data and produced the U.S. county-level food flows. At finer spatial resolution, Kinnunen et al. (2020) combined the foodsheds (self-sufficient areas with internal dependencies) approach and freight analysis and modeled food flow paths at 30 arcmin resolution. Both examples are on food flows, but the approach can also be applied to other traded commodities.

(4) Other novel datasets, such as the automatic identification system (AIS) and remote sensing, are increasingly used and have great potential for tracing and estimating trade flows (Kapsar et al. 2023). AIS is an automatic tracking system that uses transceivers on ships (Kapsar et al. 2022b), which can provide rich and real-time ship locations and movement trajectories (Mou et al. 2020). In addition, remotely sensed satellite imagery can also be used to detect and classify container ships and cargo trucks (Fisser et al. 2022, Polinov et al. 2022, Liu et al. 2023, Shao et al. 2023). In combination with auxiliary data, both AIS and remote sensing-derived data can also be used for modeling shipping activities and estimating freight flows.

Biophysical flows

The methods for estimating the flows of water, sediments, and pollutants (e.g., nitrogen, phosphorus, GHG emissions, and PM2.5) range from field observations to process-based modeling. Water flows, such as streamflow, are usually publicly available from government-led or research institute-led observation stations (e.g., the U.S. Geological Survey). For human-intervened water flows, such as China's South-to-North Water Transfer Project, the amount of transferred water across regions can be acquired from the management department or through public reports. According to the most recent report, 50 billion m^3 of water has been transported from southern to northern China from 2014 to 2021 (Xinhua News Agency 2021). Researchers can also deploy their own field observation stations to obtain related water flow data. However, the scattered observation data have drawbacks either due to limited spatial coverage or temporal availability.

Modeling approaches are often used for filling the field observation data gaps. Hydrological models, such as the Soil & Water Assessment Tool (SWAT), can be used to simulate the quantity and quality (e.g., nitrogen and phosphorus concentrations) of surface and groundwater in watersheds (Bieger et al. 2017). SWAT does not directly model flows, but the outputs can be used for estimation or as inputs for other flow models. The Model to Assess River Inputs of Nutrients to seas is a widely used flow model, which quantifies river export of nutrients (dissolved N and P) from land to sea by the source at the sub-basin level (Strokal et al. 2016). For a finer spatial scale, Bagstad et al. (2013) developed an agent-based model termed "Service Path Attribution Networks" (SPANs) on the Artificial Intelligence for Ecosystem Services modeling platform. The SPAN initializes agents from spatially explicit source (i.e., sending systems), sink, and use data, and tracks the spatially explicit paths taken by carrier agents through the network (e.g., hydrologic or transportation networks, or the atmosphere) to determine the quantity of goods or services reaching final users (i.e., receiving systems). SPAN is a powerful tool to model the flows of freshwater, riverine flood, and sediments (Bagstad et al. 2013).

In addition, remote sensing is also an important data source to characterize biophysical flows (e.g., river discharge and sediments). For example, the GRACE (Gravity Recovery and Climate Experiment) satellites are especially useful for tracking large-scale transboundary water movement and monitoring changes in underground water storage, large lakes, and rivers (Richey et al. 2015). The flows of emissions (e.g., GHG and PM2.5) through the air are more volatile and can be stimulated by applying advanced air current models (Koellner et al. 2019) and high-temporal resolution remote sensing (e.g., Sentinel-5P and MODIS - Moderate Resolution Imaging Spectroradiometer; Zhang et al. 2021).

Human and animal flows

Human migration data are recorded at multiple levels, such as the national level for international migration and the subnational level for interregional (within a nation) migration. Data can be acquired from national or state statistical administrations. For example, data on tourism flows can be collected from national visitor statistics provided by the World Tourism Organization (Chung et al. 2020). These data are usually collected through census surveys or self-reporting. Illegal human flows, however, are less accessible. Such data might be sourced from data initiatives. For example, the Counter-Trafficking Data Collaborative utilized a crowdsourcing approach and collected anonymized human trafficking data contributed by counter-trafficking organizations around the world. Recent developments in big data using human mobility trajectory from mobile phones and social media provide alternative high-resolution and instant human flow data for investigations (SafeGraph 2022). The human mobility data with detailed geospatial information can also be used to model tourism and disease transmission (e.g., COVID-19; Grantz et al. 2020, Kang et al. 2020, Xiong et al. 2020, Chang et al. 2021). Moreover, nighttime light remote sensing data, such as the Defense Meteorological Satellite Program/Operational Linescan System and the Visible Infrared Imaging Radiometer Suite on the NASA/NOAA Suomi National Polar-orbiting Partnership satellite, provide a great opportunity for monitoring human activities (e.g., human migrations) from regional to global scales (Müller et al. 2016).

Animal migration and species dispersal (e.g., species invasion) are commonly estimated based on traditional field observation, such as birdwatching by individual researchers (Koellner et al. 2019), hunting licenses (Koellner et al. 2019), and stationary camera traps (Carter et al. 2012, Miller et al. 2017, Zhang et al. 2017). Other forms of data collection approaches include citizen science (Fritz et al. 2019, Yang et al. 2019), crowdsourcing approaches (e.g., geotagged wildlife photos and videos from social media platforms; Di Minin et al. 2019), stable isotope analysis (Hobson and Wassenaar 2008), and/or modern animal wearable tracking technologies (Kays et al. 2022), including high-resolution global positioning system tracking devices and geolocators (Hulina et al. 2017). Because these approaches can only capture a sample of the whole population, species distribution models have often been used alongside these approaches (Koellner et al. 2019).

Non-material flows

In an era of information, massive amounts of information flow everywhere. To quantify the interregional flows of particular information of interest, it is important to first identify the information-sending systems and receiving systems. A sending system can be quickly identified based on the source and content of the information (such as who and where), whereas identifying the receiving systems can be challenging, especially when the number of information receivers can reach hundreds of thousands. Based on the scales or certain system boundaries, one can identify the receiving systems by examining the occurrence of news in local public media and social media. Further, the number of keywords, photos, and videos in geotagged social media (e.g., Twitter, Flickr, Sina Weibo) and digital search engines (e.g., Google Trends), or the number of newspaper articles, reports, and documentaries that report about the sending system within or through the receiving system could be used as a proxy to estimate the magnitude of information flow (Liu et al. 2015a, Koellner et al. 2019, Li et al. 2021). However, although these proxies can serve as an approximation, they might be biased in estimating the actual magnitude of information flows. The bias can be introduced by the representativeness of samples. For instance, social media participants are not a random sample of the population. Therefore, certain population groups with different demographic traits (e.g., age, education level, income) could be over- and under-represented in social media data (Li et al. 2021). Similarly, the heterogeneous coverage of social media platforms and devices across regions, as well as the uncertainties caused by potential noise of misinformation, can also bring bias in estimation. To accurately estimate information flows using social media data, there is a need to carefully handle the inherent bias in the data (Wang et al. 2015).

Knowledge transfer and technology transfer can be quantified in the same way as information flows. Depending on the types of technology, the technology transfer could also be measurable by the trade flow approach. For example, energy-related technology transfer can be measured by the trade quantity of high-tech energy equipment and materials (e.g., solar panels and rare-earth metals) (Fang et al. 2016, Fishman and Graedel 2019, Li et al. 2020).

Flows of investment and financial aid are usually measured by data from public statistical datasets, such as foreign direct investment among countries. More granular data on transboundary investment or aid have been recently compiled by individual research groups. For instance, the AidData team at William & Mary used data mining approaches to produce project-level financial flow by coding over 1.5 million development finance activities (AidData 2016, Custer et al. 2021). The Global Development Policy Center at Boston University took a similar approach and produced a high-precision dataset for China's overseas finance investment (Ray et al. 2021). These financial flow data have been used for investigating international conservation interests (Qin et al. 2022), the risk to global biodiversity (Yang et al. 2021), and the social and environmental impacts of large-scale overseas infrastructure development (Li et al. 2021).

Virtual flows

Virtual flows, or the embedded resources (or more broadly termed as footprints) in products, have emerged as a set of major indicators for evaluating the hidden socio-environmental impacts associated with the trade (Galli et al. 2012, Fang et al. 2014, Vanham et al. 2019, Xu et al. 2020a). As such, the quantification of virtual flows usually requires data on the physical flows of traded goods (Chen et al. 2023). Because the virtual resources are the portion that was used in the production process but are not physically contained in the final products, the end-users (or the product receiving systems) usually cannot see or be aware of their impacts on distant producing systems (or product sending systems). The concept of virtual flows can thus be used to inform final consumers to adjust their consumption behaviors (e.g., changing diets or sourcing products from more sustainable production systems). There are two widely used approaches for quantifying virtual flows: Multi-Regional Input Output (MRIO) analysis, and life cycle assessment (LCA).

(1) MRIO is a macroeconomic approach that tracks financial flows between countries' major economic sectors. Developed by the Nobel Prize Laureate Wassily Leontief, input-output analysis is an economic technique that relies on input-output tables. Monetary MRIO tables can be coupled with satellite accounts data on a range of environmental indicators (e.g., land, water, energy, emissions, biodiversity risk) to estimate environmental footprint flows (Lenzen et al. 2012, Zhao et al. 2015, Oita et al. 2016, Xu et al. 2019, Li et al. 2022). The basic idea is to convert

Table 2. Summary of the main global Multi-Regional Input Output (MRIO) databases. † RoW: Rest of World. ‡ FABIO is a physical IO table, while others are all monetary tables.

Database name	Countries	Sector details	Time	Extensions	Unit
EORA	World (190)	20–500 (Full Eora); 26 (Eora26)	1990–2021	GHG emissions, labor inputs, air pollution, energy use, water requirements, land occupation, N and P emissions, primary inputs to agriculture	USD
EXIOPOL-EXIOBASE	World (44 = 43+1RoW† = 27EU+16+1)	163	1995–2021	30 emissions, 60 IEA energy carriers, water, land, 80 resources	EUR
World Input-Output Database (WIOD)	World (41 = 40+1RoW = 27EU+13+1)	35	1995–2009	Detailed socioeconomic and environmental satellite accounts	USD
Global Trade Analysis Project (GTAP)	World (141 = 121+20 Regions)	65	1990, 1992, 1995, 1997, 2001, 2004, 2007, 2011, 2014	Global warming potential (GWP), land use, energy volumes, migration	USD
Global Resource Accounting Model (GRAM)	World (62)	48	2000, 2004	CO_2 emissions, material extraction, value-added, and employment	
IDE-JETRO	Asia-Pacific (8: 1975) (10: 1985–2005)	56 (1975); 78 (1985–1995); 76 (2000, 2005)	1975–2005	Employment matrices (2000, 2005)	YEN
Food and Agriculture Biomass Input-Output Model (FABIO) ‡	World (192 = 191+1RoW)	118 processes and 125 commodities	1986–2013	NA	Tonnes, Heads

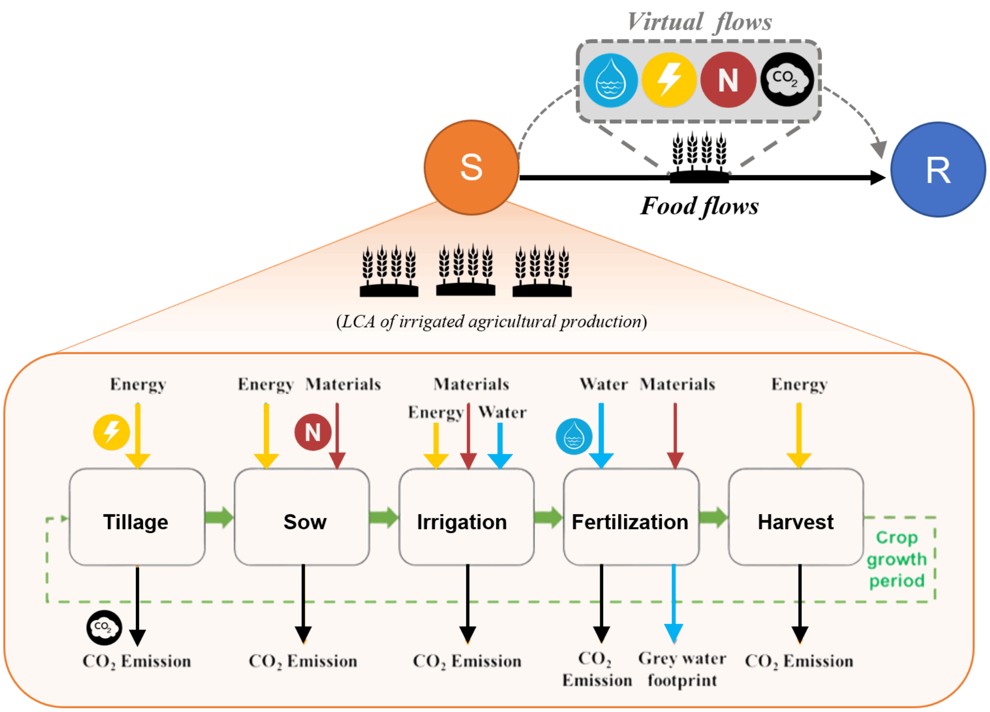
monetary values in the MRIO tables to physical or virtual footprint flows among sectors and countries based on independent data on the national price per physical unit of certain products, and on the physical resource or environmental intensity (e.g., CO_2 emissions in tons per monetary unit) by country and industry sector (Shapiro 2020). In recent years, research has been extended from not just environmental indicators, but also incorporated social indicators (e.g., employment, child labor, and gender pay gap) to assess the social risk embedded in products and services (Alsamawi et al. 2017b, Xiao et al. 2017, Wiedmann and Lenzen 2018, Malik et al. 2021a). MRIO analysis is suitable for macro-scale virtual flow analysis, and the data are broadly available at the global scale. Table 2 summarizes a list of widely used MRIO databases, detailing country, sector, and year coverages, as well as the associated satellite accounts available for use. Some countries, such as the U.S. and China, have subnational MRIO tables (i.e., IO between various sectors of multiple regions in a country). MRIO is more suitable for mapping virtual flows at the aggregated sector level or economy level but is usually not suitable for a single product.

(2) LCA was initially developed in the 1970s to estimate environmental impacts associated with a product throughout its life cycle (ISO 2006, Guinée et al. 2011, Crawford et al. 2018). Starting in the 2000s, social-LCA was proposed and developed to assess the social and sociological impacts (e.g., human rights, health, and safety) of products along the life cycle (Andrews et al. 2009, Guinée et al. 2011). LCA is a more comprehensive, high-resolution, and flexible approach compared to the MRIO approach. Combined with trade flow data, virtual flows of footprints at both macro-scale (e.g., national level) and micro-scale (e.g., corporation level and individual people level) can be quantified (Xu et al. 2020b, Malik et al. 2021b, Zhao et al. 2021a). Fig. 5 provides an example, illustrating the system boundaries and functional units for the LCA of irrigated agricultural production. In this example, carbon, energy, nitrogen, and water footprints of producing per unit of winter wheat can be calculated through the LCA method in combination with unit process parameters (Xu et al. 2020b).

LCA is a flexible approach, and the complexity varies depending on the specific processes considered and the desired outcomes. Rigorous LCA relies heavily on data collection, either from onsite investigation and laboratory tests (Tu et al. 2021), or through questionnaire surveys and literature reviews (Poore and Nemecek 2018). Yet, data needs can be reduced significantly and replaced by properly calibrated models. For example, the water footprint from crop production can be estimated by using crop evapotranspiration models because crop evapotranspiration dominates water use for food production (Xu et al. 2020b, Tamea et al. 2021). Furthermore, conducting LCA studies necessitates a clear definition of appropriate system boundaries, because different system boundary settings may result in very different results (Malik et al. 2021b). Scholars have developed several powerful LCA tools (e.g., Carbon calculator, GREET, GHGenius, GaBi, SimaPro, OPENLCA, Brightway2; Fig. S3), which make LCA a key approach for virtual flow quantifications.

In practice, because of data limitations, MRIO and LCA scholars tend to use fixed parameters by either borrowing average figures from global-scale studies or parameters that were examined in other regions at a certain time, which ignored the spatial and temporal heterogeneity in the parameters. Accurate estimations should further consider spatial variability (given the heterogeneity in climate, soils, resource endowment, and other production conditions) and temporal variability (Hoekstra 2017, Poore and Nemecek 2018).

Fig. 5. An example of quantifying virtual flows of water, energy, nitrogen (N), and CO_2 embedded in food trade by using life cycle assessment (LCA) of irrigated agricultural production. S – sending system, R – receiving systems. The subplot of LCA is adapted from Xu et al. 2020b.



Method integration for addressing complex interactions among multiple flows

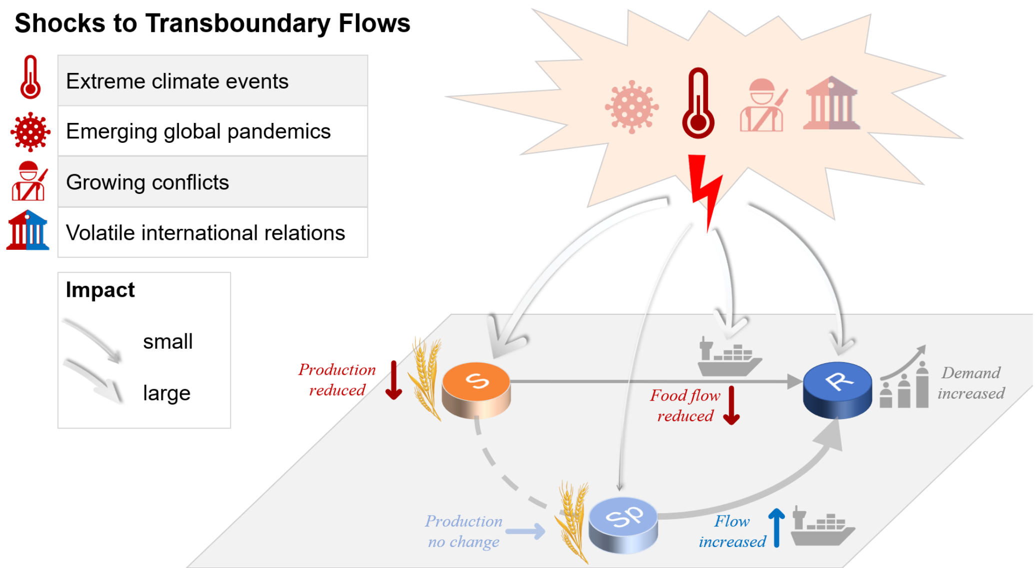
In this section, we summarize the key methods used for quantifying each type of flow, and, particularly, we highlight the new approaches, such as the use of big data and crowdsourcing, for addressing data accessibility barriers. For instance, most of the trade flows at national or regional levels were quantified by using statistical data (Fig. 4), while unconventional or illicit trade data (e.g., trafficking of humans, wildlife, and drugs) are usually not accessible. The crowdsourcing approaches provided a way to collect relevant data and address the data gap. In addition, the prevalent use of mobile phones and social media data offers rich and high-resolution geotagged and time-stamped data for modeling human flows (e.g., tourism) and disease transmission.

Importantly, given that multiple flows can be interrelated among associated systems, there is a great need to synthesize diverse data and multiple methods to address real-world sustainability challenges. For instance, Xu et al. (2019) combined trade statistics and input-output analysis, and examined six types of global flows (i.e., virtual water, energy, CO_2, nitrogen, land, and financial capital flows) and found that most of these flows tended to enhance each other through synergistic effects. McSweeney et al. (2018) integrated field data, news media data, and consolidated counterdrug database, and revealed the linkages between illicit capital flow, drug trafficking, and land grabbing (McSweeney et al. 2018). We also encourage future research to draw insights from the method portfolio presented here and move beyond examining a single flow. Instead, researchers should investigate the complex relationships, such as amplification, offsetting, and spatial overlaps, among multiple flows to gain a more comprehensive understanding of the interactions and potential impacts among systems (Liu et al. 2015a).

IMPLICATIONS OF TRANSBOUNDARY FLOWS FOR GLOBAL SUSTAINABILITY GOVERNANCE

In an increasingly metacoupled world, actions (e.g., new policies and initiatives) and changes (e.g., natural and social shocks) in one place can generate positive or negative impacts on other places through various flows (Sachs et al. 2017, Liu et al. 2018b, Li 2021, Zhao et al. 2021b, Chung and Liu 2022). It is thus critical to evaluate and manage the transboundary flows across scales, organizational levels, and over time. Transboundary flows are particularly challenging for governance and addressing sustainability issues as they usually involve multiple states or multilateral governing authorities and regimes (Munroe et al. 2019, Newig et al. 2019). Stakeholders under different governing systems can have very different interests and goals. The typology and methodology of transboundary flows we developed under the metacoupling framework can help to promote system thinking and multidisciplinary approaches to identify the potential challenges and opportunities for sustainable development across regions. Previous studies have provided in-depth conceptual structuring of telecoupling governance (Newig et al. 2019, 2020), as well as insightful discussions on transboundary governance in land systems and food systems (Eakin et al. 2017, Munroe et al. 2019). Drawing upon these conceptual foundations, the focus of

Fig. 6. Shocks that impact transboundary flows and the metacoupled systems. S – sending system, R – receiving systems, Sp – spillover system. The graph exemplifies the impacts of climate change on reducing food production in the sending system, on disrupting food transportation (e.g., port infrastructure and shipping), on changing demands in the receiving systems, and potentially on changing the food trade flows between the receiving system and the spillover system (assuming the shock has little impact on Sp).



this section is to explore how the typology and methodology of transboundary flows can help address emerging challenges, such as the increasing incidence of shocks, through the application of system modeling and scenario analysis.

Growing shocks to transboundary flows

Changing climate (e.g., global warming, extreme climate events), emerging global pandemics (e.g., COVID-19), growing conflicts (e.g., Russia-Ukraine war), and volatile international relations (e.g., the US-China Trade war) have threatened the sustainable delivery of many flows (e.g., products, and tourism) and global sustainability (Fig. 6). The impacts of these shocks have also become unprecedentedly prominent as the world becomes more interconnected and interdependent (Viña and Liu 2022).

Shocks can impact transboundary flows in various ways, which can be examined by the flow attributes (i.e., type, magnitude, direction, distance, time, and mode). For directional flows, shocks to sending systems can reduce the supplies for outflows, and shocks to receiving systems can alter inflows (Fig. 6). Certain types of flows (e.g., food flows and water flows) can be more vulnerable to shocks than others. Taking climate change-related shocks as an example, research has revealed that each degree-Celsius increase in global mean temperature would reduce global yields of maize by 7.4%, wheat by 6.0%, rice by 3.2%, and soybean by 3.1% (Zhao et al. 2017), and a large reduction in major food production regions could trigger systemic disruption: the soaring price of agricultural products and erratic food supply chains (Puma et al. 2015). Extreme climate also alters the magnitude of biophysical flows (e.g., water flows) and causes disasters (e.g., flooding and drought), threatening coupled human and natural systems. Furthermore, extreme climate can impact flow modes by disrupting transportation infrastructures/pathways. Research shows that 86% of ports globally are exposed to more than three natural hazards, potentially affecting global maritime trade flows (Verschuur et al. 2023).

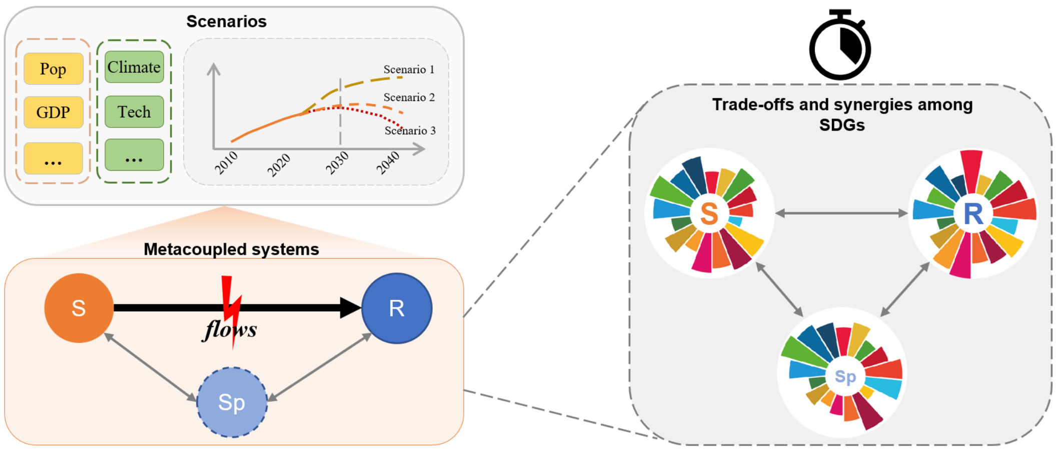
One shock can impact multiple flows simultaneously. The outbreak of epidemics (e.g., the recent COVID-19 pandemic) blocked more than 90% of the international human flows in early 2020 (Muhammad et al. 2020), and also generated severe negative impacts on global supply chains (Guan et al. 2020, Falkendal et al. 2021). Another example is the recent Russia-Ukraine war. More than 9.1 million cross-border refugees have left Ukraine (UNHCR 2022), and the war has also disrupted global flows of vital commodities such as food, energy, and fertilizer (Puma and Konar 2022, Tollefson 2022), which are expected to further affect global biodiversity and the environment (Liu et al. 2022b). Related studies on the Syrian civil war revealed that refugees fleeing can have unexpected impacts on transboundary water flows (Müller et al. 2016) and aggravate host countries' water stress even with more increased inflow of transboundary water (Bertassello et al. 2023).

Evaluating these growing shocks and their potential entwined impacts by collectively examining multiple interrelated flows and changes in their attributes can help stakeholders get a holistic picture and adopt system modeling to address transboundary sustainability challenges.

System modeling and scenario analysis for understanding dynamic flows and metacouplings

In the metacoupled Anthropocene, system interactions have become more complex than ever because of the growing number of flows among interlinked systems. Network analysis is useful

Fig. 7. Scenario analysis for investigating dynamics of transboundary flows (left), and system sustainability under the UN Sustainable Development Goals (SDG) framework (right). S – sending system, R – receiving systems, Sp – spillover system.



for visualizing the complex interactions between multiple flows and multiple systems (Sonderegger et al. 2020, Berfin Karakoc and Konar 2021, Carlson et al. 2021), but is not sufficient for understanding and modeling system dynamics. Nexus approaches were highlighted to be highly useful in uncovering synergies, detecting harmful trade-offs among multiple sectors, and unveiling unexpected consequences (Liu et al. 2018b). To implement nexus approaches, it is especially critical to adopt system modeling to simulate nexus dynamics and get a quantitative understanding of the changes in flows and dynamics of systems. Particularly, we recommend the integration of multidisciplinary flow models and scenario analysis for simulation. Scientists can work with multi-stakeholders to develop various scenarios. In addition to the common practice of including socioeconomic development and climate scenarios (Zhao et al. 2021a), shocks on transboundary flows can also be included in developing scenarios by changing various flow attributes. For instance, shocks can lead to different degrees of trade disruption. It would be better for countries or regions that rely on trade for goods and services to test the extent to which trade disruption might impact the supply for domestic needs.

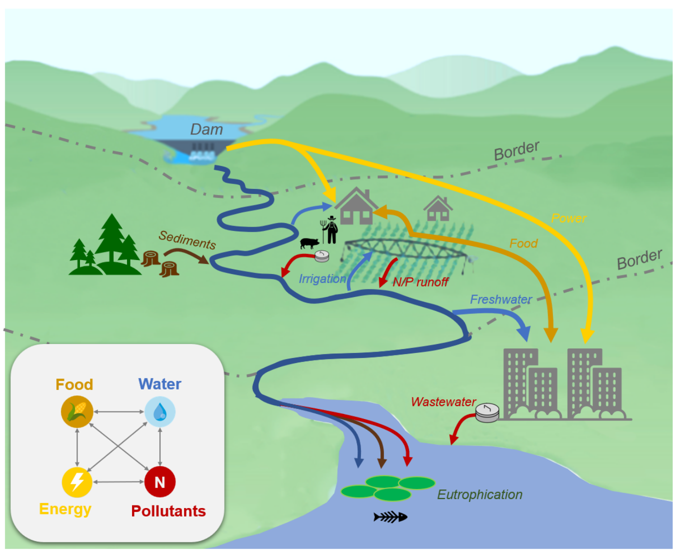
Given the broad impacts each scenario might generate on a system's sustainable development, the global indicator framework for the Sustainable Development Goals (SDGs) proposed by United Nations (UN 2019) can be particularly helpful in providing a set of indicators for cross-sector or cross-region comparison (Fig. 7). A fully integrated global social-environmental model, the Global Biosphere Management Model, has shown great potential for application in global and regional agricultural trade and impact assessment (Havlík et al. 2018). For other types of flows, such as water and energy flows, the corresponding flow models can also be integrated with scenario analysis for simulations (Munia et al. 2020, Vinca et al. 2021). Although scenario analysis has often been criticized for not being able to be validated, it is still useful for guiding policy making by revealing potential impacts. Not aiming at predicting the future, the analysis rather provides a big picture of what to avoid and how to prepare for and adapt to an uncertain future.

Enhancing global metacoupling governance with flow typology

In a metacoupled world, it is short-sighted to say that problems are caused and are to be solved where they occur (i.e., place-based governance or territorial-based governance; Sikor et al. 2013, Hoekstra and Wiedmann 2014, Eakin et al. 2017, Liu et al. 2018b, Munroe et al. 2019). Such place-based governance might lead to well-intended but unexpectedly ineffective policy results. For instance, only focusing on emission targets within one country might lead to the displacement of carbon-intensive industries to other countries with lax environmental standards, resulting in "carbon leakage" (Xu et al. 2020a). Therefore, there is an increasing need for further facilitating flow-based governance, which considers governance in a place in light of its relationships with other places by tracking and managing where flows start, progress, and end (Sikor et al. 2013, Liu et al. 2018a). Existing literature has provided insightful discussions on the theoretical and conceptual structuring of telecoupling governance (Newig et al. 2019, 2020), as well as the role of multi-stakeholders (Munroe et al. 2019). However, knowledge deficits in tracing flows are still the foremost challenge in telecoupling governance (Newig et al. 2020). A recent review paper particularly calls for developing a common language to study how telecoupling (a subset of metacoupling) can be governed toward sustainability (Cotta et al. 2022). Metacoupling governance should integrate telecoupling governance (between distant places), traditional place-based governance (within a focal place), and governance of human-nature interactions between adjacent places (Liu 2023).

The flow typology presented in this study is, therefore, timely and crucial in bridging these gaps. First, a portfolio of flow types needs to be identified when approaching transboundary governance. Research has found that existing studies have largely focused on a few flows, such as the trade of consumer-facing commodities, while other types of flows remained under researched, even though they have substantial environmental impacts (Cotta et al. 2022). Taking multiple related flows into consideration would facilitate all parties to negotiate on diverse interests in order to reach common interests that underpin joint solutions to metacoupled sustainability issues. Taking a transboundary watershed system as an example, the watershed governance needs to consider closely interlinked flows (e.g., flows of surface water, groundwater, sediments, and wastewater; food flows, fertilizer runoff, and energy flows; Fig. 8) and engage stakeholders from multiple sectors (UNEP-DHI and UNEP 2016, Müller et al. 2017, Avisse et al. 2020, Vinca et al. 2021). Second, once flows are identified, the collection of methods can be used for quantitatively measuring flow magnitude, and understanding how flows' other attributes change over time and across distance. This would be key to evaluating the associated socio-environmental impacts, and would help multi-stakeholders balance trade-offs and develop governance arrangements to tackle these interlinked challenges.

Fig. 8. Multiple interconnected flows across a transboundary river basin. Regions within a river basin are linked through their use of the water (for hydropower, domestic water use, and irrigation), and the impacts they cause through development and pollution (e.g., wastewater, agricultural nutrients, sediments, and aquatic biodiversity loss). Partly adapted from UNEP-DHI and UNEP 2016.



Moreover, flow-based governance must recognize and address the new and uncertain risks posed by increasingly frequent and destructive global shocks. As the world becomes more interconnected, vulnerability to global shocks increases (Viña and Liu 2022). Current system governance tends to focus on maintaining and enhancing a few key flows in supply chains to be efficient for short-term sustainability. However, the whole system could be susceptible to unexpected shocks to these key flows. Preserving and promoting proper redundancy and diversity of the flows within the system can improve system resilience (Puma et al. 2015). To increase resilience and adaptability, there is a need to enhance metacoupling governance by integrating multidisciplinary flow models and utilizing system modeling tools as a practical approach to comprehending the complex consequences brought about by alterations in transboundary flows.

CONCLUSION

Transboundary flows are a key component in the metacoupling framework, as they connect focal, adjacent, and distant systems. Governance of transboundary flows is inherently challenging. To address the complexity and challenges, we made a first attempt to characterize them in different dimensions (e.g., type, magnitude, direction, distance, time, and mode), and highlighted practical methodologies for characterizing them. Tracking and quantifying transboundary flows have profound implications for achieving co-benefits and minimizing trade-offs across sectors and places. Governing transboundary flows should recognize the shared risks and goals, use system thinking, and enhance multilateral cooperation. To achieve global sustainability in the Anthropocene, transboundary flows must be explicitly recognized and systematically characterized in sustainability research and governance so that effective policies and practices can be developed and implemented to safeguard humankind and its planetary support systems.

Author Contributions:

Y.L. and J.L. contributed to the conceptualization of the manuscript;
Y.L., N.J., X.Y., N.M., and X.L. performed the systematic review;
Y.L. and J.L. wrote the paper;
All authors reviewed and edited the manuscript.

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Data Availability:

The data and code that support the findings of this study are available on GitHub at https://github.com/Yingjie4Science/flow-typology

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APPENDIX 1

Systematic review

Literature search strategy

Searching for relevant literature was conducted in the Web of Science (WOS) Core Collection, and we followed the general principles by PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines for this study (Fig. S1) (Page et al., 2021). The master search strategy was run in WOS from inception to March 1, 2023. Search results were imported to and analyzed in Covidence, which is a web-based software platform that streamlines the process of title/abstract screening, full-text screening, data extraction, and keeping track of work when conducting a systematic review. Duplicates were eliminated using the Covidence build-in function. Subsequently, three authors (Y.L., N.J., and X.Y.) screened all the literature first by title and abstracts, and then the full texts according to the eligibility criteria. Finally, five authors (Y.L., N.J., X.Y., N.M., and X.L.) extracted flow attributes and other associated data from literature using Covidence.

Screening criteria

We only included original research articles published in peer-review journals written in English. Titles and Abstracts were screened for potential relevance by three authors independently. We excluded studies if they were:

1. Reviews, editorials, book chapters, letters, short communications, conference proceedings, and meeting abstracts.
2. Not original empirical studies.
3. Not in English.
4. Unrelated topics (were not relevant to metacoupling/telecoupling, or did not examine transboundary/interregional flows).

During our evaluation of the full texts, we excluded those studies that mentioned flows but did not conduct any flow-related analysis. We included studies that used either quantitative or qualitative approaches.

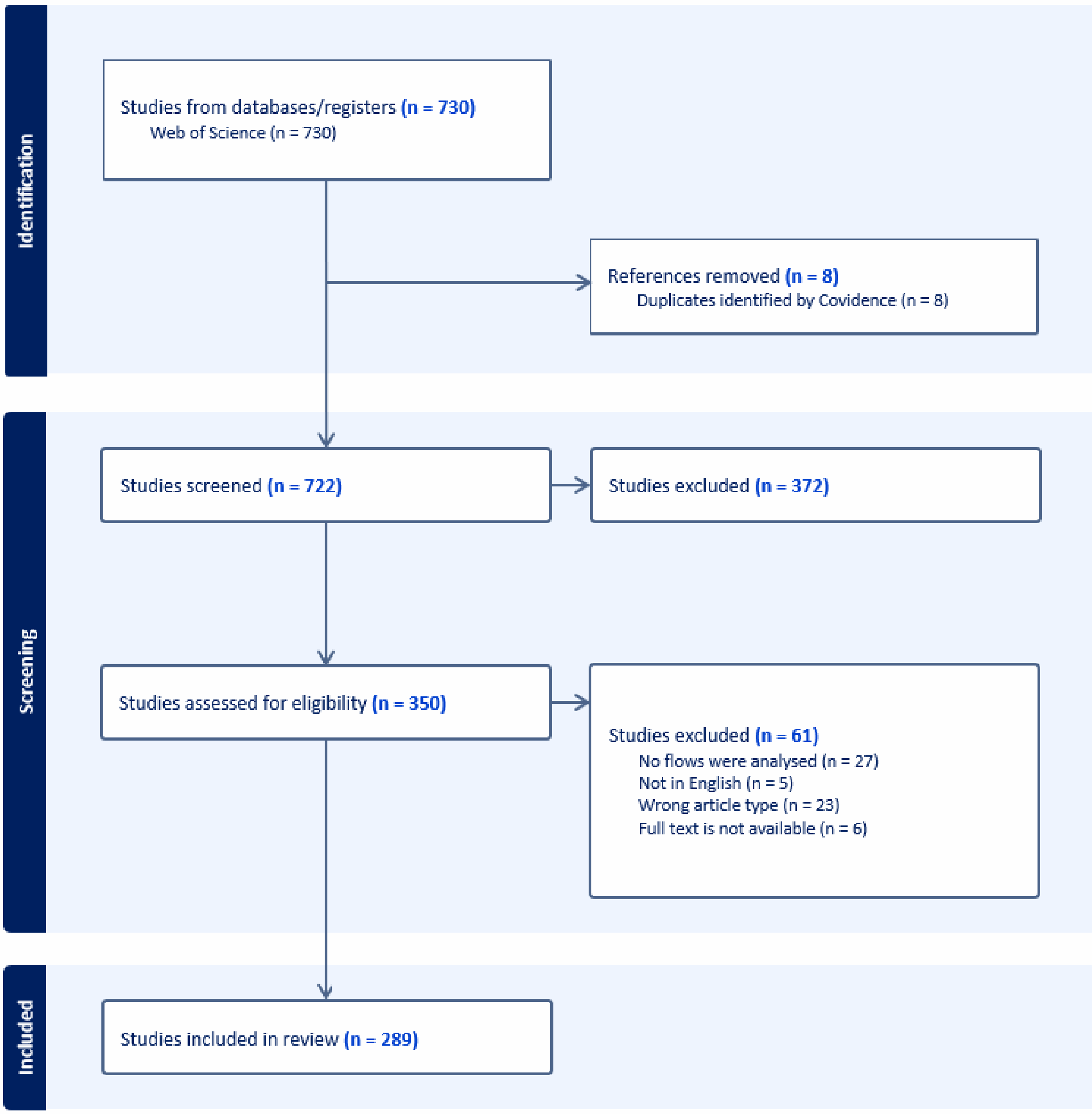

Fig. S1. The literature screening process based on the PRISMA workflow (Page et al. 2021).

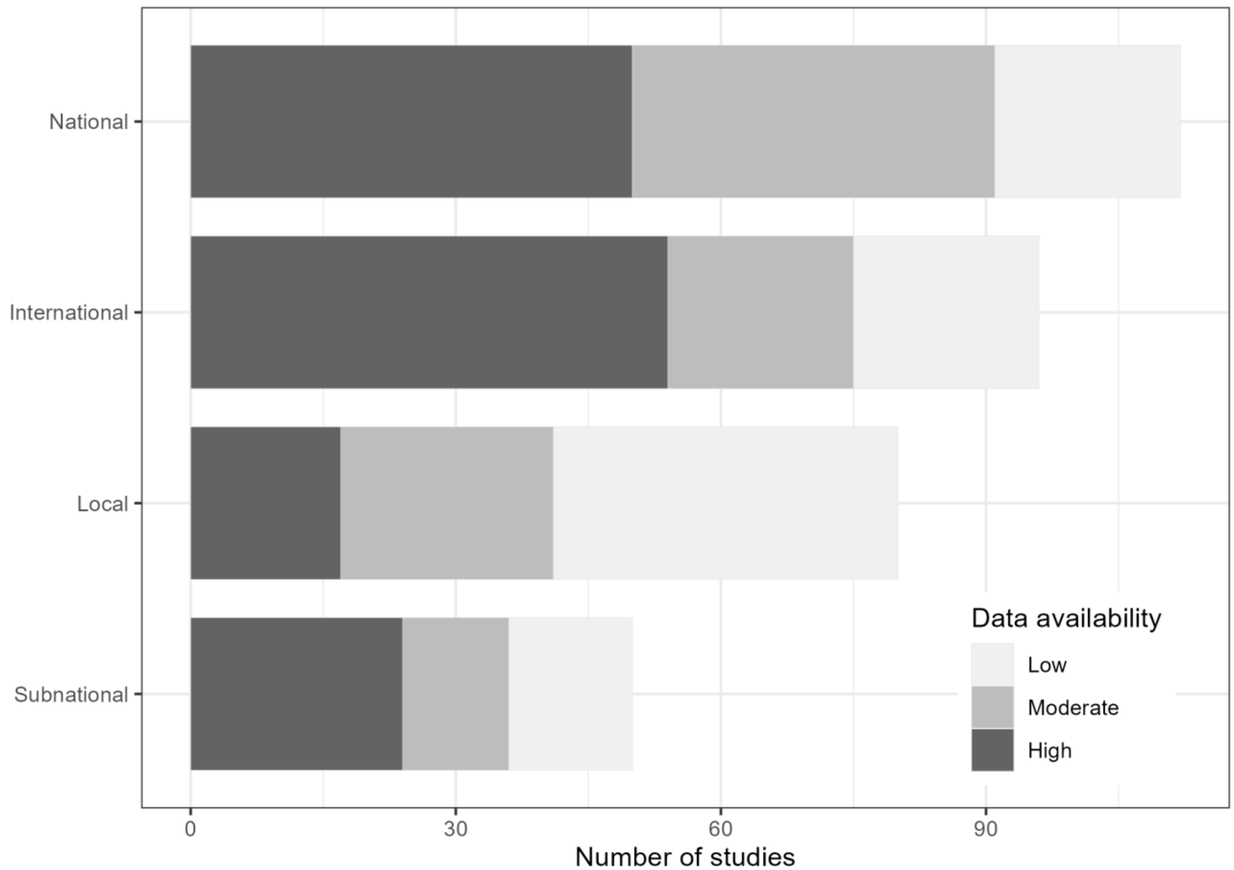

Fig. S2. The organizational levels commonly used for transboundary flow analysis and their corresponding data availability.

Fig. S3. LCA tools, Carbon calculator, GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation), GHGenius (focus on transportation fuels in Canada), GaBi Software, SimaPro, OPENLCA, Brightway2. Credits to Dr. Qingshi Tu at the University of British Columbia.

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