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Spillover systems in a telecoupled Anthropocene: typology, methods, and governance for global sustainability

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The world has become increasingly telecoupled through distant flows of information, energy, people, organisms, goods, and matter. Recent advances suggest that telecouplings such as trade and species invasion often generate spillover systems with profound effects. To untangle spillover complexity, we make the first attempt to develop a typology of spillover systems based on six criteria: flows from and to sending and receiving systems, distances from sending and receiving systems, types of spillover effects, sizes of spillover systems, roles of agents in spillover systems, and the origin of spillover systems. Furthermore, we highlight a portfolio of qualitative and quantitative methods for detecting the often-overlooked spillover systems. To effectively govern spillover systems for global sustainability, we propose an overall goal (minimize negative and maximize positive spillover effects) and three general principles (fairness, responsibility, and capability).

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Introduction

Increasing environmental and socioeconomic interactions across the world is a distinct feature of the Anthropocene [1]. Telecoupling is a newly developed umbrella concept that encompasses a broad range of socioeconomic and environmental interactions over distances [1], such as international trade [2], foreign direct investment, animal migration [3], human migration [4], tourism, travel, species invasion [5], disease spread, transfers of pollutants and waste, payments for ecosystem services, technology transfer, and knowledge transfer [6••]. Telecouplings intimately connect coupled human and natural systems around the world, and many telecouplings generate complex and profound socioeconomic and environmental impacts across local to global scales. Such impacts have important implications for achieving global initiatives such as the United Nations Sustainable Development Goals [7], the Paris Agreements [8], and the Aichi Targets [9]. Although many telecouplings have existed for a long time, their rapid expansion requires new frameworks to understand the unprecedented interconnections and feedbacks within the new and evolving contexts in the Anthropocene.

Conceptually, the telecoupling framework offers a useful analytical lens for effective sustainability research and policy [1,10]. It explicitly views global interconnectivity as flows among interrelated units of analysis, for example, sending, receiving, and spillover systems [1,11•]. Sending and receiving systems are entities that send and receive flows of information, material, energy, goods, products, capital, people, knowledge, techniques, ideas, and/or organisms. Spillover systems are entities that affect, or are affected by, interactions between sending and receiving systems. For example, spillover systems are created when an interaction between a sending and receiving system generates flows and effects that spill over to other locations. However, the classification of systems as sending, receiving, or spillover systems depend on their function as well as the research question or the analytical perspective of the researcher [12].

The notion of spillover systems is related to widely used concepts (Table 1) such as spatial externalities [13,14], off-site impacts [15], displacements [16], leakages and indirect land use changes [17,18]. However, the concept of spillover systems is more comprehensive than these related concepts which focus on effects. Spillover systems in this paper are explicitly associated with telecoupling causes, sending and receiving systems, flows, agents, and effects [6••]. The concept also goes beyond disciplinary fields, explicitly incorporating both socioeconomic and environmental linkages with sending and/or receiving systems.

Recent studies have brought increasing attention to spillover systems, including spillover effects (e.g. [19•,20,21•,22–25,26•,27,28]). However, the diffuse and elusive nature of spillover systems makes them inherently difficult to detect, study, and govern [6••]. This is in part because they are largely hidden from the main interactions between sending and receiving systems [29]. For example, in international trade, attention is focused on trade partners, while other parties are often overlooked. Identifying and understanding spillover systems is a new, important frontier in sustainability research, and the telecoupling framework helps facilitate analysis of issues beyond primary interactions [12,30]. Minimizing negative effects and amplifying positive effects of telecoupling on spillover systems is essential for achieving global sustainability goals, targets, and agreements. It urgently requires integrative research across disciplinary boundaries and a portfolio of methods to address the challenges involved with spillover systems, now and in the future.

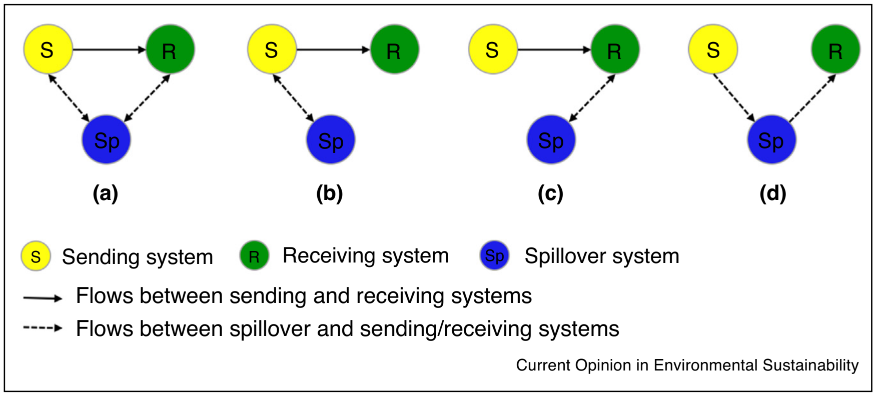
To advance spillover system research and governance, we aim to: Firstly, develop a typology of spillover systems with illustrative examples; secondly, highlight methods for investigating spillover systems; and finally, discuss spillover system governance goal and principles.

Table 1

Concepts related to spillover systems

Concept	Definition	Examples
Displacement	A decrease in demand or supply of a good or service leads to the increase in demand or supply elsewhere [89]. Displacement can furthermore describe how demand for high value products or crops can push uses of other, more extensive resources, onto more marginal lands [17]	The forest regrowth in Vietnam is contributed largely by the displacement of its domestic wood demand to other tropical countries [89]
Leakage	An action or a policy that aims to reduce the undesirable effects in a target place but leads to the occurrence of such effects elsewhere [89,90]	Conservation efforts to protect Amazon forests lead to more deforestation and disturbances in surrounding unprotected native vegetation [91]
Indirect land use	Unintended land use change caused by the intended (also called direct) land use change elsewhere [92]	Brazil's government planned a large increase in biofuel production, which led to the replacement of pastureland by crops for biofuel production, but unintendedly pushed cattle ranching into the Amazon biome [93]
Off-site impact	Biophysical impacts happen outside of the land use change unit [15]	Fertilizers and livestock on pastoral farms affect the soil biogeochemistry of adjacent forests [94]
Spatial externality	Economic or other activities in one area have effects on other spaces [14]	Land parcels that were certified organic in California Central Valley were affected by surrounding non-organic land uses [58]

Figure 1



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Four possible ways of connections between spillover and sending/receiving systems: **(a)** spillover system is connected with both sending and receiving systems; **(b)** spillover system is only connected with sending system; **(c)** spillover system is only connected with receiving system; **(d)** spillover system is connected to sending and receiving systems by being an intermediate stopover or pathway between the two systems.

Typology of spillover systems

To disentangle the complexity of spillover systems, we develop a typology of spillover systems according to six criteria: flows from and to sending and receiving systems, distances between sending/receiving systems and spillover systems, types of effects on spillover systems, sizes of spillover systems, roles of agents in spillover systems, and origins of spillover systems.

Spillover systems based on flow directions

There are four distinct ways that spillover systems connect to sending and receiving systems through various flows (Figure 1 and Table 2): (1) Sending/receiving-linked spillover systems are connected with both sending and receiving systems (Figure 1a). For example, in the global food trade system, many countries (e.g. Canada) can be viewed as spillover systems because they are affected by or affect soybean exports from Brazil (sending system) to China (receiving system, the largest soybean importing country in the world) [31••] (Figure 2). (2) Sending-linked spillover systems are only connected with sending systems (Figure 1b). In the case of China's South–North Water Transfer Project, a large quantity of water is transferred from the water source (Yangtze River in south China, sending system) to the water transfer destinations (e.g. Beijing in north China, receiving system). Connected to the sending system but not directly connected with the receiving system, the Yangtze Delta has become a spillover system and is suffering from increasing seawater encroachment due to the reduction of water from the sending system of the transfer project [32]. (3) Receiving-linked spillover systems are only connected with receiving systems (Figure 1c). For example, in the international panda loans program, zoos outside China (receiving systems) borrow giant pandas from Wolong Nature Reserve in southwestern China (sending system) [33•]. In this case, spillover systems connected with the receiving systems would include areas that grow bamboo to feed the pandas in those zoos and the areas from which people travel to see the pandas. (4) Stopover spillover systems are connected with sending and receiving systems by being an intermediate stopover or point in the pathway between the sending and receiving systems (Figure 1d). For example, during migration following the breeding season, Kirtland's warblers travel long distances from the sending systems (breeding sites in Michigan) to receiving systems (wintering grounds in the Bahamas), and make stops in between to rest and feed. Those stopover sites or staging sites are spillover systems of this migration, which has both ecological and socioeconomic implications [3].

Distant versus adjacent spillover systems

Distances between spillover systems and associated sending and receiving systems can be geographical, environmental, ecological, institutional, or social [6••,10,30,34]. That is, spillover systems and sending and/or receiving systems can be separated across geographical space (e.g. measured in kilometers) [4], or separated by institutional ties such as food and energy sectors governed by different institutional arrangements [34]. Spillover systems can also be separated socially where their agents can be physically close, yet socially distant from the sending and receiving systems [4].

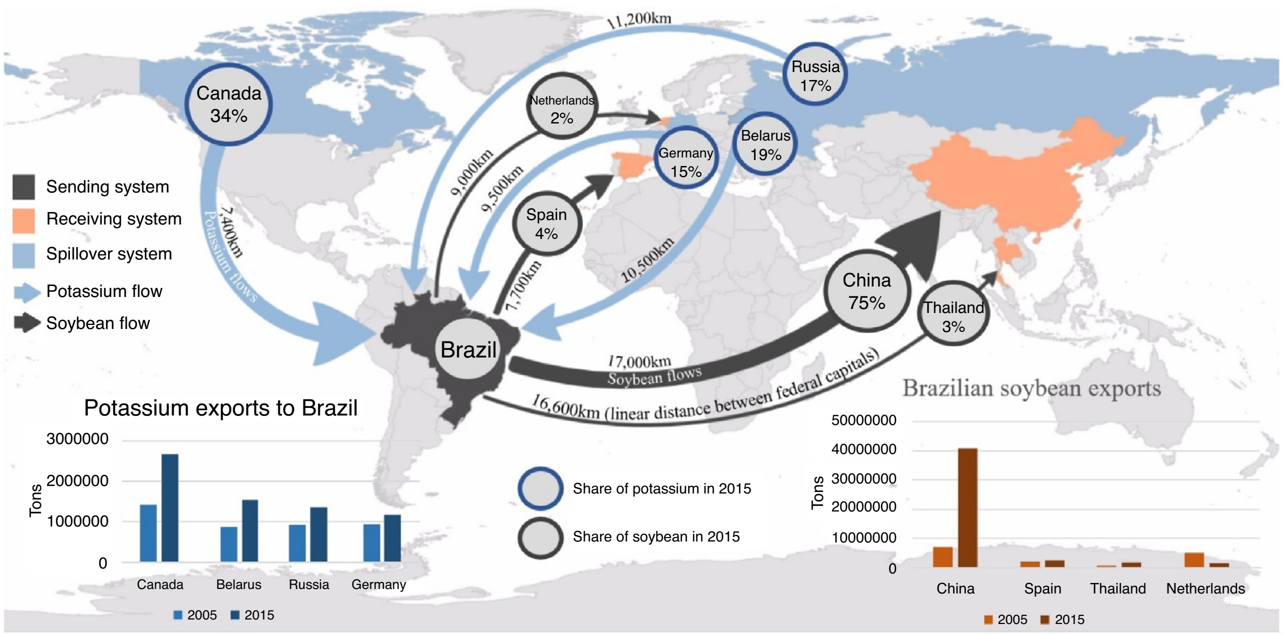
We exemplify distant versus adjacent spillover systems over geographic distances (Table 2). Spatially distant spillover systems are located far from sending and receiving systems, whereas adjacent spillover systems are nearby. In the example of soybean trade between Brazil and China [35], countries such as Canada that export fertilizers to Brazil, which produces soybeans for China, are distant (e.g. ~7,400 km between the capitals of Canada and Brazil and ~17 000 km between the capitals

Table 2

Typology of spillover systems

Criterion	Type of spillover systems	Examples	Methods for investigating spillover systems
Flows to and from sending and receiving systems	Sending/receiving-linked: Flows to and from both sending and receiving systems	Countries (e.g. those in Africa) engaging in soybean trade with Brazil and China [31••]	Statistical analysis of data on trade and other issues
	Sending-linked: Flows to and from sending systems only	Yangtze Delta with increased seawater encroachment due to the South-North Water Transfer Project [32]	Relevant measurements (e.g. water, sediments)
	Receiving-linked: flows to and from receiving systems only	Areas supplying bamboo to zoos and areas from which people travel to see the pandas in zoos that have pandas from Wolong [33•]	Interviews with visitors and news media reports
	Stopover	Stopover for Kirtland's warblers (between USA and Bahamas) [3].	Field work observations and the use of GPS tracking devices
Distance between sending/receiving and spillover systems	Distant	Canada and other countries that provide fertilizers to Brazil for soybean production intended for consumption in China (Figure 2)	Statistical analysis on international trade of fertilizers
	Adjacent	Fields and farmers in close proximity to newly irrigated areas may indirectly benefit from international development projects [36]	Interviews with farmers, focus groups with irrigators' association, analysis of field clustering using remote sensing and Geographic Information Systems, and join-count statistics
Effect	Positive	Holland received more than US $100 000 annually for providing bamboo to feed the pandas in Edinburgh Zoo from Wolong [45,46]	Interview with zoo keepers of Edinburg and bamboo growers in the Netherlands
	Negative	Northern Ohio and southern Michigan lost their drinking water supply due to zebra mussels spread through shipping [41,95]	Interviews with local residents and news media reports; Monitoring drinking water, nutrient loading, hydrology, and food web changes
Size	Large	Global increase in atmospheric CO_2 concentration due to air transport of a pair of pandas from Wolong to Edinburgh [33•]	Calculation of relationships between CO_2 emissions (measurements) and traveling methods (interviews or news reports) and distances (measurements)
	Small	New market outlets for rural villages located near the East-West Economic Corridor between Vietnam and Thailand due to nearby development with foreign aid investment [48]	Interviews with villagers and local government officials
Role of agents in spillover systems	Active	South Africa that facilitates investment from land-title-receiving countries to land-title-sending countries [24]	Interviews with relevant stakeholders
	Passive	Global increase in atmospheric CO_2 concentrations due to transportation emissions of flying and driving tourists [49]	Calculation of relationships between CO_2 emissions (measurements) and traveling methods (interviews or news reports) and distances (measurements)
Origin of spillover systems	Sending-converted: Sending systems become spillover systems	United States, a traditional top soybean sending system to China, has recently become a spillover system because of competition from Brazil [35,50•]	Statistical analysis
	Receiving-converted: Receiving systems become spillover systems	Shanghai, a megacity and a receiving system for goods, has become a spillover system because it has the world's largest container shipping port since 2008 [51]	Statistical analysis
	New spillover systems: Spillover systems that were not previously in the telecoupled systems	The invasion of fire ants from South America (sending system) to southern United States (receiving system) via shipping, and later to California (spillover system). Taiwan later became a new spillover system of fire ant invasion due to the shipping from California [5]	Molecular marker

Figure 2



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Flows of soybean from Brazil to importing countries and the spillover systems affected by the increased Brazilian demand for fertilizers. Data source, [96].

of Brazil and China, Figure 2). Adjacent spillover systems are just beyond the borders of the sending and/or receiving system. For example, globally funded development projects supporting the construction of irrigation canals and the development of new agricultural production systems in developing countries (e.g. in the Bolivian Andes) have inadvertently impacted adjacent farmers and fields through channel overflow and the adoption of the new production systems among local farmers [4,36].

Spillover systems with positive versus negative effects

Effects of telecoupling on spillover systems can be valued as either positive or negative outcomes. Distinguishing these effects depends on who experience them, research questions and perspectives, and the assumptions, values, and goals of researchers. For example, many spillover effects on the environment are negative, such as emissions of greenhouse gases [31••], pollution [37], biodiversity loss [2], deforestation [38], and socio-economic loss [39]. A specific example of a negative spillover effect is the invasion of zebra mussels (*Dreissena polymorpha*) from the Black and Caspian Seas to the Great Lakes of the United States (USA) resulting from the 1980s grain trade between the American Midwest and the Soviet Union (Table 2). Oceangoing vessels transported zebra mussels from Soviet ports in their ballast water and discharged them into the Great Lakes on their return journeys. The zebra mussels now create water quality problems in the Great Lakes by selectively filtering the non-toxic algae that would naturally compete with toxic algae [40]. The concentration of toxic *Mycrocystis* and other blue-green algae led to a recent drinking water crisis in northern Ohio and southern Michigan where 400 000 people had water deemed undrinkable for several days [41].

Examples of positive spillover effects consist of education opportunities in visiting zoos that increase environmental awareness and promote environmental actions [33•], economic benefits from tourism-related industries that manufacture and sell goods (e.g. outdoor gear) and services [42], carbon sequestration from increased biomass through conservation investments [33•], increased fish stock and catch in unprotected regions surrounding marine protected areas [43], conservation of the biodiversity (e.g. fruits and crop seeds) for agriculture [36], and incentives of desired outcomes including reduced production, input, or infrastructure costs in conversions to organic agriculture [4,14,44]. For example, a bamboo farm on the outskirts of Amsterdam, the Netherlands (a spillover system), received more than US$100 000 annually for providing organic bamboo shoots to feed the pandas in Edinburgh Zoo (receiving system) from Wolong Nature Reserve (sending system) [45,46].

Large versus small spillover systems

Spillover systems can vary drastically in size, whether considered as the geographic area covered or the number of people affected. For example, the transport of goods between two distant countries or regions generates greenhouse gas emissions that impact the rest of the world as a spillover system through climate change effects [47]. Even transporting a pair of pandas from the sending system (Wolong Nature Reserve) to Edinburgh, Scotland, via a Boeing 777 could emit 232 000 kg of CO_2 one way alone [33•]. In contrast, some spillover systems are small, such as rural villages in Bolivia [36], Laos [11•], and the East-West Economic Corridor between Vietnam and Thailand [48]. Regarding the East-West Economic Corridor in Southeast Asia [48], for example, the establishment of an economic corridor (major cities on the corridor are receiving systems) by domestic governments, foreign aid and overseas investment (as sending systems that send and facilitate investment) spurred growth and specifically, the construction of cassava processing facilities. Farmers in nearby villages (spillover systems) have also increased cassava cultivation, further catalyzed by the improved transportation infrastructure [48].

Active versus passive spillover systems

Spillover systems can also be classified as active or passive based on the role of various agents in relation to the main flows in a given telecoupled system. Agents in spillover systems can be active or passive participants in telecouplings. The role of active agents is exemplified in spillover systems that are generated in relation to international land transfers or land grabbing. For example, some agents in the spillover systems actively facilitate land transfers by providing information and introducing agents in the sending and receiving systems, that is, land demanding and land supplying countries [24]. In contrast, greenhouse gas emissions and oil spills often create passive spillover systems, where agents in these spillover systems do not generate these processes. For instance, the spillover system arising from CO_2 emissions by tourists traveling between sending and receiving systems is passive. CO_2 emissions by a tourist flying in economy class from Detroit, USA, to Chengdu, China, via Beijing would produce approximately 1 705 kg of CO_2 and the rest of the Earth system, including Beijing, is affected passively [49]. Active and passive spillover systems may coexist in the same telecoupling. In the above case, for example, Beijing is also an active spillover system whose agents provide services to tourists [33•].

Origin-based spillover systems

Spillover systems may have different origins. They can transform from sending or receiving systems of the same telecoupled system, or emerge from systems of a different telecoupling.

Spillover systems can be former sending systems (i.e. sending-converted). For instance, the USA was the largest sending system of soybeans to China between 1995 and 2012 (not including 2011, see [35]), but has been overtaken by Brazil since 2013 [35]. Thus, although the USA is still a major soybean sending system to China, it is now also a spillover system experiencing the negative effects of a declining global market share of soybean exports to China due to the competition from Brazil [50•].

Receiving systems can also transition to spillover systems (i.e. receiving-converted). The ancient city of Shanghai, for instance, has recently become the world's largest container shipping port [51]. Thus, Shanghai was and still is a receiving system for goods, but it is also a spillover (stopover) system for other international trade.

Systems that were not previously in the telecoupled system can transform into spillover systems (i.e. new spillover systems). Invasion of fire ants (*Solenopsis invicta*) is a good example. Fire ants were inadvertently introduced into the southern USA (receiving system) from South America (sending system) via sea shipping early in the last century and, more recently, introduced into California (spillover system) from southern USA [5]. Fire ants were then introduced into southern Taiwan from California [5]. In this case, Taiwan that was not invaded by fire ants and not part of the telecoupled system is a new spillover system because the flow was redirected by the shipping from California.

Systems can have multiple typologies and roles

It is important to note that these classifications may overlap. For example, a small spillover system may have positive or negative effects, and may be far away or adjacent to a sending system or receiving system. Furthermore, a system may have multiple roles, for example, a spillover system may also be simultaneously a sending or receiving system in different telecouplings such as the above-mentioned Shanghai as receiving and spillover systems simultaneously [51].

Methods for investigating spillover systems

Similar to investigating sending and receiving systems, research on spillover systems and the range of processes that create them requires a portfolio approach with integrative research that draws on qualitative, quantitative, and mixed methods (Table 2). These methods range from molecular markers and global positioning systems (GPS) to remote sensing, from interviews to archival research, from first-hand measurements to secondary data analysis, from field observations to computer simulations, and from qualitative to quantitative analysis such as modelling and spatial statistics using Geographic Information Systems (GIS) (Table 2). This range of methods is characteristic of research on spillover systems while the same methods can also be used in research on sending and receiving systems.

Qualitative methods

Many qualitative methods are useful for identifying spillover systems (Table 2). Ethnographic fieldwork and qualitative inquiry, for example, can enable the analysis of important political, cultural and environmental interactions through the experiences and narratives of the agents involved. Such methods are especially useful to capture spillover systems and non-material flows (such as the movement of information and ideas) due to their open-ended nature. For example, Friis and Nielsen [11•] used in-depth interviews with stakeholders involved in the expansion of banana plantations in northern Laos to qualitatively analyze the multiple telecouplings that link banana land systems to other land systems, near and far. By progressively contextualizing how and why the banana plantation expansion took place, detailed ethnographic data illustrated how the banana land system was not only a receiving system of major capital and migrant labor inflows, but also a spillover system of an important political conflict between China and the Philippines, affecting the banana trade and the wider relationships between those countries [30,52]. Further contextualization and triangulation of primary qualitative data with local and international news reports, archival material, secondary literature and grey sources can also provide valuable means for detecting spillover systems. In the Lao banana case, local and international media reports pointed to the existence of a spillover system in banana producing regions of China, where catastrophic typhoon events had destroyed banana plantations, thereby increasing the demand for bananas from Laos [11•].

Focus-group and community interviews are also valuable for distinguishing spillover systems and the mechanisms through which they occur. In the case of biodiversity conservation of maize in South America, Zimmerer and collaborators used interviews with farmers to identify and evaluate spillover systems and the key mechanisms involved, including the coordination of irrigation and production systems among small-size fields [4,36,53]. Furthermore, the researchers employed the triangulation technique that adds an important methodological cross-check of information. The triangulation technique incorporated focus-group interviews with the multi-member irrigators' association where diverse views and experiences were discussed and analyzed.

Quantitative methods

Investigating spillover systems also benefits from many quantitative methods (Table 2), including mathematical and statistical, network, simulation and scenario analyses. Recently, many market and trade-related telecouplings involving economic and material flows have been analyzed using land footprint accounting and input-output models (e.g. [54,55•,56,57]). In the case of land use, econometric modelling can be used for distinguishing and characterizing spillover systems [14,44,58]. Remote sensing analysis, spatial statistics, and Geographic Information Systems can also be highly useful for describing spatial patterns and processes [50•,59,60]. Indeed they are essential to estimate adjacent spillover systems, especially when combined with methods such as join-count statistics [44]. Statistical regression modelling can be used with empirical data to explore relationships between flows, causes and effects in spillover systems. For example, Dou *et al.* [61] estimated the contribution from flows and other factors (e.g. population, available land resource) to the deforestation rate in the Brazilian Cerrado biome as a spillover system. Advances in network analysis [62] enable consideration of both sending and receiving systems, as well as spillover systems simultaneously.

Combining and synthesizing quantitative methods to examine scenarios of change will be particularly important for understanding spillover effects and options for future sustainability. Computer simulation models that combine quantitative data and findings from approaches such as regression, artificial intelligence, or network analysis are particularly well-suited to investigate and predict changes in spillover systems through time, because they can simulate temporal dynamics and 'emergent' phenomena that arise through interactions among system components. Although simulation models that allow dynamic representation of global systems have existed for many decades (e.g. [63,64]), it is only with recent conceptual and computing advances that the first hybrid models that integrate multiple approaches have emerged. For example, Millington *et al.* [65•] describe the hybrid structure of a telecoupling simulation model to investigate long-term dynamics of local land use and global food trade for various socioeconomic, policy, and environmental scenarios. Dou *et al.* [61] used their Brazil telecoupling regression model with a scenario in which the Brazilian Soy Moratorium was absent in the Amazon biome to estimate the deforestation rate in the Cerrado biome spillover system.

Mixed methods

Mixed methods, which employ various combinations of quantitative and qualitative methods (including but not limited to those presented above), are often needed for detecting and analyzing spillover systems and tracking their occurrence over time and across space. They can harness the strengths of multiple complementary methods and ways of understanding the world [66,67], and can provide pragmatic approaches (sensible and realistic ways based on practical instead of theoretical considerations) to complex and multi-faceted research problems [68]. Applications of mixed methods may be achieved by employing complementary approaches in sequence, wherein the insights gained via one method build on prior findings of other methods, or by employing a number of methods in parallel for the triangulation or corroboration of results and increased analytical rigor in a single study. Different combinations of methods may be applied to data collection, analysis, inference, and interpretation to obtain new insights.

A number of spillover system studies have already used mixed methods. For instance, Leisz *et al.* [48] identified rural villages on both sides of the border between Vietnam and Thailand as spillover systems from the investment in economic activity of the East-West Economic Corridor, through spatial analysis of remote sensing data and data from interviews with government officials, university staff acting as non-formal educators and community facilitators (hereafter called extension agents), and village members. Mapping and visualization techniques are also effective mixed-methods approaches for revealing patterns of spillover systems [26•]. For example, Figure 2 demonstrates the power of maps and graphs to illustrate soybean flows from Brazil and the spillover systems arising due to Brazilian demand for fertilizer. Similarly, Xiong *et al.* [57] used chord diagrams and other visualizations to examine flows and spillover systems with embedded greenhouse gas emissions in the global metal trade.

Governance of spillover systems

It is important to integrate spillover systems into telecoupling governance in a holistic manner. Telecouplings pose important new challenges for sustainability governance [34,69,70•]. They transcend traditional territories and jurisdictional levels, implicate diverse agents across the public-private spectrum, and connect multiple production and consumption sectors. Some particular telecouplings have attracted the attention of regulatory authorities, NGOs, and other civil society groups due to pressure to address negative social and environmental impacts — for example, along supply chains and in global sourcing networks. The literatures on supply chain management [71], global value chain governance [72], and multi-stakeholder standards [73] detail many examples of attempts to govern social and environmental impacts across diverse sectors. The success of such governance arrangements remains the subject of considerable debate [74]. As spillover systems and related socioeconomic and environmental effects are widely dispersed, efforts to govern telecouplings for sustainability must take account of spillover systems.

Spillover systems are particularly challenging for governance as they rarely appear on the agendas of individual states or multilateral governing authorities and regimes, or even hybrid governing entities such as multi-stakeholder platforms and ‘roundtables’. While network governance and supply chain governance have achieved some success through various public-private and hybrid governance arrangements (e.g. codes, standards, voluntary labels, and private rules), they may miss spillover systems. In order for governance to account for impacts in spillover systems and other parts of the telecoupled systems as a whole, these impacts must become apparent. Furthermore, given the complex interconnectivity and non-linear cascading effects that give rise to spillover systems, it is likely that efforts to govern for sustainability in one place affect sustainability in other places. In this way, governance interventions — whether in the form of policy programs or other governing efforts — may themselves produce new dependencies and have ripple effects.

To effectively govern telecouplings with special attention to spillover systems, we propose an overall goal and three general principles. The overall goal is to minimize and avoid negative effects, while maximizing positive effects of telecoupled system interactions. The general principles are fairness, responsibility, and capability. First, fairness means that negative effects should be compensated for [6••] and positive effects should be shared. How to determine ways and amounts of compensation may draw experiences in payments for economic damage [75], ecosystem services [76–78], environmental pollution [79–81], as well as carbon offsets in some travel-related activities [82]. Second, responsibility refers to the duty that various agents have in relation to specific spillover effects. If agents in spillover systems do not participate in generating the effects, agents in sending and/or receiving systems should be accountable for the effects. Third, capability refers to the relevant agents’ ability to cover the cost of negative effects or reap the benefits of positive effects.

To achieve the overall goal and follow the general principles outlined above, it is important to incorporate information on spillover systems into decision making. For example, trade agreements should incorporate spillover systems by going beyond trade partners. In addition to traditional place-based governance approaches (central focus on place), it is important to take a flow-based approach, which considers a place in light of its relationships with other places, by tracking and managing where key flows start, progress, and end [3,83]. Flow-based governance can also be directly targeted at the flows themselves, for example, aimed at managing the value chains of products, through certification schemes, or the flow of money by taxation, etc.

For different types of spillover systems (Table 2), governance approaches should vary accordingly. The governance responses may include market mechanisms, regulations, regional, bilateral and international agreements. While further research is required to identify feasible and effective governance options for the various types of spillover systems, it is clear that governance responses will need to be tailored to specific systems. For instance, for negative spillover effects, responsible parties should offset the cost. On the other hand, relevant parties should share the positive spillover effects. Small and large spillover systems will require small to large degrees of cross-jurisdictional and multi-level governance. Governing adjacent spillover systems might draw upon successful experiences in working with neighbors. To revise the existing or develop new governance mechanisms for specific spillover systems, it would be most effective and efficient to engage relevant stakeholders (e.g. citizens and policy makers) across local to global levels.

To make stakeholders aware of spillover systems and to implement flow-based approaches to governance, extension programs can help stakeholders such as the World Trade Organization (WTO) and relevant government agencies frame issues within a telecoupled context. In the USA, for example, agricultural extension professionals are part of a nation-wide, non-credit education network created by the Smith-Lever Act in 1914 [84]. A parallel extension network focuses on marine, coastal and Great Lakes issues through the Sea Grant network created by the National Sea Grant College Program Act in 1966 [85]. Extension agents provide research-based information to farmers, fishermen, and other stakeholders and work to identify and address current issues and problems through public policy education, facilitation, and applied research [84,86,87]. As such, extension agents exemplify the importance of mediating agents that serve as bridges bringing together various other agents with skills to facilitate the co-design, co-production, and co-implementation of research projects on spillover systems. Mediating agents can also serve as honest brokers [88] of policy alternatives directed at telecoupled systems at the local to regional levels. It would be valuable to scale this approach to the global level, including extension efforts across the United Nations system.

Concluding remarks

Recent studies indicate that spillover systems are widespread and are a key piece of the sustainability puzzle in a telecoupled world. To untangle the complexity of spillover systems, we make a first attempt to classify them into different types based on six criteria. Even though spillover systems are often overlooked, a variety of methods have proved to be effective in uncovering them. Spillover systems have profound implications for the Sustainable Development Goals and for many other global challenges. Governing spillover systems should follow three general principles (fairness, responsibility, and capability) toward the overall goal of minimizing negative and maximizing positive spillover effects. To achieve global sustainability in the Anthropocene, spillover systems 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.

Conflict of interest

None.

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